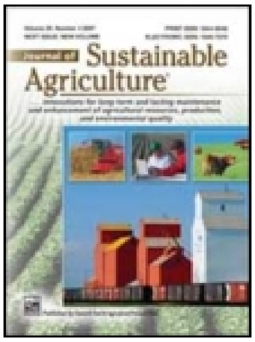

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Residue Management Practice Effects on Soybean Establishment and Growth in a Young Wheat-Soybean Double-Cropping System

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ABSTRACT. Double-cropping wheat (*Triticum aestivum* L.) and soybean [*Glycine max* (L.) Merr.] is popular throughout the mid-southern United States. To ensure an adequate stand, it is imperative that soybean be planted as soon as possible after wheat harvest due to an already

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shortened growing season following wheat. Typically, wheat residue is burned, and then conventional tillage (CT) is used to prepare a seedbed for soybean planting. However, residue burning has serious negative environmental consequences. The objective of this study was to examine effects of tillage [CT and no-tillage (NT)], residue burning (burn and no burn), and wheat-residue level (high and low) on soybean stand establishment, growth, and production over three cropping cycles at two locations on silt-loam Alfisols in eastern Arkansas. Soybean plant populations between 10 and 30 days after planting were higher ($p < 0.02$) under NT than CT in most year-location combinations, while most without wheat residue burning were equivalent to those with burning. Soybean plant populations were unaffected by N rate/wheat-residue level in most year-location combinations. Mid-season soybean leaf area index was higher ($p < 0.03$) under NT than CT for two of four year-location combinations. Soybean yields under NT were equivalent to yields under CT in all year-location combinations. Results indicate that the alternative pre-plant field preparation combination of no residue burning followed by NT can perform as well as the more traditional combination of burning followed by CT in the wheat-soybean double-crop system in the mid-southern United States. doi:10.1300/J064v29n02_08

KEYWORDS. No-tillage, burning, yield, soybean, wheat, double-crop, residue, Arkansas

INTRODUCTION

In the United States, long-term sustainability of farmland and escalating production costs are increasing concerns of today's growers. Alternative soybean management systems, such as double-crop production, can serve to promote sustainability and increase farm earnings. The wheat-soybean double-crop combination is popular throughout the mid-South, especially in Arkansas. Between 1995 and 2004, approximately 1.3 million ha of soybean were planted per year in Arkansas (AASS, 2004), and double-crop soybean has accounted for an average of 25% of the land area planted to soybean in Arkansas over the past 20 years (NASS, 2003). Benefits of the double-crop system include increased profits due to more efficiently used inputs, decreased erosion, and reduced soil-water losses by runoff and evaporation (Sanford, 1982).

Wheat is typically harvested in late spring, and soybean yield loss commonly occurs if planting is delayed beyond June 15 (UACES, 2000); thus expeditious planting of soybean after wheat harvest is imperative. Many growers burn wheat residue directly after wheat harvest to improve seedbed preparation and eliminate possible sites for insect pests and plant pathogens. Aside from these advantages, NeSmith et al. (1987) concluded that burning residue was a matter of convenience and was of no agronomic benefit.

Burning plant residues adds carbon dioxide (CO_2) to the atmosphere and, therefore, prevents return of carbon (C) to the soil. Generally, soils in eastern Arkansas have relatively low levels of organic matter, and the return of plant materials to the soil would help build organic matter and soil C levels. Returning organic materials to the soil enhances soil quality and reduces soil erosion and runoff.

Though residue burning is popular, some growers have adopted alternative post-wheat harvest operations such as conservation tillage or no-tillage (NT). New and improved equipment has made planting after minimal tillage more feasible in high-residue conditions (Kelley and Sweeney, 1998). New methods produce comparable yields to conventional tillage (CT) and reduce production costs (Touchton and Johnson, 1982). In addition, current legislation in California bans crop residue burning (CARB, 2004). Such laws are not in effect in the mid-South, but there is a national trend towards banning agricultural crop residue burning.

NeSmith et al. (1987) reported that soybean grown after moldboard tillage had a faster vegetative growth rate than after NT, but NT produced comparable yield. Dickey et al. (1994) also reported that NT had no influence on soybean yield for the first 3 years in an 8-yr soybean-grain sorghum (*Sorghum bicolor* (L.) Moench) double-crop experiment, but in the last 5 years, NT produced higher soybean and grain sorghum yields. However, other studies have demonstrated that tillage system, whether CT or NT, often has little to no effect on soybean yield regardless of time under a specific tillage system (Bharati et al., 1986; Elmore, 1987; Elmore, 1990).

Though recognized as a soil conservation practice, the NT system is not recommended for all situations. Equivalent or increased yields under NT compared to other tillage systems have been observed on coarse and medium textured soils (Hairston et al., 1990). Conversely, others have observed negative yield responses to NT on finer-textured soils and have suggested incorporating occasional deep tillage to alleviate a developing traffic pan as one way to combat this negative effect on yield (Hairston et al., 1984; Dick and Van Doren, 1985; Vyn et al., 1998).

Caviness et al. (1986) and Hairston et al. (1987) reported that wheat residue might have an allelopathic effect on soybean leading to decreased germination and early growth. Surface residue can also be a herbicide barrier (Banks and Robinson, 1982; Daniels and Scott, 1991). With the adoption of glyphosate-resistant soybean cultivars, the need for pre-emergence herbicides has been greatly reduced.

