DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Conservation Tillage Systems for Cotton in the Tennessee Valley

E. B. Schwab, D. W. Reeves,* C. H. Burmester, and R. L. Raper

ABSTRACT

Yield reductions from no-tillage cotton (*Gossypium hirsutum* L.) jeopardized adoption of conservation systems in the Tennessee Valley region of north Alabama in the early 1990s. We conducted a study from 1995 to 1999 on a Decatur silt loam (fine, kaolinitic, thermic Rhodic Paleudults) to develop a practical conservation tillage system with competitive yields for the region. Treatments included a factorial combination of fall ridging (ridged and nonridged) and fall non-inversion deep tillage (none, in-row subsoiling, paratilling), along with spring strip tillage and conventional tillage (fall chisel-spring disk). All treatments, except conventional tillage, were established with a rye (*Secale cereale* L.) cover crop. Tillage systems were evaluated for soil temperature, penetration resistance, a soil compaction index, soil water, plant population, and seed cotton yield. Paratilling reduced soil compaction index 29 and 31% compared with conventional tillage and no-tillage, respectively. Subsoiling reduced the compaction index 12 and 15% compared with conventional tillage and no-tillage, respectively. Soil water content was decreased with the fall paratilled and subsoiled conservation tillage systems, compared with conventional tillage and no-tillage, suggesting increased rooting. Fall non-inversion deep tillage, either paratilling or in-row subsoiling with a narrow-shanked subsoiler, resulted in the highest seed cotton yields; 16% greater than conventional tillage (2660 kg ha^{-1}), and 10% greater than strict no-tillage (2810 kg ha^{-1}) across a 4-yr duration. In this region, non-inversion deep tillage under the row in fall, coupled with a rye cover crop to produce adequate residue for moisture conservation and erosion control, is a highly competitive and practical conservation tillage system.

Soils of the Tennessee River Valley in northern Alabama are inherently productive, but have predominantly been cropped to cotton since before the U.S. Civil War. Since cotton, a low residue crop, has been produced continuously for an extended period of time, soil degradation has occurred as a result of erosion and loss of organic matter.

Degradation of soil quality and increasing governmental regulations on the 50 to 60% of cropland classified as highly erodible land in the region resulted in some farmers turning to conservation tillage systems in the early 1990s. The predominant system implemented was to plant without tillage directly into existing cotton stubble with no winter cover crop. Although equivalent or greater yields have been reported for cotton grown with conservation tillage compared with conventional tillage on loessial soils in northern Mississippi and western Tennessee (Stevens et al., 1992; Bradley, 1993; Triplett et al., 1996), conservation tillage practiced on silty clay soils in northern Alabama resulted in 8 to 15% yield reductions compared with conventional tillage (Brown et al., 1985; Burmester et al., 1993). Slow accumulation of growing degree day-units (base 15.5°C) in the spring and the potential for early fall freezes complicates management decisions in conservation tillage systems for the region (Norfleet et al., 1997). Consequently, many farmers were reluctant to adopt conservation tillage on a large scale, despite possible long term benefits of improved soil quality.

Specific problems with conservation tillage must be overcome before widespread adoption of such systems will occur in the region. Conservation tillage systems that produce large amounts of crop residue can moderate soil temperature because residue acts as insulation (Lal, 1976; NeSmith et al., 1987). Planting cotton on ridges or removing residue from the soil surface may alleviate soil temperature problems. Ridges have been found to provide better aeration and a warmer seedbed, which allows for earlier planting and enhanced cotton development (Boquet and Coco, 1993). Shinners et al. (1994) found that a residue free band (i.e., strip tillage) increased soil temperatures for corn (*Zea mays* L.) growth in southern Wisconsin.

An increase in soil compaction has also been implicated for poor cotton performance with conservation tillage in the region (Burmester et al., 1993). In-row subsoiling at planting is frequently used to alleviate soil compaction for cotton grown on sandy coastal plain soils (Vepraskas and Guthrie, 1992; Raper et al., 1994; Reeves and Mullins, 1995; Mullins et al., 1997). However, in a conservation tillage system, Touchton et al. (1986) reported no cotton yield response to spring in-row subsoiling in the Tennessee River Valley. Spring tillage in the silty clay soils of this region forms clods, leaving a rough seed bed that is frequently difficult to plant into, and which may suppress yields. The objective of our research was to develop a conservation tillage system for cotton on Tennessee Valley soils that would manage soil compaction, maintain competitive yields, and facilitate widespread adoption of conservation tillage in the region.

MATERIALS AND METHODS

The study was initiated in November of 1994 at the Tennessee Valley Research and Extension Center of the Alabama Agriculture Experiment Station, in Belle Mina, AL. The soil

E.B. Schwab, D.W. Reeves, and R.L. Raper, USDA-ARS Soil Dynamics Research Unit, 411 S. Donahue Dr., Auburn, AL 36832; C.H. Burmester, Dep. of Agronomy and Soils, 202 Funchess Hall, Auburn University, Auburn, AL 36849. Joint contribution of the USDA-ARS and Auburn University Alabama Agric. Exp. Stn. Research supported in part by the Alabama Cotton Commission. Received 21 June 2001. *Corresponding author (wreeves@acesag.auburn.edu).

Published in Soil Sci. Soc. Am. J. 66:569–577 (2002).

Abbreviations: DAP, days after planting; RCB, randomized complete block design.

type is a Decatur silt loam, the major soil type in the region. For 4 yr prior to the study, the experimental area had been cropped continuously to no-till cotton without a cover crop.

The experimental design was a randomized complete block design (RCB) of four replications, with a two by three augmented factorial treatment arrangement. Plots consisted of eight 102-cm wide rows which were 15.2 m long. Treatments were a factorial combination of fall ridging (ridged and nonridged) in combination with non-inversion fall deep tillage (none, in-row subsoiling, and paratilling). The augmented treatments were spring strip tillage and conventional tillage. Nonridging without deep tillage, that is, strict no-tillage, is considered the no-tillage control treatment. All treatments were accomplished with four-row equipment. Subsoiling was implemented under the row with a KMC (Kelley Manufacturing Co., Tifton, GA)[1] ripper bedder to a depth of 43 cm. Paratilling was completed with a Paratill (Bigham Brothers, Inc., Lubbock, TX) to a depth of 45 cm. In the fall of 1994, all ridging operations were accomplished using a KMC ripper bedder equipped with disk bedders. The ripper subsoiler shanks were removed for implementation of fall ridging without deep tillage and ridging with paratilling. Data from the fall ridging with subsoiling treatment is not available for 1995 because of difficulties implementing this treatment in the fall of 1994; however, in fall of 1995 and consecutive years, all ridged plots were successfully created with ridging listers rather than disk bedders. Spring strip tillage in 1995 was implemented with an experimental Yetter (Yetter Farm Equipment, Colchester, IL) implement. This implement has an in-row subsoiler that ran 20 to 25 cm deep and has a series of in-row disks, coulters, and spider tines to create a disturbed zone 25 to 35 cm wide. In all other years (1996–1999) a specially designed KMC implement was used for the spring strip tillage treatment. This implement has a shorter subsoil shank that ran 15 to 17 cm deep in the row, and a series of in-row disks and coulters that disturbed a zone 25 to 30 cm wide. Conventional tillage consisted of fall disking and chiseling (22 to 28 cm deep) followed by disking and field cultivating in the spring.

