From Forest Nursery Notes, Summer 2011

177. Rolled rye mulch for weed suppression in organic no-tillage soybeans. Smith, A. N., Reberg-Horton, S. C., Place, G. T., and Meijer, A. D. Weed Science 59:224-231. 2011.

Rolled Rye Mulch for Weed Suppression in Organic No-Tillage Soybeans

Author(s): Adam N. Smith, S. Chris Reberg-Horton, George T. Place, Alan D. Meijer, Consuelo Arellano, and J. Paul Mueller

Source: Weed Science, 59(2):224-231. 2011.
Published By: Weed Science Society of America
DOI: 10.1614/WS-D-10-00112.1
URL: http://www.bioone.org/doi/full/10.1614/WS-D-10-00112.1

Weed Science 2011 59:224–231

Rolled Rye Mulch for Weed Suppression in Organic No-Tillage Soybeans

Adam N. Smith, S. Chris Reberg-Horton, George T. Place, Alan D. Meijer, Consuelo Arellano, and J. Paul Mueller*

Rising demand for organic soybeans and high price premiums for organic products have stimulated producer interest in organic soybean production. However, organic soybean producers and those making the transition to organic production cite weed management as their main limitation. Current weed management practices heavily rely on cultivation. Repeated cultivation is expensive and has negative consequences on soil health. Research is needed to improve organic reduced tillage production. Rye cover crop mulches were evaluated for weed suppression abilities and effects on soybean yield. Experiments were planted in 2008 and 2009 at three sites. Rye was planted in the fall of each year and killed at soybean planting with a roller/crimper or flail mower, creating a thick weed-suppressing mulch with potential allelopathic properties. The mulch was augmented with one of three additional weed control tactics: preemergence (PRE) corn gluten meal (CGM), postemergence (POST) clove oil, or postemergence high-residue cultivation. Roll-crimped and flail-mowed treatments had similar weed suppression abilities at most sites. There were no differences between CGM, clove oil, or cultivation at most sites. Sites with rye biomass above 9,000 kg ha^{-1} of dry matter provided weed control that precluded soybean yield loss from competition. In Goldsboro 2008, where rye biomass was 10,854 kg ha^{-1} of dry matter, the soybean yield in the rolled rye treatment was not significantly different from the weed-free treatment, yielding at 2,190 and 2,143 kg ha^{-1}, respectively. Likewise, no difference in soybean yield was found in Plymouth 2008 with a rye biomass of 9,256 kg ha^{-1} and yields of 2,694 kg ha^{-1} and 2,809 kg ha^{-1} in the rolled rye and weed-free treatments, respectively. At low rye biomass levels (4,450 to 6,606 kg ha^{-1}), the rolled rye treatment soybean yield was 628 to 822 kg ha^{-1} less than the weed-free treatment. High rye biomass levels are critical to the success of this production system. However, high rye biomass was, in some cases, also correlated with soybean lodging severe enough to cause concern with this system.

Nomenclature: Clove oil; corn gluten meal; soybean, *Glycine max* (L.) Merr.; rye, *Secale cereale* L.

Key words: Cover crop mulch, weed suppression, roller/crimper, organic herbicides.

The sale of organic products has increased from one billion dollars in 1990 to 20 billion dollars in 2007, making the organic food sector one of the fastest-growing markets in the country. In 2006, sales grew 20.9% (OTA 2008). In North Carolina, organic sales follow similar trends. In 1997, North Carolina had 397 ha (980 acres) in organic production (Wossink and Kuminoff 2002). In 2007, there were 383 organic farms in North Carolina farming 1,223 ha (3,021 acres). In addition, 3,146 hectares (7,775 acres) were in the process of being converted to organic production (NC Ag Census 2007). Organic soybean demand for the mid-Atlantic region is not being met and the majority of organic soybeans are being imported from other states (Braswell Milling, personal communication). Conventional soybean prices for 2009 were approximately $10.40 per bushel (USDA 2009a), whereas feed grade organic soybeans were priced at $18.65 per bushel (USDA 2009b).

Organic producers and those currently making the transition to organic soybean production cite weed management as their most difficult challenge (Walz 1999). A 19% yield reduction (when compared to a chisel-till/herbicide program) has been reported for organic soybeans, with the majority of that reduction likely due to weed pressure (Cavigelli et al. 2008). Most soybean producers rely on herbicide and transgenic crop technology as their primary tools in weed management programs, both of which are prohibited by USDA organic standards (NOP 2002). Without synthetic herbicides, organic producers must rely on multiple tactics to suppress weeds effectively (Liebman and Gallandt 1997). Although organic producers have a variety of weed management tactics available (crop rotations, cover crops, flaming, biocontrol, weed seed predation, allelopathy, smother crops, competition, organic herbicides, and primary and secondary cultivation), frequent cultivation is the core of most organic weed control programs. Intensive cultivation has negative consequences on soil health such as soil erosion (Beale et al. 1955), soil compaction (Raper et al. 2000), decreased soil residue cover (Hargrove 1990), and increased CO_2 release into the atmosphere (Paustian et al. 1998). Intensive cultivation also increases labor and equipment costs (Weersink et al. 1992) and fossil fuel consumption (Hargrove 1990). Conservation tillage agriculture has the potential to alleviate some of the negative consequences of cultivation (Arshad et al. 1990; Six et al. 1999).

Rye is a widely used cover crop known for its high biomass levels and allelopathic potential (Barnes and Putnam 1987; Weston 1990). In no-till systems, the rye is killed by chemical or mechanical means to create a mulch. The mulches can inhibit weed growth by providing a physical barrier to weeds (Teasdale and Mohler 2000), intercepting light before it reaches weeds (Teasdale and Mohler 1993), and by releasing allelochemicals (Barnes and Putnam 1987). The level of weed suppression depends on the amount of rye mulch, with an exponential relationship between mulch mass and weed emergence (Teasdale and Mohler 2000). Sufficient weed control can be provided for 4 to 16 wk into the season (Mohler and Teasdale 1993; Weston 1996).