Wheat grown in a double-crop rotation with soybean in Arkansas requires large amounts of water for maximum yield (Scott et al., 1987). The high water demand by the wheat crop can leave the soil depleted of water at the time of soybean planting (Daniels and Scott, 1991; Sanford, 1982; Pearce et al., 1993). Dao (1993) reported that seedling emergence is negatively affected, and early vegetative growth and seedling development are affected more by a soil-water deficit than by any other input or environmental factor. NeSmith et al. (1987) reported that NT paired with non-burning resulted in 30- 40% higher soil-water contents than CT in the upper 10 cm of soil. Vyn et al. (1998) also stated that soil water increased when soybean was planted into standing wheat residue compared to CT practices.

In much of the US, cool, wet soils can delay planting and seed germination. However, soybean planted in a double-cropping system in Arkansas must often germinate in hot, dry conditions of early summer. The water-conserving effect of wheat residue could potentially increase soybean germination rates and increase stand establishment in reduced or NT systems. No-tillage planting without residue burning might also improve seed quality by increasing plant available water. Tyler and Overton (1982) showed that incidence of purple stain and wrinkled seed coats decreased and soybean germination increased when soybeans were planted using NT.

Many studies have addressed the effect of NT on soybean yield, but few have dealt with the effect of burning on soybean production in a wheat-soybean double-crop system in the mid-South. Few of these studies have been conducted within the past 10 years. The availability of glyphosate-resistant soybean cultivars and current NT drills further justifies the need for new and additional research into the wheat-soybean double-crop production system. In addition, potential prohibitive legislation and increased environmental awareness require demonstration of the viability and cultural soundness of alternative wheat-residue management practices. Therefore, the objective of this study was to evaluate the effects of alternative wheat residue management practices (i.e., CT vs. NT, burn vs. no burn, and high vs. low wheat residue levels) on soybean establishment, growth, and grain yield within the first three cycles of a wheat-soybean double-crop production system in the Mississippi Delta region of eastern Arkansas.

MATERIALS AND METHODS

Site Description

A 3 yr field study was conducted at two locations in east-central Arkansas. Locations were the University of Arkansas Pine Tree Branch Station (PTBS; 35° 7′ 10.54′′N and 90° 45′ 51.56′′ W) and the Cotton Branch Experiment Station (CBES; 34° 44′ 2.26′′ N and 90° 45′ 51.56′′ W). The soil was a Calhoun silt loam (fine-silty, mixed, thermic, Typic Glossaqualf) at PTBS and a Calloway silt loam (fine-silty, mixed, thermic, Glossaquic Fragiudalf) at CBES (Gray and Catlett, 1966; Gray, 1977; SSD, 2004).

The 30 yr mean annual temperature in the region containing both study locations is 15.6°C with a mean January minimum of −2.4°C and a mean July maximum of 32.8°C (NOAA, 2002). The 30 yr mean annual precipitation in the region is 128 cm (NOAA, 2002).

Experimental Design

A three-factor, split-strip-plot experimental design was used in this study. The three factors were (1) residue burning (i.e., burn vs. no burn), (2) tillage (i.e., NT vs. CT), and iii) wheat-residue level (i.e., high vs. low, achieved with different N fertilization levels). The burn factor was arranged as a randomized complete block with two replications. The tillage factor was arranged as a randomized complete block with three replications and was stripped across burn treatments. Wheat-residue level formed a split-plot factor within each tillage-burn combination; thus the entire study area at each location consisted of a total of 48 plots.

Field Management and Operations

Prior to the initiation of this study, both study locations were cropped under CT methods; thus the results of this study represent a short-term NT history. Grain sorghum and soybean were previously grown in a non-double-cropped system at PTBS and CBES, respectively.

In Fall 2001, field preparation included disking twice to a depth of approximately 7.5 cm with a tandem disk followed by landplaning and field cultivation at PTBS. At CBES, the field was prepared by disking twice to a depth of approximately 7.5 cm with a tandem disk followed by field cultivation prior to planting. Before wheat planting at CBES in 2001, 20 kg N ha^{-1}, 22.5 kg P ha^{-1}, and 56 kg K ha^{-1} were broadcast applied to the entire study area. In addition, 1120 kg ha^{-1} of pelletized limestone was broadcast at CBES to adjust pH prior to wheat planting. No lime or fertilizer was applied prior to wheat planting at PTBS. In November 2001, "Coker 9663" wheat was drill-seeded with a 19 cm row spacing at a rate of 110 kg ha^{-1} at PTBS and 112 kg ha^{-1} at CBES. In Spring 2002, forty-eight 3 m by 6 m plots were established at both locations. All plots were broadcast fertilized with 101 kg N ha^{-1} as urea (46% N) in early March 2002. To obtain different levels of wheat residue, the high-residue plots were fertilized with an additional 101 kg N ha^{-1} broadcast application of urea during the late-jointing stage in late March 2002. Since different N rates were used to establish different residue levels this treatment is hereafter referred to as the N rate/wheat-residue level treatment. The N fertilization rates applied were chosen based on the optimum N rate for wheat grown on silt-loam soils in Arkansas (101 kg N ha^{-1} total; UACES, 1999) such that excess N remaining in the soil following uptake by the wheat would be minimal; thus it was assumed that carry-over N was not a factor affecting the subsequent soybean crop.

Wheat was harvested with a plot combine in early June 2002 at both locations. After wheat harvest, one-half of the plots were burned by igniting one side of the block of plots with a propane torch. Burning took place immediately after harvest at PTBS, but was delayed at CBES until just prior to soybean planting. Following burning, the CT treatment was imposed, which consisted of disking twice to a depth of approximately 7.5 cm with a tandem disk and seedbed smoothing (i.e., mechanical break down of soil clods) with a soil conditioner prior to planting.

