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Soil & Tillage Research 66 (2002) 55–68

Soil & Tillage Research

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Impact of conservation tillage and nutrient management on soil water and yield of cotton fertilized with poultry litter or ammonium nitrate in the Georgia Piedmont

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Received 11 January 2001; received in revised form 24 January 2002; accepted 26 February 2002

Abstract

Cotton has become a dominant crop in the southeastern USA, but only about 12% of the 620,000 ha of cotton (*Gossipium hirsutum* L.) in Georgia, for example, is under conservation tillage. Georgia and bordering states produce about 42% of the poultry in the United States and in Georgia alone, this results in over 1.6 million Mg of poultry litter (PL) annually. The fertilizer value of PL is well-recognized but much of it is applied to pastures and only a small percentage is applied to crop land. Limited information is available on the response of cotton to PL as fertilizer in conservation tillage systems in the Southeast. The performance of cotton under two tillage and two fertilizer treatments was evaluated from 1996 to 1999 to highlight management options for increased adoption of conservation tillage and PL use. Cotton, followed by a rye (*Secale cereale* L.) cover crop, was grown under a factorial arrangement of tillage (no-till (NT) vs conventional tillage (CT)) and fertilizer (ammonium nitrate, as conventional fertilizer (CF) vs PL) on a Cecil sandy loam (clayey, kaolinitic thermic Typic Kanhapludult; Chromi-Alumic Acrisol) near Watkinsville, Georgia. Average lint yield from 1996 to 1999 was in the sequence no-till poultry litter (NTPL) > no-till conventional fertilizer (NTCF) > conventional tillage poultry litter (CTPL) > conventional tillage and fertilizer (CTCF). Differences were significant at $P \leq 0.05$ for NTPL vs CTPL, NTPL vs CTCF, and NTCF vs CTCF. Average yield differences were also significant between NT and CT but not PL and CF. PL yielded more than CF only in 1997. NT generally had a more favorable soil water regime than CT. Yield differences among treatments occurred during the first 3 years only. Drought in the fourth year reduced yield across all treatments and negated treatment effects. Lint yield would increase in the southeastern USA and an additional outlet for the PL would be created by adopting NT and fertilizing with PL in cotton production. Published by Elsevier Science B.V.

Keywords: Georgia, USA; Chromi-alumic acrisol; Conservation tillage; No-till; Cotton; Poultry litter; Nutrient management

1. Introduction

The Southern Piedmont is a 16.5 million hectare region in southeastern USA that extends along the east face of the Appalachian Mountains from Virginia to

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0167-1987/02/$ – see front matter. Published by Elsevier Science B.V.
PII: S0167-1987(02)00013-2

Alabama, and that is severely eroded as a result of over 200 years of intense row crop agriculture (Bruce and Langdale, 1997). Much of the row crop agriculture in the region is conventionally tilled and fertilized. Conventional tillage (CT) refers to full width tillage involving plowing, or intensive (numerous) tillage trips, which disturb all the soil surface and is performed prior to, during and/or after planting (CTIC, 1998). Crops are grown on sloping land, and on soils that are relatively infertile, highly erodible, low in organic matter, and easily compacted by rainfall and machine traffic (Carreker et al., 1977). The soils respond well, however, to good management practices, including adequate levels of nutrients, and cropping systems that restore organic matter and soil structure, increase available water, and reduce machine traffic.

Conservation tillage, defined as any tillage and planting system that leaves 30% or more of crop residue on the soil surface after planting (CTIC, 1998), is one such good management practice. A cover crop, usually grown in winter, is often required to achieve this level of residue. Benefits credited to conservation tillage include soil and water conservation, lower production costs, higher yields, and greater production efficiency (CTIC, 1998; Domitruk and Crabtree, 1997; Langdale et al., 1992).

Adoption of conservation tillage for major crops such as cotton and soybean (*Glycine max* L. Merr.) has risen in recent times in the Southeast. About 12% of the cotton and 34% of the soybean are under conservation tillage in Georgia (CTIC, 1998). The favorable climate in Georgia, which includes 200–250 frost-free days and rainfall that is generally well distributed throughout the year, supports the cotton production and a wide range of other crops also. However, although annual average rainfall is about 1250 mm, short-term summer droughts are common. Yield is curtailed when such droughts occur during flowering and boll formation period of growth. Cotton under CT is more at risk of suffering moisture stress during these drought periods because of factors such as crusting and pore size distribution and connectivity, which reduce soil water reserve. Conservation tillage conserves water by reducing evaporation. It also creates a more favorable soil water regime by improving surface soil properties that favor more infiltration and conduction of water to lower soil profile and, consequently, more reserve of soil water.