Much of the previous research on rye mulches utilized herbicides or mowing to kill the rye (Creamer et al. 1995; Weston 1990). Mowed mulches show an increased rate of decomposition when compared to rolled mulches (Creamer et al. 1995; Lu et al. 2000), thus reducing the amount of time the residue persists on the soil surface. A recent technology, the roller/crimper,[1] terminates rye by rolling it down into a

DOI: 10.1614/WS-D-10-00112.1

* First, second, third, and sixth authors: Graduate Research Assistant, Assistant Professor, Research Associate, and Professor, Department of Crop Science, North Carolina State University, Raleigh, NC 27695; fourth author: Extension Associate, North Carolina State University Department of Soil Science, Vernon G. James Research and Extension Center, Plymouth, NC 27962; fifth author: Assistant Professor, Department of Statistics, North Carolina State University, Raleigh, NC 27695. Corresponding author's Email: chris_reberg-horton@ncsu.edu

Table 1. Dates for rye and soybean planting and other weed management activities.

Year/Location	Planting		Rye kill[a]	CGM[b]	Clove oil	Cultivation
	Rye	Soybeans				
2007/2008						
Goldsboro	November 9	May 14	May 14	May 14	June 23	—
Kinston	November 2	May 26	May 26	May 26	June 17	July 8
Plymouth	November 5	June 18[c]	May 23	June 18[c]	July 21	—
2008/2009						
Goldsboro	November14	June 3	June 3	June 3	July 10	July 10
Kinston	October 16	May 27	May 27	May 27	July 9	July 9
Plymouth	October 21	May 28	May 28	May 28	July 14	July 14

[a] Rye kill dates denote when rye was either flail-mowed or rolled. Clove oil was applied when soybeans were at V3/V4 growth stages.
[b] Abbreviation: CGM, corn gluten meal.
[c] Soybeans replanted at this later date due to complete failure of the first planting.

mat and crimping the stems without breaking them (Davis 2010; Mirsky et al. 2009). This allows the rye to persist longer on the soil surface by slowing down decomposition rates when compared to mowing (Creamer and Dabney 2002).

The roller-crimper consists of a hollow drum (with the option of being filled with water) and blunted blades meant to maximize force against the cover crop without cutting the stems (Rodale Institute 2009). Recent innovations in design have reduced vibrations and improved comfort for tractor operators (Kornecki et al. 2009). Rolling implements require substantially less energy than a flail mower (Hunt 1977).

Although rye mulch has been shown to provide a certain level of weed control, additional weed management measures sometimes are needed (Yenish et al. 1996). Organic herbicides can provide additional weed control. Several of the organic herbicides are based on essential plant oils, which are allowed in organic systems due to their low environmental persistence and natural origin (Tworkoski 2002). The phytotoxicity of clove oil[2] via disruption of cell membranes has been demonstrated with many weed species (Bainard et al. 2006; Tworkoski 2002). Tworkoski (2002) also concluded that essential plant oils cause injury by increasing membrane permeability, leading to increased electrolyte leakage.

Clove oil acts as a nonselective contact herbicide; it can be applied postemergence using a directed spray. Previous research has shown that at 10 to 40% concentrations, clove oil can provide significant weed control (Boyd and Brennan 2006). Burning nettle (*Urtica urens* L.) was reduced 90% with 12 to 61 L clove oil ha^{-1}, and common purslane (*Portulaca oleracea* L.) was reduced 90% with 21 to 38 L clove oil ha^{-1} (Boyd and Brennan 2006). Other research has reported a 10% concentration to provide inconsistent weed control, ranging from 10 to 40% control (Ferguson 2004). Tworkoski (2002) found 100% injury ratings for johnsongrass [*Sorghum halepense* (L.) Pers.], common lambsquarters (*Chenopodium album* L.), and common ragweed (*Ambrosia artemisiifolia* L.) at clove oil concentrations of 5 and 10%. Another weed control option available for organic use as a preemergent is corn gluten meal.[3] Corn gluten meal has been found to decrease plant survival, shoot length, and root development in 22 weed species (Bingaman and Christians 1995). This option is effective, particularly in turf where 95% control of crabgrass (*Digitaria* spp.) is possible at a rate of 582 g m^{-2} (Christians 1993).

The potential advantages of the rolled rye system for organic soybean production have led to a recent proliferation in rolled rye research. Results so far are inconclusive, with organically comparable weed control provided in some regions (Davis 2010) and insufficient control in others (Reeves et al. 2005). No results have been published previously from the southeastern United States where climatic conditions favor a much more robust rye cover crop (Snapp et al. 2005), but also provide an environment where rye mulch decomposition rates are expected to be faster. Weed management also can be an even greater concern due to the longer growing season, compared to more northern locations where the use of this system has been more prevalent (Rodale Institute 2009). The objective of this study was to examine how the rolled rye–organic soybean system would perform in the southeastern United States in terms of weed control and soybean yield. We also investigated whether auxiliary weed control was needed in the system, either with high-residue cultivators or organically approved herbicides. Finally, we tested whether the roller/crimper provided enough advantage over flail mowing to justify the investment in a new piece of equipment for producers.