Glyphosate-resistant soybean, "Pioneer 95B32", maturity group 5.3, was planted in mid-June 2002 at 100 kg ha^{-1} at PTBS and 47 kg ha^{-1} at CBES. A higher seeding rate was needed at PTBS because of extremely low soil moisture conditions at time of planting and to ensure stand development at a similar time as that of CBES. Soybean was drill-seeded with different drills at both locations on a 19 cm row spacing. Due to prolonged hot and dry conditions, sprinkle irrigation was also used at PTBS approximately 10 d after planting to ensure adequate stands. The use of a plot combine for harvesting was not possible in 2002 due to prolonged wet soil conditions, thus soybean was hand-harvested for yield determination in early November 2002 by collecting the total aboveground biomass from two adjacent 1-m row sections of the middle rows in each plot.

The remaining soybean stubble was left standing in the plots. Soybean aboveground biomass samples were dried for 3 d at 70°C. Seeds were subsequently collected with a stationary thresher and weighed.

Wheat (Coker 9663) was drill-seeded in mid-November 2002 with a 19 cm row spacing at a rate of 90 kg ha^{-1} at both locations. In Spring 2003, the same 3 m by 6 m plots as used the previous year were broadcast fertilized with 101 kg N ha^{-1} as urea in early March followed by an additional 101 kg N ha^{-1} broadcast application of urea applied to the high-residue plots during the late-jointing stage in early April. No P or K was applied in 2003. Wheat was harvested with a plot combine in early June 2003 at PTBS, but harvest was delayed about two weeks due to rain at CBES. Burning and tillage treatments were imposed immediately after wheat harvest at both locations. The CT treatment imposed in 2003 was the same as that imposed in 2002.

Glyphosate-resistant soybean (Pioneer 95B32, maturity group 5.3) was planted in mid-June 2003 at 90 kg seed ha^{-1} at PTBS and in late June at 107 kg seed ha^{-1} at CBES. Soybean was drill-seeded with different drills at both locations with 19 cm row spacing. Soybean was harvested with a plot combine from the middle 1.5 m by 6 m length of all plots in late October 2003 at both locations.

Wheat (Coker 9663) was drill-seeded in mid-November 2003 with a 19 cm row spacing at a rate of 90 kg ha^{-1} at both locations. In Spring 2004, the same 3 m by 6 m plots as the previous year were broadcast fertilized with 101 kg N ha^{-1} as urea in early March followed by an additional 101 kg N ha^{-1} broadcast application of urea applied to the high-residue plots during the late-jointing stage in early April. Wheat was harvested with a plot combine in early June 2004 and burning and tillage treatments were imposed immediately after wheat harvest at both locations. The CT treatment imposed in 2004 was the same as that imposed the previous two years.

Due to prolonged wet-soil conditions, soybean planting in 2004 was delayed over one month at both locations. Glyphosate-resistant soybean (Pioneer 95B32, maturity group 5.3) was planted in early July 2004 at PTBS and late July at CBES at similar rates as in 2003. Soybean was drill-seeded with different drills at both locations with 19-cm row spacing. Soybean was harvested with a plot combine from the middle 1.5 m by 6-m length of all plots in early November 2004 at PTBS, but harvest was delayed until early December at CBES due to prolonged wet-soil conditions. Soybean was subsequently hand-harvested at CBES for yield determination by collecting the total aboveground biomass from a representative 1-m^2 area in each plot. Soybean aboveground biomass samples were dried for 3 d at 70°C. Seeds were collected with a stationary thresher and weighed. Soybean yields each year were adjusted and reported on a 13% moisture basis.

Each year plots were flood irrigated at PTBS and furrow irrigated at CBES based on visual observations of soil moisture and plant stress throughout the season. Weeds and insects were controlled according to University of Arkansas Cooperative Extension Service recommendations (UACES, 2003a,) on an as-needed basis.

Pre-Soybean Soil Properties

Prior to planting soybean in 2002, ten 2 cm diameter soil cores were collected and composited from the 0- to 10 cm depth of each plot. Soil samples were oven dried at 70°C for 48 h, crushed, sieved through a 2 mm mesh screen, and used for particle-size analysis using the hydrometer method (Arshad et al., 1996). Dried and sieved soil was also extracted with Mehlich-3 extractant solution (Tucker, 1992) in a 1:10 soil-to-extractant-solution ratio and analyzed for extractable phosphorus (P) and potassium (K) using inductively coupled argon-plasma spectrophotometry (CIROS CCD model, Spectro Analytical Instruments, MA). Soil pH and electrical conductivity (EC) were determined with an electrode on a 1:2 soil-to-water solution. Organic matter was determined by weight-loss-on-ignition after 2 h at 360°C (Schulte and Hopkins, 1996). Total N and C were determined by high-temperature combustion using a LECO CN-2000 analyzer (LECO Corp., St. Joseph, MI). Soil C:N ratios were calculated from measured total N and C concentrations.

Plant Measurements

Following wheat harvest, but prior to tillage, residue burning, and soybean planting each year, the residue that had passed through the combine was uniformly spread by hand back onto the plot from which it came and all residue was cut to the soil surface with a tractor-mounted rear rotary mower. Mowing is a practice not commonly conducted in eastern Arkansas, but was done to create a residue-covered surface that, depending on amount of residue present, would affect early season soybean growth and establishment. Surface residue levels were measured each year prior to soybean planting by cutting and collecting the residue within a 0.5 by

0.5-m metal frame in each non-burned plot (i.e., n = 24). Residue samples were oven dried at 55°C for 3 d and weighed.

In 2002 and 2003, soybean plant populations were recorded at 8, 10, or 30 days after planting (DAP) at both locations from two 1 m row sections of each plot and averaged for one observation per plot. In 2004, soybean plant populations were measured in two 1-m row sections of each plot and averaged at 18 and 26 DAP at CBES and PTBS, respectively. Leaf area index was measured non-destructively at approximately the R-6 growth stage roughly 90 DAP in 2002 and 2003 with a LI-COR LAI-2000 (LI-COR, Inc., Lincoln, NE) plant canopy analyzer (Wells and Norman, 1991). Since the soybeans were drill-seeded, one above- and one below-canopy light measurement was performed to constitute one LAI measurement per plot either in the early evening with a low sun angle or during a uniformly overcast day.