Poultry production is a growing $10 billion agribusiness in Georgia (Rodekohr and Rahn, 1997). In 1998, the USA poultry industry produced almost 8 billion broilers (GASS, 1999). At a total production rate of 1.46 kg manure per bird (Perkins et al., 1964), almost 12 million Mg of litter, a mixture of bird excreta, feathers, waste feed, and bedding material, was produced. Poultry litter (PL) is typically applied to pasture and crop land because it contains plant nutrients including N, P and K (Moore et al., 1995), and because it is considered to be a safe practice (Edwards and Daniel, 1992). However, it is not used to its full potential since only a small percentage is applied to crop land. There are several reasons why PL is not used to its full potential. Among these are: (1) availability of PL at the appropriate time for application to row crops is often a major limitation; (2) variability in nutrient content, so farmers may consider it risky compared to conventional fertilizer (CF); (3) failure to recognize how and where to use it; (4) lack of information on how it performs with conservation tillage and on different crops.

Considerable experience is accumulating with regard to no-till (NT) (a form of conservation tillage) production of cotton on the alluvial and loess soil of Arkansas, Louisiana, Mississippi, and Tennessee (e.g. Keisling et al., 1992; Kennedy and Hutchinson, 1993). Information is, however, lacking on the impact of different tillage and nutrient management systems on cotton production on the dominant soils in the southeastern USA. Recommendations by the University of Georgia indicate that N is the most important fertilizer used in cotton production in Georgia, and that PL in cotton production should be managed to provide the desired rates of N (GCES, 1997). The objective of this research was to evaluate yields of NT and conventionally tilled cotton either fertilized with PL or fertilized with ammonium nitrate, as CF, on a Cecil soil, the dominant soil series in the Southern Piedmont land resource area of southeastern United States.

2. Materials and methods

2.1. Experimental site and soil

The experiment was conducted from 1996 to 1999 at the USDA-ARS, J. Phil Campbell Sr. Natural

Resource Conservation Center, Watkinsville, GA, USA (33°54′N, 83°24′W). The site consisted of 12 instrumented and subsurface-drained 10 m × 30 m plots, located on nearly level (0–2% slope) Cecil sandy loam (clayey, kaolinitic thermic Typic Kanhapludult; Chromi-Alumic Acrisol per FAO, 1998). Typic Kandhapludults cover two-thirds of 14.1 million hectare available for cropping in the Southern Piedmont (Langdale et al., 1992).

The area has a warm temperate climate, long growing seasons, and ample rainfall. Hendrickson et al. (1963) and Bruce and Langdale (1997) give details of some pertinent climatic parameters. Average daily temperatures range between 23.9 and 26.7 °C in the summer (June–August) and 4.4–7.2 °C in winter (December–February). Mean annual temperature is 17 °C. Average frost-free growing season is from 200 to 250 days. Mean annual rainfall is 1252 mm while mean annual pan evaporation is 1564 mm. The highest mean monthly rainfall (115–140 mm) occurs in the winter months. Mean monthly rainfall is least (77–86 mm) in the fall (September and October). The spring–summer rains are intermediate in magnitude but can have high intensity and can be highly erosive. Minimum and maximum mean monthly rainfall varies from 0 to 29 and from 220 to 400 mm, respectively. Short-term summer drought can occur with negative impact on crop productivity.

Physical, chemical and biological characterization data for the soil in the research area have been reported by Bruce et al. (1983) and Perkins (1987). The Cecil soil series generally consists of deep well drained moderately permeable soils. These soils are deeply weathered and have largely developed in residuum from underlying schist, gneiss, granite. The profile is generally acidic and pH decreases with depth. The cation exchange capacity is around 6 cmol kg^{-1}. Base saturation is about 50%. Kaolinite makes up over 50% while vermiculite/chlorite makes up 10–30% of the clay mineralogy. Soil layers consist of an Ap, BA, Bt, BC and C horizons. Ap is a brown sandy loam, about 20 cm thick, with 60–70 g kg^{-1} clay and 740–780 g kg^{-1} sand. BA is a red sandy clay loam to clay loam, 6–10 cm thick, with 230–370 g kg^{-1} clay and 430–540 g kg^{-1} sand. Bt consists of red clay about 100 cm thick followed by about 30 cm thick red loam to clay loam BC horizon. The C horizon is a loamy saprolite.

