TILLAGE

Comparison of Tillage Types and Frequencies for Cotton on Southern Piedmont Soil

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ABSTRACT

Tillage to disrupt root-restricting, consolidated soil zones can improve rooting capacity and crop production, but costs increase with the need for more powerful tractors. Between 1992 and 1996, agronomic and economic consequences of annual or less frequent soil disruption treatments were evaluated for cotton (*Gossypium hirsutum* L.) on a Typic Kanhapludult. Two soil-disruptive treatments, fall paratillage (PT) and in-row chisel (IC) at planting (spring), were compared with two shallow-tillage treatments, coulter planting plus weed control with sweeps (ST) and conventional disk tillage (DT). The IC, PT, and ST treatments were applied annually or in Years 3, 4, and 5. Lint yield with annual IC was 15 to 20% greater than with DT each year. In 1994, yields ranged from 0.53 to 0.84 Mg ha^{-1} with annual IC and were better than with annual ST or PT. In 1995, yields ranged from 0.92 to 1.29 Mg ha^{-1}, with the top yield associated with current-year IC application. In 1996, no differences in yield were observed among tillages; however, yields of two IC treatments were among the top five. For Years 3, 4, and 5, cotton yields were numerically greater with annual IC than with annual PT and ST. Yields with PT, ST, and DT were not different. Average annual net returns from annual IC were \$450, \$403, and \$287 ha^{-1} greater than those with annual DT, PT, and ST, respectively. In-row chisel appears to be a more economically viable production practice for heavy Piedmont soils compared with PT, ST, and DT.

Nearly two-thirds of the Southern Piedmont region is covered by Cecil series and related soils (clayey, kaolinitic, thermic Typic Kanhapludults) (Hendrickson et al., 1963). These soils have a zone of high strength at 0.15 to 0.25 m below the surface usually near the top of the Bt horizon (NeSmith et al., 1987; Radcliffe et al., 1988; Tollner et al., 1984). Hardpan development in these soils has been associated with fall disk tillage (NeSmith et al., 1987), wheel traffic (Radcliffe et al., 1989), and disturbance of the low-organic-matter, weakly structured horizons by deep tillage (Radcliffe et al., 1989). Annual use of deep tillage can disrupt the hardpan in these soils (Radcliffe et al., 1989), thereby improving infiltration (Mills et al., 1988), root penetration, and water use.

A number of studies have investigated the effects on crop yield of root-restricting compacted soil layers and the effects of subsoiling to shatter the compacted zones. Results are contradictory. Taylor and Bruce (1968) found that subsoiling soils in Alabama resulted in increased cotton yields at two locations, did not affect yields at four locations, and decreased yields at the remaining two locations. Langdale et al. (1981) reported an improvement in corn (*Zea mays* L.) yield with subsoiling compared with no-till planting. Tollner et al. (1987) found that paraplowing effects on soil physical properties in the Piedmont persisted for more than 2 yr but crop yield was not improved. Clark et al. (1993) concluded fall chiseling with a paratill needed to be conducted annually for Piedmont soils to ensure minimizing the effects of soil compaction on crop growth.

Several studies have compared the effects of using different types of deep tillage implements and the effects of deep tillage vs. conventional tillage and no-tillage (Busscher et al., 1988; Reeder et al., 1993; Kanwar et al., 1997; Raper et al., 2000a, 2000b). Few studies have compared tillage type and frequency, especially for soils of the Southern Piedmont and cotton production systems. Raper et al. (2000a) showed that shallow in-row chiseling in the fall was equally or more effective than deeper tillage to disrupt an impeding clay layer and increase cotton yield on a Decatur silt loam (clayey, kaolinitic, thermic Rhodic Paleudult) in Alabama. Subsoiling in the autumn was equally effective as spring subsoiling and was more beneficial to time management. In Mississippi, soybean [*Glycine max* (L.) Merr.] production with fall deep tillage had 9% greater net returns than fall paratillage on a Tunica clay (clayey over loamy, smectitic, nonacid, thermic Vertic Haplaquept) (Wesley et al., 2000). Yields and returns were within 5% of annual deep tillage when deep tillage was performed every second or third year.