All plots except the conventional-tilled plots were seeded in rye with a grain drill immediately after fall tillage. The cover crop was terminated prior to spring planting with an application of glyphosate [N-(phosphonomethyl) glycine]. A four-row John Deere Maxi-Emerge (Deere & Company, Moline, IL) planter equipped with Martin (Martin & Company, Elkton, KY) row cleaners was used to plant ‘DP 51’ cotton on 12 May 1995, ‘NuCOTN 33[B]’ on 1 May 1996, ‘DP 20[B]’ on 7 May 1997, and ‘PM 1220 BG/RR’ on 6 and 5 May in 1998 and 1999, respectively. Seeding rate for all treatments and years was 145 000 seed ha^{-1}. Rapidly changing technologies with transgenic varieties, heavy insect pressure from the tobacco budworm [*Heliothis virescens* (Fabricius)] in 1995, and mass adoption of newer varieties by farms in the region resulted in the use of different cotton varieties from year to year in this study. Consequently, any variety effects are confounded with environmental factors (e.g., differences in rainfall distribution and amounts, temperature patterns, cloud cover, and insect and disease pressures) that are normally confounded in year effects. Following planting, 17 kg N and 7 kg P ha^{-1} was applied in a band over the row. Nitrogen was also sidedressed at a rate of 100 kg ha^{-1} in all years. An additional 34 kg N ha^{-1} was applied in 1996 as a result of visual N deficiency at first bloom. Auburn University Extension recommendations were used to apply all insecticides and defoliants. Preemergence weeds were controlled by the application of [1,1-dimethyl-3-(a,a,a-trifluoro-*m*-tolyl)] urea and paraquat dichloride [1,1′-dimethyl-4,4′-bypridinium dichloride]. Cyanazine {2[[4-chloro-6-(ethylamino)-s-triazin-2-yl]amono]-2-methylpropionitrile} and MSMA (monosodium acid methanearsonate) were applied for postemergence weed control in all years. In 1998 and 1999, labeled applications of glyphosate were applied over-the-top of the glyphosate-resistant cultivar PM 1220 BG/RR.

Soil temperature was measured hourly in-row at a depth of 10 cm for the first 14 DAP in two replications in 1995 and 1996. Soil temperature readings were measured with thermocouple wires and recorded with a CR 10 measurement and control module data logger (Campbell Scientific, Inc., Logan, UT). Average daily soil temperature and the daily soil temperature range (daily maximum − daily minimum) were subjected to ANOVA.

Average volumetric water content was determined in the top 38 cm of soil approximately twice a week from squaring to 10% open bolls in 1995 and 1996, and from early bloom to 10% open bolls in 1997. This determination was performed in-row, in the nontrafficked middle, and in the trafficked middle at one location in each plot. A Tektronix 1502B (Tektronix, Inc., Beaverton, OR) cable tester was used for soil water determination using time-domain reflectometry (Topp, 1980). Two stainless steel guide rods (0.64-cm diameter) spaced 5.1 cm apart were placed into the soil and connected to the cable tester with coaxial cable. The volumetric water content was subjected to ANOVA. Row position and measurement days (as DAP) were analyzed as an expansion of the original ANOVA RCB model to a split-plot (row position as subplots) and split-split plot model (DAP as sub-subplots), respectively.

A tractor-mounted, hydraulically-driven, soil cone penetrometer was used for determination of soil strength after planting in 1995, 1996, and 1997 (Raper et al., 1999). The tractor-mounted penetrometer determined soil strength in five positions simultaneously: (i) in-row, (ii) 25 cm from the row in the trafficked middle, (iii) 50 cm (midway) from the row in the trafficked middle, (iv) 25 cm from the row in the nontrafficked middle, and (v) 50 cm (midway) from the row in the nontrafficked middle. A cone with a base area of 323 mm^2 was used on each of the penetrometers (American Society of Agricultural Engineers, 1998). Readings were taken continuously throughout the soil profile to a depth of 40 cm and were averaged every 5 cm.

A soil compaction index was also determined for the evaluation of soil strength. Data were plotted to give scaled contour graphs using Surfer for Windows (Golden Software Inc., Golden, CO). Using this software, the area of the graph (cm^2) occupied by each incremental 0.5 MPa of soil strength was determined. This procedure results in a separate value of area for each of the 0 to 0.5, 0.5 to 1.0, 1.0 to 1.5, 1.5 to 2.0, 2.0 to 2.5, and so on MPa cone index ranges. Each of these area values was multiplied by the cone index at the upper end of each increment and summed for all increments according to the following formula:

$$SCI = \frac{1}{100} \sum_{I=1}^{N} (A_{(I/2)} - A_{(I/2-1/2)}) \frac{I}{2},$$

where SCI is the soil compaction index (MPa − 100 cm^2), A is the respective scaled area (cm^2) of contour graph between the isoline of cone index equal to (I/2) − (1/2) MPa and isoline of cone index equal to (I/2) MPa, I is the cone index of the isoline multiplied by 2 (MPa), and N is maximum cone index isoline multiplied by 2 (MPa).

In-row bulk density was determined in 1996 at 12 DAP.

[1] Reference to a trade or company name is for specific information only and does not imply approval or recommendation of the company by the USDA or Auburn University to the exclusion of others that may be suitable.

Table 1. Preplanned single degree of freedom contrasts used for mean comparisons.

Contrast	Tillage systems
Fall ridging vs. nonridged	Fall ridging with subsoiling, Fall ridging with paratilling, Fall ridging without deep tillage vs. nonridged with subsoiling, Nonridged with paratilling, Nonridged without deep tillage
Fall ridging vs. conventional tillage	Fall ridging with subsoiling, Fall ridging with paratilling, Fall ridging without deep tillage vs. conventional tillage
No-tillage vs. conventional tillage	Nonridged without deep tillage vs. conventional tillage
Paratilling vs. subsoiling	Fall ridging with paratilling, Nonridged with paratilling vs. Fall ridging with subsoiling, Nonridged with subsoiling
Paratilling vs. no deep tillage	Fall ridging with paratilling, Nonridged with paratilling vs. Fall ridging without deep tillage, Nonridged without deep tillage
Subsoiling vs. no deep tillage	Fall ridging with subsoiling, Nonridged with subsoiling vs. Fall ridging without deep tillage, Nonridged without deep tillage

Three undisturbed soil samples (5.3-cm diameter) were taken from the top 6 cm of soil in each plot with a double cylinder, hammer driven core sampler. These undisturbed soil cores were dried in a forced air oven for 72 h at 105°C and bulk density was calculated (Blake and Hartge, 1986).