2.2. Tillage and fertilizer treatments

A factorial combination of two tillage (NT vs CT) and two nitrogen (N) fertilizer treatments (ammonium nitrate, as CF vs PL), with three replications of each treatment, were arranged in a randomized complete block design over the 12 plots. The CT consisted of a 30 cm deep chisel plowing, to break possible hard pans, followed by a 1–2 passes of disc harrowing to a depth 20 cm, and a subsequent disking to 8 cm to smooth the seed bed. The only tillage operation in the NT was the use of a coulter disk for planting. Tillage treatments had been in place since the fall of 1991.

Target N application rates for cotton as recommended by University of Georgia were used for fertilizer treatments. Rates were: ammonium nitrate at 60 kg available N ha^{-1} and PL at 4.5 Mg ha^{-1} (30% moisture) assumed to provide the same N rate as ammonium nitrate. Mineralization rate of N in PL was assumed to be 50% (Vest et al., 1994). PL was from a local poultry house that generates three flocks per cleaning from concrete floors covered with saw-dust and shavings. Each flock takes 6–8 weeks to produce. Fresh litter was transported to the research site and kept under cover for not more than 2 weeks before being applied on the plots with a specially designed spreader. Total N from the PL averaged 3.6% on a dry basis. Based on moisture content, the equivalent total N was 116 kg ha^{-1}. Available N would then have been 58 kg ha^{-1}. This compares well with the target application rates of 120 kg ha^{-1} total and 60 kg ha^{-1} available N.

Soil tests were used to determine K and P fertilizer needs and application rates following standard practice as recommended by University of Georgia. All N, P and K fertilizers were applied immediately (2–3 days) before cotton planting each year. Potassium was applied as potassium chloride to all plots at rates of 56 kg K ha^{-1}. Phosphorus (56 kg P ha^{-1}) was applied as triple super phosphate in 1998 and 1999 only to plots not receiving PL. These rates were based on soil test results made available a week or so before planting dates.

2.3. Cropping system and operation

The cropping system consisted of rye grown in winter/spring (November–May) as a cover crop followed by cotton grown in the summer/fall (May–November). Rye was chosen as cover crop because it has a greater residue producing potential compared to other cereals like wheat (*Triticum aestivum* L.). Light disking was carried out in CT plots for seed bed preparation 2–3 days prior to planting rye. Ammonium nitrate (56 kg N ha^{-1}) and potassium chloride (45 kg K ha^{-1}) were then applied on all plots. Next, the fertilizers were incorporated into the soil by light disking in CT but not NT plots. A rye cultivar 'High Gainer' was planted during the first 2 weeks in November at rates of 84 kg ha^{-1}. The rye remained about 0.3 m tall until March. There was accelerated growth after that and rye height reached 1.2–1.5 m in early May. Residue amounted to 3–5 Mg ha^{-1} of dry matter. Glyphosate was applied at 2.2 kg a.i. ha^{-1} to kill rye about 2 weeks prior to cotton establishment in mid to late May. Glyphosate also helped with weed suppression for the upcoming cotton crop. Emerging advantages of some cover crops is that they serve as a reservoir for beneficial insects which have become increasingly important in pest control such as boll weevil. The lady beetle (*Hippodamia convergens*), green lynx spider (*Peucetia viridans*) and praying mantids (*Mantis religiosa*) were the most conspicuous beneficial insects in the 4 years of this research.

The cotton cultivar used was 'Stoneville 474', an early maturing variety. Cotton pesticides were: aldicarb, an insecticide for control of thrips and nematodes at 4.4 kg a.i. ha^{-1}; fluometuron, a broadleaf herbicide applied at 1.6 kg a.i. ha^{-1}; and pendimethalin, a herbicide for annual grass control applied at 0.84 kg a.i. ha^{-1}. Except for aldicarb, which was applied at the same time as planting, fertilizers and pesticides were applied 2–3 days before planting and were incorporated into the soil by light disking immediately afterwards in CT and applied only to the soil surface in the NT treatment.

Cotton was planted in 0.86 m rows at 10–13 plants per meter in 1996 and 1997. Planting dates were 30 May 1996 and 14 May 1997, and harvesting was on 1 November 1996 and 4 November 1997. In 1998 and 1999 cotton was planted in 0.76 m rows at 10–13 plants per meter. Planting dates were 14 May 1998 and 16 May 1999, and harvesting dates were 12 November 1998 and 10 November 1999. Availability of planting equipment dictated the change in row spacing.