Materials and Methods

Research was conducted in 2008 and 2009 at the Tidewater Research Station near Plymouth, NC, Caswell Research Farm near Kinston, NC, and the Center of Environmental Farming Systems near Goldsboro, NC. The soil type at Tidewater was Portsmouth fine sandy loam (Fine-loamy over sandy or sandy-skeletal, mixed, thermic, Typic Umbraquult). Kinston 2008 soil type was Pocalla loamy sand (Loamy, siliceous, subactive, thermic Arenic Plinthic Paleudults) and 2009 soil type was Johns loamy sand (Coarse-loamy, siliceous, semiactive, thermic Aeric Paleaquults). Goldsboro 2008 and 2009 soil type was Wickham loamy sand (Fine-loamy, mixed, semi-active, thermic Typic Hapludults) with a 0 to 2% and 2 to 6% slope, respectively. Plots were 15.2 m long and contained four rows spaced 76.2 cm apart. A rye ('Rymin') cover crop was established at all three locations in the fall (Table 1) of each year using a no-till drill with 14.0 cm spacing between rows at a rate of 134 kg ha^{-1}. Rye was planted perpendicular to proposed soybean planting and rye rolling-crimping patterns in order to maximize weed suppression and light interception by the rolled rye.

Prior to planting rye, all fields were disked and field cultivated to remove any existing vegetation. Rye received a 50 to 60 kg N ha^{-1} urea/ammonium nitrate (UAN) application in February to March to promote growth and tillering. Other than nitrogen applications, management practices were conducted in accordance with organic practices with the exception of weed-free check plots. The Goldsboro 2009 trial was conducted on land in transition to organic production; it received manure compost with a nitrogen equivalent of 56 kg N ha^{-1}.

The rye cover crop was terminated at early milk (Feekes growth stage 11) either with a roller/crimper or a flail mower. Soybeans ('Hutcheson'), maturity group V, were planted at 370,500 live seed ha^{-1} in rows spaced 76.2 cm with a Monosem no-till planter[4] in the same direction as the roller/crimper and flail mower patterns. Planting dates varied from May 14 to June 18 across sites and locations (Table 1). The Monosem was equipped with trash clearers, fluted discs, and an additional 45 kg of weight on each planter box to ensure penetration of the mulch. The rye was either augmented with PRE organic corn gluten meal herbicide, POST organic clove oil herbicide, high-residue between-row cultivation, or received no additional treatments. All organic weed control treatments were tested against weed-free and weedy check treatments. For weed-free and weedy check plots, rye was removed in late winter with a tractor-mounted rotary tiller. All check plots were tilled again at soybean planting with a rotary tiller and field cultivated. All weed-free checks (with the exception of Goldsboro 2009) were treated 3 wk after planting (WAP) with imazethapyr at 74.7g ai ha^{-1} and *S*-metolachlor at 1.91 kg ai ha^{-1} and were periodically hand-weeded as needed. The Goldsboro 2009 location was maintained weed-free by regular hand hoeing due to herbicide restrictions at the site.

Granular corn gluten meal was applied at soybean planting with a hand pushed drop spreader.[5] Openings in the spreader were taped closed so that corn gluten meal was applied in a 17.8 cm band over the soybean row at a rate of 907 kg ha^{-1}. Clove oil was applied 6 WAP as a directed under-canopy, in-row spray at a rate of 18.7 liters ai ha^{-1} (10% concentration). High-residue between-row cultivation was done 6 to 7 WAP using a Sukup cultivator[6] with sweep blades that spanned 55.9 cm.

Measurements taken were soybean stand counts, soybean height, rye biomass levels, rye biomass decomposition rates, weed control, and soybean yield. Soybean stand counts were taken on a 1-m row in each plot approximately 4 and 8 WAP at each site. Stand heights were taken on two randomly selected plants per plot approximately 4 WAP. Weed control was measured using both percent weed coverage and weed counts (count m^{-2}). For each plot, percent weed coverage was rated and weed counts were taken using weed counts of the two middle rows (20.9 m^2) for each plot. Coverage and count measurements were taken in July and August. Soybean yield was measured in October or November from 12.2 m of the two center rows in each plot using a small plot combine.

Rye biomass was cut from six 0.5-m^2 quadrats and fresh weights were taken at soybean planting. The collected rye biomass was dried at 60 C for 72 h to quantify percent moisture and to derive total rye biomass for each location. Rye biomass decomposition rates were measured by collecting litter bags filled with either rolled or flail-mowed rye at 2-wk intervals over the course of the season. Litter bags were made of 15.2 by 30.4 cm, 100 mesh aluminum screen, and filled either with flailed rye or rolled rye. Litter bags were prepared and dispersed at soybean planting. Fresh rye weight was measured for each litter bag prior to random positioning throughout plots with a matching type (flailed vs. rolled). Five litter bags were collected every 2 wk, dried at 60 C for 72 h, and weighed to determine percent moisture and percent dry matter loss for each litter bag. Use of litter bags has been criticized for not providing a realistic assessment of decomposition rates (Coleman et al. 2004). They can be effective, however, for comparing relative rates of decomposition among different mulch types.

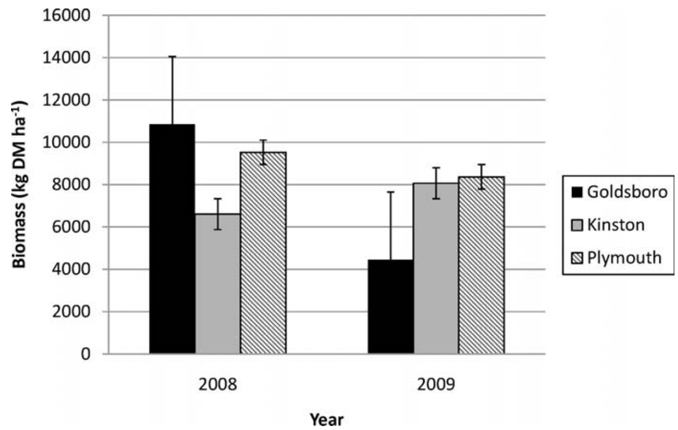

Figure 1. Mean rye biomass levels for each site location. Error bars represent ± 1 SE.

