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ENGINEERING AND GINNING

Effects of Different Rollers and Rye Termination Methods on Soil Moisture and Cotton Production in a No-Till System

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ABSTRACT

In the southern U.S., rollers/crimpers are used to terminate cover crops approximately 3 weeks before planting cotton when the cover crop reaches > 90% termination. When spring is wet or cold, the 3-week period is reduced to keep recommended planting dates. A 3-year experiment was initiated in Alabama to determine the effectiveness of a 4-stage roller/crimper in increasing termination rates for cereal rye compared to 2-stage and spiral rollers/crimpers in rolling 1, 2, and 3 times over rye along with a single-pass smooth roller with glyphosate application. Effects of rye termination at 7, 14, and 21 days after rolling were assessed as were the effects on soil water conservation, cotton population, and yield. Seven days after rolling, the 4-stage, 2-stage, and spiral rollers rolling 3 times generated 96, 92, and 81% termination, respectively. Termination with the smooth roller with glyphosate was 94% and the control (no rolling) was 37%. At 14 days, termination among rollers was 91 to 98% and at 21 days no differences were found among rollers (99-100%). The 4-stage roller 3 times had the highest average soil volumetric water content (VWC) of 16.1%, whereas the spiral roller 1 time had the lowest (13.6%). Rolled rye had higher VWC content averaging 14.7% (12-cm surface layer) compared to the control (12.7%). Rolling treatments affected cotton emergence only in 2015; cotton population and yield were not affected. Seven days after rolling, the 4-stage and 2-stage roller/crimpers exceeded 90% rye termination making earlier cotton planting possible if required by climatic conditions.

Cover crops are a vital part of conservation systems to reduce soil erosion and runoff, and to increase soil organic carbon and water content, and infiltration. Effective termination of cover crops is key for successful planting of cash crops directly into the residue cover. In the U.S., rollers/crimpers are used to terminate cover crops. Glyphosate herbicide has been applied with rolling to speed-up cover-crop termination, but due to environmental concerns, there is a need to reduce herbicide use. In addition, synthetic herbicides cannot be used in organic production systems. Typically, in the southern U.S., the time between cover-crop termination and cash-crop planting is 21 d to reach > 90% cover-crop termination and to eliminate competition of soil resources with the cash crop.

A commonly used cover crop in the southern U.S. is cereal rye (*Secale cereale* L.), which produces up to 10,000 kg ha^{-1} of biomass (Bowen et al., 2000). Major benefits of cover crops include soil protection from impact of rainfall energy, reduced runoff, decreased soil compaction, and increased infiltration (Kern and Johnson, 1993; McGregor and Mutchler, 1992; Reeves, 1994). Cover crops also provide a physical barrier on the soil surface that inhibits weed emergence and growth (Creamer et al., 1996). In addition to providing a physical barrier, rye has allelopathic properties that provide control similar to applying a pre-emergence herbicide (Barnes and Putman, 1986; Hoffman et al., 1996). Long-term soil quality effects are associated with improved soil physical/chemical properties due to increased soil organic carbon, which results in better crop growth for sustainable agricultural practices.

With support from the USDA's Natural Resources Conservation Service (NRCS), farming communities are using cover crops to protect soil, their most valuable asset. Since 2014, NRCS has helped landowners plant approximately six million acres of cover crops by providing both financial and technical assistance (Taylor, 2015). This substantial increase in using cover crops in conservation systems also promotes using rolling/crimping technology to manage and terminate cover crops.

In conservation systems, cutting or mowing is not a standard option. When the cover crop is mowed, cutting and scarification cause the crop to

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dry out significantly quicker and decompose faster and benefits are lost including weed suppression and moisture retention. Mowing can leave residue unevenly distributed across the soil surface enabling sunlight to reach the bare soil surface allowing weeds to germinate successfully and compete with an establishing cash crop. Moreover, when mowing, loose cover crop can interfere with planting operation by accumulating on planting units. Rolling/crimping technology has been used to manage tall cover crops such as cereal rye in conservation systems. A roller/crimper driven through a field flattens a living cover crop, and a crimping bar attached to the roller's drum crimps the cover-crop stems, which scarifies them to promote desiccation. When the cover crop is terminated and dried out, the residue forms a thick mulch that covers the soil surface; this reduces soil erosion, reduces weed germination and growth, and conserves water for the following cash crop (Derpsch, 1991; Derpsch et al., 2010).

Crimping cover-crop tissue causes injury and accelerates its termination rate. In southern U.S. conservation systems, cover crops should be terminated 21 d prior to planting the cash crop. Typically, 21 d after rolling, the termination rate for rye is > 90% when rolling is performed at an optimal growth stage (Ashford and Reeves, 2003; Kornecki et al., 2006). Most agricultural extension services recommend cover crop termination at least 14 d prior to planting the cash crop to prevent competition for valuable spring soil water that could be used by the main cash. Hargrove and Frye (1987) reported that the minimum time from cover-crop termination should be at least 14 d to enable soil water recharge prior to planting the cash crop.

When late winter months and early spring months are unusually cold and wet or too dry, producers must wait longer for the cover crop to produce optimum biomass and to achieve the appropriate growth stage for mechanical termination, thus the timeliness of planting cash crops could be compromised. Conversely, using herbicides such as glyphosate, in addition to rolling, can effectively accelerate cover-crop termination and reduce the waiting time between termination and planting the cash crop, allowing more time for the cover crop to produce more biomass. Results from a field study by Kornecki et al. (2009) indicated that when applying glyphosate in addition to rolling, termination rates for cereal rye 7 d after rolling varied only by 2% (i.e., between 96-98%).

Synthetic herbicides (glyphosate) are prohibited in organically grown crops such as cotton (*Gossypium hirsutum* L.), and organic herbicides are ineffective and expensive. Organic cotton production continues to increase in the U.S., stimulated by consumer and corporate demands, higher prices for farmers, and regulatory changes that result in clear labeling for organic cotton products. According to the Organic Trade Association (2014), in 2012 the U.S. harvested approximately 4,000 ha of organically grown cotton producing 1,930 metric tons. Based on USDA-Agricultural Marketing Service (2014) data, in 2013 the U.S. produced 2,413 metric tons of organic cotton, a 15% increase compared to 2012. A survey conducted by the Textile Exchange (2014) indicated that the U.S. is among the top five countries (after India, China, Turkey, and Tanzania) producing organic cotton, accounting for 97% of the global organic cotton production.

Because commercial herbicides cannot be used in organic production systems, mechanical termination using improved rollers/crimpers (with possible need for repeated rolling/crimping operations) must be as efficient as chemical termination. Mechanical termination must also be as effective as chemical termination if unfavorable weather conditions in the spring (i.e., wet and cold) push cover-crop termination too close to recommended dates for planting cotton. Previous research evaluating earlier types of rollers/crimpers and their termination rates indicated that rolling/crimping 3 times over the same cover-crop area increased cover-crop termination rates (Kornecki et al., 2013). Therefore, the objectives of this study were twofold: (1) compare the effectiveness of a patented, new 4-stage roller/crimper design to a patented 2-stage, curved bar and smooth drum design in terminating rye cover crop in single, double, and triple runs over the same area; and (2) determine the effects of different rollers and multiple pass rolling/crimping on volumetric soil water content (VWC), cotton emergence, population, and cotton yield in a conservation system.