After cotton emergence, a variety of additional chemical and mechanical means were used to control persistent weeds that the pesticide application just before planting did not eliminate. A hand operated rear tine rototiller was used for weed control in CT plots about 3 and then 7 weeks after germination. The NT plots were sprayed with 0.22 kg a.i. ha^{-1} of fluazifop-p-butyl for grass control. Glyphosate was applied at 1.1 kg a.i. ha^{-1} in NT plots for spot weed control. Common weeds encountered included crabrgass (*Digitaria sanguinalis*), pigweed (*Amaranthus retroflexus*), ragweed (*Ambrosia trifida*), prickly sida (*Sida spinosa*), morningglory (*Ipomoea hederacea*) and sicklepod (*Cassia obtusiflius*). An infestation of boll worm in 1997 only was treated with cypermethrin applied at 0.044 kg a.i. ha^{-1} three times every 7 days.

Growth of cotton was controlled on all plots in 1996 and 1997 with mepiquat chloride, a growth regulator, applied at a rate of 0.024 kg a.i. ha^{-1} soon after first bloom and 10 days later. Due to persisting drought conditions, mepiquat chloride was not applied in 1998 and 1999. Dimethipin, a defoliant, and ethephon, a boll opener, were applied at 0.34 and 0.84 kg a.i. ha^{-1}, respectively, 2 weeks prior to harvest. Cotton was hand harvested first for yield determination and the rest was mechanically harvested. Stalks were shredded after harvest with a rotary mower.

2.4. Plant measurements

Whole plots were sub-divided into three $10\,\text{m} \times 10\,\text{m}$ subsections for sampling for yield and biomass. Yield was determined by hand harvesting cotton in each subsection. These were then added to determine yield for the whole plot. In 1996 and 1997, 1.5 m was sampled in each of five randomly chosen rows in each subsection. Yield was extrapolated to per hectare basis based on row length in the whole plot. In 1998 and 1999 three full randomly chosen rows (excluding 0.5 m from the edges) were sampled in each subsection. Yield was extrapolated to a per hectare basis based on plant counts in harvest rows and in whole plots. Less than normal precipitation soon after planting in 1998 and 1999 affected emergence and stand. Some CT plots had reduced stands in some spots so that plant cover was not as even as during the first 3 years. Basing yield on actual plant counts was felt to give better yield estimate. After hand harvest, samples were weighed dry after 2–3 weeks in ovens kept at 12.5–18.5 °C. Lint yield was then expressed as 40% of seed cotton weight at 10% moisture.

In 1998, dry plant weights for leaf, petiole, stem and bolls were measured on six randomly selected plants from each of the 12 plots just before defoliation. Plant height and leaf area were also measured. Plants were sampled, separated into different plant parts, dried in an oven and weighed.

2.5. Soil water characteristics and content

The Cecil soil series has low water holding capacity. Water content at a matric potential of -0.01 to -0.03 MPa (field capacity) for the Ap (0–20 cm), BA (20–30 cm) and Bt1 (30–100 cm) horizons averages 0.18, 0.20, and 0.37 $\text{cm}^3\ \text{cm}^{-3}$, respectively. Average corresponding water content at a matric potential of -1.5 MPa (permanent wilting point) is 0.05, 0.13, 0.30 $\text{cm}^3\ \text{cm}^{-3}$. Available water for the Ap, BA and Bt1 horizons is, therefore, 0.13, 0.07, and 0.07 $\text{cm}^3\ \text{cm}^{-3}$, respectively. Total available water from the top 100 cm of soil is approximately 10 cm. These values do not take into account changes due to long-term tillage manipulations.

Soil water was monitored over the cotton growing period in 1998 in one plot from each treatment (four total) using the TDR-based MoisturePoint system (model MP-917, ESI, Vic., BC, Canada). The system consists of a 1.2 m long probe inserted vertically into the ground that is capable of sensing soil water content in five segments: 0–15, 15–30, 30–60, 60–90, and 90–120 cm. Measurements were made through a portable interface and then downloaded to a computer. Each of these four plots was instrumented with two probes. Soil water content was measured 2–3 times per week. Changes in soil water content between two readings (positive or negative) were cumulatively added to give the temporal net soil water change from each of the four plots. Similar measurements were taken in 1999 except that two plots of each treatment were instrumented with one probe each (eight plots total).

2.6. Weather and related data

A Georgia Automated Environmental Monitoring Network weather station (Hoogenboom, 1996) located at the research site was used to access daily weather data that included precipitation, air temperature and humidity, solar radiation, net radiation, and soil heat flux at 15 min intervals.

2.7. Data analysis

Data were analyzed as split plot design with tillage treatments in whole plots, as first main factor, and fertilizer treatments in sub-plots, as second main factor, in a framework of randomized complete block design using the MIXED procedure of SAS (Littell et al., 1996). Degrees of freedom were calculated using the SATTERTH option in the MODEL statement. In addition, yield was analyzed as repeated measures for years, with heterogeneous compound symmetry (CSH) error structure providing the best fit of variance and covariance among the residuals. All significant differences are reported at $P \leq 0.05$.