Cover crop dry matter production was determined prior to termination within a 0.25-m^2 area from each plot except conventional tillage. Cotton populations were determined in 1995, 1996, 1997, and 1998 by counting the number of plants in two 1.5-m sections of row from each plot prior to harvest. From 1995 to 1998, the number of bolls and the percentage open bolls were determined before defoliation from 3 m of row in each plot. In all years, the middle four rows were harvested with a spindle picker for determination of seed cotton yield.

Data were subjected to ANOVA using the Statistical Analysis System (SAS Institute, 1988). Where year × treatment interactions occurred for response variables, data were analyzed and are presented by year. Preplanned single degree of freedom contrasts (Table 1) and Fisher's protected LSD were used for mean comparisons. A significance level of $P < 0.100$ was established a priori.

RESULTS AND DISCUSSION

Cover Crop Dry Matter Production

Cover crop dry matter production can be important for increasing soil organic matter and improving soil quality in cropping systems with a low residue crop such as cotton. The rye cover crop was more mature at termination in 1995 than in other years, resulting in greater average rye dry matter production in 1995 (6.0 Mg ha^{-1}) compared with all other years (4.1 Mg ha^{-1} in 1996, 3.5 Mg ha $-^1$ in 1997, 2.6 Mg ha^{-1} in 1998, and 1.3 Mg ha^{-1} in 1999) (Table 2). In 1997 and 1999, fall ridged treatments had significantly lower cover crop dry matter production than nonridged treatments (3.33 vs. 3.86 Mg ha^{-1}, $P < 0.038$ in 1997; 1.05 vs. 1.44 Mg ha^{-1}, $P < 0.046$ in 1999). Reductions in dry matter in fall ridged treatments are believed to be the result of poor rye stands on top of the ridges because of difficulty in maintaining a proper planting depth and seeds washing off ridged slopes. However, better stands were obtained in 1996, and in this year fall ridging (4.56 Mg ha^{-1}) produced significantly greater cover crop dry matter than the nonridged treatments (3.77 Mg ha^{-1}, $P < 0.053$). The data also suggest some increased dry matter production as a result of fall deep tillage. Nonridging with subsoiling produced greater cover crop dry matter than any other treatment in 1997 (4.66 Mg ha^{-1}). In 1996 and 1999, fall subsoiling resulted in greater cover crop dry matter production than treatments without deep tillage (4.68 vs. 3.75 Mg ha^{-1}, $P < 0.060$ in 1996; 1.34 vs. 0.89 Mg ha^{-1}, $P < 0.062$ in 1999). Fall paratilling also increased cover crop dry matter production compared with treatments without deep tillage in 1998 and 1999. Overall, nonridged treatments with non-inversion deep tillage in the fall (subsoiling or paratilling) tended to increase rye cover crop dry matter production.

Table 2. Dry matter production of the rye cover crop as affected by tillage system.

Tillage system	1995	1996	1997	1998	1999	Mean
	Mg ha^{-1}					
Conventional tillage†	–	–	–	–	–	–
Nonridged without deep tillage‡	6.93	3.17	3.23	2.37	1.26	3.39
Nonridged with subsoiling	6.34	4.41	4.66	2.79	1.63	3.97
Nonridged with paratilling	5.89	3.74	3.68	2.86	1.44	3.52
Fall ridging without deep tillage	4.91	4.33	3.00	1.89	0.52	2.93
Fall ridging with subsoiling§	–	4.95	3.57	2.79	1.06	3.09
Fall ridging with paratilling	5.97	4.39	3.41	3.43	1.56	3.75
Spring strip tillage	5.87	3.49	2.67	2.43	1.45	3.18
$LSD_{(0.10)}$	ns¶	ns	0.71	0.76	0.56	0.44

† Rye cover crop was not planted in the conventional tilled treatment.
‡ Nonridged without deep tillage is considered the no-tillage control.
§ Fall ridging with subsoiling was not implemented in 1995.
¶ ns = not significant.

Soil Temperature

In-row soil temperature for 14 DAP, a critical factor in cotton emergence, did not differ greatly among tillage systems (Table 3). In 1996, single degree of freedom contrasts (Table 1) showed fall ridging had a greater average soil temperature the first 14 DAP than nonridg-

Table 3. In-row average and soil temperature range for the first 14 d after planting in 1995 and 1996, as affected by tillage system.

	Soil temperature			
	1995		1996	
Tillage system	Average	Range	Average	Range
	°C			
Conventional tillage	25.5	13.9	24.5	8.9
Nonridged without deep tillage†	23.6	8.6	22.1	6.0
Nonridged with subsoiling	23.7	7.3	21.5	5.2
Nonridged with paratilling	23.5	8.7	21.8	5.7
Fall ridging without deep tillage	24.7	14.4	22.3	7.0
Fall ridging with subsoiling‡	–	–	22.1	5.5
Fall ridging with paratilling	24.3	11.4	22.8	6.5
Spring strip tillage	24.3	10.8	22.5	5.9
$LSD_{(0.10)}$	ns§	2.25	1.04	ns

† Nonridging without deep tillage is considered the no-tillage control.
‡ Fall ridging with subsoiling was not implemented in 1995.
§ ns = not significant.

ing (22.4 vs. 21.8°C, $P < 0.097$). Conventional tillage also resulted in a greater average soil temperature (24.5°C) compared with all other treatments in 1996.

In 1995, soil temperature range (daily maximum − daily minimum) was significantly affected by tillage system (Table 3). Both fall ridging without deep tillage and conventional tillage resulted in a greater soil temperature range the first 14 DAP compared with all other treatments in 1995. Fall ridging with paratilling and spring strip tillage also resulted in greater variation in soil temperatures than all the nonridged conservation tillage systems. These treatment differences are likely the result of less surface residue (Table 2) and drier soil in the row of ridged and tilled treatments compared with nonridged conservation-tilled treatments. Less residue and lower soil water would allow the soil to warm faster in morning and cool faster at night. In 1996, when there was considerably less surface residue than in 1995, soil temperature range was not affected by tillage system. Despite minor differences in soil temperatures among tillage systems in 1995 and 1996, most daily minimum soil temperatures during the first 14 DAP (data not shown) were greater than the 18°C critical temperature needed for cotton emergence in field conditions (Wanjura et al., 1967).