The experimental design was a randomized complete block design with six replicates. Treatments were arranged in a 2 by 4 factorial design, with two rye modes of kill and four auxiliary weed management treatments. Weed-free and weedy checks were added to make 10 treatments fully randomized within each block. A combined analysis was attempted on the six trials, but significant treatment by environment interactions prevented a pooled analysis. Each site was analyzed separately with mean separations generated with Fisher's Protected Least Significant Differences (LSD) and orthogonal contrasts. Within each site, treatments were fixed and blocks were random effects. Rye decomposition rates were determined using simple linear regression in Proc MIXED (SAS 2006).

Results and Discussion

Rye Biomass and Decomposition. Total rye biomass levels varied among locations and years (Figure 1). Goldsboro resulted in the largest difference between years with dry biomass totals of 10,854 kg ha^{-1} for 2008 and 4,450 kg ha^{-1} for 2009. Averages are consistent with other research. Ashford and Reeves (2003) averaged 9,725 kg dry rye biomass ha^{-1} in Alabama, and Yenish et al. (1996) averaged 5,140 and 4,540 kg ha^{-1} in North Carolina. Masiunas et al. (1995) ranged from 3,200 kg ha^{-1} to 11,500 kg ha^{-1}, but averaged (over location and year) at approximately 6,763 kg ha^{-1} in Kentucky, Illinois, and Indiana. In 2009, the rye cover crop received less rain, which might have reduced rye growth. Moreover, the differences seen between Goldsboro 2008 and 2009 likely were compounded by a soil compaction issue on the field used in 2009.

Differences in decomposition rates between roll crimped and flail-mowed rye were not detected (Figure 2). Both mulch types lost approximately 40% of the original biomass over the course of the season to decomposition. Flail-mowed legumes have high decomposition rates with major losses of mowed

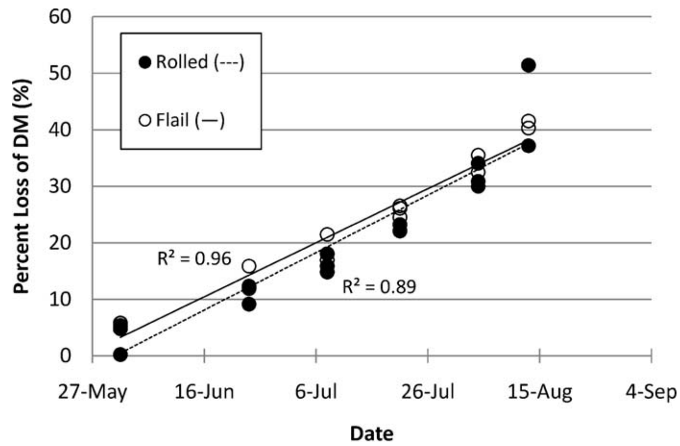

Figure 2. Rye decomposition rates for flail-mowed and rolled rye, Plymouth, NC, 2009.

mulches over the course of the season (Creamer and Dabney 2002; Masiunas et al. 1995; Teasdale and Mohler 1993). The slow decomposition of rye, mostly attributed to its high C : N ratio (Ranells and Wagger 1996), permitted flail-mowed rye mulch to persist better throughout the season than other flail-mowed cover crops.

Weed Control. All treatments were applied based on soybean development and the onset of weed emergence (Table 1). The predominant weed species at most site locations was pigweed (*Amaranthus* sp.) with weedy check plots averaging 11 to 65 plants m^{-2}. At two locations (Kinston and Plymouth 2008), large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and broadleaf signalgrass [*Urochloa platyphylla* (Nash) R.D. Webster] were the dominant species at 40 to 60% weed coverage in rye plots.

In 2008, rolled-rye plots had significantly less weed density than flail-mowed rye in Goldsboro (Table 2) where rye biomass was 10,852 kg ha^{-1}. In 2009, roll-crimped and flail-mowed weed density means were not different for all three sites (Tables 2 and 3). Although there were no differences seen between rye modes of kill, the roller could provide logistical benefits over the flail mower. The roller-crimper uses substantially less energy than the flail mower, thus potentially making the roller-crimper a beneficial long-term investment from an energetics standpoint (Hunt 1977). The roller-crimper also works better at faster tractor speeds (> 5 mph), thus reducing time and energy spent in the field, whereas a flail mower requires a lower tractor speed (2 to 5 mph) to effectively mow the cover crop. However, the flail mower might be a more common implement that many producers already own.

Weed density was higher with the CGM treatment at one site when compared to the rye-only treatment (Table 3). When compared to clove oil or cultivation, weed density was higher with CGM at three sites (Table 3). CGM might have acted as an N fertilizer for emerging weeds later in the season. CGM contains approximately 9% N by weight and has been shown to provide a sufficient source of N for turf (Christians 1993). Christians (1993) also concluded that CGM acts as a slow-release N source. Research has shown that rye's high C : N ratio can lead to N immobilization (Rosecrance et al. 2000). This addition of CGM could have stimulated growth and survival of pigweed seedlings in an N-depleted environ-

Table 2. ANOVA results for soybean yield, weed density, and weed coverage.[a]

	Soybean yield					Weed density				Weed coverage					
	Goldsboro	Kinston		Plymouth		Goldsboro		Kinston	Plymouth	Goldsboro		Kinston		Plymouth	
	2008	2008	2009	2008	2009	2008	2009	2009	2009	2008	2009	2008	2009	2008	2009
Main effects[b]															
MOK	NS	—	**	—	NS	**	NS	NS	NS	*	NS	—	NS	—	NS
WM	*	NS	NS	NS	**	**	**	NS	*	NS	NS	NS	NS	NS	NS
WM × MOK	NS	—	NS	—	NS	NS	NS	NS	NS	NS	NS	—	NS	—	NS
Contrasts															
WF check vs. ALL	NS	**	**	NS	NS	—	—	—	—	—	—	—	—	—	—
Weedy check vs. ALL	—	—	—	—	—	—	**	**	**	—	NS	—	**	—	**

[a] Mode of kill consisted of flail-mowed and rolled-crimped treatments. Weed management tactics consisted of corn gluten meal, clove oil, rye-only, or high-residue cultivation. The contrast (WF check vs. ALL) is a comparison of the weed-free (WF) check to the average of the four weed management tactics. The contrast (Weedy check vs. ALL) is a comparison of the weedy check weed control to the average of the four weed management tactics. Plymouth 2008 and Kinston 2008 had one mode of kill (roll-crimped).