Limited data are available on response of cotton to annual or less frequently applied shallow or deep tillage (in-row chiseling or paratill) in Southern Piedmont soils. We evaluated the combination of reduced tillage with shallow or deep tillage to improve water penetration or with ST to control weeds, and residual effects of these tillages on cotton yield. Economic evaluations determined net return and profitability of the various tillage management systems.

MATERIALS AND METHODS

Tillage and residual tillage effects were evaluated on a slightly eroded Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludult) near Watkinsville, GA, beginning in the fall of 1991. The study was located on a site between terraces at

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Abbreviations: DT, disk tillage (treatment); IC, in-row chisel (treatment); PT, paratillage (treatment); ST, secondary tillage (treatment).

Table 1. Mean depth of soil profile horizons, bulk density, and soil texture† for the tillage study.

Horizon	Depth	Bulk density	Sand	Silt	Clay
	m	g cm^{-3}		%	
Ap1	0.03 to 0.13	1.28	73	20	7
Ap2	0.13 to 0.24	1.53	67	23	10
Bt1	0.24 to 0.36	1.53	43	20	37
Bt2	0.36 +	1.41	30	20	50

† Radcliffe et al., 1989.

a summit position on uniform slopes of 3%. Soil characteristics that were measured in 1991 are given in Table 1.

The experimental design was a randomized complete block with three replications and 16 treatments (tillage by year of tillage combinations). The four tillage treatments evaluated were IC, PT, ST, and DT. The IC treatment was applied in the spring and consisted of a 4.2-mm smooth coulter followed by a 230-mm chisel with 38-mm-wide points ahead of each double-disk planter. The PT treatment was applied in the fall with a Tye Paratill plow (Bigham Brothers, Lubbock, TX)[1] equipped with six legs (three right and three left) spaced 0.61 m apart and angled at 45° to the side and outfitted with a 6.4-mm serrated coulter ahead of each leg. Planting in the spring was with a reduced tillage planter having two 4.2-mm smooth coulters ahead of a double-disk no-till planter. The ST treatment was planted with the same reduced tillage equipment, and weeds between the rows during the summer crop season were controlled by ST using 0.6-m sweeps. The DT treatment was applied in the spring using a 3.05-m-wide offset disk harrow to a depth of 0.1 to 0.13 m followed by planting with the reduced tillage planter. Years of tillage application and treatment designations are given in Table 2.

Each plot consisted of eight rows on 0.76-m spacing (6.1 by 22.8 m) with wheel traffic confined to areas between alternating rows. Rows were re-established so that tillage, planting, and traffic occurred in the same location each year. The study was started in the fall of 1991 by disking the entire area to a depth of 0.1 to 0.13 m with a 120-kW Hesston 180-90 tractor (weight 6550 kg; Fiat Agric., Modena, Italy)[1] and offset disk harrow. The same tractor was used each fall following summer crop harvest to paratill designated PT plots (Table 2) approximately 0.30 to 0.36 m deep. In the fall of 1992, soils were wet and PT was delayed until May 1993. The tillage depth was the maximum that could be achieved and was at approximately the top of the Bt horizon. The 120-kW tractor was used in the spring to disk-harrow DT plots and plant designated IC plots. A 56-kW John Deere 3020 tractor (weight 4458 kg; John Deere and Co., Moline, IL)[1] was used in the spring to plant remaining plots with the four-row reduced tillage planter and in the fall to plant cover crops on all plots with a conservation

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

Table 2. Treatment designations for the annual and alternate-year tillages and year(s) of application.

	Year(s) of tillage application				
Treatments†	1992	1993	1994	1995	1996
IC1, PT1, ST1, DT1	X	X	X	X	X
IC2, PT2, ST2	X		X		
IC3, PT3, ST3	X			X	
IC4, PT4, ST4	X				X
IC5, PT5, ST5	X				

† IC, in-row chisel; PT, paratill; ST, secondary tillage; DT, disk tillage. Numbers are used to designate tillage frequency treatments.

tillage grain drill. Field operation dates are presented in Table 3. Management followed standard recommended practices from the University of Georgia Extension Service.

