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Cultural Strategies for Managing Weeds and Soil Moisture in Cover Crop Based No-Till Soybean Production

M. Scott Wells, S. Chris Reberg-Horton, and Steven B. Mirsky*

A four site-year study was conducted in North Carolina to evaluate the effects of soybean planting timing and row spacing on soil moisture, weed density, soybean lodging, and yield in a cover crop-based no-till organic soybean production system. Soybean planting timing included roll-kill/planting and roll-kill/delayed planting where soybean planting occurred either on the same day or approximately 2 wk later, respectively. Soybean row spacing included 19, 38, and 76 cm, and all treatments included a weedy check and weed-free treatment. Rye biomass production averaged above 10,000 kg ha^{-1} dry matter, which resulted in good weed control across all sites. Despite having good weed control throughout all treatments, weed coverage was highest in the 76-cm row-space treatment when compared to both the 19-cm and 38-cm row spacing in two of the four site-years. Soybean lodging is a potential consequence of no-till planting of soybeans in high residue mulches, and of the three row spacings, the 19-cm spacing exhibited the greatest incidence of lodging. Row spacing also influenced soybean yield; the 19- and 38-cm row spacing out yielded the 76-cm spacing by 10%. Soil volumetric water content (VWC) was higher in the cereal rye mulch treatments compared to the no rye checks. Furthermore, delaying soybean planting lowered soil water evaporation. However, the increased soil VWC in the rolled-rye treatment did not translate into increased soybean yield. The rolled-rye treatment exhibited significant ($P < 0.01$) increases in soil VWC when compared to the no-rye treatment at three of the four site-years. These results highlight planting date flexibility and potential risk to lodging that producers face when no-till planting organic soybeans.

Nomenclature: Glyphosate; s-metolachlor; imazethapyr; redroot pigweed, *Amaranthus retroflexus* L.; cereal rye, *Secale cereal* L.; DM, dry matter.

Key words: Cereal rye cover crop, conservation-tillage, no-till, organic soybean, roll-kill, roller-crimper, rotational no-till, soil moisture.

Weed management in organic soybean production utilizes a multi-faceted approach that may encompass crop rotations (Cavigelli et al. 2013), the use of cover crop mulches (Mirsky et al. 2013), and frequent cultivations (Place et al. 2009). Mechanical cultivation is commonly used to control weeds in organic soybean production, and in a setting of high weedseed bank densities, mechanical control of weeds via cultivation must occur several times during the critical weed-free period; for soybeans this is 30 d after planting (Gunsolus 1990; Lovely et al. 1958). These intensive and frequent cultivation events directly degrade soil health resulting in a loss of soil function (Mathew et al. 2012) including lower soil organic matter, reduced soil aggregate stability (Stenberg et al. 2000), greater erosion or risk (Holland 2004), and increased fuel and labor costs (Bernstein et al. 2011; Mirsky et al. 2012; Ryan 2010).

To balance the trade-offs between the need for weed control and soil conservation in organic soybean production, researchers and farmers across the United States have been developing a cover crop based approach that allows for no-till planting of soybean through a roll-crimped cereal rye mulch. This practice has shown promise in many regions of the United States (Delate et al. 2012; Mirsky et al. 2013; Wells et al. 2013). The use of roller-crimpers to manage cover crops was originally developed, and has been in use for many years, in Brazil (Derpsch et al. 1991). However, roller-crimper technology increased in popularity in the United States after the U.S. Department of Agriculture–Agricultural Research Service National Soil Dynamics Laboratory improved the design and the Rodale Institute popularized it (Kornecki et al. 2009; Rodale Institute 2012). The roller-crimper, a ground-driven implement, functions to terminate near-mature cover crops before the planting of the cash

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crops (Davis et al. 2010; Mirsky et al. 2013; Reberg-Horton et al. 2012).

Cover crop mulches have a complex impact on soil moisture. Mulches can reduce soil evaporation (Clark et al. 1997) and increase water infiltration (Munawar et al. 1990). However, cover crops can seriously reduce soil water content during their growth via transpiration, leading to lower soil moisture at planting (Price et al. 2009). Davis (2010) reported reduced soil moisture post termination in roll-killed treatments when compared to burn down treatments, and as a result, he discovered positive correlation between soil moisture after roll-kill and soybean yield. Herbicides enable farmers to terminate their rye earlier; however, organic farmers must rely on the roller-crimper alone for termination. At anthesis, commercially available roller crimpers can achieve approximately 85% control of the rye (Feekes 11.1) (Mirsky et al. 2009) and greater than 90% control by soft-dough (Feekes 11.2) stage (Ashford and Reeves 2003; Mischler et al. 2010; Reberg-Horton et al. 2012). A delay in cover crop termination extends the duration of transpiration, resulting in greater soil water deficiency at cash crop planting. Therefore, it has been suggested to synchronize planting the cash crop, post cover crop termination, with a precipitation event (Ashford and Reeves 2003; Price et al. 2009).