Cotton Population

Contrary to previously reported research from the Tennessee Valley Region (Touchton et al., 1984; Brown et al., 1985) conventional tillage did not produce greater cotton populations compared with any of the conservation tillage treatments in any year, with the exception of 1997, when conventional tillage resulted in significantly greater plant population than all nonridged conservation tillage treatments (Table 4). A similar trend was found in 1995, when the no-tillage control (nonridged without deep tillage) had lower plant population compared with conventional tillage (78 200 vs. 97 700 plants ha^{-1}, $P < 0.123$). Single degree of freedom contrasts in 1996 showed paratilling (88 000 plants ha^{-1}) and subsoiling (81 400 plants ha^{-1}) resulted in greater plant stands than treatments without deep tillage (64 800 plants ha^{-1}, $P < 0.025$ and 0.098, respectively). In 1998, fall subsoiling had lower plant populations than no fall deep tillage (66 600 vs. 90 800 plants ha^{-1}, $P < 0.016$). In 1997, fall ridging resulted in greater plant population compared with nonridged treatments (118 200 vs. 88 400 plants ha^{-1} $P < 0.001$). In 1995 and 1996 (when soil temperatures were measured), fall ridging maintained a greater average soil temperature than the nonridged treatments, which could be related to the differences in plant population (Table 3). Wanjura et al. (1967) reported a direct relationship between cotton emergence and soil temperature. However, despite inconsequential and inconsistent differences in plant populations, adequate stands were obtained in all treatments for all years. Delaying planting until 1 May or later and removing residue in the seeding zone with planter-equipped row cleaners likely minimized the soil temperature effects on cotton stands. In coordinated research using long-term climatological data, we determined that 50 degree day-units (base 15.5°C), the optimum required for rapid cotton emergence, are normally not accumulated until May 1 in the Tennessee Valley (Norfleet et al., 1997).

Soil Compaction

Conventional tillage had the greatest soil compaction, as indicated by the soil compaction index, compared with all other treatments in 1995 (Table 5). Reduced soil compaction was seen in all treatments with fall subsoiling and paratilling in 1995 compared with conventional tillage, spring strip tillage, and the no-tillage control treatment. In 1996, soil compaction was greater in treatments without deep tillage compared with fall subsoiling and paratilling treatments (6.165 vs. 4.905 MPa-100 cm^2 and 4.322 MPa-100 cm^2, $P > 0.0001$ and $P > 0.0001$, respectively) (Table 5). Fall paratilling also reduced soil compaction index compared with fall subsoiling in 1996 (4.322 vs. 4.905 MPa-100 cm^2, $P > 0.036$). Similar to 1995 and 1996, both fall subsoiling and paratilling reduced compaction, compared with treatments without deep tillage in 1997 (6.880 and 5.656 vs. 8.080 MPa-100 cm^2, $P > 0.0005$ and $P > 0.0001$, respectively) (Table 5). Soil compaction as indicated by the soil compaction index was also found to be greater in the no-tillage control, fall ridging without deep tillage, and spring strip tillage systems in 1997. Unlike in 1995 and 1996, conventional tillage was not significantly different from the subsoiling treatments in 1997, which resulted in a treatment × year interaction. However, the 3-yr soil compaction index mean clearly shows the benefit

Table 4. Effect of tillage system on cotton plant populations, 1995 to 1998.

Tillage system	1995	1996	1997	1998
	plants ha^{-1}			
Conventional tillage	97 700	81 100	116 000	86 300
Nonridged without deep tillage†	78 200	73 800	83 700	80 700
Nonridged with subsoiling	94 400	75 800	73 100	60 500
Nonridged with paratilling	77 400	86 700	93 300	79 100
Fall ridging without deep tillage	96 000	55 700	121 000	100 800
Fall ridging with subsoiling‡	–	87 100	117 500	72 600
Fall ridging with paratilling	100 000	89 400	116 000	79 100
Spring strip tillage	93 600	83 500	97 300	83 100
$LSD_{(0.10)}$	ns§	ns	15 550	ns

† Nonridged without deep tillage is considered the no-tillage control.
‡ Fall ridging with subsoiling was not implemented in 1995.
§ ns = not significant.

Table 5. Effect of tillage system on soil compaction index (40-cm depth, 1995–1997).

Tillage system	1995	1996	1997	Mean
	MPa-100 cm^2			
Conventional tillage	6.763	6.320	6.605	6.563
Nonridged without deep tillage†	6.045	6.088	8.192	6.775
Nonridged with subsoiling	5.157	5.180	6.985	5.774
Nonridged with paratilling	4.041	4.398	5.610	4.683
Fall ridging without deep tillage	5.646	6.242	7.968	6.619
Fall ridging with subsoiling	‡	4.630	6.774	5.702
Fall ridging with paratilling	4.255	4.246	5.701	4.734
Spring strip tillage	6.013	6.851	7.752	6.872
$LSD_{(0.10)}$	0.528	0.631	0.713	0.402

† Nonridged without deep tillage is considered the no-tillage control.
‡ Fall ridging with subsoiling was not implemented in 1995.