MATERIALS AND METHODS

A quadruple replicated field experiment was initiated in 2014 in central Alabama (E.V. Smith Research Center), U.S., on a Compass loamy sand (thermic Plinthic Paleudults) soil series by planting a rye cover crop in fall 2014 (10 Nov. 2014) at a rate of 100 kg ha^{-1}. Field activities for each of the three growing seasons are given in Table 1. The experiment was a randomized complete-block design for which treatments were randomized individually within each block. The blocking was necessary because of a slight slope (gradient) that could cause higher soil moisture in the lower-level plots and possible flooding especially after intense rainfall events, which are frequent at this location in the growing season. Blocks were oriented perpendicularly to the gradient. The experimental units were grouped into blocks to minimize variability within each block while maximizing variability among blocks. Randomization process was performed according to the procedure described by Gomez and Gomez (1984) for which 14 random numbers with sequence from 1 to 14 and corresponding ranks from the highest (treatment 14) to the lowest (treatment 1) random number were used to assign the treatment to each plot (9.1-m long and 1.8-m wide) within each block. The experimental layout with four blocks (total of 56 plots with randomly assigned treatments to each block) is shown in Fig. 1; description of each treatment replicated 4 times is showed in Table 2.

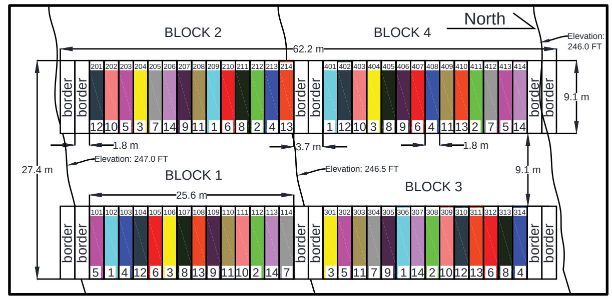

Figure 1. Experimental layout: randomized complete block design. Three-digit numbers from 101 to 414 (numbers on the top of rectangular plot) represent experimental unit number, e.g., for 414 experimental unit, the first digit is the replication number (4), second and third digits are plot numbers (14). The lower number(s) are treatment number, i.e., for plot 101, the treatment number is 5: 4-Stage roller/crimper, rolling twice, replication 1 (treatment description from Table 2).

Table 1. Field activities during the 2015, 2016, and 2017 growing seasons at the E.V Smith Research Center in central Alabama

Field Activity	Growing season		
	2015	2016	2017
Planting cereal rye cover crop	10 Nov 2014	05 Nov 2015	17 Nov 2016
Rolling/crimping cover crop	23 Apr 2015	25 Apr 2016	26 Apr 2017
Evaluation 7 d after treatment	30 Apr 2015	02 May 2016	03 May 2017
Evaluation 14 d after treatment	07 May 2015	09 May 2016	10 May 2017
Evaluation 21 d after treatment	14 May 2015	16 May 2016	17 May 2017
Planting cotton	14 May 2015	25 May 2016	18 May 2017
Applying Nitrogen	10 Jul 2015	07 Jul 2016	06 Jul 2017
Harvesting cotton	19 Oct 2015	14 Oct 2016	26 Oct 2017

Table 2. Description of the 14 treatments used

Treatment #	Roller Type	Passes	Replicates (n)
1		1	
2	2-Stage roller/crimper	2	4
3		3	
4		1	
5	4-Stage roller/crimper	2	4
6		3	
7		1	
8	Spiral roller/crimper	2	4
9		3	
10		1	
11	Smooth roller drum	2	4
12		3	
13	Smooth roller w/Roundup	1	4
14	Standing Rye	0	4

For the three growing seasons, rolling treatments were applied when rye was at the milk growth stage (Zadoks #77) (Zadoks et al., 1974), and its termination was evaluated 7, 14, and 21 d after rolling. Types of experimental rollers/crimpers were: 2-stage (Fig. 2), 4-stage (Fig. 3) (Kornecki, 2011), and spiral roller (Fig. 4) to roll rye 1, 2, and 3 times (passes). These tested rollers (not commercially available) were developed at the USDA-ARS National Soil Dynamics Laboratory (NSDL) in Auburn, AL. A smooth roller with a sprayer applying glyphosate was also tested (Fig. 5) and standing rye (untreated) was the control. All rollers were 3-point hitch mounted on a John Deere 6410 tractor equipped with a 77-kW diesel engine. Application rate for a systemic, nonselective glyphosate (Roundup™ Weather Max) was a continuous spray at 1.6 L ha^{-1} (660 g of active ingredient of glyphosate in 1.0 L of potassium salt solution, i.e., 1.06 kg a.i. ha^{-1} with water spraying dilution of 140 L ha^{-1}).

Rye termination was estimated using a handheld light-sensor chlorophyll meter SPAD 502 (Konica-Minolta, Ramsey, NJ). This portable sensor is capable of instantly measuring the chlorophyll content or "greenness" of plants. The SPAD 502 quantifies slight changes or trends in plant health long before they are visible to the human eye and provides a noninvasive measurement. The meter was clamped over leafy tissue and an indexed chlorophyll content reading (usually from 0-50.00) is recorded in less than 2 s. The data logging version of the SPAD 502 (item 2900DL) allowed for easier compiling of readings for statistical analysis. Because plant greenness is related to chlorophyll activity (e.g., ≥ 50 for healthy plants and 0 for a dead plant with no chlorophyll activity), this method was used to detect different stages of cover-crop termination due to plant senescence from injury caused by mechanical termination using roller/crimpers or by glyphosate treatment. To obtain a reading per plot, five readings of plant tissue were collected in each plot by manually clamping the chlorophyll meter on randomly selected plants and storing the readings in the data logger. These five readings were averaged for each plot. Cereal rye termination rates on a scale of 0% (no injury) to 100% (complete death) were based on a procedure described in Kornecki et al. (2012). Evaluation was performed 7, 14, and 21 d after the rolling treatments. Similarly, volumetric soil water content (VWC in %) was measured (5 readings per each plot and averaged) at 7, 14, and 21

Figure 2. 2-stage roller/crimper. US patent number: 7,987,917 B1.

Figure 4. Spiral roller/crimper.

Figure 3. 4-stage roller/crimper. US patent number: 7,987,917 B1.

Figure 5. Smooth roller drum without or with herbicide applicator (shown).

d after rolling treatment application using a portable TDR 300 moisture meter with 0.12-m long rods (Spectrum Technologies, Plainfield, IL). Selection of 0.12-m long stainless-steel rods was based on the need to determine VWC and water availability for cotton seeds after planting and at the root zone on emerged plants (~0.06-m depth). Cotton (Phytogen 333WRF variety) was planted using a John Deere 1700 Max Emerge Plus planter and DAWN^{TM} row cleaners (0.9-m row spacing with a seeding rate of 160,600 seeds ha^{-1}).