Another factor that governs water availability is row spacing. Soybeans express a high degree of morphological plasticity, which allows the plant to compensate for different row spacings (Heiffig et al. 2009). While narrow rows (i.e., 38 cm or less) often yield higher than wide rows, the yield advantage is minor, ranging from 5 to 8% (Cox and Cherney 2011; Pedersen and Lauer 2003). However, narrow row spacing is thought to make soybeans more vulnerable to late season drought (Walker et al. 2010; Heatherly and Spurlock 1999). The cultural practice of planting soybean in narrow rows also carries important weed control implications for organic farmers. Crop competitiveness over weeds increases as plant density becomes more equidistant through an increase in light interception via the soybeans (De Bruin and Pedersen 2008; Shibles and Weber 1966; Weber et al. 1966). However, should physical suppression through a mulch or competition from a soybean crop fail to control weeds, there are no economical options for supplemental control in organic soybean production. With wide row spacing (i.e., 76 cm or greater), high residue cultivation is a supplemental weed control option (Smith et al. 2011). Wider row spacings (38 to 76 cm) can be carried out with a planter, while narrow row spacings require a drill. While no-till drills have improved greatly over the last decade, they do not have the same number of options for residue management such as double row cleaners (Grisso et al. 2009). Any potential advantage reducing row spacing may have in terms of equidistant plant spacing can be lost if poor seed to soil contact results in patchy stands.

The objective of this study was to develop basic agronomic recommendations for soybean management in rolled mulch systems. Three row spacings were tested, 19, 38, and 76 cm, and two soybean planting dates post rye roll-kill termination (intended to synchronize planting with a precipitation event) to examine their impacts on soil moisture and soybean yield. Finally, the interactions of these factors with weed management were assessed by including a weed-free check for every treatment combination; thus allowing a direct quantification of yield loss due to weeds for every treatment.

Material and Methods

Field experiments were conducted at three locations including the Center for Environmental Farming Systems in Goldsboro, NC (2012) (35.38291°N, −78.035846°W), Caswell Research Farm in Kinston, NC (2011 and 2012) (35.273206°N, −77.623816°W), and Piedmont Research Station in Salisbury, NC (2012) (35.68503°N, −80.60338°W). All site-years were managed organically, with two exceptions; the weed-free checks received PRE and POST herbicide weed control, and rye cover crop fertility requirements were met via urea ammonium nitrate (UAN).

The soil type in Goldsboro was a Wickham loamy sand (fine-loamy, mixed, semiactive, thermic Typic Hapludults) with 2 to 6% slope; Kinston was a Johns loamy sand (fine-loamy over sandy or sandy-skeletal, siliceous, semiactive, thermic Aquic Hapludults) with 0 to 2% slope; Kenansville was a loamy sand (loamy, siliceous, subactive, thermic Arenic Hapludults) with 0 to 3% slope; and Salisbury was a Mecklenburg clay loam (fine, mixed, active, thermic Ultic Hapludalfs) with 2 to 8% slope, moderately eroded.

The experiment was a compete factorial using a split-plot experimental design with six replicates. Treatments consisted of three factors: (1) soybean row spacing as the main plots (19 cm, 38 cm, and 76 cm), (2) soybean planting date (“Early” vs. “Late”), and (3) weed management (“+ Herbicide” and "−Herbicide"). In addition to the 12 treatments resulting from crossing these factors, four supplementary check plots were added that had no rye residue. These check plots were all planted on 76-cm row spacing. The additional checks were (1) no rye, early, + herbicide, (2) no rye, early, −herbicide, (3) no rye, late, + herbicide, and (4) no rye, early, −herbicide. Since the additional checks were planted on 76-cm row spacing, they were randomly assigned to subplots within 76-cm main plots.

For all site-years, fields were disked and field cultivated to remove any existing vegetation in the fall prior to cover crop planting. Lime, phosphorus, and potassium were applied according to soil tests before cover crop establishment. To ensure maximum cereal rye biomass, fall (30 kg ha^{-1}) and spring (60 kg ha^{-1}) nitrogen was applied as UAN at three of the four locations where N carryover was minimal due to lack of manure history and soil type. Salisbury 2012 received only 60 kg ha^{-1} of N based on credits from manure carryover. A cereal rye ('Wheeler') cover crop was drilled (13-cm row spacing at 135 kg ha^{-1}) at all site-years. Redroot pigweed seeds were frost sown to ensure uniform weed seedbank densities at three of the four site-years. Frost seeding was not necessary at Salisbury (2012) since their long-term no-till fields have high and uniform pigweed densities. No-rye weed-free (NR+H) and weedy checks (NR−H) were established to elucidate the combined and independent effects of a cereal rye cover crop and herbicides on weed control and subsequent soybean performance. The no cereal rye check plots were established in early spring for all site-years with a burn down application of glyphosate (Honcho® Plus, at 0.85 kg ai ha^{-1}, Monsanto Company, 800 N Lindbergh Blvd, St. Louis, MO). During mid to late May, the cover crop was roll-killed at soft-dough (Feekes growth stage 11.2; Zadoks growth stage 85) with a 3.1-m roller-crimper (I&J Manufacturing, Gap, PA) parallel to the cover crop drilling direction (Table 1).

Following cover crop termination, a class VI maturity group soybean [*Glycine max* (L.) Merr.] was planted parallel to rolling at 20.7 plants m^{-1} in the 38- and 76-cm row spacing treatments. The 38- and 76-cm row spacing treatment was achieved with a no-till planter (Model 7200 Max Emerge, Conservation Tillage, John Deere, Moline, IL) equipped with Yetter Shark Tooth® residue managers (Yetter Profitable Solutions, P.O. Box 358, 109 S. McDonough, Colchester, IL 62326) to assist planting into the rye residue. Since we lacked splitter units for the no-till planter, the 38-cm row spacing treatment was achieved with two passes of the above-described no-till 76-cm row spaced planter. The impact of making two passes (extra tire tracks) with the 76-cm row spaced planter could help kill the rolled rye, but since the rye maturity was at or past soft dough, no additional control of the rye was observed. Soybeans were no-till drilled (Model 1560 No-till Drill, John Deere, Moline, IL) to implement the 19-cm treatment at 12.7 plants m^{-1}. Planting dates for all three spacings occurred either on the same day as the roll-kill termination of the rye (Table 1) or 14 d later.