Hybrid pearl millet (*Pennisetum glaucum* L.) (4.5 kg ha^{-1}) was planted following crimson clover (*Trifolium incarnatum* L.) (17 kg ha^{-1}) in 1992 and 1993. The cropping system was switched to cotton (17 kg ha^{-1}) following winter rye (*Secale cereale* L.) (78 kg ha^{-1}) in 1994, 1995, and 1996 because millet yields were being limited by bird damage and disease. Cover crops were planted on all plots in the fall and were killed with paraquat (1,1′-dimethyl-4, 4′-bipyridinium ion) or glyphosate (*N*-phosphonomethyl glycine) following emergence on DT1 plots and in the spring 14 to 21 d before planting summer crops in all other plots (Table 3). Yield of millet was measured from the middle two rows with a plot combine in 1992, and the remaining millet was harvested with a field combine (weight 4825 kg; AC Gleaner Model F3, Allis Chalmers, Independence, MO)[1] with wheels spaced 3.04 m, straddling the center nontrafficked areas. In 1993, yield was not collected with the small-plot combine, and the entire experiment was harvested with the field combine. Cotton was harvested with a two-row cotton picker (weight 5900 kg; Model 299, John Deere and Co., Moline, IL), and yield was determined from 18.3 m of the middle two rows of each plot. Remaining rows were harvested with the same two-row picker. Although some equipment was six rows and some four rows, we maintained consistent wheel traffic rows with these combinations to ensure that deep tillage occurred in the same rows.

Crop enterprise budgets were developed for the 3 yr of cotton production using the Farm Suite whole-farm planning system (Lamb et al., 1992). Farm Suite is a whole-farm planning system designed to optimize farm and financial planning decisions by developing formal farm plans specific to each farm operation. It can be used to monitor costs for multiple farm enterprises on different fields and create summarized information for each field, crop, or whole farm. We used Farm Suite to calculate variable and fixed costs for each tillage treatment and estimate total costs, total returns, and net returns. For each tillage treatment, equipment and production inputs (seed, fertilizer, chemicals, etc.) were entered into Farm Suite as different fields. Variable costs were estimated from actual application rates for seed, herbicides, insecticides, harvest aids, and fertilizers used and historic data on average costs paid by farmers for these materials (Givan, 1994, 1995,

Table 3. Dates of major field operations.

	Summer crop year				
Field operation	1992	1993	1994	1995	1996
Fertilize	20 Sept. 1991	2 Dec. 1992	7 Oct. 1993	9 Nov. 1994	18 Oct. 1995
Paratill	28 Sept. 1991	17 May 1993	7 Oct. 1993	9 Nov. 1994	18 Oct. 1995
Kill cover crop	22 May 1992	6 May 1993	1 Apr. 1994	4 Apr. 1995	13 Apr. 1996
Plant summer crop	1 June 1992	21 May 1993	9 May 1994	4 May 1995	10 May 1996
Harvest	17 Nov. 1992	27 Sept. 1993	7 Nov. 1994	12 Oct. 1995	22 Oct. 1996

† Due to a wet fall, the paratill operation for 1993 was delayed until the spring.

1996; Georgia Agric. Stat. Serv., 2001; Dr. Steve Brown, personal communication, 2002; Mr. Jimmy Adams, personal communication, 2002). Variable costs for labor (\$6.25 h^{-1}), fuel (\$0.24 L^{-1}), and equipment maintenance were estimated within the Farm Suite software based on data from University of Georgia enterprise budgets (Givan, 1994, 1995, and 1996). Fixed costs included costs of tractors, self-propelled equipment, and implements (Benson et al., 1996). The fixed cost for a machine is a sum of the costs for depreciation (over 10 yr), interest (8%), repairs (major), taxes, and insurance. Fixed costs per hectare for equipment were allocated across an equal area (100 ha of cotton on a 200-ha farm) to avoid bias toward one of the implements used in the study. Gross return was calculated annually as the product of treatment yield and Georgia market-year average prices for 1994, 1995, and 1996, respectively, for lint of \$1.60, \$1.65, and \$1.54 kg^{-1} and for cottonseed of \$105, \$93, and \$93 Mg^{-1}. For DT1, IC1, PT1, and ST1 tillage, costs were charged annually while for the other tillage treatments, costs were prorated on an annual basis to allocate a cost incurred during 1 yr over all 5 yr of the study. As an example, in-row chisel is used in IC2 during Years 1 and 3 while in the remaining years, the plots were planted with a no-till planter. In this case, average annual tillage cost is the average of 2 yr of IC and 3 yr of no-till. No charges were included for land, management, or general farm overhead. Net return was calculated as the difference between gross income and total specified costs. Three-year average net returns for cotton were calculated from the annual net return from 1994, 1995, and 1996.