[b] Abbreviations: ALL, an average of corn gluten meal, clove oil, rye-only, and high-residue cultivation treatments; MOK, mode of kill; NS, not significant; NS, not significant; WF, weed-free; WM, weed management.

* Significant at 0.05 level;

** Significant at 0.01 level.

Table 3. Rye method of kill and weed management treatment effects on weed density. The predominant weed species was pigweed (*Amaranthus* sp.). All weeds above the soybean canopy for two data rows were counted (20.9 m^2).[a]

Treatment	2008 Goldsboro	2009 Goldsboro	2009 Kinston	2009 Plymouth
	count m^{-2}			
Weed management				
CGM[b]	0.68 a	13 a	1.3 a	0.1 ab
Clove oil	0.21 b	6.9 b	0.93 a	0.05 bc
Rye-only	0.43 ab	7.5 b	1.2 a	0.13 a
cultivation	—	7.3 b	0.99 a	0.006 c
Weedy check vs. All	—	29*	11*	0.65*
Mode of kill				
Flail-mowed	0.63 a	8.6 a	1.1 a	0.08 a
Rolled	0.25 b	8.4 a	1.0 a	0.06 a

[a] Within columns and main effects, means followed by the same letter are not significantly different based on Fisher's Protected LSD test at $P < 0.05$.

[b] Abbreviation: CGM, corn gluten meal.

* Denotes when the contrast of weedy check vs. the average of all four weed management tactics is significant at the 0.05 level.

ment, which might increase weed competition rather than control weeds in some situations.

Clove oil reduced weed density at one location when compared with the rye-only treatment (Table 3). It was observed that clove oil injured most weed species, but only killed some (data not shown). Similar injury was seen by Tworkoski (2002). Bainard et al. (2006), comparing clove oil response on common lambquarters and redroot pigweed (*Amaranthus retroflexus* L.), found that pigweed was more susceptible to clove oil due to its lack of epicuticular wax, resulting in a 99% reduction in seedling growth. Weed height might have played a role in the lack of control by clove oil. An important consideration when applying clove oil was soybean height. The soybean canopy had to be tall enough to allow for a directed under-canopy clove oil application and prevent excessive injury to the soybeans. Although weed height was taken into consideration, the more important factor was soybean height. Given this, weed height varied among sites and could be partly responsible for differences seen in the data and/or lack of sufficient control.

High-residue cultivation was not significantly different from other treatments at most sites (Table 4). It resulted in better weed control when compared to CGM in Goldsboro 2009, and in Plymouth 2009, high-residue cultivation controlled weeds more effectively than the rye-only treatment (Table 3). During the experiment, it was observed that the cultivator pushed the rye from the row middle, exposing the soil and creating an opening for weed germination. However, at two of three sites, August weed counts were not significantly different among treatments. The high-residue cultivator was used just prior to canopy closure (7 WAP) at all sites. Weeds emerging after cultivation likely were shaded out by the closing soybean canopy. All treatments had significantly lower weed densities than the weedy check treatment (Table 2).

Few differences were observed among treatments with regard to weed coverage; the only differences were seen between the weedy check treatment vs. all other treatments (Figure 3; Table 2). Goldsboro 2008 (high rye biomass) resulted in a difference between CGM and clove oil. For weed coverage, all locations were grouped into three rye mulch levels (low, medium, and high); groupings were based on the range of rye biomass levels naturally achieved at the various sites. Results suggest that with increasing rye biomass levels, percent weed coverage decreases (Figure 3). Rye mulch levels have been shown previously to play an important role in weed suppression (Barnes and Putnam 1983; Mohler and Teasdale 1993; Teasdale and Mohler 2000).

Increasing total rye biomass was found to correlate with increased weed suppression. The two sites with the highest biomass, Goldsboro and Plymouth 2008, had biomass values of 10,854 and 9,526 kg ha^{-1}, respectively and resulted in sufficient weed suppression to maintain soybean yield. Teasdale and Mohler (2000) showed that increasing mulch levels exponentially decreased weed pressure, concluding that mulch levels greater than 9,000 kg ha^{-1} reduced weed pressure by 90%. Weeds in the soybean row appeared to comprise the majority of weeds in locations with low and medium biomass sites. During soybean planting, the no-till planter created a furrow in the rye and exposed approximately 10 cm of the soil surface, allowing for weeds to be in direct competition with soybeans. The ineffectiveness of CGM and clove oil at controlling in-row weeds suggest this system is inadequate in years where rye growth is limited. Even medium levels of biomass (7,000 to 9,000 kg ha^{-1}) could be a problem, and foregoing the use of trash clearers might be necessary at medium biomass levels. With high rye biomass,

Table 4. Rye method of kill and weed management treatment effects on soybean yield.[a]

Treatment	2008 Goldsboro	2008 Kinston	2008 Plymouth	2009 Kinston	2009 Plymouth
Main effect	kg ha^{-1}				
Weed control[b]					
CGM	1,976 b	2,681 b	2,499 a	1,195 b	2,460 a
Clove oil	2,345 a	2,849 b	2,876 a	1,114 b	2,072 b
Rye-only	2,190 ab	2,903 b	2,694 a	1,112 b	2,388 a
cultivation	—	2,611 b	—	1,275 b	2,570 a
WF check	2,143 ab	3,583 a	2,809 a	2,616 a	2,506 a
Mode of kill					
Flail-mowed	2,188 a	—	—	1,027 a	2,360 a
Rolled	2,147 a	2,761	2,690	1,321 b	2,385 a

[a] Within columns and main effects, means followed by the same letter are not significantly different based on Fisher's Protected LSD test at $P < 0.05$. Two data rows were harvested and weights are reported at 13% moisture. Kinston and Plymouth 2008 did not have a flail-mowed treatment.