Statistical Analyses

Soil physical and chemical properties, measured following the first wheat harvest and prior to imposing any treatments for the first soybean crop, were subjected to *t*-tests, with or without equal variance depending on a homogeneity of variance test, to evaluate inherent soil property differences between locations using Minitab (Version 13.31, Minitab, Inc., State College, PA). Coefficients of variation (CV) were also calculated for initial soil chemical properties to assess uniformity among plots at each location.

Due to dissimilar cropping histories between locations, the recent establishment of the NT production system, and dissimilar rainfall patterns at soybean planting among years, year was not explicitly tested as a factor affecting any soybean measurement in this study. Similarly, due to dissimilar fertilization schemes prior to the initial wheat crop and dissimilar soybean seeding rates between locations and years, location was also not explicitly tested as a factor affecting soybean response to tillage, burning, or N rate/wheat-residue level. Therefore, for each of the six year-location combinations, a three-way analysis of variance (ANOVA) was conducted to determine the effects of burning, tillage, N rate/wheat-residue level, and their interactions on early-season soybean plant population, mid-season LAI, and yield using the general linear model of SAS (Version 8.1, SAS Institute, Cary, NC). Least significant differences (LSD) for significant interactions were calculated according to table 14.10 in Kuehl (1994). A similar ANOVA was conducted for each year-location combination separately to evaluate whether the two levels of N fertilizer applied to the previous wheat crop actually produced two different levels of above-ground residue following wheat harvest and mowing into which the subsequent soybean crop was planted. Linear correlations were also performed between soybean plant populations, LAI, and yield.

RESULTS AND DISCUSSION

Pre-Soybean Soil Properties

Prior to the initial soybean growing season in 2002, soil physical and chemical properties in the top 10 cm differed between locations (Table 1). Sand content was 0.04 kg kg^{-1} higher ($p < 0.001$), while clay content was 0.04 kg kg^{-1} lower ($p < 0.001$) at CBES than PTBS, but the surface soil texture at both locations was silt loam. In addition, soil pH, EC, organic matter, total C, and total N concentration, and C:N ratio were lower (p <

TABLE 1. Selected soil properties from the top 10 cm for two locations in eastern Arkansas prior to the initial (2002) soybean growing season. Mean values[±standard errors (SE)] and coefficients of variation (CV) are reported (n = 48).

Soil property	Location 1 (PTBS)		Location 2 (CBES)	
	$\bar{x}$ (SE)	CV (%)	$\bar{x}$ (SE)[a]	CV (%)
Physical				
Sand (kg kg^{-1})	0.12 (<0.01)	21.7	0.16 (<0.01)*	15.2
Silt (kg kg^{-1})	0.73 (<0.01)	2.3	0.73 (<0.01)	3.3
Clay (kg kg^{-1})	0.15 (<0.01)	15.6	0.11 (<0.01)*	29.8
Chemical				
pH	7.56 (0.03)	3.2	6.77 (0.02)*	2.5
Electrical conductivity (dS m^{-1})	0.19 (<0.01)	10.5	0.16 (<0.01)*	18.8
Extractable P (kg ha^{-1})	23.4 (0.7)	21.8	52.9 (1.1)*	15.0
Extractable K (kg ha^{-1})	78.1 (0.9)	8.3	165 (2.8)*	11.7
Organic matter (g kg^{-1})	26.4 (0.04)	10.0	18.6 (0.03)*	12.6
Total N (g kg^{-1})	0.99 (0.03)	17.5	0.86 (0.03)*	22.3
Total C (g kg^{-1})	12.6 (0.2)	12.3	7.55 (0.2)*	13.8
C:N ratio	12.8 (0.2)	10.4	8.85 (0.1)*	10.8

[a]An asterisk (*) denotes a significant difference ($p \leq 0.001$) between locations based on a two-sample t-test with or without equal variances.

0.001), but extractable soil P and K were higher ($p < 0.001$) at CBES than PTBS. Differences in 0 to 10 cm soil properties between locations further justify exclusion of location as a factor affecting soybean establishment and growth measurements in this study.

Wheat Residue Levels

Additional N added to wheat at the late-jointing stage produced significantly more wheat residue ($p = 0.025$) compared with plots receiving the single N application in only one of the six-year-location combinations (2003 at CBES; Table 2). However, in four of the other five non-significant year-location combinations, mean wheat residue mass was numerically higher for the high than the low N rate/wheat-residue treatment indicating a potential trend if the within-treatment variability had been lower. The lack of statistical significance with the high vs. low N rate/wheat-residue treatment comparison was likely a result of mowing following harvest causing increased variability among plots in the amount of residue on the soil surface into which soybean was subsequently planted.

TABLE 2. Effect of N application on soil surface wheat residue levels following mowing and prior to soybean planting at two locations in eastern Arkansas, Cotton Branch Experiment Station (CBES) and Pine Tree Branch Station (PTBS), in 2002, 2003, and 2004. A single application of 101 kg N ha^{-1} was used to establish the Low and a split application of 101 + 101 kg N ha^{-1} was used to establish the High wheat-residue-level treatment. Mean wheat residue levels are reported (n =12) with standard errors in parentheses.

	Wheat residue level (kg ha^{-1})	
Year/Location	Low	High
2002		
CBES	3916 (367)	3254 (237)
PTBS	2939 (371)	3157 (341)
2003		
CBES	4137 (334)	6168 (635)*
PTBS	1908 (155)	2629 (253)
2004		
CBES	6026 (532)	7677 (848)
PTBS	3916 (384)	4892 (783)

* Significant treatment difference ($p = 0.025$).