In each growing season after visible cotton emergence, cotton stand data were collected (four random counts per plot) starting in May and finishing in June, with the final count in July using a 1.5-m long linear edge. Cotton stand (number of plants) was measured several times during plant emergence. The linear edge was positioned parallel to the cotton row at three random locations, and the number of emerged plants was counted along the edge length in the two middle rows in each 4-row plot. To compare plant emergence rates across treatments, emergence rate index (ERI) in % per day was calculated using the procedure described by Erbach (1982) and Aikins et al. (2019):

$$ERI = \sum_{n=first}^{last} \frac{[\%n - \%(n-1)]}{n}$$

where: %n = percent plants emerged on day n,
%(n-1) = percent plants emerged on day n-1,
n = number of days after planting,
first = number of days after planting that the first plant emerged (first counting day), and
last = number of days after planting when emergence was considered complete (last counting day).

Higher ERI values indicate faster emergence of plants; conversely, lower ERI values indicate slower plant emergence.

Cotton population in each plot was calculated using number of plants along a 6.1-m distance and 0.9-m row spacing. In each year, cotton was harvested the third week of October, using a 2-row cotton picker (John Deere model 9920). The two middle rows of each 4-row plot were harvested and bagged in the field. The bags were then weighed to determine the seed cotton yield. Based on the seed cotton yield, the lint yield was calculated using a 0.38 factor (38%), which is a common percentage of the lint fiber in central Alabama (UGA, 2017). Percentages of cover-crop termination rates were transformed using an arcsine square-root transformation method (Steel and Torie, 1980), but this transformation did not result in a change in the analysis of variance (ANOVA), thus, non-transformed means are presented.

Cover crop and rolling treatments were considered fixed effects and years were random effects (Gomez and Gomez, 1984). Where differences in each year for dependent variables were significant, and when interactions between treatments and years or weeks (for rye termination and VWC) occurred, data were analyzed separately. Data were subjected to analysis of variance using the ANOVA GLM procedure and treatment means were separated with Fisher's protected least significant differences (LSD) test at the 5% (α = 0.05) probability level (SAS, 2009).

RESULTS AND DISCUSSION

Significant statistical differences were detected in cereal rye biomass production, rye termination rates, VWC, ERI, cotton population, and cotton lint yield among the three years (*p*-values ranged from < 0.0001-0.0049); therefore, each year was analyzed separately. In addition, significant differences among weeks for cereal rye termination rates and VWC occurred, therefore data for these variables were analyzed separately for each week during the 21-d evaluation period after applying rolling treatments. There were significant differences among the blocks with respect to cotton emergence ERI ($p = 0.0053$), cotton population ($p = 0.0330$), and seed cotton lint yield ($p < 0.0001$); therefore, blocking in this experimental design was justified. Respective *F*-values and probabilities are shown in Table 3.

Cover-Crop Production. Average cereal rye cover-crop production from the three growing seasons was 7,680 kg ha^{-1}, approximately 10% greater than the Alabama average production of 7,000 kg ha^{-1} (Kornecki et al., 2015). Average plant height for cereal rye was 1.57 m. There were significant statistical differences among the three growing seasons (years) both for plant height and biomass production ($p < 0.0001$). Rye height and biomass amounts during each growing season are shown in Table 4. The greatest rye biomass was produced in 2015 (9,750 kg ha^{-1}; height 1.56 m), followed by 7,880 kg ha^{-1} at a height of 1.63 m in 2016 and the lowest biomass was produced in 2017 (5,410 kg ha^{-1}, height of 1.51 m). Rye growth and production of biomass was most likely weather related. For example, between November 2014 and

April 2015, 553 mm of cumulative rainfall fell on the experimental area contributing to the largest amount of rye biomass in 2015. During the same period in 2016, total rainfall was 1,287 mm and did affect rye biomass in 2016. In December of 2015, unusually high rainfall of 368 mm occurred, followed by 218 mm in January and February of 2016 which saturated soil, causing too wet soil condition that most likely suppressed cereal rye growth. In 2017, the total rainfall between November and April was 610 mm, however the lowest rye biomass in 2017 might be attributed to unusually high maximum average temperature in the last week of March and April (27^{O} C) for consecutive 24 days and low rainfall amounts during March and April (~100 mm). These conditions increased soil evaporation and lowered soil moisture in the period when rye growth is most vigorous and dependent on stored soil water.

Cover-Crop Termination. Rolling treatment effects on rye termination 7, 14, and 21 d after rolling/crimping are shown in Table 5. In 2015, 7 d after rolling, the largest termination was obtained by the 4-stage roller rolled 3 times (94%), 2-stage roller rolled 3 times (91%), smooth roller with glyphosate (91%), and smooth roller rolled 3 times (89%). Spiral roller generated termination from 81 to 86%; the control was 40%. At 14 d after rolling, no statistical differences among rollers were found (95-97%); the control was 49%. Similarly, 21 d after rolling no statistical differences were detected among rollers (99-100%); the control was 88%. Results from 2015 indicated that 7 d after rolling, the 4-stage and the 2-stage rollers rolling 3 times had termination > 90%, which was similar to the smooth roller and glyphosate. Fourteen days after rolling, no statistical differences among rolled treatments were found and the termination rates ranged from 95 to 97%. For comparison, the untreated standing rye control was 49%. At 21 d after rolling, all rolled treatments generated termination rates of 100%, whereas standing rye control was 80%.

In 2016, 7 d after rolling the highest termination was recorded for the 4-stage roller rolling 2 and 3 times (96%), the smooth roller with glyphosate (96%), and the 2-stage roller/crimper rolling 3 times (95%). Spiral roller and smooth drum rolling 1, 2, and 3 times had lower termination (69-75%); the control was 29%. Fourteen days after rolling, termination rates for 2-stage, 4-stage, and spiral roller/crimpers ranged from 94 to 99%. Termination rates for the smooth roller, rolling once, had lower termination rates (89%) and higher rates for rolling 2 and 3 times (95%). The lowest termination rate was for the control (50%). At 21 d after rolling all rollers and number of rollings generated similar termination rates (98-100%) without significant statistical differences among the rollers. The standing control had the lowest termination rate (82%).