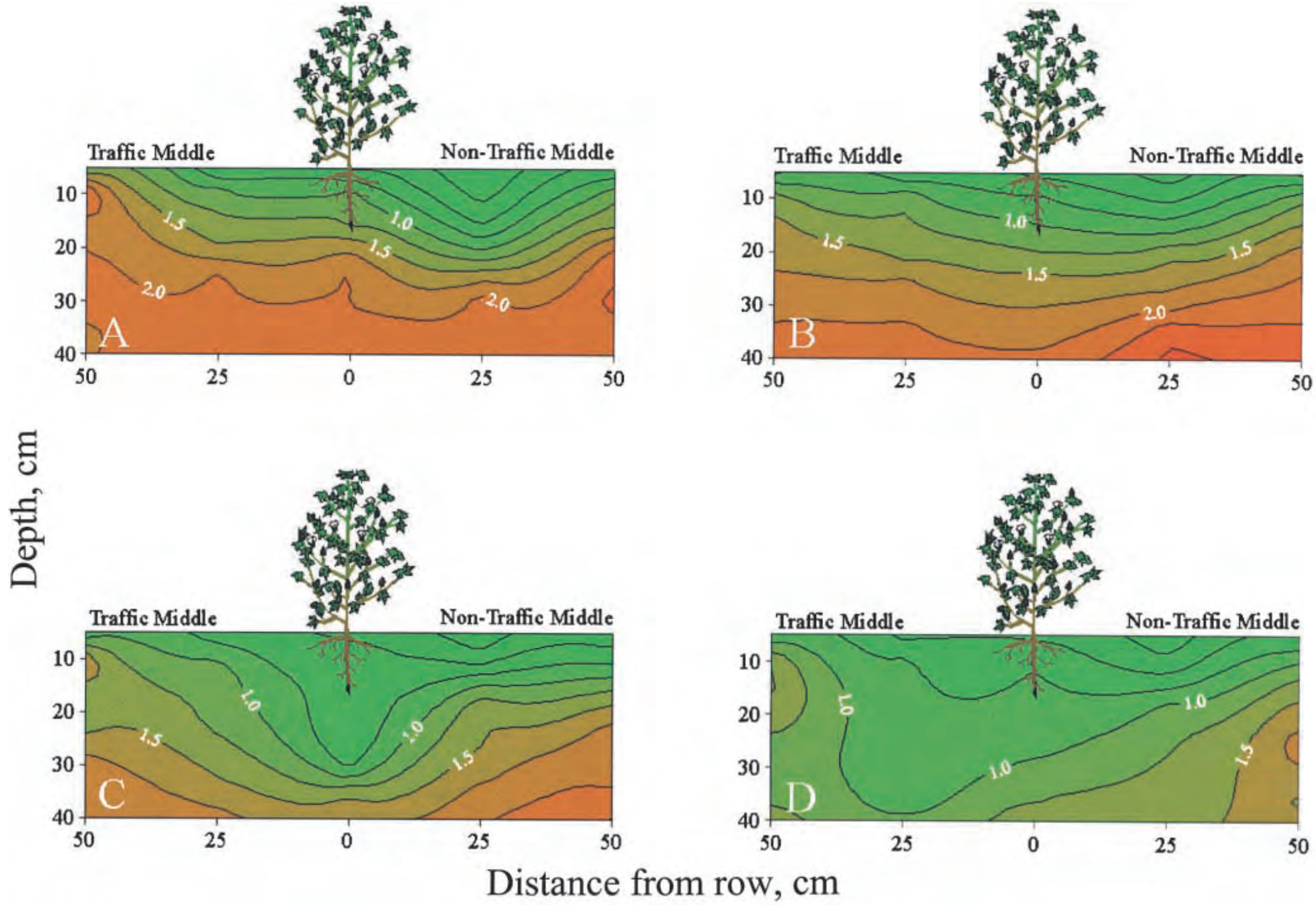

Fig. 1. Cone index of conventional tillage (A), no-tillage control (non-ridged without deep tillage) (B), non-ridged with subsoiling (C), and non-ridged with paratilling (D) in spring of 1996. Non-traffic middle and traffic middle refers to the traffic from tillage and planting operations; random traffic from spraying and harvesting also occurred.

of non-inversion fall paratilling or subsoiling to reduce soil compaction (Table 5).

The soil compaction index was derived from contour graphs of the extensive cone penetration resistance data taken across five positions relative to the cotton row. Cone penetration resistance was found to have a significant treatment × row position × depth interaction in 1995, 1996, and 1997. An example of cone penetration resistance data from 1996 for four selected treatments [conventional tillage, nonridged without deep tillage (no-tillage control), nonridged subsoiled, and nonridged paratill] is shown in Fig 1. The data are too extensive to show completely; 1996 measurements were chosen to illustrate treatment effects because tillage systems had been established for a year and rainfall patterns were more normal than in 1997. These selected tillage systems reflect the dominant treatment effects shown in the soil compaction index data, as well as the dominant effects shown in yield data (discussed later).

In the data example in Fig. 1A, cone penetration resistance of the conventional tillage treatment increased rapidly below the depth of tillage (20–25 cm), reaching a uniform 2.0 MPa across the row and row middles. An area of increased compaction is noted within 10 cm of the soil surface in the row middle that received planting and spraying traffic. In Fig. 1B, the no-tillage control with a rye cover crop, the pattern of soil strength is similar to the conventional tillage system; however, there is slightly less intensity of compaction, and less effect of traffic on compaction at the soil surface. In Fig. 1C, fall subsoiling without ridging coupled with a rye cover crop, the zone of disruption of the subsoiler decreased cone resistance under the row to a depth of 35 to 40 cm. In Fig. 1D, fall paratilling without ridging coupled with a rye cover crop, the zone of disruption is deeper (>40 cm), and broader than with the narrow-shanked subsoiler. Unlike the parabolic subsoiler shank, the bent shank of the paratill lifts the soil, causing a wider zone of disruption. However, despite the wider zone of disruption, and consequent reduced soil compaction index, seed cotton yields were similar between the two methods of deep tillage.

Soil surface bulk density, taken in 1996 within the seedbed, indicated a nonsignificant trend for reduced bulk density in the row with fall ridged, conventional tillage, and spring strip-tilled systems (Table 6). However, contrasts indicated increased soil surface compaction in the no-tillage control treatment (1.44 Mg m^{-3}) compared with conventional tillage (1.33 Mg m^{-3}, $P <$ 0.06). Fall ridging (with or without deep tillage) had significantly lower bulk density compared with non-ridged treatments (with or without deep tillage) (1.34 vs.

Table 6. Effect of tillage system on in-row surface (0–6 cm) soil bulk density 12 d after planting in spring 1996.

Tillage system	Bulk density
	Mg m^{-3}
Conventional tillage	1.33
Nonridged without deep tillage†	1.44
Nonridged with subsoiling	1.41
Nonridged with paratilling	1.42
Fall ridging without deep tillage	1.39
Fall ridging with subsoiling	1.32
Fall ridging with paratilling	1.31
Spring strip tillage	1.34
LSD$_{(0.10)}$	ns‡

† Nonridged without deep tillage is considered the no-tillage control.
‡ ns = not significant.

1.42 Mg m^{-3}, $P < 0.01$). There was no clear relationship between bulk density and plant populations or yield in the 1 yr (1996) that bulk density was determined in the seed zone.

Soil Water

In all years that soil moisture data were collected (1995, 1996, and 1997), there was a significant tillage system × row position interaction on mean soil water contents (0- to 38-cm depth) during the measurement period (squaring through 10% open boll in 1995 and 1996, and from early bloom through 10% open boll in 1997) (Table 7). Positional effects were more dominant during the 2 yr (1995 and 1997), with below normal rainfall during this period (Fig. 2). With the exception of the nonridged subsoiled treatment in 1997, there were no differences in mean soil water contents in trafficked middles among tillage systems. However, in this extremely dry year, the deep tilled (subsoiled or paratilled) nonridged conservation tillage treatments demonstrated reduced mean soil water contents in the nontrafficked row middles, suggesting that deep tillage promoted root growth and increased soil water extraction in nontrafficked middles.

The main differences in soil water content were generally found between the in-row and trafficked-middle positions, with traffic middles maintaining the highest soil water content and the in-row position having the lowest. The pattern of highest soil water contents in tracked middles and lowest soil water contents in the in-row position are consistent with expected differences in cotton rooting, that is, greater root growth and soil water extraction under the row and limited rooting in row middles compacted by equipment traffic. In 1995, soil water content maintained in the in-row position was reduced in both subsoiling and paratilling without ridging systems, as well as the fall ridging with paratilling system. The most consistent (1995–1997 seasons) differences in water content between row positions was found in the ridged treatments with deep tillage (subsoiling or paratilling), and the lowest soil water contents were maintained under the row of the fall ridged with paratilling system in all three seasons.