[b] Abbreviations: CGM, corn gluten meal; WF, weed-free.

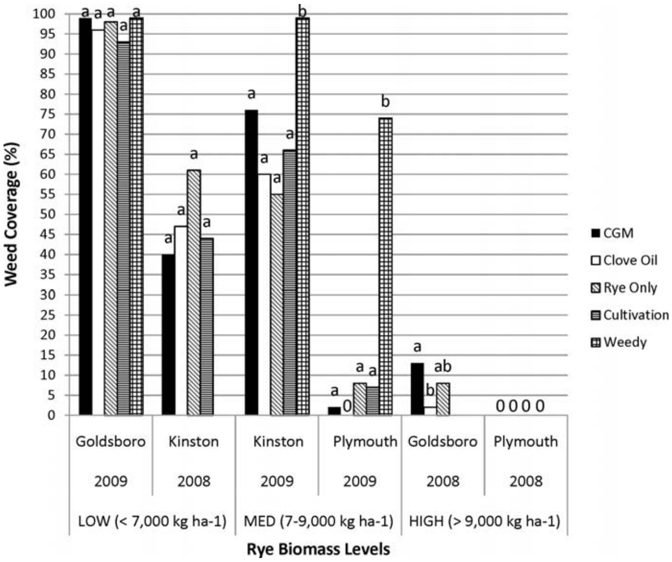

Figure 3. Weed management treatment effects on weed coverage. Weed coverage was estimated using visual ratings. Each site location was analyzed separately and LSD letters represent differences within each site location at $P < 0.05$. Site locations were grouped into three biomass levels: low, medium (med), and high. Goldsboro 2008 did not receive the cultivation treatment.

trash clearers do not result in excessive establishment of in-row weeds, and a consistent soybean stand would be difficult to achieve without them on many planters.

Soybean Yield. There were no differences in soybean stand counts or soybean heights among treatments, including the weed-free treatment. Rye biomass did not seem to interfere with stand establishment. Moreover, sites with rye biomass $> 9{,}000$ kg ha^{-1} had equivalent soybean yields between the rye-only and weed-free treatments, suggesting that the presence of rye biomass does not affect soybean yield directly.

Soybean yield was collected at five sites. Goldsboro 2009 yield data were lost due to mechanical failure of the combine. The rye-only treatment had an equivalent soybean yield to the weed-free treatment at three sites (Table 4). Reports with chemically desiccated rye suggest little to no soybean yield loss (Liebl et al. 1992; Moore et al. 1994). Davis (2010) found a much higher yield loss of at least 20% with rolled rye (6,000 to 7,100 kg ha^{-1} of rye biomass) although less loss occurred in rye killed with glyphosate. In Kinston 2008, where rye biomass levels were low (6,606 kg ha^{-1}) the weed-free treatment yielded 23% higher than the rye-only treatment (Tables 2 and 4). In Kinston 2009, rye biomass was higher (8,367 kg ha^{-1}), but the weed-free treatment still yielded 135% higher than the rye-only treatment (Tables 2 and 4). If the relationship between mulch biomass and weed emergence is one of exponential decay, as suggested by Teasdale and Mohler (2000), then only a 1,000 to 2,000 kg ha^{-1} difference in rye biomass can determine the success or failure of this system in high weed-pressure environments, as was the case when comparing Kinston 2009 to Goldsboro 2008.

CGM reduced yield when compared to the clove oil treatments at Goldsboro and Plymouth 2008 (Table 4). Higher weed density (Table 3) was observed in the CGM treatment at Goldsboro 2008, likely resulting in the yield differences. Neither clove oil nor CGM was significantly different from the rye-only treatment at most locations. In Plymouth 2009, clove oil treatment yield was 316 kg ha^{-1} less than rye-only treatment yields. More burn on the crop was observed at this location.

Kinston 2009 was the only location where a soybean yield advantage was detected for rolled rye vs. flailed rye (Tables 2, 4). No difference in weed control density had been detected at this site, suggesting either another mechanism for yield advantage for the rolled rye or weed control differences were present but not detected statistically. Goldsboro 2008 is the site where yield differences between flail-mowed and rolled rye were expected. Despite having 2.5 times fewer weeds, the rolled rye plots had almost identical yield as the flail-mowed plots (Table 4). The weeds that emerged in the flail-mowed plots emerged late, mostly from the between-row area. They were able to grow above the soybean canopy, but were not robust plants. The in-row weeds that developed in lower rye-biomass environments were far more robust and would be expected to be more yield-damaging.

An important consideration in drawing conclusions from the study is that organic conditions were maintained only at most stations during the soybean production phase. Conventional sites were utilized to permit comparison with conventional weed management (weed-free checks) and for the logistical ease of fertilizing the rye cover crop conventionally. All locations had not been previously under organic management. Research in organic cropping systems has suggested that crops might be more tolerant of weeds in an organically managed field than in a conventionally managed field (Ryan et al. 2009). If crops are more tolerant of weed competition under organic conditions, the roller system also might work at lower rye biomass levels than suggested by these data. Another question is how often organic growers can expect rye growth similar to the high biomass sites in this study. To adopt this system, more attention to the cover crop is required. Inadequate nitrogen or planting too late could severely limit chances of obtaining enough rye biomass. Under current organic practices in North Carolina, the biomass of a rye cover crop could vary widely between farms. Depending on maturity rates and the number of legumes in the rotation, the amount of N available to a cover crop on an organic farm can vary from excessive to deficient (Roberts et al. 2008). Planting dates for this study, mid-November, were fairly late for the region. Planting much earlier, September or October, is possible in fields following corn harvest and might lead to even greater rye biomass than reported in our study (Griggs 2006).