Plant Populations

Burning, tillage, and N rate/wheat-residue level each affected early-season soybean plant population at some point during the 3-yr study (Table 3). There was a significant burn × tillage interaction by 8 DAP in 2002 at CBES, where soybean planted under NT following residue burning had a higher mean plant population (2.7 plants m^{-1}) than soybean planted under NT without burning (0.9 plants m^{-1}) and soybean planted under CT following residue burning (1.7 plants m^{-1}) (Figure 1A). Nitrogen rate/wheat-residue level did not affect soybean plant populations by 8 DAP at CBES in 2002. By 8 DAP in 2002 at PTBS, there was also a significant N rate/wheat-residue level × burn interaction, where the combination of high N rate/wheat-residue level followed by burning resulted in a significantly lower soybean population (1.3 plants m^{-1}) than the combination of low N rate/wheat-residue level followed by non-burning (3.1 plants m^{-1}) (Figure 2A). Neither tillage nor burning alone affected soybean plant populations by 8 DAP at PTBS in 2002.

By 10 DAP in 2003, only tillage affected soybean population at CBES (Table 3), where the soybean population under NT (10.0 plants m^{-1}) was higher ($p = 0.005$) than that under CT (7.3 plants m^{-1}). Similarly, none of the treatment factors affected soybean populations by 10 DAP at PTBS in 2003.

By 30 DAP, it is reasonable to expect similar effects on soybean populations as were evident earlier in the growing season (i.e., at 8 or 10 DAP). However, there were no consistent effects on soybean population by 30 DAP. By 30 DAP in 2002 at CBES, a significant burn × N rate/wheat-residue level interaction occurred (Table 3), such that higher plant populations resulted from the low N rate/wheat-residue treatment followed by burning (3.2 plants m^{-}) than from the high N rate/wheat-residue treatment without burning (1.8 plants m^{-1}) (Figure 2B).

In contrast to the effects on soybean populations by 30 DAP at CBES in 2002, only tillage affected soybean populations by 30 DAP at PTBS in 2002, where soybean populations were higher ($p = 0.014$) under NT (13.3 plants m^{-1}) than under CT (3.7 plants m^{-1}). Since plant available water was limited at PTBS for several days after soybean planting in 2002, plots were sprinkle irrigated to promote adequate stand establishment. Therefore, the residue remaining on the soil surface under NT likely reduced water loss by evaporation resulting in slightly higher soil moisture contents, a well-documented and common result under NT (NeSmith et al.,

TABLE 3. Analysis of variance results for the effects of burning (Burn), tillage (Till), and N rate/wheat-residue level (Res) on soybean plant population at various days after planting (DAP) at two locations in eastern Arkansas, Cotton Branch Experiment Station (CBES) and Pine Tree Branch Station (PTBS), in 2002, 2003, and 2004.

			2002				2003				2004	
			8 DAP		30 DAP		10 DAP		30 DAP		18 DAP	26 DAP
Main effect/ Interactions	tdf[a]	edf[b]	CBES	PTBS	CBES	PTBS	CBES	PTBS	CBES	PTBS	CBES	PTBS
			P									
Burn	1	1	0.012	0.846	0.213	0.869	0.846	0.234	0.381	0.930	0.136	0.417
Till	1	2	0.397	0.062	0.404	0.014	0.005	0.497	0.007	0.079	0.024	0.092
Res	1	5	0.415	0.007	0.490	0.660	0.651	0.946	0.004	0.501	0.763	0.840
Burn × Till	1	5	0.042	0.407	0.296	0.180	0.343	0.958	0.041	0.363	0.060	0.054
Burn × Res	1	5	0.141	0.009	0.030	0.564	0.652	0.072	0.395	0.646	0.072	0.773
Till × Res	1	5	0.800	0.472	0.086	0.620	0.578	0.230	0.381	0.095	0.051	0.388
Burn × Till × Res	1	5	0.953	0.460	0.433	0.694	0.508	0.342	0.868	0.072	0.156	0.203

[a] tdf = treatment degrees of freedom.
[b] edf = error degrees of freedom.

FIGURE 1. Interaction of tillage [conventional (CT) vs. no-tillage (NT)] and burning treatments on early-season soybean population at 8 days after planting (DAP) in 2002 (A) and 30 DAP in 2003 (B) at the Cotton Branch Experiment Station (CBES) in eastern Arkansas. The least significant difference (LSD) at α = 0.05 to compare means with the same tillage and different burn treatments is 0.8 plants m^{-1} for 8 DAP in 2002 and 2.8 plants m^{-1} for 30 DAP in 2003. The LSD at α = 0.05 to compare means with the same burn and different tillage treatments is 0.9 plants m^{-1} for 8 DAP in 2002 and 1.4 plants m^{-1} for 30 DAP in 2003. The LSD at α = 0.05 to compare means with different burn and different tillage treatment is 0.8 plants m^{-1} for 8 DAP in 2002 and 2.8 plants m^{-1} for 30 DAP in 2003.