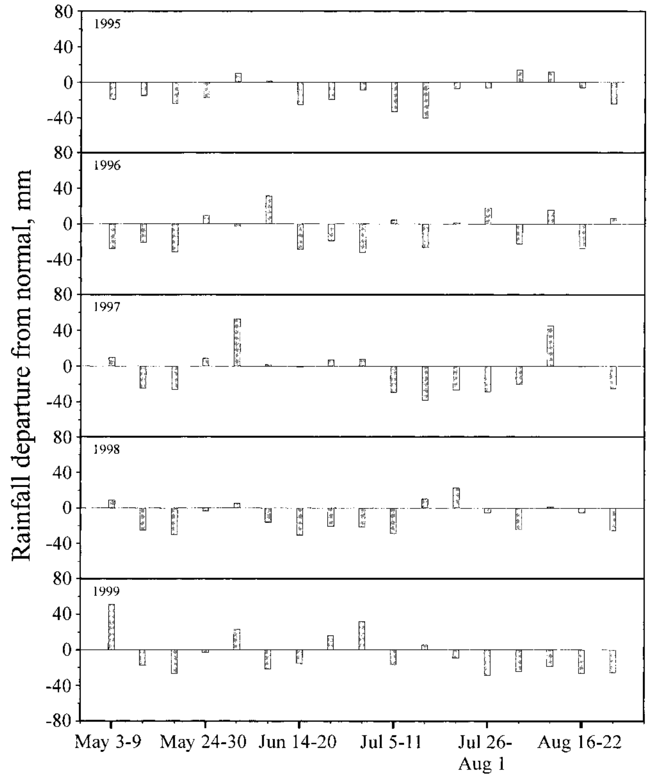

Fig. 2. Weekly departure from normal rainfall for Belle Mina, AL, 1995 to 1999.

As expected, due to rainfall variations, there were tillage system × measurement day (DAP) interactions

Table 7. Average soil volumetric water content by row position, as affected by tillage system in 1995, 1996, and 1997.

Tillage system	1995 Nontraffic	1995 In-row	1995 Traffic	1996 Nontraffic	1996 In-row	1996 Traffic	1997 Nontraffic	1997 In-row	1997 Traffic
	Soil water content, m^3 m^{-3}								
Conventional tillage	0.246	0.238	0.269	0.345	0.311	0.351	0.316	0.286	0.331
Nonridged without deep tillage†	0.255	0.237	0.269	0.314	0.312	0.329	0.328	0.296	0.318
Nonridged with subsoiling	0.254	0.195	0.270	0.317	0.295	0.323	0.293	0.282	0.290
Nonridged with paratilling	0.245	0.187	0.268	0.323	0.294	0.319	0.286	0.286	0.314
Fall ridging without deep tillage	0.255	0.225	0.273	0.333	0.318	0.355	0.342	0.288	0.356
Fall ridging with subsoiling‡	–			0.337	0.292	0.344	0.320	0.246	0.338
Fall ridging with paratilling	0.238	0.144	0.264	0.283	0.243	0.350	0.326	0.239	0.326
Spring strip tillage	0.236	0.208	0.248	0.330	0.294	0.325	0.306	0.271	0.316
LSD$_{(0.10)}$, comparing two tillage means.		0.0417			0.0465			0.0435	
LSD$_{(0.10)}$, comparing two row position means.		0.0451			0.0474			0.0385	

† Nonridged without deep tillage is considered the no-tillage control.
‡ Fall ridging with subsoiling was not implemented in 1995.

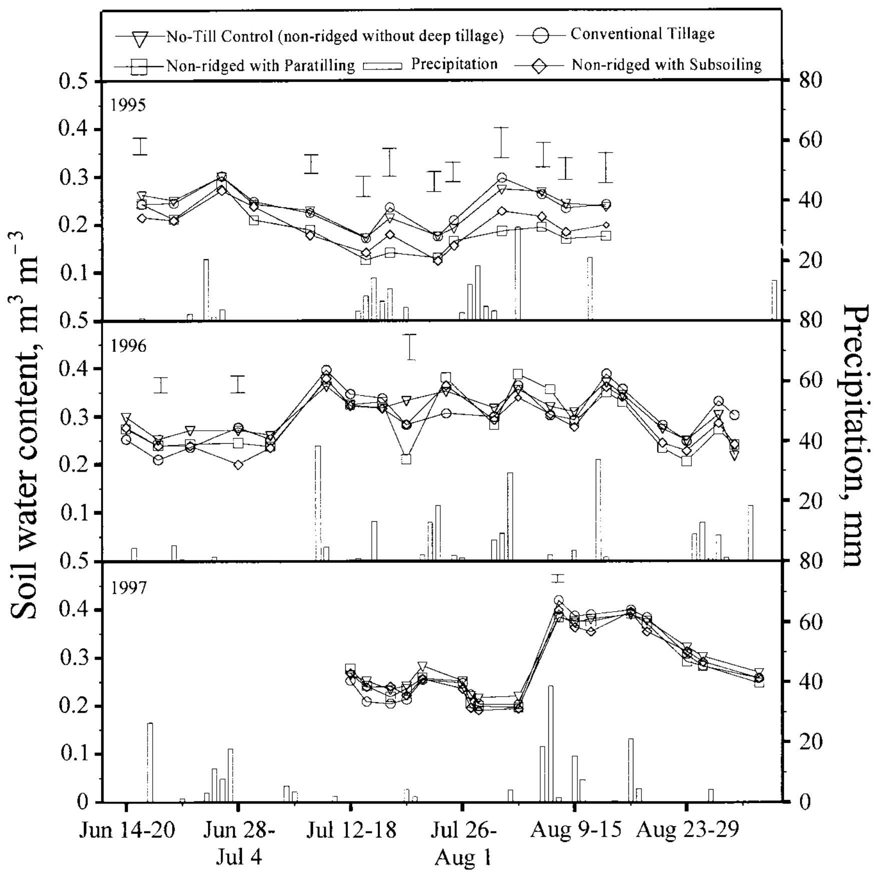

Fig. 3. Precipitation and in-row volumetric soil water content of conventional tillage, the no-tillage control, non-ridged with subsoiling, and non-ridged with paratilling system, 1995 to 1997. The vertical bars are $LSD_{(0.10)}$.

as well. Presentation of soil water content data by day and row position for all eight tillage treatments would be extensive and confusing. Daily soil water contents for the in-row position during the measurement period are shown in Fig. 3 for four tillage systems: conventional tillage, deep tillage without ridging (the no-tillage control), subsoiling without ridging, and paratilling without ridging. These four treatments for the in-row position are chosen to illustrate soil water content variations during the measurement period, as they represent significant trends in the data and also because these treatments demonstrated variations in seed cotton yields. Throughout the sampling period in 1995, conventional tillage and the no-tillage control treatment maintained a higher daily soil water content compared with nonridging with subsoiling and nonridging with paratilling. A similar pattern was seen in 1996, but because of rainfall distribution, differences in daily soil water content were minor. An extended drought with only one significant rainfall event late in the growing season (when cotton water use would be minimal) (Fig. 2) resulted in similar daily soil water content among treatments in 1997.