Statistical analysis of treatment effects on cotton yield and net return was evaluated using the MIXED model procedure in the Statistical Analysis System (SAS Inst., 1990; Littell et al., 1996). Year, replication, year × replication, and year × treatment were considered random effects while treatment was considered a fixed effect in the mixed-model analysis. Significance of year was determined using the likelihood ratio statistic (Littell et al., 1996). Degrees of freedom were determined using Satterthwaite's procedure. Specific single degree-of-freedom contrasts were used to compare treatments across and within years. All means were estimated as Best Linear Unbiased Predictors (Littell et al., 1996). Differences were considered significant at $\alpha = 0.10$ unless otherwise stated. Treatment effects on plant populations for each year were determined using the GLM procedure of SAS (SAS Inst., 1990).

RESULTS

Climate

The three growing seasons were different in terms of heat unit accumulation [growing degree days with a base of 15.6°C (60°F), DD_{60}], rainfall amount, and rainfall distribution (Fig. 1). In 1994, rainfall from planting to 1 September was 695 mm although limited rainfall occurred from mid-August to mid-September. Above-average fall rainfall combined with early cool temperatures delayed and impeded boll development in 1994. Heat unit accumulation was insufficient to complete crop maturation (1596 by 1 September with 2100 to 2200 DD_{60} needed for crop maturation). There were many unopened bolls present at harvest in early November.

Temperature was more favorable for boll development in 1995 and 1996; however, rainfall from planting to 1 September was limited in 1995 (426 mm) and 1996 (303 mm) with very poor distribution, particularly in 1995. During 1995, a long dry period from mid-June to mid-August made it necessary to irrigate to avoid total crop failure. Water (approximately 45 mm ha^{-1}) was applied using a traveling gun over a 3-d period (1 d per replication) on 18 to 20 July and again on 26 to 28 July. In 1996, rainfall was more limited but more evenly distributed. Abundant spring rain that resulted in significant stored water helped eliminate the need for irrigation to avoid crop failure. However, the limited amount of rain during the growing season certainly depressed cotton yield.

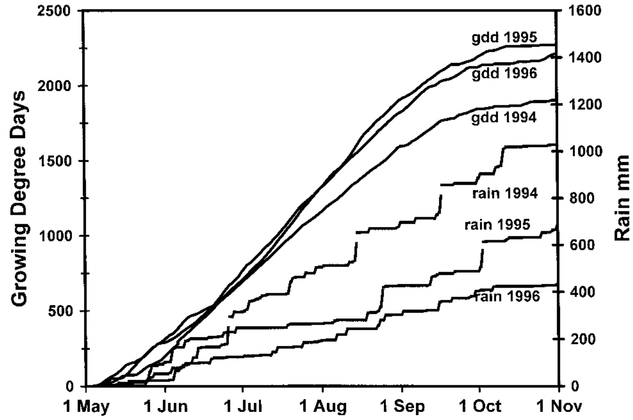

Fig. 1. Growing degree days (gdd) and rainfall for the 1994, 1995, and 1996 cotton growing seasons at Watkinsville, GA.

Plant Stand

Stand establishment was influenced by tillage treatments in all 3 yr ($p < 0.02$). Cotton population ranged from 4.4 to 15.9 plants m^{-2} in 1994, 4.1 to 12.9 in 1995, and 7.0 to 13.5 in 1996 (Table 4). Optimum cotton production occurs with a population of 7 to 9 plants m^{-2}, with no benefit from higher populations (Bednarz et al., 2000). Population was greatest for IC treatments during the year of application. Although planting equipment was nearly identical, the chisel may have created better seedbed conditions compared with other treatments. Potential effects of population on crop yield are discussed below.