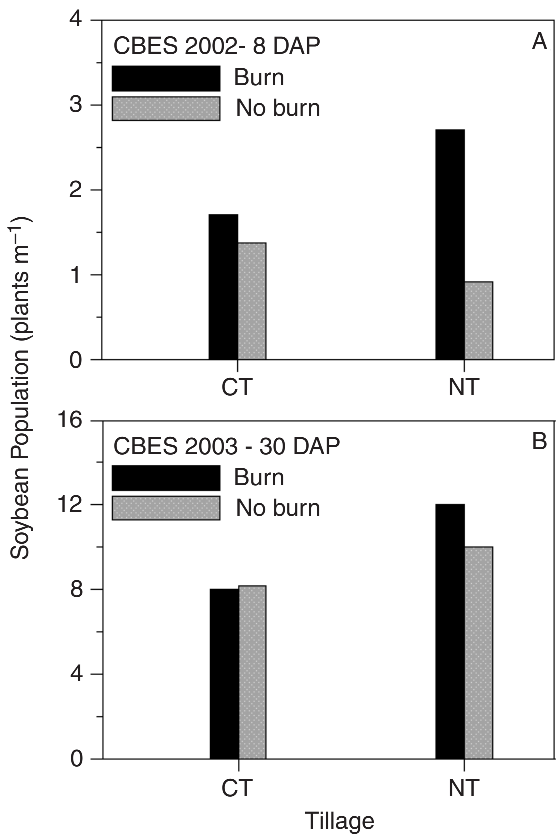
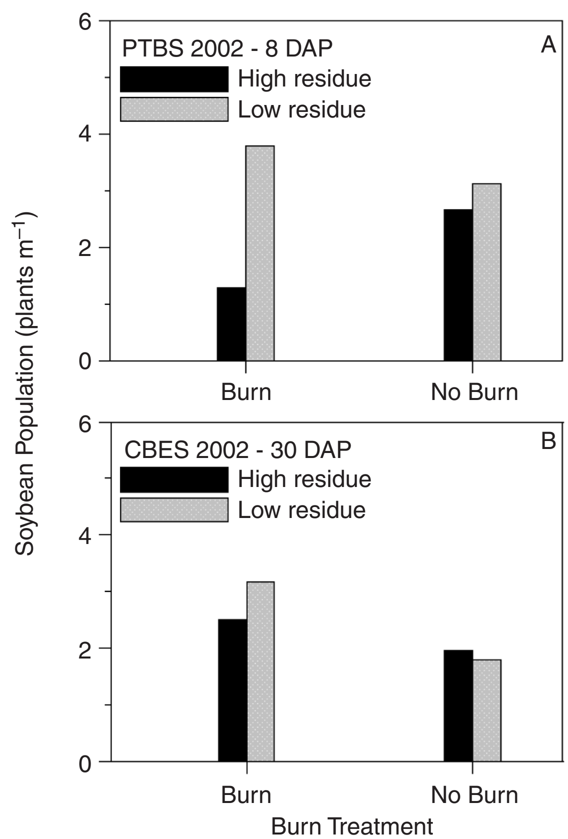


FIGURE 2. Interaction of burning and N rate/wheat-residue level [high (H) vs. low (L)] on early-season soybean population at 8 days after planting (DAP) at the Pine Tree Branch Station (PTBS; A) and 30 DAP at the Cotton Branch Experiment Station (CBES; B) in eastern Arkansas in 2002. The least significant difference (LSD) at α = 0.05 to compare means with the same N rate/wheat-residue and different burn treatment is 2.0 plants m^{-1} for 8 DAP at PTBS and 1.0 plants m^{-1} for 30 DAP at CBES. The LSD at α = 0.05 to compare means with the same burn and different N rate/wheat-residue treatment is 1.1 plants m^{-1} for 8 DAP at PTBS and 0.9 plants m^{-1} for 30 DAP at CBES. The LSD at α = 0.05 to compare means with different burn and different N rate/wheat-residue treatment is 2.0 plants m^{-1} for 8 DAP at PTBS and 1.3 plants m^{-1} for 30 DAP at CBES.



1987; Vyn et al., 1998), that probably stimulated seed germination and increased soybean populations between 8 and 30 DAP at PTBS in 2002.

Similar to 10 DAP, neither tillage, burning, nor N rate/wheat-residue level affected soybean populations by 30 DAP in 2003 at PTBS (Table 3). There was a significant burn x tillage interaction at by 30 DAP at CBES in 2003, where soybean under NT and either burning treatment had significantly higher plant populations than under CT and either burning treatment (Figure 1B). In addition to a significant tillage effect, N rate/wheat-residue level alone affected soybean population by 30 DAP at CBES in 2003, such that soybean planted into the high N rate/wheat-residue treatment resulted in a higher ($p = 0.004$) population (10.9 plants m^{-1}) than soybean planted in the low N rate/wheat-residue treatment (8.2 plants m^{-1}).

Similar to 10 DAP in 2003, by 18 DAP in 2004 at CBES soybean populations were higher ($p = 0.024$) under NT (4.5 plants m^{-1}) than CT (1.9 plants m^{-1}) (Table 3). Neither burning nor wheat-residue level affect soybean populations by 18 DAP at CBES in 2004. Similar to 30 DAP in 2003, neither tillage, burning, nor N rate/wheat-residue level affected soybean populations by 26 DAP at PTBS in 2004.

Leaf Area Index

Neither burning nor N rate/wheat-residue level alone affected soybean LAI approximately 90 DAP at either location in 2002 or 2003 (Table 4). However, tillage significantly ($p < 0.03$) affected soybean LAI at PTBS in both years. There was a significant ($p = 0.013$) tillage $\times$ N rate/wheat-residue level interaction at PTBS in 2002 (Figure 3B), such that soybean LAI was significantly higher under NT than under CT in either N rate/wheat-residue-level treatments and soybean under the CT and low wheat-residue level combination had significantly lower LAI (1.7 m^2 m^{-2}) than soybean under the CT and high N rate/wheat-residue level combination (2.5 m^2 m^{-2}). In addition, there was a significant ($p = 0.006$) burn $\times$ tillage interaction at CBES (Figure 3A), where soybean in the residue burning followed by NT treatment combination had significantly higher LAI (4.4 m^2 m^{-2}) than soybean grown under NT without residue burning (2.7 m^2 m^{-2}).