Seed Cotton Yield

In all 5 yr, seed cotton yield from all conservation tillage treatments were greater than or equal to conventional tillage yields (Table 8). In 1995, seed cotton yield averaged 1660 kg ha^{-1}, despite extreme drought and severe outbreaks of tobacco budworm, which visually appeared to have the most feeding pressure on the larger, less drought-stressed treatments, especially paratilled treatments. This resulted in no significant differences in yield among treatments.

In 1996, seed cotton yield averaged 3960 kg ha^{-1}. This was an improved year for cotton production in the region due to more adequate rainfall during the critical bloom period (Fig. 2) and the use of Bt varieties to control *Heliothis*. In 1996, nonridging resulted in greater seed cotton yields compared with fall ridging (4210 vs. 3870 kg ha^{-1}, $P < 0.060$). Paratilling without ridging had significantly greater yield than both fall ridged deep tillage treatments (subsoiling and paratilling), spring strip tillage, conventional tillage, and the no-tillage control treatment. Little rainfall in May of 1996 resulted in dry soil conditions for 4 wk after planting (Fig. 2). This early season short term drought may have impacted treatments with fall ridging more so than nonridged treatments. Raised beds may have increased drainage from the volume of soil occupied by young cotton roots, consequently increasing drought stress and reducing yield potential relative to nonridged treatments. Differences in seed cotton yield may also have been affected by cotton maturity (Table 8). In 1996, cotton fruiting on the fall ridged treatments was delayed compared with conventional tillage, as indicated by the percentage open bolls just prior to defoliation (33.8 vs. 54.7%, $P <$

Table 8. Effect of tillage system on seed cotton yield (1995–1999) and percentage open bolls prior to defoliation (1995–1998).

	Seed cotton yield						Open bolls			
Tillage system	1995	1996	1997	1998	1999	1996–1999§	1995	1996	1997	1998
	kg ha^{-1}						%			
Conventional tillage	1690	3510	2870	1980	2270	2660	81.2	54.7	57.3	93.1
Nonridged without deep tillage†	1670	3920	2580	2440	2310	2810	79.3	43.1	58.3	92.5
Nonridged with subsoiling	1750	4230	3070	2520	2710	3130	74.8	33.0	54.7	92.3
Nonridged with paratilling	1480	4490	2930	2370	2440	3060	72.7	38.9	45.9	93.5
Fall ridging without deep tillage	1820	4180	2830	2070	2580	2910	84.8	34.6	49.8	92.1
Fall ridging with subsoiling‡	–	3800	2910	2320	2420	2860	–	35.4	70.0	90.6
Fall ridging with paratilling	1710	3620	2840	2370	2650	2860	74.4	31.4	53.6	93.2
Spring strip tillage	1730	3960	2940	2430	2520	2960	83.0	34.9	58.7	90.7
LSD$_{(0.10)}$	ns¶	518	ns	259	215	199	ns	9.0	ns	ns

† Nonridged without deep tillage is the no-tillage control.
‡ Fall ridging with subsoiling was not implemented in 1995.
§ Mean excludes 1995 data because of unusually heavy insect pressure which disproportionately affected treatments with greatest yield potential.
¶ ns = not significant.

0.05). There was a trend ($P < 0.14$) for nonridged treatments to have more open bolls (38.3%) at defoliation than ridged conservation treatments (33.8%).

Unlike 1996, 1997 weekly rainfall was near or above normal from 2 wk after planting until the first week in July (Fig. 2). However, in the critical blooming period (July through early August), rainfall was 87% below normal. Subsoiling, with or without fall ridging (2990 kg ha^{-1}) had significantly greater yield than treatments without deep tillage (2700 kg ha^{-1}, $P < 0.08$) in 1997. Fall subsoiling reduced soil compaction compared with treatments without deep tillage, as indicated by the soil compaction index (Table 5). This reduction in soil compaction is believed to have resulted in increased rooting, allowing plants to cope with drier weather during the critical fruiting period. Although treatments with paratilling also reduced soil compaction, yields were not significantly greater than treatments without deep tillage (2880 kg ha^{-1} vs. 2700, $P < 0.27$). Percentage open bolls at defoliation, an indication of cotton maturity, was found to be significantly greater with subsoiling compared with paratilled treatments (62.3 vs. 37.3%, $P < 0.02$). We believe this delay in maturity with paratilling was responsible for the reduced yield compared with subsoiled treatments.

Similar to 1996, 3 of the first 4 wk of the 1998 season had lower than average rainfall (Fig. 2). This early season drought continued to the middle of July (midway into the critical blooming period), resulting in 67% of the normal rainfall. As in 1996, fall ridging (2250 kg ha^{-1}) significantly reduced yields compared with nonridged treatments (2440 kg ha^{-1}, $P < 0.06$). Once again, we believe that early season drought stress resulted in lower yields with fall ridged treatments. All conservation tillage treatments, with the exception of fall ridging without deep tillage, had greater yields than conventional tillage (Table 8).

In 1999, there was an extended drought from July through August, the critical fruiting period (Fig. 2). Subsoiling without ridging resulted in greater seed cotton yield than subsoiling with ridging, paratilling without ridging, the no-tillage control (nonridged without deep tillage) and conventional tillage (Table 8). Fall ridging (2550 kg ha^{-1}) also had significantly greater yield than conventional tillage (2270 kg ha^{-1}, $P < 0.012$). Unlike 1996 and 1998, with drought stress in early June, fall ridged treatments were not significantly disadvantaged compared with other treatments in 1999.

Excluding 1995, a year in which unusually heavy insect pressure disproportionately affected treatments with the greatest yield potential, average seed cotton yields during the study (1996–1999) were greater for all conservation tillage systems compared with conventional tillage. Numerically, the highest yields were obtained with fall non-inversion deep tillage, either subsoiling or paratilling, in the absence of ridging. Without ridging, fall paratilling or subsoiling under the row increased yields compared with ridged treatments (regardless of deep tillage) and strict no-tillage. Shallow strip tillage in spring resulted in yields statistically similar to paratilling or subsoiling but not statistically greater than strict no-tillage. However, this practice is difficult and operationally inefficient on these heavy soils. Also, Raper et al. (2000) found no benefit to strip-tillage in spring on this soil type when a rye cover crop was used, compared with strict no-tillage.