Cotton Yield

Significant year ($P = 0.02$) and treatment ($P = 0.08$) effects were present in the yield analysis while year × treatment effects were not significant ($P = 0.39$). There was a trend for greater yield response to IC than for other tillages (Tables 4 and 5). Annual IC had a greater positive effect on cotton yield than did annual PT and ST (Tables 4 and 5). Averaged across years, yield with IC1 was 298, 261, and 216 kg ha^{-1} greater than with DT1, PT1, and ST1, respectively. Response to IC tended to be greatest during the year of application as indicated by the absence of a significant difference between IC1 and IC2 in 1994 or IC1 and IC3 in 1995 although IC1 resulted in greater yield than IC4 in 1996 due to unknown reasons. Yield with IC1 was greater than that in plots that had not received a second IC by 29% in 1994

Table 4. Cotton population, yield, and annualized net return for 1994, 1995, and 1996, and average annual tillage costs for each treatment.

Tillage†	Population			Lint yield‡				Net return‡				Tillage cost
	1994	1995	1996	1994	1995	1996	3-yr avg.	1994	1995	1996	3-yr avg.	
	plants m^{-2}			kg ha^{-1}				\$ ha^{-1}				
DT1	15.4	8.3	11.3	555	940	735	743	102	500	219	274	78.23
IC1	13.2	12.9	13.5	851	1260	1014	1042	558	895	718	724	42.90
IC2	15.9	7.0	8.5	773	1120	902	932	344	813	560	572	39.64
IC3	4.7	12.0	10.3	736	1169	916	940	450	750	583	594	39.64
IC4	8.0	8.0	12.6	578	943	718	746	111	557	315	328	39.64
IC5	7.2	7.0	8.9	677	1091	850	873	353	683	488	508	38.56
PT1	6.8	4.7	7.0	601	974	768	781	124	558	282	321	70.84
PT2	6.2	4.0	8.8	618	1007	836	821	243	648	293	395	50.81
PT3	5.0	8.2	12.0	628	1048	800	825	283	609	422	438	50.81
PT4	10.2	6.9	10.8	694	1046	849	863	274	736	452	488	50.81
PT5	7.4	6.9	9.8	712	1097	891	900	342	745	473	520	44.14
ST1	7.6	6.4	9.6	650	1020	807	826	236	663	413	437	62.94
ST2	5.9	5.3	9.5	649	1001	800	817	186	668	385	413	47.65
ST3	7.9	6.0	9.0	606	950	729	762	103	580	346	343	47.65
ST4	4.4	6.6	11.7	698	1062	884	881	319	762	411	498	47.65
ST5	6.0	5.9	7.2	558	950	746	751	144	539	257	313	42.56
Least sq. diff.§	5.0	2.8	3.5	na¶	na	na	na	na	na	na	na	na

† Tillage treatments are as in Table 2.
‡ Yields and net returns are best linear unbiased predictor means.
§ Least square difference for fixed-effect models.
¶ na, for the mixed model analysis, contrasts were estimated for differences between specific treatments (see Tables 5 and 6).

(IC3, IC4, and IC5; $P = 0.020$), 27% in 1995 (IC4 and IC5; $P = 0.005$), and 17% in 1996 (IC5; $P = 0.091$). Yield with IC1 was greater than that in plots treated the previous year in 1995 (IC2) but not in 1996 (IC3) (Table 5). The IC treatment provided improved soil conditions that enhanced cotton stand establishment, growth, and yield predominantly in the year of application.

Yield of cotton was not differentially influenced by annual or alternative-year PT treatments (Tables 4 and 5). In each year, yield with PT1 was similar to that in plots receiving PT during that cropping season (Table 5). Interestingly, the 3-yr average indicated greater yield for plots with the longest history of no paratillage (compare PT1 with PT5). Our results may have been affected by poor stands in PT plots associated with a rough soil surface, but that effect was not consistent. On the infrequently paratilled plots (PT2, PT3, PT4 and PT5), the winter rye cover crop may have helped establish more permanent root networks and macropore channels of less resistance due to the absence of disturbance (Bruce et al., 1995; Triplett et al., 1996). Raper et al. (2000b) found that including a winter cover crop increased yield on Piedmont soils more effectively than did deep tillage. When deep tillage was combined with a cover crop, yield tended to decrease compared with treatments that did not include deep tillage. Annual PT was expected to produce results similar to IC1 due to disruption of the soil profile. Effectiveness of paratillage can be reduced in wet soils (because they are less likely to fracture), with additional traffic, and from natural settling of the soil profile.