Table 1. Planting dates, cover crop growth stages, and percent control via roller crimper at Goldsboro, Kinston and Salisbury, NC (2011 to 2012).

Site-year	Soybean planting dates: Early	Soybean planting dates: Late	Cover drop maturity at roll-kill[a]: Rye[b]	Cover crop control via roller crimper
2011				
Kinston	May 2	May 23	11.2	100%
2012				
Goldsboro	May 15	June 6	11.2	100%
Kinston	May 10	June 1	11.2	100%
Salisbury	May 22	June 4	11.4	100%

[a] Roll-kill termination of the cover crop occurred once at each location during the "Early" soybean planting date.
[b] Rye growth stage taken at roll-kill using the Feekes scale.

Targeted plant populations were 21 seeds m^{-1} of row for both the 76- and 38-cm row spacings or 545,000 and 272,000 seeds ha^{-1} on an area basis. Matching populations based on seeds m^{-1} as opposed to seeds ha^{-1} was chosen for two reasons. First, previous studies in the region found that most weed escapes were near row and not between row for both soybeans (Smith et al. 2011) and corn (Parr et al. 2011). Second, with good weed control, both populations should be well above the population necessary to achieve maximum yield. The targeted plant population for the 19-cm row spacing was only 13 m^{-1}. This target was chosen because it is near the maximum rate achievable by many drills. Also, this rate results in 670,000 seeds ha^{-1}, which is considered an extremely high rate for the region and further increases could result in severe lodging if good stand establishment were achieved.

The primary weed control method consisted of preplant burn down of the NR+H and NR−H with glyphosate. In addition to preplant burn down of the NR+H treatments and rolled-rye with herbicide

(RC+H), weed control received S-metolachlor as pre-emergent (Metal® II, at 1.91 kg ai ha^{-1}, Syngenta Crop Protection, LLC, P.O. Box 18300, Greensboro, NC 27419). In addition to the PRE, imazethapyr (Pursuit®, at 74.7g ai ha^{-1}, BASF Corporation, 26 Davis Dr., Research Triangle Park, NC 27709) was applied 3 wk after soybean planting (WAP) to achieve POST weed control. Herbicide treatments consisted of glyphosate and S-metolachlor (Metal II, at 1.91 kg ai ha^{-1}, Syngenta Crop Protection) on the day of rolling and imazethapyr (Pursuit at 74.7 g ai ha^{-1}, BASF Corporation) 3 WAP. The no rye, −herbicide (NR−H) plots can be viewed as the weedy checks for the experiment and serve as indicators of weed emergence at each location. Hand-weeding was done in addition to herbicide applications, as needed, to ensure weed free conditions throughout the season in the NR+H and RC+H plots.

To quantify the effects of planting date, row spacing, and weeds on soybean performance, we collected an array of plant and soil metrics. Plant metrics included cereal rye biomass, weed cover, soybean stand counts, soybean lodging, soybean yield, and soil water content. Cover crop biomass was collected on the same day the rye was roll-killed using 0.5 m^2 quadrats and dried at 60 C for 72 h prior to recording dry weight. Weed cover was visually rated across the entire plot for all treatments at 12 WAP on a percent basis, with no cover as 0% and complete weed coverage as 100%. Prior to soybean harvest, soybean lodging ratings were visually scored for all site-years. The lodging rating scale ranged from no lodging represented as a rating of 0, and extreme lodging where the soybeans would not be harvestable rated as a 4. Before soybean harvest, plot edges were mowed down to 12.2 m to minimize any potential edge effect. Soybean yield data were collected on the four (38 cm) and two (76 cm) interior soybean rows. The 19-cm row spacing (i.e., drilled plots) treatments were harvested according to the width of the plot combine header (152 cm) rows. All yield calculations were adjusted to take into account both harvest length and width, and reported at 15.5% moisture. In 2012, soil volumetric water content (VWC) measurements were added to the list of parameters. VWC (Fieldscout TDR 300 Soil Moisture Meter, Spectrum Technologies, Plainfield, IL) was monitored across all plots at both planting dates (Table 1) to a depth of 10 cm.

All parameters were analyzed using PROC MIXED, and treatments were modeled as fixed effects, and blocks and site-years (soybean yield only) were random effects (SAS 2006). The lack of homogeneous variance associated with the percent weed cover and percent soybean emergence data across all treatments was corrected via the arcsine of the square root of the dependent variable (Steel et al. 1996). Transformed means were back-transformed for presentation, and all means were separated using preplanned contrasts (SAS 2006; Steel et al. 1996).

Table 2. Mixed-model ANOVA averaged over site-years to test generality for soybean percent emergence, soybean yield, and percent weed coverage.

Fixed effects	% Soybean emergence of total planted[a]	Soybean yield[b]	% Weed cover[c]
	ANOVA		
Row spacing (S)	***	**	NS
Planting date (D)	NS[d]	NS	NS
Herbicide (H)	—	NS	—
S × D	NS	NS	NS
S × H	—	NS	—
D × H	—	P < 0.12	—
S × × D	—	NS	—
Site-year (Y)	NS	**	NS
Y × D	NS	NS	P < 0.11
Y × S	P < 0.07	NS	*
Y × H	—	NS	—
Y × S × D	**	NS	NS
Y × H × D	—	NS	—
Y × S × H	—	P < 0.13	—
Y × S × H × D	—	NS	—

[a] Soybean % emergence of total planted was averaged over "Herbicide," and soybean emergence data were $\sin^{-1}(x)^{0.5}$ transformed to meet ANOVA assumptions.