Table 3. *F*-values and corresponding probabilities for rye biomass, ERI, cotton population, and seed cotton yield

Source	^{z}DF	Rye Biomass		ERI		Cotton Population		Seed Cotton Lint Yield	
		F Value	Pr > *F*	*F* Value	Pr > *F*	*F* Value	Pr > *F*	*F* Value	Pr > *F*
Year	2	92.51	<0.0001	5.67	0.0049	11.62	<.0001	209.79	<.0001
TRT*Year	26	1.00	0.4797	0.88	0.6390	0.30	0.9995	1.37	0.1438
BLOCK	3	1.83	0.1477	4.55	0.0053	3.05	0.0330	20.46	<.0001
TRT	13	0.91	0.5473	0.68	0.7733	0.57	0.8709	0.51	0.9114
TRT(BLOCK)	39	0.45	0.9967	0.83	0.7316	0.57	0.9743	1.12	0.3267

^{z} DF = degrees of freedom

Table 4. Average rye height (m) and biomass ((kg ha^{-1}) during three growing seasons

Rye Cover crop production	Year			*P*-value	LSD	3-yr average
	2015	2016	2017			
Height (m)	1.56 b^{z}	1.63 a	1.51 c	< 0.0001	0.0233	1.57
Biomass (kg ha^{-1})	9750 a	7880 b	5410 c	< 0.0001	532	7680

^{z} Comparisons between means are valid only within each row. Treatment means are compared for each year and location using LSD procedure in SAS (2009). Treatment means followed by the same letter are not statistically different. Treatment means with different letters are statistically different, in that the mean with the higher letter has a mean statistically lower than the mean is it compared to (e.g., b < a).

Table 5. Cereal Rye termination rates (%) during the three growing seasons (2015–2017)

TRTmt name	No. of pass.	Growing Season								
		2015			2016			2017		
		Days after rolling/crimping								
		7	14	21	7	14	21	7	14	21
2-stage roller crimper	1	87 bcd[z]	95 a	100 a	82 bc	96 abc	99 a	86 cde	97 abc	100 a
	2	86 cde	97 a	100 a	86 b	99 a	100 a	93 abc	98 ab	100 a
	3	91 ab	97 a	100 a	95 a	99 a	99 a	90 bcd	99 ab	100 a
4-stage roller crimper	1	86 cde	96 a	100 a	78 bcd	97 abc	99 a	82 efg	99 a	100 a
	2	89 abcd	97 a	100 a	96 a	98 ab	99 a	93 abc	99 a	100 a
	3	94 a	96 a	100 a	96 a	99 a	100 a	98 a	100 a	100 a
Spiral roller/ crimper	1	82 e	95 a	100 a	71 de	96 abc	98 a	81 efg	92 cd	100 a
	2	86 cde	95 a	100 a	73 de	94 c	98 a	76 g	90 de	100 a
	3	85 de	96 a	100 a	72 de	97 abc	99 a	85 def	92 bcd	100 a
Smooth drum roller	1	88 bcd	96 a	100 a	71 e	89 d	98 a	77 g	85 ef	100 a
	2	87 bcd	97 a	100 a	69 e	95 bc	98 a	82 efg	88 de	100 a
	3	89 abcd	97 a	100 a	75 cde	95 bc	99 a	78 fg	81 f	100 a
Smooth drum + Roundup		91 abc	96 a	100 a	96 a	98 ab	100 a	96ab	100 a	100 a
Standing Rye		40 f	49 b	89 b	29 f	50 d	82 b	43 h	62 g	87 b
P- value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

[z] **Comparisons between means are valid only within each column. Treatment means are compared for each year and location using LSD procedure in SAS (2009). Treatment means followed by the same letter are not statistically different. Treatment means with different letters are statistically different, in that the mean with the higher letter has a mean statistically lower than the mean is it compared to (e.g., b < a).**

In 2017, the 2-stage and 4-stage roller/crimpers rolling 2 and 3 times generated higher termination rates (90-98%). The smooth drum roller with glyphosate generated 96% of rye termination. Lower termination rates were associated with the spiral and the smooth drum rollers (76-85%) and the lowest rate, 43%, was for the control. Fourteen d after rolling, 2-stage, 4-stage, and spiral rollers rolling 1, 2, and 3 times had higher termination rates ranging from 92 to 100%. The smooth roller generated lower rates from 81 to 88%. The lowest termination rate was found for the control (62%). At 21 d after rolling, there were no statistical differences among the rollers and number of rolling passes generating 100% termination rates. The control had a significantly lower rate of 87%.

Across the three growing seasons, data indicated that rolling rye 3 times using the 4-stage or 2-stage rollers might be needed in cases where mechanical termination is the only option applicable for organically grown crops or when the time between cover-crop termination and planting the cash crop is limited to 7 d to achieve a termination rate above 90%, which is recommended to plant the cash crop into desiccated residue cover (Ashford and Reeves, 2003).

The overall average correlation between biomass of cereal rye and termination was extremely low (0.0036). Similarly, across the three growing seasons, correlation with respect to time after rolling between rye biomass and its termination was also low: -0.022, 0.057, and -0.054, for 7, 14, and 21 d, respectively. These results indicate that rye biomass amounts are independent of rolling treatments. Weather and soil conditions at each growing season are key factors for cover-crop production especially in the winter and early spring prior to termination.

Volumetric Soil Water Content. The VWC measurements 7, 14, and 21 d after rolling/crimping rye are shown in Table 6. In 2015, 1 d before the scheduled VWC measurement during the first week after rolling, there was a rain event of 27 mm, which resulted in a VWC average value > 20%. The lowest VWC was measured for standing rye (17.4 %) and the highest for the 2-stage roller rolling 2 times (22.2%) and the 4-stage roller rolling rye 3 times (22.1%). No rainfall occurred during 7, 14, and 21 d after rolling. Fourteen days after rolling the lowest VWC (10.7%) was measured for standing rye, and highest VWC (14.9%) was measured for the

4-stage roller/crimper rolling 3 times. Twenty-one days after rolling, the lowest VWC was associated with the 2-stage roller rolling one time (9.2%) and standing rye (9.4%); in contrast, the highest VWC was for the 2-stage roller (12.3%) and the 4-stage roller (13.7%) rolling three times.

In 2016, three rain events totaling 38 mm fell on the experimental area 3 d preceding the first 7 d of VWC evaluation after rolling. No statistical differences in VWC were found among the rolling treatments (21.5%) and the control (20.0%) during the 7 d after rolling. Fourteen days after rolling, the control plot had the lowest VWC (11.0%), followed by the smooth roller drum rolled once (11.2%) and 3 times (12.1%), and spiral roller rolling once (12.3%); whereas the 4-stage roller rolling 3 times had the highest VWC (15.1%), but not statistically significantly different than the 2-stage roller rolling 1 and 2 times, and for the spiral roller rolling 2 times, ranging from 14.2 to 14.5%. A similar trend with VWC levels continued 21 d after rolling, although VWC was slightly lower compared with 14 d after rolling. Again, the lowest VWC was associated with the control (10.2%) and the smooth drum rolling once (11.0%). The highest VWC was found for the 4-stage roller rolling 3 times (13.9%), but no different than the 4-stage roller rolling twice (13.0%), the 2-stage roller rolling twice (13.0%), and the smooth drum with glyphosate (13.5%).