As with PT, no differences in yield were apparent among ST plots that received annual secondary tillage and those that received less frequent secondary tillage (Table 4 and 5). The ST treatment caused some disturbance of the soil surface but minimal burial of crop residues. Keeping residues on the soil surface is impor-

Table 5. Linear contrast comparisons between specific treatments to evaluate differences in lint cotton yield within and across years.†

Treatment comparison‡	1994		1995		1996		3-yr average	
	kg ha^{-1}	Prob > t	kg ha^{-1}	Prob > t	kg ha^{-1}	Prob > t	kg ha^{-1}	Prob > t
DT1-IC1	−296.3	0.0033	−319.8	0.0017	−278.7	0.0055	−298.2	0.0016
DT1-PT1	−46.7	0.6231	−33.2	0.7264	−32.9	0.7292	−37.6	0.6759
DT1-ST1	−95.3	0.3189	−79.2	0.4063	−72.0	0.4496	−82.2	0.3625
IC1-PT1	249.5	0.0120	286.6	0.0044	245.8	0.0132	260.6	0.0052
IC1-ST1	201.0	0.0399	240.6	0.0151	206.6	0.0349	216.1	0.0192
PT1-ST1	−48.5	0.6147	−46.0	0.6339	−39.2	0.6846	−44.6	0.6205
IC1-IC2	78.2	0.4123	140.0	0.1462	111.7	0.2436	110.0	0.2245
IC1-IC3			91.1	0.3402	98.1	0.3047	101.6	0.2613
IC1-IC4					296.0	0.0034	295.4	0.0017
IC1-IC5					163.8	0.0907	168.9	0.0646
PT1-PT2	−16.8	0.8598	−33.5	0.7240	−68.3	0.4735	−39.5	0.6604
PT1-PT3			−74.7	0.4330	−31.9	0.7368	−44.3	0.6224
PT1-PT4					−81.2	0.3945	−81.9	0.3639
PT1-PT5					−123.1	0.1998	−119.1	0.1890
ST1-ST2	0.6	0.9948	19.0	0.8411	6.9	0.9416	8.9	0.9214
ST1-ST3			69.2	0.4678	78.2	0.4122	63.7	0.4794
ST1-ST4					−77.2	0.4181	−55.8	0.5354
ST1-ST5					60.7	0.5234	74.3	0.4102

† Contrasts are between best linear unbiased predictor means for each treatment.
‡ Tillage treatments are as in Table 2.

Table 6. Linear contrast comparisons between specific treatments to evaluate differences in net return from cotton within and across years.†

Treatment comparison	1994		1995		1996		3-yr average	
	$ ha^{-1}	Prob > *t*	$ ha^{-1}	Prob > *t*	$ ha^{-1}	Prob > *t*	$ ha^{-1}	Prob > *t*
DT1-IC1	−456.26	0.0363	−394.73	0.0483	−499.05	0.0304	−450.01	0.0005
DT1-PT1	−21.55	0.8412	−57.48	0.6049	−62.54	0.5760	−47.19	0.7008
DT1-ST1	−133.31	0.2903	−162.94	0.2224	−193.88	0.1716	−163.38	0.1867
IC1-PT1	434.71	0.0400	337.25	0.0654	436.51	0.0397	402.82	0.0017
IC1-ST1	322.95	0.0710	231.79	0.1283	305.16	0.0788	286.63	0.0227
PT1-ST1	−131.35	0.2957	−105.46	0.3784	−111.76	0.3560	−116.19	0.3457
IC1-IC2	214.80	0.1457	81.60	0.4780	158.07	0.2320	151.49	0.2203
IC1-IC3			145.48	0.2597	135.43	0.2847	129.69	0.2931
IC1-IC4					403.22	0.0464	396.33	0.0020
IC1-IC5					230.14	0.1299	215.85	0.0829
PT1-PT2	−119.51	0.3306	−90.43	0.4382	−11.54	0.9142	−73.82	0.5481
PT1-PT3			−51.41	0.6412	−140.18	0.2725	−117.03	0.3423
PT1-PT4					−170.42	0.2085	−166.43	0.1787
PT1-PT5					−191.09	0.1755	−198.62	0.1099
ST1-ST2	49.33	0.6540	−4.95	0.9631	27.71	0.7974	24.03	0.8448
ST1-ST3			83.44	0.4694	67.23	0.5503	94.41	0.4430
ST1-ST4					1.59	0.9882	−60.27	0.6237
ST1-ST5					156.05	0.2362	124.14	0.3141