[b] Soybean yield averaged over all four site-years: Kinston (2011 and 2012), Goldsboro (2012), and Salisbury (2012).

[c] The plus herbicide treatments were removed when calculating % weed cover, and % weed coverage data were $\sin^{-1}(x)^{0.5}$ transformed to meet ANOVA assumptions.

[d] Abbreviation: NS, not significant.

*, **, and *** represent significance of F tests at $\alpha = 0.05$, 0.01, and 0.001, respectively.

A combined analysis of soybean yield across the four site-years was attempted, but due to large F values for three-way interaction of herbicide and row spacing with site-year (P < 0.13) further investigation to ascertain if treatments were uniform over site-years was required (Table 2). Using the Alterative Log Likelihood Ratio Test to test the reduced model (i.e., the null hypothesis) where site-year does not interact with the treatments vs. the full model that includes all site-year by treatment interactions produced a $\chi^2_{1df} = 1.1$ with

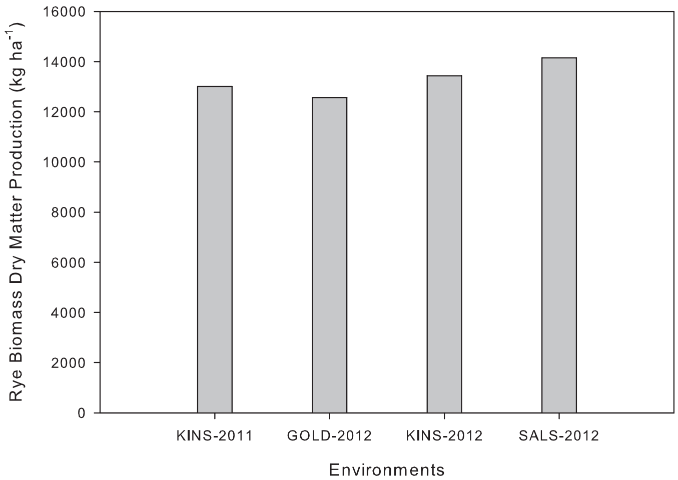

Figure 1. Cereal rye cover crop biomass production at roll-kill for Goldsboro, Kinston, and Salisbury, NC (2011 to 2012). GOLD, Goldsboro; KINS, Kinston; SALS, Salisbury.

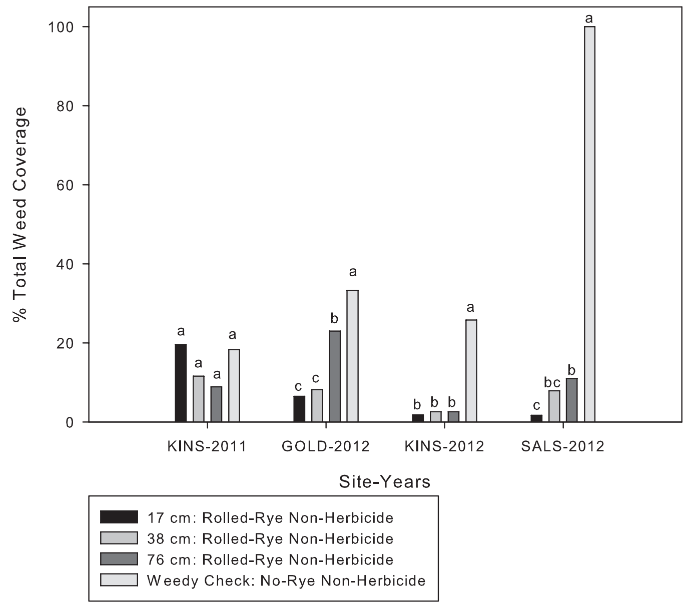

Figure 2. Soybean postcanopy closure percent weed coverage analysis for each site-year: Kinston (2011 and 2012), Goldsboro (2012), and Salisbury (2012). Data reflect only the no-herbicide treatments averaged over the planting date effects. There was neither significant planting date nor interactions with planting date and soybean row spacing. The weedy check treatments represent a bareground no-till no-herbicide treatment with the purpose of illustrating the relative weed densities at each site-year. Means followed by the same letter are not significantly different based on Fisher's protected LSD test at $P < 0.05$. GOLD, Goldsboro; KINS, Kinston; SALS, Salisbury.

an corresponding P value of 0.15 thus failing to reject the Null hypothesis (i.e., reduced model) (Huelsenbeck and Crandall 1997). The failure to reject and the nonsignificant site-year by treatment interactions provides adequate evidence to generalize soybean yield over the four site-years (Steel et al. 1996). Performing a combined analysis on percent weed coverage, percent volumetric water, and percent soybean emergence data across site-years was not possible due to the significant site-year by treatment interactions (Table 2) (Steel et al. 1996).