Similar to 2002, soybean LAI was significantly higher under NT (3.2 m^2 m^{-2}) than CT (2.7 m^2 m^{-2}) at PTBS in 2003. Neither tillage, burning, nor N rate/wheat-residue level affected soybean LAI at CBES in 2003.

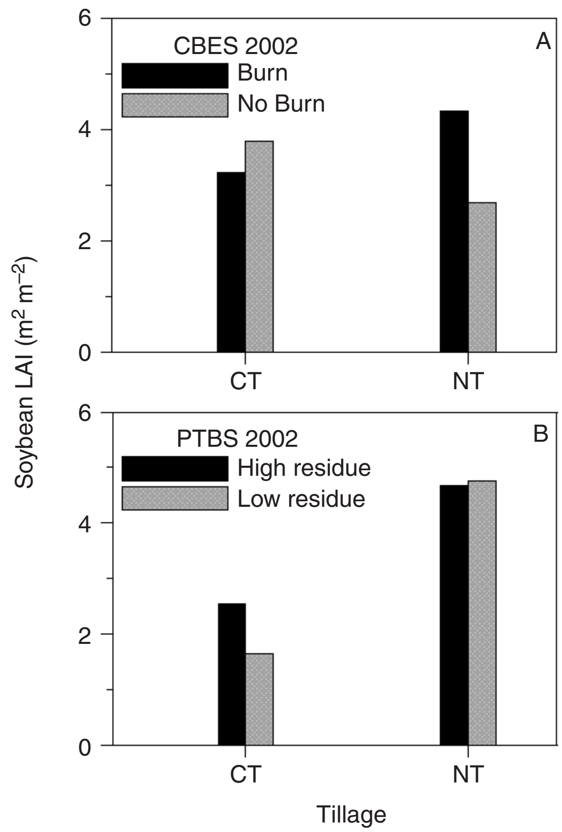
Previous research suggests that double-crop soybean needs to achieve a LAI of 3.1 to 4.0 m^2 m^{-2} to provide a profitable yield (Shibles and

TABLE 4. Analysis of variance results for the effects of burning (Burn), tillage (Till), and N rate/wheat-residue level (Res) on mid-season leaf area index in 2002 and 2003 and soybean yield in 2002, 2003, and 2004 at two locations in eastern Arkansas, Cotton Branch Experiment Station (CBES) and Pine Tree Branch Station (PTBS).

Main effect/ Interactions	tdf[a]	edf[b]	Leaf area index 2002 CBES	Leaf area index 2002 PTBS	Leaf area index 2003 CBES	Leaf area index 2003 PTBS	Grain yield 2002 CBES	Grain yield 2002 PTBS	Grain yield 2003 CBES	Grain yield 2003 PTBS	Grain yield 2004 CBES	Grain yield 2004 PTBS
							P					
Burn	1	1	0.407	0.098	0.500	0.220	0.428	0.549	0.206	0.066	0.914	0.631
Till	1	2	0.994	0.018	0.522	0.028	0.158	0.259	0.114	0.124	0.054	0.893
Res	1	5	0.492	0.067	0.145	0.248	0.821	0.073	0.464	0.601	0.082	0.764
Burn × Till	1	5	0.006	0.417	0.847	0.404	0.838	0.710	0.746	0.388	0.083	0.627
Burn × Res	1	5	0.391	0.165	0.864	0.343	0.339	0.348	0.814	0.588	0.923	0.951
Till × Res	1	5	0.627	0.013	0.587	0.154	0.557	0.930	0.785	0.844	0.878	0.159
Burn × Till × Res	1	5	0.414	0.435	0.598	0.462	0.093	0.640	0.599	0.942	0.046	0.665

[a] tdf = treatment degrees of freedom.
[b] edf = error degrees of freedom.

FIGURE 3. Interactions of (A) tillage [conventional (CT) vs. no-tillage (NT)] and burning at the Cotton Branch Experiment Station (CBES) and (B) tillage and N rate/wheat-residue level at the Pine Tree Branch Station (PTBS) on mid-season soybean leaf area index (LAI) in 2002. For CBES (A), the least significant difference (LSD) at $\alpha = 0.05$ to compare means with the same burn and different tillage treatment is 1.1 $m^2\ m^{-2}$, the same tillage and different burn treatment is 1.0 $m^2\ m^{-2}$, and different burn and different tillage treatment is 1.2 $m^2\ m^{-2}$. For PTBS (B), the LSD at $\alpha = 0.05$ to compare means with the same tillage and different N rate/wheat-residue treatment is 0.5 $m^2\ m^{-2}$, the same N rate/wheat-residue and different tillage treatment is 0.7 $m^2\ m^{-2}$, and different N rate/wheat-residue and different tillage treatment is 0.8 $m^2\ m^{-2}$.



Weber, 1966; Jones et al., 2003). Similarly, the amount of time required for a crop canopy to reach full closure can affect yield. In both years of this study and at both locations, soybean grown under NT exceeded this threshold LAI value near the R-6 stage, while soybean LAI under CT was only slight over or did not exceed the minimum threshold value. The positive effect of NT on soybean LAI may again be due to increased soil water contents (NeSmith et al., 1987; Vyn et al., 1998), which then increases the amount of plant available water for growth and development. Increased plant available water is known to result in increased turgor pressure, cell elongation, growth, and leaf area (Jones et al., 2003). Given the generally significantly higher LAI under NT than CT, which translates directly into increased capacity for photosynthesis and carbohydrate production under NT then CT in this study, one might expect that soybean yield under NT would be at least similar, if not significantly higher, than that under CT.