In the 2017 growing season, the day after rolling/crimping application (27 and 28 April 2017), 33 mm of rain fell on the experimental area increasing soil water content. Another rain event (21 mm) occurred on 1 May. Following these two rain events, on 3 May 2017, the first VWC was measured 7 d after rolling, for which there were no statistical differences among all rolling treatments and the control (p = 0.1009) with a VWC from 13.7 to 16.7%. A rain of 23 mm fell between 7 and 14 d after rolling, maintaining VWC levels. Fourteen days after rolling, significant statistical differences among treatments were found with the highest VWC (13.3%) for the 4-stage roller rolling 3 times, followed by the 4-stage roller/crimper rolling twice (12.7%). The lowest VWC was obtained for standing rye (9.2%) and smooth drum roller (10.2%). Treatments including rolling 2 or 3 times by the 2-stage roller/crimper, 3 times by spiral roller/crimper, and smooth drum with glyphosate had

Table 6. Volumetric soil water content (%) of the surface soil (top 12 cm) for rollers/crimpers during three growing seasons

TRTmt name	No. of pass.	Growing Season								
		2015			2016			2017		
		Days after rolling/crimping								
		7	14	21	7	14	21	7	14	21
2-stage roller/ crimper	1	19.8 de[z]	11.7 fg	9.2 d	20.4	14.2 abc	12.2 bcd	15.0	10.6 cd	13.6
	2	22.2 a	14.3 abc	12.1 ab	20.4	14.3 ab	13.0 abc	15.4	11.6 bc	14.2
	3	20.7 bcd	14.3 abc	12.3 ab	20.5	13.5 bcd	12.4 bcd	15.4	11.8 bc	13.4
4-stage roller/ crimper	1	21.7 abc	13.1 bcdef	10.3 bcd	21.1	13.6 bcd	12.5 bcd	16.7	12.7 ab	13.6
	2	21.2 abcd	14.2 abcd	12.4 ab	21.5	14.0 bcd	13.0 abc	14.6	11.4 bcd	12.6
	3	22.1 ab	14.9 a	13.7 a	20.4	15.1 a	13.9 a	15.6	13.3 a	14.9
Spiral roller/ crimper	1	19.1 e	12.6 def	9.3 cd	20.0	12.3 efg	11.2 def	14.5	10.7 cd	12.6
	2	20.4 cde	12.5 def	11.3 bcd	21.0	14.5 ab	12.4 bcd	15.0	10.6 cd	12.9
	3	21.7 abc	14.4 ab	11.2 bcd	20.2	13.2 cde	12.5 bcd	15.9	11.6 bc	13.9
Smooth drum roller	1	19.8 de	12.6 cdef	10.9 bcd	20.5	11.3 gh	11.0 ef	15.2	10.2 de	11.9
	2	20.9 abcd	12.9 bcdef	10.4 bcd	20.7	13.1 def	11.5 def	14.8	10.8 cd	12.6
	3	21.0 abcd	13.5 abcde	11.5 abc	20.4	12.1 fg	11.6 de	13.7	10.6 cd	12.8
Smooth drum + Roundup (1 pass)		20.5 cde	12.3 efg	10.7 bcd	20.8	13.8 bcd	13.5 ab	15.7	11.9 bc	12.4
Standing Rye		17.4 f	10.7 g	9.4 cd	20.0	11.0 h	10.2 f	14.3	9.2 e	12.1
P-value		<0.0001	0.0056	0.0464	0.607	<0.0001	0.0018	0.101	0.0011	0.206

[z] Comparisons between means are valid only within each column. Treatment means are compared for each year and location using LSD procedure in SAS (2009). Treatment means followed by the same letter are not statistically different. Treatment means with different letters are statistically different, in that the mean with the higher letter has a mean statistically lower than the mean is it compared to (e.g., b < a).

VWC values from 11.6 to 11.9%. Additional rain of 12 mm occurred between 14 and 21 d after rolling. At 21 d after rolling, there were no statistically significant differences among the rolling treatments, and the VWC for the standing rye (12.1%) and the 4-stage roller/crimper rolling 3 times (14.9%) was adequate to plant the cotton into the rye residue cover.

Overall, across three years of experiments, the highest VWC averaged over 21 d of evaluation was associated with the 4-stage roller, rolling 3 times (16.1%), whereas the lowest VWC (13.6%) was found for the spiral roller rolling once. This higher VWC by the 4-stage roller might be related to greater damage to the plant due to higher crimping occurrence over the length of the stalk, which leads to faster plant death, allowing soil water conservation that is important during the 21-d period from termination for optimum cotton planting conditions. For all rolled rye treatments, VWC averaged over growing seasons and evaluation periods, was higher (14.7%) compared to the untreated control (12.7%). The lowest VWC by the control was most likely related to evapotranspiration of actively living plants and a partially exposed soil surface between plants that prompted higher evaporation of water from the soil.

Cotton Emergence Rate Index (ERI). The ERI results (% per day) from the three growing seasons are shown in Table 7. In 2015, the rolling treatments influenced ERI ($p = 0.0365$). A statistically significant higher ERI was associated with the spiral roller rolling 2 times (11.0) but no different than the spiral roller rolling 3 times (10.2), the 4-stage roller rolling once (10.7), the 2-stage roller/crimper rolling once (10.3) and twice (10.1), and the smooth drum roller rolling 1, 2, and 3 times (10.1-10.8); standing rye (control) was 10.4. The ERI for the 2-stage roller rolling 3 times and for the spiral roller rolling once was 9.4, and the smooth roller with glyphosate was 9.3. Statistically significant lower ERIs were obtained for the 4-stage roller rolling 2 times (8.8) and 3 times (7.4). This lower ERI was associated with the weather; some of the experimental area where the 4-stage roller treatment was placed had rainfall of 308 mm in May and June 2015 (AWIS, 2015) that flooded this area and inhibited cotton emergence. These results also might be associated with leaching of allelopathic chemicals from roller-terminated cereal rye residue. Studies conducted by Barnes and Putnam (1983) and Masiunas et al. (1995) showed that cereal rye residues left on the soil surface after termination were effective against broad-leafed weeds. Leaching of these chemicals can be intensified by rainfall, as water flowing through the mulch residue during its decomposition process speeds up leaching of allelopathic chemicals. This can suppress cotton germination for the abovementioned rolling treatments prone to be affected by rainfall and consequent flooding, which is noted by lower ERI values in these locations. Nakano et al. (2003) studied effects on chemicals leaching from plants in presence of water and stated that allelopathic leachate can be dissolved easily in water and released out to the environment. Higher ERI (10.4) for the control (standing rye) might be associated with plant tissue being undamaged allowing slowed decomposition process, so allelopathic chemicals do not leach out from the plant.

In the 2016 growing season, roller type and number of rolling passes did not statistically affect cotton emergence ($p = 0.9420$). The ERI ranged from 9.6 (smooth drum rolling 3 times) to 11.1 (spiral roller rolling 3 times). A similar trend continued in 2017, generating ERI from 10.0 to 11.1 without differences among rolling treatments ($p = 0.4334$). These ERI values indicated that there was no restriction from the cover-crop residue that might otherwise inhibit cotton germination. The ERI values averaged across the three growing seasons were also independent of rolling treatments ($p = 0.6367$) with ERI values ranging from 9.5 (4-stage roller rolling 3 times) to 10.8, both for the spiral roller and the smooth drum, rolling twice.