Results and Discussion

Cover Crop Performance. Cover crop biomass production across all four site-years exceeded 12,000 kg ha^{-1} dry matter (Figure 1). At each location, rye biomass production far exceeded the suggested critical threshold for optimal weed suppression in the southeastern United States of 9,000 kg ha^{-1} (Smith et al. 2011). Only one of the site years was conducted on a field with a long (dairy and poultry) manuring history. The other site-years were amended with N to mimic the conditions of most organic farms in the region where years of dairy and poultry manure application created substantial N carryover (Engoke 2012). For farms with less history of manure or less N carryover due to soil type, these rye biomass levels are overly high. Due to the low organic matter soils of the southeastern United States and warmer soil temperatures, N fertility is critical in optimizing biomass production. Rye biomass production in the southeastern United States has been repeatedly reported above 9,000 kg ha^{-1} (Reberg-Horton et al. 2012; Wells et al. 2013).

Weed Control. High cereal rye biomass resulted in low weed cover at three of the four site-years, which resulted in minimal impact on soybean performance across all four site-years (Figure 2). ANOVA conducted on weed cover and site-year by planting date interaction prevented averaging over site-year (Table 2). Planting date did not affect weed coverage data across all four site-years. The lack of a planting date effect on weed converge was surprising since the delay in planting (after roller-crimping) would have allowed weeds to germinate and emerge prior to soybean establishment. Row spacing did impact weed cover at two of the four site-years where lowest weed cover estimates were obtained in the 19- and 38-cm row spacing treatments at Goldsboro and the 19-cm row spacing at Salisbury (Figure 2). At Kinston (2011), Goldsboro, and Salisbury, there was greater weed coverage in the RC−H when compared to the RC+H treatments ($P < 0.05$), where the RC+H plots were weed-free. Weed competitiveness potential, as defined by percent ground cover in the NR−H (i.e., weedy check) plots, was low at Kinston (2011) (mean = 18.3, standard error [SE] = 14.1) and Goldsboro (2012) (mean = 33.3, SE = 3.6)

(Figure 2). Salisbury weed cover was the greatest as compared to observations made across all site-years (mean = 100, SE = 4.8) (Figure 2).

At Goldsboro 2012 and Salisbury 2012, weed cover was significantly affected by soybean row spacing, where the 76-cm row spacing had the greatest percent weed coverage when compared to the 38- and 19-cm row spacings (Figure 2). The 38-cm row spacing provides an advantage for between row weeds since the between rows are shaded by the soybean canopy sooner (Burnside and Moomaw 1977; Chandler et al. 2001; Dalley et al. 2004; Harder et al. 2007; Mickelson and Renner 1997; Young et al. 2001). The decision to match seeding rates between the 76- and 38-cm row spacings on a seed count per length of row basis also results in different populations on a per area basis and lends further advantage to the 38-cm treatments. However, for near-row weeds, the 38-cm can be construed as a disadvantage when row cleaners are used because more mulch is disturbed on an area basis. The mixed results observed on weed coverage (Figure 2) suggest these tradeoffs could play out differently in each environment. However, the precision with which optimal row spacing could be assessed in this study was comprised by the low numbers of weeds observed. When mulch biomass reaches these levels, the finer grained effects of row spacing may be difficult to discern. The performance of the 19-cm spacing is better than expected. Despite poor emergence in some locations, the drilled plots still resulted in robust canopies by July and low weed coverage. The limitations of a drill, which resulted in less than 50% emergence at some locations (Figure 3), were largely overcome at these site years by having a sufficiently high seeding rate. On an area basis, the populations were still in excess of the minimal populations recommended for achieving maximal yield in the region (J. Dunphy, personal communication).

Even though the rye biomass at soybean planting was in excess of 10,000 kg ha^{-1} dry matter (Figure 1), weeds were present in the roll-killed rye minus herbicide treatments (RC−H) (Figure 2). Yetter Shark Tooth (Yetter Profitable Solutions) residue managers were utilized to ensure proper soybean seed placement during planting along with reducing the hair pinning of the rye in the soybean furrow. The residue managers both cut and move mulch elements from the row in which the crop is planted, allowing light penetration to the soil surface in the 38- and 76-cm row spacing. As a result, weed growth and development was primarily from the within the soybean row compared to between the crop rows.

Soybean Emergence and Lodging. An individual analysis for each site-year was performed for soybean emergence and lodging. Soybean emergence was excellent for the 38- and 76-cm row spacings at all four site-years (including the 76-cm No-Rye Check), where more than 80% of the soybeans planted emerged (Figure 3). Row spacing significantly impacted percent emergence at three of the four site-years where greater emergence was observed in both the 38- and 76-cm row spacings ($P < 0.05$) (Figure 3). With exception to Goldsboro, the drilled treatments (i.e., 19-cm spacing) had approximately 50% lower emergence proportional to target planting populations when compared the percent soybean emergences of total planted in the 38- and 76-cm treatments (Figure 3). The no-till drill was ineffective at cutting through 10,000 kg ha^{-1} rye biomass. Even with the assist of hydraulic down force, the coulters failed to effectively cut through the rye, leaving the soybean seed either on the surface of the rye or hair-pinned in the rye mulch. Despite not being able to consistently achieve proper seed placement with the no-till drill, emergence at Goldsboro, and Kinston (2012) to a lesser degree, was better than the other two site years. On the other hand, Goldsboro had nearly 90% emergence of the drilled soybeans (Figure 3). One possible explanation for the increased soybean emergence, in lieu of seed placement issues, was the series of precipitation events occurring prior and post planting at Goldsboro and Kinston (2012). Both locations received greater than 2-cm of precipitation over a 5-d period (data not presented). During this time frame, the soybean could have germinated in the mulch layer increasing the overall percent emergence.