Soybean Grain Yield

Early- and mid-season soybean establishment, growth, and development patterns would be expected to manifest themselves by the end of the growing season in soybean yield. Soybean plant population by 30 DAP at CBES in 2003 ($p = 0.006$ and $r = 0.39$) and mid-season LAI at both locations in 2003 ($p = 0.041$ and $r = 0.30$ at CBES; $p = 0.001$ and $r = 0.46$ at PTBS), and soybean plant population by 18 DAP at CBES in 2004 ($p = 0.004$ and $r = 0.41$) were significantly, though relatively weakly, correlated with soybean yield. However, despite significantly higher soybean LAI under NT than CT in 2002 and 2003 and a significant correlation between LAI and yield in 2003 at both locations, there were no significant main effects on soybean yield at either location in any year of this study (Table 4). However, there was a significant three-way interaction ($p = 0.046$; Table 4). Soybean yield averaged 4.2 [standard error (SE) = 0.2] Mg ha^{-1} at CBES and 3.1 (SE = 0.2) Mg ha^{-1} at PTBS in 2002. In 2003, soybean yield decreased somewhat from that in 2002, averaging 3.6 (SE = 0.1) Mg ha^{-1} at CBES and 2.3 (SE = 0.1) Mg ha^{-1} at PTBS. In 2004, soybean yield decreased again somewhat from that in the previous two years, primarily due to a shortened growing season after planting was delayed, averaging 0.9 (SE $<$ 0.1) Mg ha^{-1} at CBES and 1.5 (SE = 0.1) Mg ha^{-1} at PTBS.

Soybean yields recorded in this study in 2002 and 2003 were similar to the 16 yr (i.e., 1983 to 1998) average (2.9 Mg ha^{-1}; UACES, 2004) for irrigated, double-crop soybean grown in Arkansas. Though a formal year comparison was not conducted for soybean yield, the apparent yield decrease from 2002, the first wheat-soybean double crop cycle, to 2003, the second cropping cycle, can not be attributed to a negative effect of time with the wheat-soybean double-cropping system because only two cropping cycles are too few to discern any definitive trend.

The results of this study were similar to those of Dickey et al. (1994) who reported that soybean yields were equal regardless of tillage in the first 3 years of an 8-year study on a silty-clay loam. NeSmith et al. (1987) also concluded that soybean yields were unaffected by tillage and residue burning. However, in North Carolina, Wagger and Denton (1989) reported that soybean produced under NT resulted in double-crop soybean yields 30% higher than those under CT in a 3-year tillage/crop rotation study.

Sanford (1982) evaluated five double-crop burn/tillage combinations that included a NT/no-burn treatment. All but one of the treatment combinations, the no-burn plus CT, was determined to be more profitable than a full-season monocrop soybean system. At the time of the Sanford (1982) study, state-of-the-art NT drills that allowed easy penetration of wheat residue were not available. Sanford (1982) stated that weed control was a problem when leaving residue on the soil surface because cultivation was not possible, and herbicide interference was caused by standing residue. This concern has now decreased due to the availability of glyphosate- resistant soybean cultivars.

Vyn et al. (1998) reported that the higher amounts of wheat residue left on the soil surface had a negative effect on soybean emergence, vegetative growth, and yield. Increased residue led to an increase in soil moisture and lower soil temperatures. In the Vyn et al. (1998) study, full-season soybean were planted into wheat residue in Ontario, Canada where wet soils and cooler temperatures can inhibit soybean germination and emergence. This "residue effect" may prove to be an asset throughout the mid-South, especially in Arkansas, since soybeans are generally planted in hot and dry conditions during early June. Touchton and Johnson (1982) reported results similar to those of Vyn et al. (1998) in that NT planting was detrimental and produced lower soybean yields. The need for deep tillage is often evident on fine-textured soils or soils with a plow pan.

Kelley and Sweeney (1998) observed that burning wheat residue had no significant effect on soybean yield and that leaving residue on the soil surface resulted in adequate soybean stands. NeSmith et al. (1987) stated that burning was of no agronomic benefit and determined that NT with burning wheat residue resulted in soybean plant populations and yields that were greater than or equal to those of more conventional methods.

CONCLUSIONS AND IMPLICATIONS

Numerous consistencies were noted throughout the 3-yr duration of this study. Soybean plant populations between 10 and 30 DAP were significantly higher under NT than CT for four of six year location combinations. Soybean plant populations between 10 and 30 DAP without wheat residue burning were equivalent to those with burning for five of six year-location combinations. Soybean plant populations between 10 and 30 DAP were unaffected by N rate/wheat-residue level for four of six year-location combinations. Mid-season soybean LAI was significantly higher under NT than CT for two of four year-location combinations. Soybean yields under NT were statistically equivalent to yields under CT in six of six year-location combinations. In the case of tillage, fewer passes across a field under NT than CT likely results in lower on-farm expenses to prepare for soybean planting in the wheat-soybean double-crop production system.

The lack of significant tillage, burning, or their interaction effects on soybean yield are important results indicating that the alternative pre-plant field preparation combination of no residue burning followed by NT performed equally as well as the more traditional pre-plant field preparation combination of residue burning followed by CT. The no-burn/NT combination is not feasible in all situations, but it should be considered a practical alternative in the mid-southern United States on well-drained and medium- to coarse-textured soils. Equipment that allows easy planting into standing residue is readily available, weed control is not as difficult as in the past, and soybean germination and emergence in the mid-South can benefit from slightly moister soils provided from a residue-covered soil surface.

With these benefits in mind and with the likelihood of possible pollution-related legislation eventually coming into effect that would limit or prohibit crop-residue burning, growers need to consider alternative wheat-residue management options and make the proper choice for their particular circumstances. Results of this study indicate no consistent advantage of wheat-residue burning over non-burning and that the combination of non-burning wheat residue and NT can be sound management alternatives that can maintain soybean production at a high level.

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