Cotton Population. Cotton population for the three growing seasons is shown in Table 8. The average cotton population was not affected by the rolling treatments ($p = 0.4648$), ranging from 126,922 (4-stage roller rolling 3 times) to 144,413 plants ha^{-1} (spiral roller/crimper rolling 3 times). Likewise, in 2015, the rolling treatments did not affect the cotton population ($p = 0.4467$), which averaged 146,815 plants ha^{-1}, ranging from 124,679 plants ha^{-1} (4-stage roller rolling 3 times) to 158,316 plants ha^{-1} (spiral roller/crimper rolling 2 times). However, there were significant statistical differences among blocks ($p < 0.0001$). Cotton population in Block 1 and Block 3 were 162,865 and 162,737 plants ha^{-1}, respectively, and were statistically significantly higher compared to Block 2 (146,463 plants ha^{-1}) and Block 4 (115,197 plants ha^{-1}), which had the lowest cotton population (LSD = 10,740 plants ha^{-1}). The main reason was that partial areas of Blocks 2 and 4 were flooded after a rain of 137 mm from 26 to 29 May 2015 (AWIS, 2015) that affected cotton emergence.

Table 7. Emergence rate index (ERI) in % per day for rollers/crimpers and passes during three growing seasons

Treatment name	No. of passes	Growing Season 2015	2016	2017	Average over three growing seasons
2-stage roller/ crimper	1	10.3 abc[z]	10.6	10.9	10.6
	2	10.1 abc	10.1	11.0	10.4
	3	9.4 bc	10.2	11.0	10.2
4-stage roller/ crimper	1	10.7ab	10.3	10.5	10.5
	2	8.8 cd	10.8	10.8	10.1
	3	7.4 d	10.4	10.7	9.5
Spiral roller/ crimper	1	9.4 bc	10.4	11.1	10.3
	2	11.0 a	10.8	10.7	10.8
	3	10.2 abc	11.1	10.2	10.5
Smooth drum roller	1	10.8 ab	9.7	10.2	10.2
	2	10.3 abc	10.4	11.6	10.8
	3	10.1 abc	9.6	10.0	9.9
Smooth drum + Roundup (1 pass)		9.3 bc	10.6	11.4	10.4
Standing Rye		10.4 ab	9.9	10.8	10.4
P-value		0.0365	0.9420	0.4334	0.6367
LSD		1.53	N/S	N/S	N/S

[z] Comparisons between means are valid only within each column. Treatment means are compared for each year and location using LSD procedure in SAS (2009). Treatment means followed by the same letter are not statistically different. Treatment means with different letters are statistically different, in that the mean with the higher letter has a mean statistically lower than the mean is it compared to (e.g., b < a).

Table 8. Cotton population (plants ha^{-1}) for rollers/crimpers and passes during three growing seasons

Treatment name	No. of passes	Growing Season 2015	2016	2017	Average over three growing seasons
2-stage roller/ crimper	1	145,310	131,855	131,407	136,190
	2	142,619	124,231	132,752	133,201
	3	150,691	127,819	137,686	138,732
4-stage roller/ crimper	1	150,243	132,752	124,231	135,742
	2	137,237	129,613	123,334	130,061
	3	124,679	121,988	134,098	126,922
Spiral roller/ crimper	1	146,207	135,443	131,855	137,835
	2	158,316	139,031	131,407	142,918
	3	156,073	144,413	132,752	144,413
Smooth drum roller	1	153,831	125,128	121,989	133,649
	2	147,104	128,716	132,752	136,190
	3	148,898	126,473	121,092	132,154
Smooth drum + Roundup (1 pass)		142,170	129,613	126,473	132,752
Standing Rye		152,037	127,819	130,958	136,938
P-value		0.4467	0.8266	0.9671	0.4648
LSD		N/S	N/S	N/S	N/S

Cotton population in 2016 was not dependent on rolling treatments (p = 0.8266), which ranged from 121,988 (4-stage roller rolling 3 times) to 144,413 (spiral roller/crimper rolling 3 times). Similar cotton population results were obtained in the 2017 growing season, as no significant statistical differences among roller type and number of passes were measured (p = 0.9671). The cotton population ranged from 121,092 plants (smooth roller rolling 3 times) to 137,686 plants ha^{-1} (2-stage roller/crimper rolling 3 times). In addition, over three growing seasons there were no interactions between rolling treatments and cotton population (p =

0.9985), suggesting rolling treatments for rye did not affect cotton population including any accumulative effects. Each growing season is independent and starts from planting cereal rye that grows through fall, winter, and spring until its recommended growth stage (i.e., milk growth stage) suitable for mechanical termination. Overall, the cotton population was related to soil water conditions during the time of plant establishment.

Cotton Lint Yield. Across the three growing seasons the cotton yield (lint fiber) averaged 1,368 kg ha^{-1} and was not dependent on the rolling treatments for rye (p = 0.9355) (Table 9). Average cotton seed yield in the 2015 growing season was 1,557 kg ha^{-1}, and as with the cotton population, rolling treatments did not influence cotton yield (p = 0.4287). Cotton yield ranged from 1,415 ha^{-1} (4-stage roller/crimper rolling 3 times) to 1,645 kg ha^{-1} (spiral roller/crimper rolling once) with p = 0.4287. However, over the three growing seasons, there were significant differences among blocks (p < 0.0001), specifically in 2015, the variable Block had p-values < 0.0001, indicating a high level of statistical significance and cotton yield difference. Cotton yield in Block 3 was the highest (1,691 kg ha^{-1}) followed by Block 1 (1,606 kg ha^{-1}). Statistically significantly lower cotton seed yield was produced in Block 4 (1,498 kg ha^{-1}) and Block 2 (1,434 kg ha^{-1}), although there were no statistically significant differences in cotton seed yield between Block 2 and Block 4 (LSD = 74 kg ha^{-1}). Slightly lower seed cotton seed yield in Blocks 2 and 4 was associated with the lower cotton emergence caused by the flooded parts of the experimental area. In contrast, in 2016, no statistically significant differences were measured among blocks (p = 0.3108) with cotton yield ranging from 1,069 to 1,130 kg ha^{-1}. Cotton yield averaged over treatments was lower (1,107 kg ha^{-1}) than in 2015 (p < 0.0001). In 2016, there were no statistically significant differences among roller types and number of passes (p = 0.0869). The seed cotton yield ranged from 976 ha^{-1} (2-stage, rolling 3 times) to 1,205 kg ha^{-1} (smooth drum roller plus glyphosate). The lowest cotton yield was in 2016 and was most likely due to low rainfall (359 mm) from May to October (AWIS, 2015). In contrast, during the same period in 2015 and 2017, total rain was 644 mm and 962 mm, respectively. These higher rainfall amounts helped maintain higher seed yields in 2015 and 2017. In 2017, the cotton yield was higher than in 2016 (1,441 kg ha^{-1}) but lower than in 2015. There were statistically significant differences in the yield among the blocks (p < 0.0001). Cotton yield in Blocks 1 and 3 was higher, 1,537 kg ha^{-1} and 1,557 kg ha^{-1}, respectively, followed by lower yield in Block 2 (1,413 kg ha^{-1}) and lowest yield in Block 4 (1,256 kg ha^{-1}). No difference in lint yield was measured among rolling treatments. The range for the cotton yield was between 1,284 ha^{-1} (smooth roller with glyphosate) and 1,563 kg ha^{-1} (4-stage roller rolling 3 times). Across the three growing seasons, rolling treatments did not affect the yield; however, the different weather conditions of each growing season, most likely affected the cotton lint yield.