Soybean lodging was observed at Kinston (2011 and 2012) and Salisbury (2012) (Figure 4). At the three site-years where soybean lodging was observed, the no-rye treatments exhibited the lowest incidence of lodging when compared to the roll-rye treatments (Figure 4). With exception to Kinston (2011), the no-rye treatments exhibited significantly lower lodging than the rolled-rye treatments where decreasing row spacing resulted in increased prevalence in soybean lodging (Figure 4). The phenomenon of soybean lodging in the high residue mulched cover crop system is not fully understood. It is possible that the observed soybean lodging is a consequence of planting soybeans into high residue cover crop

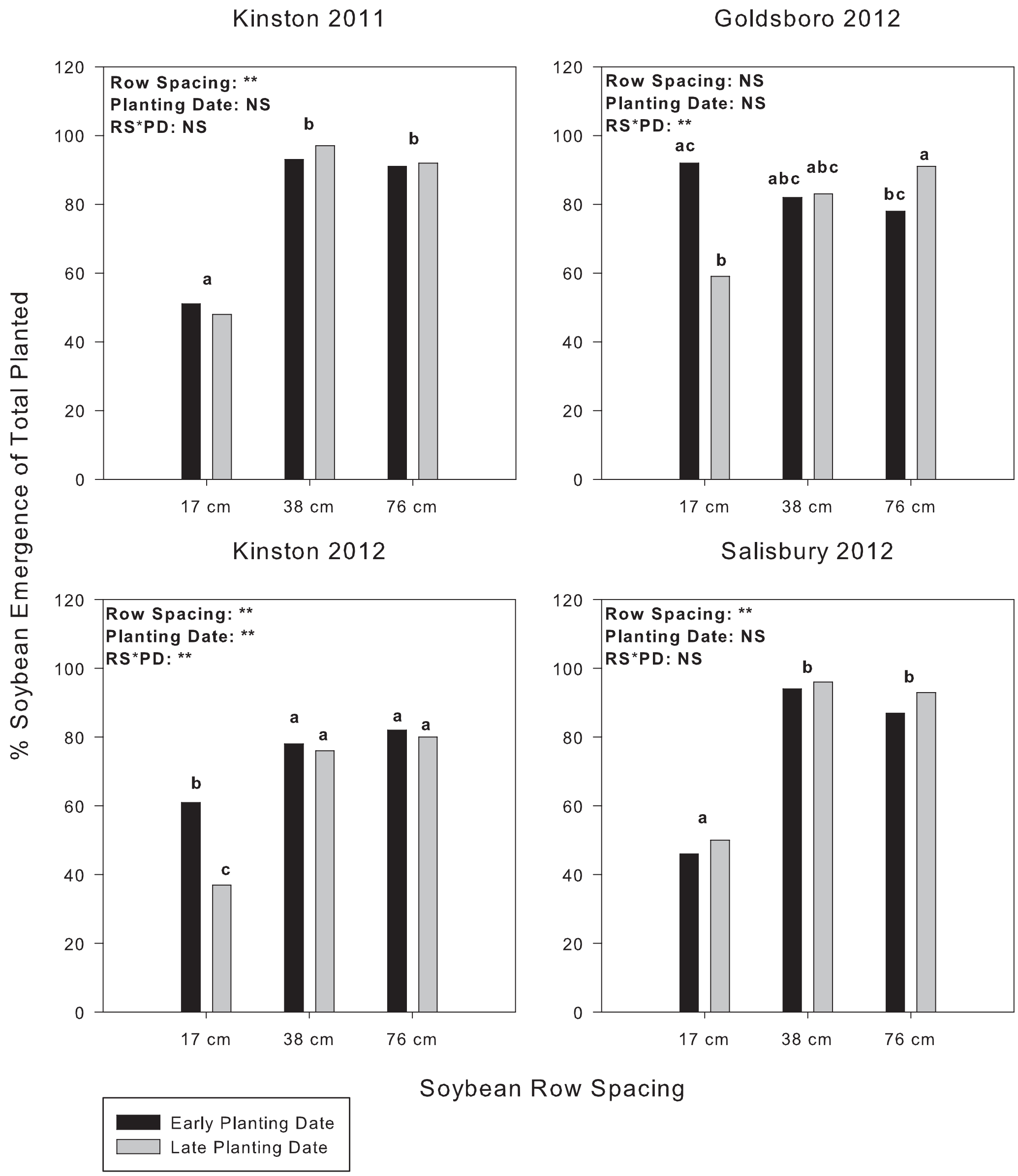

Figure 3. Soybean emergence as a percentage of the total planted for each site-year. Means followed by the same letter are not significantly different based on Fisher's protected LSD test at P < 0.05.

mulches. Smith et al. (2011) reported similar lodging of soybeans produced in high residue mulch system where lodging persisted in the roll-killed rye treatments, whereas no lodging was observed in the no-rye check treatments. It is important to note that even though the soybeans at three out of four site-years did experience lodging, there was no effect on soybean yield; however, harvest time was increased due to the reduction in combined speed necessary to harvest the lodged soybeans.

Soybean Yield and Soil Moisture. Soybean yield analysis was averaged across all four site-years where soybean row spacing was found to significantly ($P < 0.01$) impact yield (Table 2). Even though there was observed weed coverage at all four site-years (Figure 2), the weed coverage did not lead to a detectable yield decline as evident by the equivalent soybean yields between the no-till weed-free check (NR+H) and the 76 cm row spacing (Table 3). Recall that soybean populations in all three row spacing treatments were greater than 185,000 ha^{-1}, which is enough to maximize yield in the absence of weeds. At all four site-years, the narrow and intermediate row spacings (19 and 38 cm) outyielded both the 76-cm RC−H and NR+H treatments (Table 3). The increased yield observed in narrow row soybeans is consistent with non-mulched systems results. Several studies have demonstrated yield increases with narrower row spacing (ranging between 39.1 and 76 cm) (Bullock et al. 1998; De Bruin and Pedersen 2008; Grau et al.