† Contrasts are between best linear unbiased predictor means for each treatment.
‡ Tillage treatments are as in Table 2.

tant in these soils to reduce soil crusting and runoff and increase infiltration associated with depletion of organic matter in the top 0.025 m (Bruce et al., 1995). Although we used herbicides in the ST plots for early-season weed control, secondary tillage was usually sufficient for weed control and could be considered for sustainable or organic systems where economic returns on lower yields could be offset by greater premiums for organic cotton (usually 3 to 1).

Plant population was significantly correlated to yield during all 3 yr. The correlation was 32% in 1994, 54% in 1995, and 29% in 1996. Reduced yield due to stand density occurred only with very low plant populations. Although low population may have influenced yield for some treatments, the greater yield response to IC is attributed to additional effects like greater water infiltration and penetration of the soil profile by cotton roots because plant population with several other treatments was similar to that with IC1 although yield was consistently lower for these treatments. Bednarz et al. (2000) found that plant population may have little effect on final cotton yield because of changes in boll retention and position as plant population changes.

Economic Analysis

Net return was significantly influenced by year ($P = 0.04$) and treatment ($P = 0.07$), but the year × treatment interaction was not significant. Because of the significant influence of yield on returns, treatments with greater yields in general produced greater net returns as expected; however, differences in tillage costs were also present and had additional influence. Net return averaged across the three cotton years ranged from $275 to $725 ha^{-1} annually, depending primarily on cotton yield (Tables 4 and 6). Cost for tillage operations (based on the tillage and planting to equal the operations in the IC treatment) ranged from $40 to $100 ha^{-1}. Operational cost of IC1 was greatest, but average annual net return was also greatest (Table 6). Surprisingly, operational cost of DT1 was nearly two times that for IC1, which along with a lower yield, reduced profits compared with IC1 (Table 6). The yield advantage with IC1 resulted in a greater net return over that of PT1 and ST1 (Table 6). Differences among IC treatments in net return were similar to those found for yield. Net return for PT increased from PT1 to PT5, which was unexpected. The PT1 plots were paratilled each year while those of PT2, PT3, and PT4 were paratilled two times, with the second paratillage operation occurring in succeeding years (Table 2). There were no differences in net return among the ST treatments. The ST treatments resulted in net returns similar to those of the PT and DT treatments and less than those of the IC treatments.

DISCUSSION

Variable growing conditions experienced during the 3 yr of cotton illustrate why many producers have adopted cotton as a reliable crop in the southeastern USA. Even with poor growing conditions, cotton yield was generally greater than 700 kg ha^{-1} for most treatments (Table 4). Although not always significant, cotton yield on the reduced tillage plots receiving annual tillage tended to be greater than that on conventional tillage plots (Table 5). Previous work at the same location demonstrated beneficial effects of conservation tillage on soil physical, biological, and chemical properties (Bruce et al., 1995; Langdale et al., 1990; Franzluebbers et al., 1999). Bruce et al. (1995) showed that for Cecil soils in the Southern Piedmont, reduced tillage and increased crop residue inputs increase soil organic matter and water-stable aggregates at the soil surface. Infiltration rate was 51% greater in no-till than in conventional tillage plots and remained greater even when surface residues were removed before infiltration measurements. Triplett et al. (1996) observed that cotton yields increased over the last 3 yr of a 5-yr study with NT relative to conventional tillage on Mississippi loess soils.