Table 9. Cotton lint (fiber) yield (kg ha^{-1}) calculated from collected seed cotton yield (multiplied by 0.38, an average lint content in Alabama) for rollers/crimpers and number of passes during three growing seasons

Treatment name	Number of passes	Growing Season			Average over three growing seasons
		2015	2016	2017	
2-stage roller/ crimper	1	1582	1065	1427	1358
	2	1620	1116	1504	1413
	3	1552	976	1490	1339
4-stage roller/ crimper	1	1564	1075	1455	1365
	2	1496	1115	1459	1357
	3	1415	1020	1563	1333
Spiral roller/ crimper	1	1645	1094	1415	1385
	2	1531	1150	1446	1376
	3	1582	1132	1480	1398
Smooth drum roller	1	1536	1173	1449	1386
	2	1609	1133	1451	1398
	3	1503	1105	1412	1340
Smooth drum + Roundup (1 pass)		1601	1205	1284	1363
Standing Rye		1563	1146	1335	1348
P-value		0.4287	0.0869	0.2026	0.9355
LSD		N/S	N/S	N/S	N/S

Economic Considerations. Commercial availability of the roller/crimpers tested here is limited. Designs that are currently commercially available from different vendors are chevron and staggered straight-bar types both of which are not as effective as the multiple-stage rollers developed at the USDA-NSDL. The availability of designs (shop drawings for personal fabrication) offered are for producers who contact the USDA-NSDL and request particular specifications (working width, pull type, or 3-point hitch mounting, front or rear) that fit their own farm operation. Fabrication cost for the tested prototype of the experimental 2-stage roller/crimper (1.8-m wide) was $3,500, whereas the cost for the 4-stage roller (1.8-m wide) was $5,000 (internal USDA-NSDL data), keeping in mind that prototype costs are usually more compared to commercial production.

Effective mechanical termination of cover crops is especially crucial in sustainable organic agriculture where use of synthetic herbicides is prohibited. Comparing termination rates 7 d after rolling, cereal rye rolled by the smooth drum (no crimping) with glyphosate application was not statistically different than the 2-stage and 4-stage rollers/crimpers especially in 2016 and 2017 growing seasons. By utilizing effective, patented rolling technology, the cost and time of herbicide applications can be eliminated. Results from a previous field study conducted by Duzy and Kornecki (2019) indicated that the cost of herbicide application (including glyphosate) was $5.34 ha^{-1}. According to MSU (2016) data, the cost of labor was $13.40 h^{-1} for a machine operator and fuel cost was $0.528 L^{-1}. Rolling once using the 4-stage roller/crimper (equivalent to three of the 2-stage rollers in one assembly) can be treated as combining rolling 3 times over the same area by the 2-stage roller/crimper and curved roller. Cost savings per hectare (rolling once versus 3 times) was based on the labor and fuel cost (MSU, 2016). The average diesel consumption for rolling operation by a John Deere 6410 tractor with 77 kW engine at 4.8 km h^{-1} was 7.5 L h^{-1} (Kornecki, 2016). Based on these data, the cost of rolling once was $19.78 ha^{-1}. Therefore, savings of rolling once by 4-stage roller versus rolling 3 times by 2-stage and curved rollers would be $39.56 ha^{-1} along with substantial environmental benefits. According to the U.S. Environmental Protection Agency (2005), greenhouse gas emissions from 1.00 L of diesel fuel (containing 734 g of C) equates to 2,664 g (2.66 kg) of CO_2. Based on the above, saving 17 L ha^{-1} of fuel would reduce CO_2 amount by 45.5 kg ha^{-1}. Consequently, utilizing the 4-stage roller/crimper by merging three separate rolling operations into one run is an effective no-till farming practice that both reduces labor cost and provides environmental benefits in reducing CO_2 emissions into the environment.

SUMMARY AND CONCLUSIONS

Results from the three growing seasons indicated that the patented experimental roller/crimpers after rolling 2 or 3 times over the same cover-crop area were as effective in terminating the cereal rye cover crop as rolling rye with the smooth drum with an application of glyphosate. Data indicate that these rollers alone generated termination rates above 90% and are suitable for use in organic systems where applying synthetic herbicides is prohibited. In contrast, the curved roller did not generate effective termination due to a lack of dynamic forces from crimping bars that are essential in mechanical cover-crop termination. All rolled rye treatments had a higher soil water content (2% on average) compared to the standing rye indicating that the rolled residue covered soil surface, thus conserving soil water more effectively compared to the standing rye. Also, as determined in many studies, the layer of residue cover is beneficial in preventing weed germination due to mulch and allelopathic effects. In 2015, the rolling treatments affected the cotton ERI, but not in 2016 and 2017. Likewise, in the three growing seasons studied, cotton population and seed cotton yield were not affected by the rolling treatments, but weather likely did affect cotton yield. Generally, the new patented concept of the 4-stage roller/crimper performed successfully in cover-crop termination and provided an advantage in conserving soil water (VWC = 15.4%) during a 21-d period (from rye termination to planting cotton), which was 1.0% higher than other rollers, 0.8% higher than smooth roller with glyphosate, and 2.7% higher than the untreated rye. The VWC did not have significant effects on ERI and cotton yield, as these variables were dependent on soil moisture and residue cover during seed emergence and cotton boll development throughout the growing season. Because rye termination rates generated by the 4-stage roller/crimper were as effective as chemical termination (glyphosate), this innovative rolling technology can eliminate the cost of herbicide application. When comparing single rollers with the 4-stage roller, (combining three single rollers in one assembly, e.g., one run of 4-stage roller vs. three runs for single rollers), there is a reduction of labor cost, operation time, fuel usage, and emission of CO_2, therefore providing monetary benefits while protecting the environment.

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DISCLAIMER

The use of trade names or company names does not imply endorsement by the USDA-ARS.

REFERENCES

Agricultural Weather Information Service [AWIS]. . 2015. Agricultural Weather Information Service. Online at http://www.awis.com/ (verified 29 Oct. 2020).

Aikins, K.A., D.L. Antille, T.A. Jensen, and J. Blackwell. 2019. Performance comparison of residue management units of no-tillage sowing systems: A review. Eng. Agric., Environ. Food. 12:181–190. https://doi.org/10.1016/j.eaef.2018.12.006.

Ashford, D.L., and D.W. Reeves. 2003. Use of a mechanical roller crimper as an alternative kill method for cover crop. Am. J. Alternative Agric. 18:37–45.