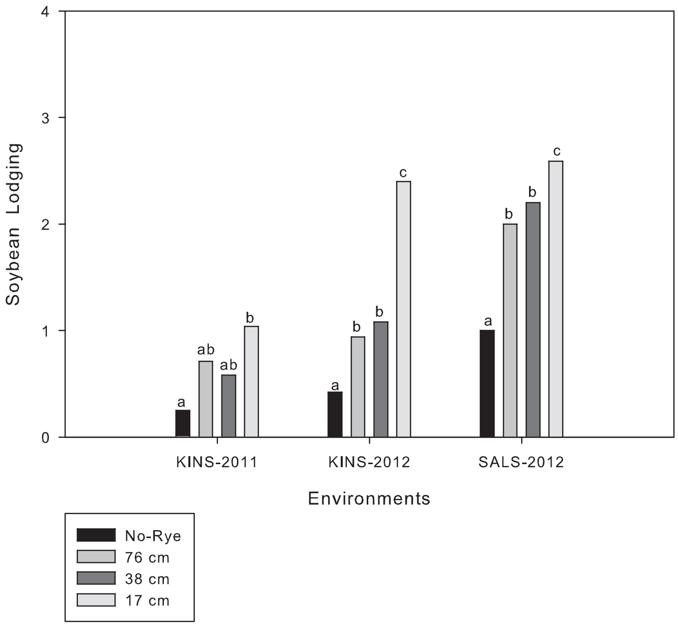

Figure 4. Soybean lodging at Kinston and Salisbury (2011 to 2012) with no lodging represented by a rating of 0, and not harvestable rated as a 4. There was no observed lodging at Goldsboro (2012). Lodging data were averaged over planting date effects. Means followed by the same letter are not significantly different based on Fisher's protected LSD test at P < 0.05. KINS, Kinston; SALS, Salisbury.

1994). Contrary to our hypothesis, no planting date (i.e., Early and Late) effect on soybean yield was detected (Table 3). Previous studies have found lower yields on sandy soil for same-day plantings due to cover crop extraction of soil moisture (Price et al. 2009; Reberg-Horton et al. 2012; Reeves 1994). The lack of response to planting date on crop performance may be attributed to an unusually wet spring. In 2012 at Goldsboro, Kinston, and Salisbury, the month of May received above average precipitation (Figure 5).

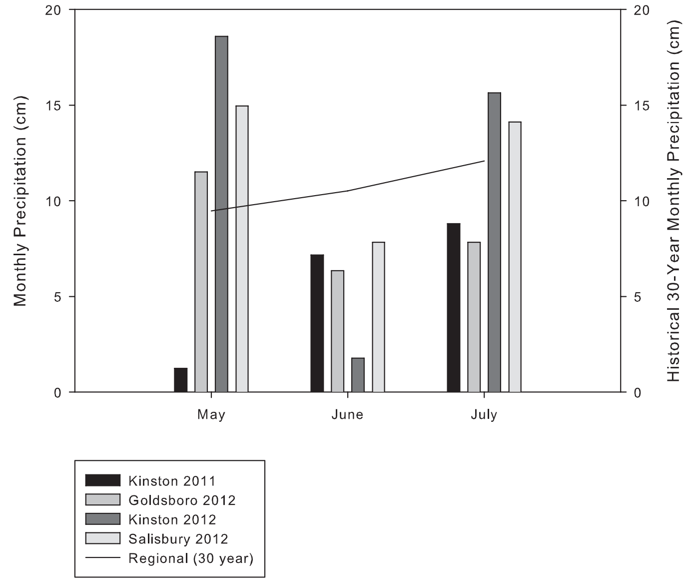

Figure 5. Monthly precipitation (cm) and 30-yr normal for Goldsboro (2012), Kinston (2011 and 2012), and Salisbury (2012). Weather data provided by the State Climate Office of North Carolina.

By the late soybean planting date, nearly 3 wk had passed following roll-kill termination of the rye cover crops and early soybean planting. During this time frame, the roll-killed rye cover crop was fully desiccated, and at all three site-years, the rolled-rye treatments had greater (P < 0.01) soil VWC when compared to the no-rye treatments (Figure 6). Surprisingly there was no detectable planting date effect on %VWC. By early June, at the late soybean planting date, monthly precipitation was nearly half of the 30-yr average (Figure 5). Thick mulches have several mechanisms for increasing soil moisture, including enhanced water infiltration and reduced evaporative stress (Aase and Tanaka 1987; Wagner-Riddle et al.

Table 3. ANOVA of soybean yield averaged over site-years, planting date, and herbicide for Kinston (2011 to 2012), Goldsboro (2012), and Salisbury (2012), NC.