Historically, dry weather during the critical cotton fruiting period in the Tennessee Valley Region is common (Ward et al., 1959). During this period, from the last week of June to the second week of August, a minimum of one-third of the days will be drought days (plant-available soil water is reduced to zero) in 50% of the years (Ward et al., 1959). Three years out of ten, a minimum of 65% of the days during this period will be drought days. For these soils, a conservation system that includes deep tillage under the row in fall, to reduce soil compaction and increase the volume of soil available for rooting and water storage, coupled with a cover crop to produce adequate residue for soil and water conservation, can reduce the risks of drought-induced yield reductions.

CONCLUSIONS

Previous research on conservation tillage cotton grown on these silty clay soils reported reduced yields compared with fall plowing/spring disking conventional tillage systems (Brown et al., 1985; Burmester et al., 1993). These reported reductions were greatest with the system that growers adopted in the early 1990s, that is, no-tillage without a winter cover; and grower experience validated these earlier findings. Our research demonstrated that no-tillage with a rye cover crop produces cotton yields highly competitive to conventional tillage on silty clay soils in the Tennessee Valley. Raper et al. (2000) also found that a rye cover crop was the most critical factor in increasing yields of conservation tillage cotton on this soil. Potential stand establishment problems from residue-induced cold/wet soil conditions can be avoided by delaying planting until 1 May and using row cleaners to clear residue from the seed zone. The fall bedding (ridging) and spring strip-tillage systems did not increase yields compared with strict no-tillage, and are operationally difficult. Paratilling or in-row subsoiling in fall with a narrow-shanked subsoiler resulted in the least soil compaction and highest seed cotton yields; 16% greater than conventional tillage, and 10% greater than strict no-tillage across a 4-yr duration. Our results suggest that non-inversion tillage under the row in fall, coupled with a rye cover crop to reduce compaction and provide moisture conserving residue, is a practical conservation tillage system for this region.

REFERENCES

American Society of Agricultural Engineers. 1998. ASAE standards—Standards, engineering, and data. ASAE Standard S313.2. ASAE, St. Joseph, MI.

Blake, G.R., and K.H. Hartge. 1986. Particle Density. p. 377–382. *In* A. Klute (ed.) Methods of soil analysis. Part 1. Physical and Mineralogical Methods. 2nd ed. SSSA Book Ser. 9. ASA and SSSA, Madison, WI.

Boquet, D.J., and A.B. Coco. 1993. Cotton yield and growth responses to tillage and cover crops on Sharkey clay. p. 100–105. *In* P.K. Bollich (ed.) Proc. Southern Conservation Tillage Conference for Sustainable Agriculture, Monroe, LA. 15–17 June 1993. Manuscript no. 93-86-7122. Louisiana State Agric. Exp. Stn., Baton Rouge, LA.

Bradley, J.F. 1993. Success with no-till cotton. p. 46–48. *In* M.R. McClelland, T.D. Valco, and R.E. Frans (ed.) Conservation-tillage systems for cotton—A review of research and demonstration results from across the Cotton Belt. Spec. Rep. 160. Arkansas Agric. Exp. Stn., Fayetteville, AR.

Brown, S.M., T. Whitwell, J.T. Touchton, and C.H. Burmester. 1985. Conservation tillage system for cotton production. Soil Sci. Soc. Am. J. 49:1256–1260.

Burmester, C.H., M.G. Patterson, and D.W. Reeves. 1993. No-till cotton growth characteristics and yield in Alabama. p. 30–36. *In* P.K. Bollich (ed.) Proc. Southern Conservation Tillage Conference for Sustainable Agriculture, Monroe, LA. 15–17 June 1993. Manuscript no. 93-86-7122. Louisiana State Agric. Exp. Stn., Baton Rouge, LA.

Lal, R. 1976. No-tillage effects on soil properties under different crops in Western Nigeria. Soil Sci. Soc. Am. J. 40:762–768.

Mullins, G.L., C.H. Burmester, and D.W. Reeves. 1997. Cotton response to in-row subsoiling and potassium fertilizer placement in Alabama. Soil Tillage Res. 40:145–154.

NeSmith, D.S., W.L. Hargrove, D.E. Radcliffe, E.W. Tollner, and H.H. Arioglu. 1987. Tillage and residue management effect on properties of an ultisol and double cropped soybean production. Agron. J. 79:570–576.

Norfleet, L., D.W. Reeves, C.H. Burmester, and D. Monks. 1997. Is planting cotton before May risky business in North Alabama? Highlights Agric. Res. 44(4):14–17.

Raper, R.L., D.W. Reeves, C.H. Burmester, and E.B. Schwab. 2000. Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and energy requirements. Appl. Eng. Agric. 16(4): 379–385.

Raper, R.L., D.W. Reeves, E.C. Burt, and H.A. Torbert. 1994. Conservation tillage and traffic effects on soil condition. Trans. ASAE 37:763–768.

Raper, R.L., B.H. Washington, and J.D. Jerrell. 1999. A tractor-mounted multiple-probe soil cone penetrometer. Appl. Eng. Agric. 15:287–290.

Reeves, D.W., and G.L. Mullins. 1995. Subsoiling and potassium placement effects on water relations and yield of cotton. Agron. J. 87: 847–852.

SAS Institute. 1988. SAS/STAT User's Guide. Version 6.03. SAS Inst., Cary, NC.

Shinners, K.J., W.S. Nelson, and R. Wang. 1994. Effects of residue-free band width on soil temperature and water content. Trans. ASAE 37:39–49.

Stevens, W.E., J.R. Johnson, J.J. Varco, and J. Parkman. 1992. Tillage and winter cover management effects on fruiting and yield of cotton. J. Prod. Agric. 5:570–575.

Topp, G.C. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour. Res. 16:574–582.

Touchton, J.T., D.H. Rickerl, C.H. Burmester, and D.W. Reeves. 1986. Starter fertilizer combinations and placement for conventional and no-tillage cotton. J. Fert. Issues 3:91–98.

Touchton, J.T., D.H. Rickerl, R.H. Walker, and C.E. Snipes. 1984. Winter legumes as a nitrogen source for no-tillage cotton. Soil Tillage Res. 4:391–401.

Triplett, G.B., Jr., S.M. Dabney, and J.H. Siefker. 1996. Tillage systems for cotton on silty upland soils. Agron. J. 88:507–512.

Vepraskas, M.J., and D.S. Guthrie. 1992. Identifying soils where subsoiling can increase yields of tobacco, corn, and cotton. J. Prod. Agric. 5:482–488.

Wanjura, D.F., E.B. Hudspeth, and J.D. Bilbro. 1967. Temperature emergence relations of cottonseed under natural diurnal fructuation. Agron. J. 59:217–222.

Ward, H.S., C.H.M. van Bavel, J.T. Cope, L.M. Ware, and H. Bouwer. 1959. Agriculture drought in Alabama. Bull. 316. Alabama Agric. Exp. Stn., Auburn, AL.