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.L. Putnam. 1986. Evidence for allelopathy by residues and aqueous extracts of rye (*Secale cereale*). Weed Sci. 34(3):384–390.

Bowen, G., C. Shirley, and C. Cramer. 2000. Managing Cover Crops Profitably, 2nd ed. Sustainable Agriculture Network Handbook Series, Book 3. National Agricultural Library, Beltsville, MD.

Creamer, N.G., M.A. Bennett, B.R. Stinner, J. Cardina, and E.E. Regnier. 1996. Mechanisms of weed suppression in cover crop-based production systems. Hort. Sci. 31(3):410–413.

Derpsch, R.R. 1991. Controle da erosão no Paraná, Brazil: Sistemas de cobertura do solo, plantio directo e prepare conservacionista do solo. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. Eschborn, SP 245, Germany.

Derpsch, R., T. Friedrich, A. Kassam, and L. Hongwen. 2010. Current status of adoption of no-till farming in the world and some of its main benefits. Int. J. Agric. Biol. Eng. 3(1):1–25. DOI: 1934-6344.2010.01.001-025.

Duzy L.M., and T.S. Kornecki. 2019. Effects of cover crop termination and cotton planting methods on cotton production in conservation systems. Renewable Agric. Food Sys. 34:406–414. DOI: 10.1017/S1742170517000631.

Erbach, D.C. 1982. Tillage for continuous corn and corn-soybean rotation. Trans. ASAE. 25(4):906–911, 918.

Gomez, K.A., and A.A. Gomez. 1984. Statistical Procedures for Agricultural Research. 2nd Ed. John Wiley & Sons, Inc., New York, NY.

Hargrove, W.L., and W.W. Frye. 1987. The need for legume cover crops in conservation tillage production. p. 1–5. *In* J.F. Power (ed.), The Role of Legumes in Conservation Tillage Systems. Soil Conservation Society of America, Ankeny, IA.

Hoffman, L.M., L.A. Weston, J.C. Snyder, and E.E. Reginer. 1996. Allelopathic influence of germinating seeds and seedlings of cover crops and weed species. Weed Sci. 44(3):579–584.

Kern, J.S., and M.G. Johnson. 1993. Conservation tillage impacts on national soils and atmospheric carbon levels. Soil Sci. Soc. Am. J. 57(1):200–210.

Kornecki, T.S. 2011. Multistage crop roller. U.S. Patent Number 7,987,917 B1. Date issued: 2 Aug. 2011.

Kornecki, T.S. 2016. The effects of combined cover crop termination and planting in a cotton no-till system. Appl. Eng. Agric. 32(5):551–560. DOI: 10.13031/aea.32.11568.

Kornecki, T.S., A.J. Price, and R.L. Raper. 2006. Performance of different roller designs in terminating rye cover crop and reducing vibration. Appl. Eng. Agric. 22(5):633–641.

Kornecki, T.S., A.J. Price, R.L. Raper, and J.S. Bergtold. 2009. Effectiveness of different herbicide applicators mounted on a roller/crimper for accelerated rye cover crop termination. Appl. Eng. Agric. 25(6):819–826. DOI:10.13031/2013.29233.

Kornecki, T.S., F.J. Arriaga., and A.J. Price. 2012. Evaluation of methods to assess termination rates of cover crops using visual and non-visible light active sensors. Trans. ASABE. 55(3):733–741. http://dx.doi.org/10.13031/2013.41505.

Kornecki, T.S., F.J. Arriaga, A.J. Price, and K.S. Balkcom. 2013. Effects of recurrent rolling/crimping operations on cover crop termination, soil moisture, and soil strength for conservation organic systems Appl. Eng. Agric. 29(6):841–850. DOI: 10.13031/aea.29.10186.

Kornecki, T.S., A.J. Price, and K.S. Balkcom. 2015. Cotton population and yield following different cover crops and termination practices in an Alabama no-till system. J. Cotton Sci. 19:375–386.

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

McGregor, K.C., and C.K. Mutchler. 1992. Soil loss from conservation tillage for sorghum. Trans. ASAE. 35(6):1841–1845.

Mississippi State University [MSU]. 2016. 2016 Row Crop Input files. Online. Department of Agricultural Economics, Mississippi State University; Available at http://www.agecon.msstate.edu/whatwedo/budgets/generator/index.php

Nakano, H., E. Nakajama, Y. Fujii, K. Yamada, H. Shigemori, and K. Hasegawa. 2003. Leaching of allelopathic substance, L-tryptophan from the foliage of mesquite (*Prosopis juliflora* [Sw.]) plants by water spraying. Plant Growth Regul. 40:49–52.

Organic Trade Association. 2014. 2012 and Preliminary 2013. U.S. Organic Cotton Production & Marketing Trends. Jan. 2014. Available online at https://ota.com/sites/default/files/indexed_files/2012%20and%202013%20Organic%20Cotton%20Report.pdf (verified 29 Oct. 2020).

Reeves, D.W. 1994. Cover crops and rotations. p: 125-172. *In* J.L. Hatfield and B.A. Stewart (eds.), Advances in Soil Science, Crops Residue Management. Lewis Publishers, Boca Raton, FL. Available online at https://www.ars.usda.gov/ARSUserFiles/60100500/csr/ResearchPubs/reeves/reeves_94e.pdf (verified 05 Dec. 2020)

SAS. 2009. Proprietary Software Release 9.2. SAS Institute Inc., Cary, NC.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and Procedures of Statistics. A Biometrical Approach, 2nd ed. McGraw-Hill Publishing Co., New York, NY.

Taylor, C. 2015. Cover crops provide multiple benefits, higher yields. Farms.com. Jan 23, 2015. Online at https://www.farms.com/commentaries/cover-crops-provide-multiple-benefits-higher-yields-87095.aspx (verified 29 Oct. 2020).

Textile Exchange. 2014. Organic cotton is proven to cause less environmental damage than conventional cotton, new study shows. Available online at: https://www.prweb.com/pdfdownload/12341886.pdf (Verified 02 Dec 2020).

University of Georgia [UGA]. 2017. Cotton enterprise budgets. Online. College of Agricultural and Environmental Sciences, Agricultural and Applied Economics. Available at https://agecon.uga.edu/extension/budgets/historical-budgets.html#cotton.

USDA-Agricultural Marketing Service. Organic Cotton Market Summary. 2014, Volume 5, August, 2014. https://apps.ams.usda.gov/Cotton/AnnualCNMarketNewsReports/OrganicMarketSummary/2013-2014%20Organic-Cotton.pdf

United States Environmental Protection Agency. 2005. Office of Transportation and Air Quality. Emission Facts. EPA420-F-05-001. EPA, Washington, DC.

Zadoks, J.C., T.T. Chang, and C.F. Konzak. 1974. A decimal code for the growth stages of cereals. Weed Res. 14(6):415–421. http://dx.doi.org/10.1111/j.1365-3180.1974.tb01084.x.