	Combined analysis[a]	Kinston 2011	Goldsboro 2012	Kinston 2012	Salisbury 2012
	kg ha^{-1}				
Row space (cm)	**	—	—	—	—
19	3,308 a[c]	2,036	1,818	3,340	4,521
38	3,292 a	2,024	2,037	3,444	4,450
76	2,968 b	1,806	1,680	3,101	3,955
No-Rye + Herbicide 76	2,957 b	1,845	1,723	3,114	3,932
Soybean planting date[b]	NS[d]	—	—	—	—
Early	2,868	1,986	1,784	3,284	4,178
Late	2,840	1,869	1,843	3,218	4,252

[a] Soybean yield generalized over Kinston (2011 and 2012), Goldsboro (2012), and Salisbury (2012).
[b] Roll-kill and soybean planting date: early planting date refers to roll-kill of cover crops and planting of soybeans occurring on the same day. Late planting date refers to soybeans planting date that occurred (approximately) 2 wk after roll-kill of the rye cover crops.
[c] Means followed by the same letter are not significantly different based on Fisher's protected LSD test at P < 0.05.
[d] Abbreviations: NS, not significant at P < 0.05; * significant at 0.05 level; ** significant at 0.01 level.

1994). Despite the potential of cover crop mulches to deplete early spring water content via transpiration, cover crop mulches can increase moisture conservation throughout the summer and potentially enhance yields during a drought stressed season (Campbell et al. 1984; Clark et al. 1997).

In conclusion, this study demonstrated the utility of a cover crop-based approach to organic no-till soybean production. Our results support our initial hypothesis that a soybean planting date occurring 2 wk post-termination of the cereal rye cover crop will mitigate soil moisture loses. Specifically, our work highlights that once a soil profile is recharged with water post cover crop termination, a cover crop mulch will conserve soil moisture during the growing season via reduced evaporation. In our case, the improved water retention did not translate into improvements in soybean emergence and yield since the study was conducted during years of adequate summer precipitation. These findings are important during drier seasons, when the gains in soil VWC by the late planting date and continued moisture conservation of roll-killed cover crop mulches could minimize drought severity (Campbell et al. 1984; Clark et al. 1997).

Narrowing the soybean row spacing significantly improved soybean yield and weed control across all site-years. Despite out-yielding the 76-cm row spacing, more research is required both into innovated high-residue no-till drill improvements that ensure proper seed placement admit high biomass mulches before recommending the adoption of 19-cm spaced soybeans. Since the 38-cm row spacing performed equivalently in soybean yield and weed control of the 19-cm spacing, we recommend the 38-cm row spacing due to reduced incidence of lodging when compared to the 19-cm spacing. This research highlights that during years of average and above average precipitation, delayed planting following the roll-kill termination of cover crop mulches can have no impact on soybean performance. Rye biomass production at roll-kill along with planter technologies that ensures proper soybean seed placement, while minimizing disturbance to the cover crop mulch, is paramount in providing favorable settings for optimal soybean yield in an organic setting. Further research is needed to quantify what mechanisms are responsible for soybean lodging in the high residue mulch systems.

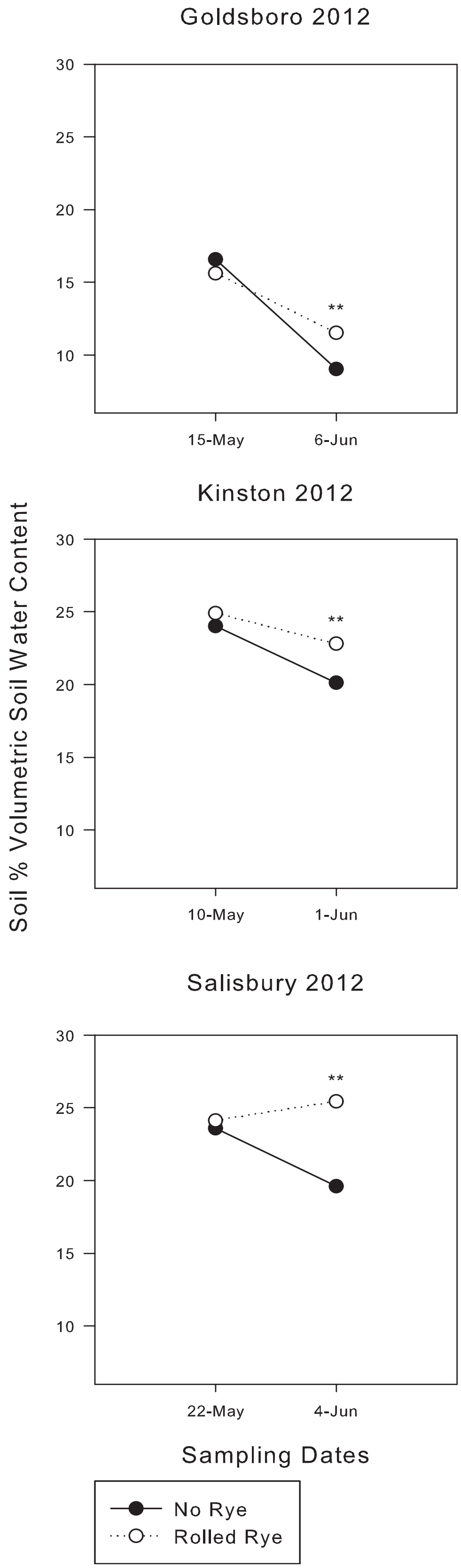

Figure 6. Percent soil volumetric water content (VWC) shown for Kinston, Goldsboro, and Salisbury (2012). Sampling intervals for all three locations correspond to soybean planting dates (i.e., Early and Late) where planting date was not found to

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influence %VWC. Percent VWC was measured across all treatments at a depth of 12 cm and averaged over planting date effects. * Significant at 0.05 level; ** Significant at 0.01 level.

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