The cumulative effect was attributed to increases in water availability due to development of improved soil structure. Franzluebbers et al. (1999) found that at a depth of 0 to 150 mm, soil aggregate mean-weight diameter averaged 1.03 mm with DT, 1.12 with PT, 1.17 with ST, and 1.23 with IC for plots in the current study. Biophysical improvement of surface soil structure would lead to greater water infiltration and presumably improved water use efficiency. Improving soil biophysical properties becomes more critical in drought-affected periods like those experienced in 1995 and 1996 when benefits of the IC treatment became more obvious.

The benefit of current-year IC was apparent all 3 yr. In 2 out of 3 yr, the annual IC (IC1) and current-year IC resulted in similar yield. Better yield due to current-year IC probably resulted from better stand establishment and increased water and nutrient availability associated with improved root penetration of soil layers. Langdale and Wilson (1987) found similar results on Cecil soil for grain sorghum [*Sorghum bicolor* (L.) Moench] where yields for in-row chisel were 0.31 and 0.50 Mg ha^{-1} greater than for disk till and no-till, respectively. The results are also similar to those of Raper et al. (2000a), indicating that shallow in-row chiseling in the fall was equally or more effective than deeper tillage to disrupt an impeding clay layer and increase cotton yield on a Decatur silt loam (clayey, kaolinitic, thermic Rhodic Paleudult) in Alabama.

Results for PT were surprising because this tool creates deeper soil profile disturbance compared with the other tillage treatments, which should increase water infiltration in the winter and improve soil exploration by cotton roots. Several authors have reported reduced soil density with paratillage (Tollner et al., 1987; Clark et al., 1993; Radcliffe et al., 1989; Wesley et al., 2000). Wesley et al. (2000) found that soybean yields on a nonirrigated clay soil in the Mississippi River flood plain were identical following annual fall paratillage or annual subsoil treatment but were significantly reduced with disk tillage. Several factors may have contributed to the reduced response to PT. Paratillage is most effective when applied to a dry soil profile. Our PT treatment occurred in the fall when the soil profile may have been wetter than desired, thus resulting in insufficient fracturing. Because of the lifting and fracturing action of paratillage, continuity of macropores can be destroyed, thus reducing saturated hydraulic conductivity, infiltration, and water storage (Biki and Guo, 1991). Most likely the absence of a positive response to PT was the result of reconsolidation of the soil profile between the fall and cotton-growing season. Reconsolidation of the profile may have occurred naturally during the following months and was further enhanced by field operations (planting the rye cover crop, herbicide application to kill the cover crop, and cotton planting) (Reeder et al., 1993). Natural reconsolidation is correlated to rainfall during the winter season and would be greater in wet years (W.J. Busscher, personal communication, 2002).

Although tractor traffic was confined to the same area in the plots each year, some variation across plots during field operations may have occurred. Clark et al. (1993) and Radcliffe et al. (1989) indicate that in Cecil soil, wheel traffic contributes to hardpan formation at 0.15 to 0.25 m below the surface. Reeder et al. (1993) found that soil strength following paraplowing returned to pre-subsoiling strength during the first growing season, and this effect may have been due to the bent-leg design allowing for more rapid consolidation than might occur with other subsoiling equipment. In other studies, changes in soil physical properties associated with paratillage persisted for more than 2 yr, but effects on yields were not apparent, probably due to yield-limiting factors not associated with tillage (Tollner et al., 1987). Because IC was performed at planting, negative effects of wheel traffic would be minimized compared with fall PT where planting and killing of the cover crop and planting the summer crop occurred following the profile disruption. The absence of traffic following IC is most likely the reason that yields were consistently greater in the year IC was performed.

Our results indicate that for Cecil and similar soils, IC provides an increased return and time savings over that of PT and DT while PT did not improve economic return. Cost associated with PT was greater than that for IC because of the requirement for an additional tractor operation (time and labor). Additional savings with IC could be realized using a smaller tractor with lower operating and reduced maintenance costs. Therefore, IC appears to be a more reliable choice on these Southern Piedmont soils over fall PT. Clark et al. (1993) concluded from cone index and water infiltration data that moderately and severely eroded soils of the Southern Piedmont require annual chiseling to ensure minimizing the effect of soil compaction on crop growth. Our results along with other studies demonstrating variable response to paratillage indicate that IC is probably a better option for Piedmont soils; however, response to tillage often depends on site, soil, and cropping history.

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