Future research is needed to develop a decision tree to help producers decide when this system will work. Inevitably, some winters will produce less rye biomass than is needed for weed suppression. Ideally, producers would benefit from a prediction system that could estimate their chance of success in early spring, based on rye growth thus far and expected weed pressure for a particular field. Waiting until planting time to decide between no-till and clean-till is too late because rye residue would be too large to incorporate into the soil. More research also is needed to determine whether the system could work with rye biomass levels at 7,000 to 9,000 kg ha^{-1}. New organic herbicides are being developed (Webber et al. 2009) that might be more effective for in-row weed control than those tested here. Perhaps the largest concern is soybean lodging. Soybean lodging was observed at sites with $> 7{,}000$ kg ha^{-1} of rye biomass. Soybean lodging was severe at some sites with all plots severely lodged except for check plots lacking rye mulch. Although the soybeans were still harvestable, the degree of lodging slowed combine speeds substantially. Research is needed to determine why the presence of rye biomass induced soybean lodging, what physical or chemical factors play a role, and which management strategies can be employed to prevent lodging.

Sources of Materials

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

[2] Clove oil, Matratec AG, Clawel Specialty Products, 211 West Route 125, Pleasant Plains, IL 62677.

[3] Corn gluten meal, Grain Processing Corporation, 1600 Oregon St., Muscatine, IA 52761.

[4] Monosem no-till planter, Monosem, Inc., 1001 Blake St., Edwardsville, KS 66111.

[5] Drop spreader, Gandy Company, 528 Gandrud Rd., Owatonna, MN 55060.

[6] Sukup High-residue cultivator, Sukup Manufacturing Company, 1555-255th St., Sheffield, IA 50475.

Literature Cited

Arshad, M. A., M. Schnitzer, D. A. Anger, and D. A. Ripmeester. 1990. Effects of till vs. no-till on the quality of soil organic matter. Soil Biol. Biochem. 22:595–599.

Ashford, D. L. and D. W. Reeves. 2003. Use of a mechanical roller-crimper as an alternative kill method for cover crops. Am. J. Altern. Agric. 18(1):37–45.

Bainard, L. D., M. B. Isman, and M. K. Upadhyaya. 2006. Phytotoxicity of clove oil and its primary constituent eugenol and the role of leaf epicuticular wax in the susceptibility to these essential oils. Weed Sci. 54:833–837.

Barnes, J. P. and A. R. Putnam. 1983. Rye residues contribute weed suppression in no-tillage cropping systems. J. Chem. Ecol. 9:1045–1057.

Barnes, J. P. and A. R. Putnam. 1987. Role of benzoxazinones in allelopathy by rye (*Secale cereale* L.). J. Chem. Ecol. 13:889–906.

Beale, O. W., G. B. Nutt, and T. C. Peele. 1955. The effects of mulch tillage on runoff, erosion, soil properties, and crop yields. Soil Sci. Soc. Am. J. 19:244–247.

Bingaman, B. R. and N. E. Christians. 1995. Greenhouse screening of corn gluten meal as a natural control product for broadleaf and grass weeds. Hortscience 30:1256–1259.

Boyd, N. S. and E. B. Brennan. 2006. Burning nettle, common purslane, and rye response to a clove oil herbicide. Weed Technol. 20:646–650.

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

Christians, N. E. 1993. The use of corn gluten meal as a natural preemergence weeds control in turf. Chapter 35. Int. Turfgrass Soc. Res. J. 7:284–290.

Coleman, D. C., D. A. Crossley, and P. F. Hendrix. 2004. Fundamentals of Soil Ecology. 2nd ed Elsevier: Burlington, MA. 386 p.

Creamer, N. G. and S. M. Dabney. 2002. Killing cover crops mechanically: Review of recent literature and assessment of research results. Am. J. Altern. Agr. 17(1):32–40.

Creamer, N. G., B. Plassman, M. A. Bennett, R. K. Wood, B. R. Stinner, and J. Cardina. 1995. A method for mechanically killing cover crops to optimize weed suppression. Am. J. Altern. Agr. 10(4):157–162.

Davis, A. S. 2010. Cover-crop roller-crimper contributes to weed management in no-till soybean. Weed Sci. 58:300–309.

Ferguson, J. J. 2004. Evaluation of organic herbicides. Hortscience 39:876.

Griggs, T. C. 2006. Fall and winter spring forage production and quality of winter cereals seeded at three fall dates. Forage and Grazinglands doi: 10.1094/FG-2006-0711-01-RS. http://www.plantmanagementnetwork.org/fg/. Accessed: March 9, 2010.

Hargrove, W. L. 1990. Role of conservation tillage in sustainable agriculture. Pages 28–32 *in* J. P. Mueller and M. G. Wagger, eds. Conservation Tillage for Agriculture in the 1990s: Proceedings of the 1990 Southern Regional Conservation Tillage Conference. Raleigh, NC: North Carolina State University.

Hunt, D. 1977. Farm Power and Machinery Management—Laboratory Manual and Workbook. 7th ed. Ames, IA: Iowa State University Press. 365 p.

Kornecki, T. S., A. J. Price, R. L. Raper, and A. J. Arriaga. 2009. New roller crimper concepts for mechanical termination of cover crops in conservation agriculture. Renewable Agric. Food Syst. 24:165–173.

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

Liebman, M. and E. Gallandt. 1997. Many little hammers: ecological approaches for management of crop-weed interactions. Page 78 *in* L. E. Jackson, ed. Agricultural Ecology. San Diego, CA: Academic.

Lu, Y. C., K. B. Watkins, J. R. Teasdale, and A. A. Adbul-Baki. 2000. Cover crops in sustainable food production. Food Rev. Int. 16:121–157.

Masiunas, J. B., L. A. Weston, and S. C. Weller. 1995. The impact of rye cover crops on weed populations in the tomato cropping system. Weed Sci. 43:318–323.

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

Mohler, C. L. and J. R. Teasdale. 1993. Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. Weed Res. 33:487–499.

Moore, M. J., T. J. Gillespie, and C. J. Swanton. 1994. Effect of cover crop mulches on weed emergence, weed biomass, and soybean (*Glycine max*) development. Weed Technol. 8:512–518.

[NOP] National Organic Program. 2002. National List of Allowed and Prohibited Substances. http://www.ams.usda.gov/AMSv1.0/ams.fetchTemplateData.do?template=TemplateN&navID=NationalListLinkNOPNationalOrganicProgramHome&rightNav1=NationalListLinkNOPNationalOrganicProgramHome&topNav=&leftNav=&page=NOPNationalList&resultType=&acct=nopgeninfo. Accessed: November 11, 2009.

[NC Ag Census] North Carolina Agricultural Census. 2007. Table 48: Organic Agriculture. http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_1_State_Level/North_Carolina/st37_1_048_048.pdf. Accessed: November 11, 2009.

[OTA] Organic Trade Association. 2008. Organic Facts. http://www.ota.com/pics/documents/Mini%20fact%201-08%20confirming.pdf. Accessed: June 2, 2010.

Paustian, K., C. V. Cole, D. Sauerbeck, and N. Sampson. 1998. CO_2 mitigation by agriculture: an overview. Clim. Change 41:1480–1573.

Ranells, N. N. and M. G. Wagger. 1996. Nitrogen release from grass and legume cover crops monocultures and bicultures. Agron. J. 88:777–782.

Raper, R. L., D. W. Reeves, E. B. Schwal, and C. H. Burmester. 2000. Reducing soil compaction of Tennessee Valley soils in conservation tillage systems. J. Cotton Sci. 4:84–90.

Reeves, D. W., A. J. Price, and M. G. Patterson. 2005. Evaluation of three winter cereals for weed control in conservation-tillage nontransgenic cotton. Weed Technol. 19:731–736.

Roberts, C. J., D. H. Lynch, R. P. Voroney, R. C. Martin, and S. D. Juurlink. 2008. Nutrient budgets of Ontario organic dairy farms. Can. J. Soil Sci. 88(1):107–114.

Rodale Institute. 2009. No-Till Revolution. http://www.rodaleinstitute.org/no-till_revolution. Accessed: March 15, 2010.

Rosecrance, R. C., G. W. McCarty, D. R. Shelton, and J. R. Teasdale. 2000. Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) cover crop monocultures and bicultures. Plant Soil 227:283–290.

Ryan, M. R., R. G. Smith, D. A. Mortensen, J. R. Teasdale, W. S. Curran, R. Seidel, and D. L. Shumway. 2009. Weed–crop competition relationships differ between organic and conventional cropping systems. Weed Res. 49:572–580.

[SAS] Statistical Analysis Systems. 2006. Procedures Guide. Release 9.1.3. 2nd ed. Cary: NCSAS Institute.

Six, J., E. T. Elliott, and K. Paustian. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63:1350–1358.

Snapp, S. S., S. M. Swinton, R. Labarta, D. Mutch, J. R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. 2005. Evaluating cover crops for benefits, costs, and performance within cropping system niches. Agron. J. 97:322–332.

Teasdale, J. R. and C. L. Mohler. 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron. J. 85:673–680.

Teasdale, J. R. and C. L. Mohler. 2000. The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci. 48:385–392.

Tworkoski, T. 2002. Herbicide effects of essential oils. Weed Sci. 50:425–431.

USDA. 2009a. North Carolina Grain Prices Paid to Producers by Location. North Carolina Department of Agriculture Market News. http://www.ams.usda.gov/mnreports/ra_gr110.txt. Accessed: January 5, 2010.

USDA. 2009b. National Organic Grain and Feedstuffs. USDA Livestock and Grain Market News. http://www.ams.usda.gov/mnreports/lsbnof.pdf. Accessed: January 5, 2010.

Walz, E. 1999. Third Biennial National Organic Farmers' Survey. Santa Cruz, CA: Organic Farming Research Foundation. 126 p.
Webber, C. L., III, J. W. Shrefler, L. P. Brandenberger, M. J. Taylor, and R. A. Boydston. 2009. Organic herbicide update. Pages 237–239 *in* Proceedings of the 28th Horticulture Industries Show. Ft. Smith, AR.
Weersink, A., M. Walker, C. Swanton, and J. E. Shaw. 1992. Costs of conventional and conservation tillage systems. J. Soil Water Conserv. 47:328–334.
Weston, L. A. 1990. Cover crop and herbicide influence on row crop seedling establishment in no-tillage culture. Weed Sci. 38:166–171.
Weston, L. A. 1996. Utilization of allelopathy for weed management in agroecosystems. Agron. J. 88:860–866.
Wossink, G.A.A. and N. Kuminoff. 2002. Organic Agriculture in North Carolina. North Carolina Cooperative Extension Service: North Carolina State Economist. September/October., Pp. 1–4.
Yenish, J. P., A. D. Worsham, and A. C. York. 1996. Cover crops for herbicide replacement in no-tillage corn (*Zea mays*). Weed Technol. 10:815–821.

Received July 29, 2010, and approved October 25, 2010.