3. Results

3.1. Lint yield

Average yield over the 4 years for each treatment is shown in Fig. 1. Yield per year for each treatment is presented in Fig. 2. Tillage, year, tillage × year, and fertilizer × year all had significant fixed effects on yield.

NT impacted yield as a main effect and in each of the fertilizer treatments over 4 years (Fig. 1) but from 1996 to 1998 only in individual years (Fig. 2). There was no NT treatment effect in 1999. Yield from NT was significantly higher than from CT by 23% over 4 years (Fig. 1A) and by 27, 21, and 36% in 1996 through 1998, respectively (Fig. 2A). Yield from no-till conventional fertilizer (NTCF) was significantly higher than from conventional tillage and fertilizer (CTCF) by 27% over the 4 years (Fig. 1B) and by 35 and 31% in 1996 and 1997, respectively (Fig. 2B). There was no statistical difference in yield between NTCF and CTCF in 1998 (Fig. 2B). Yield from no-till poultry litter (NTPL) significantly exceeded that from conventional tillage poultry litter (CTPL) by 20% over 4 years (Fig. 1B) and by 39% in 1998 (Fig. 2B). There was no statistical difference in yield between NTPL and CTPL in 1996 and 1997.

PL did not increase yield significantly over ammonium nitrate as a main effect (Fig. 1A) and in each of

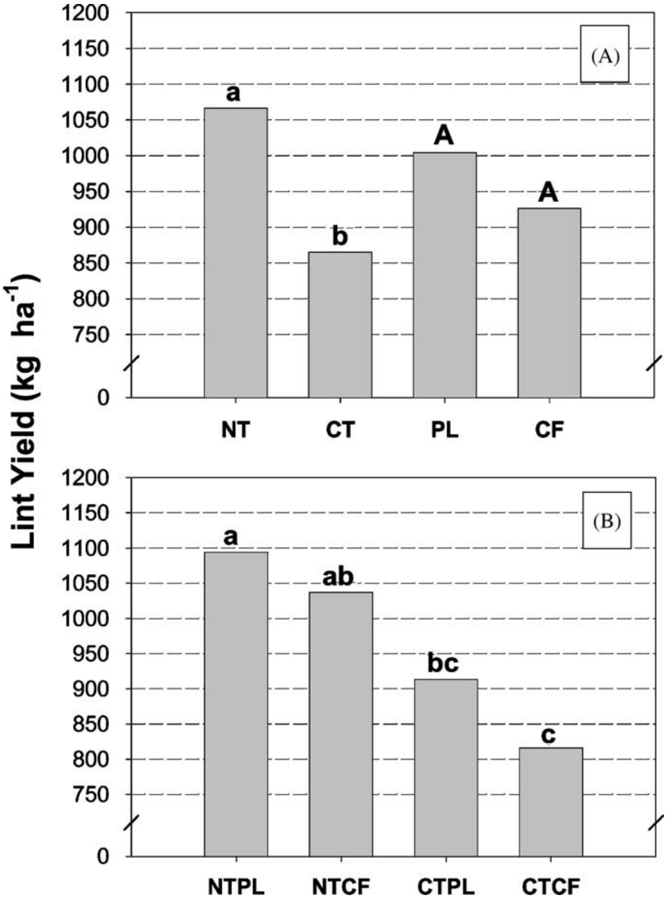

Fig. 1. Average lint yield (kg ha^{-1}) from 1996 to 1999: (A) NT, CT, PL, and CF; (B) NTPL, NTCF, CTPL and CTCF. Treatments with the same letters above the bars are not significantly different (in (A) small letters are used for NT vs CT, and capital letters for PL vs CF).

the tillage treatments averaged over 4 years (Fig. 1B). It also did not significantly increase yield over ammonium nitrate in any year except 1997 (Fig. 2A), when yield for PL was greater than CF because CTPL had 20% significantly higher yield than CTCF (Fig. 2B). Ammonium nitrate did better than PL in 1999, but that effect was not significant (Fig. 2A and B).

The largest differences in yield occurred between NTPL and CTCF. Yield from NTPL was significantly greater than yield from CTCF by 34% over 4 years (Fig. 1B) and by 43, 35, and 50%, in 1996, 1997, and 1998, respectively (Fig. 2B). In 1999, however, CTCF had slightly better yield than NTPL, but that difference was not significant (Fig. 2B).

Drought suppressed yield across all treatments in 1999 and negated significant treatment differences (Fig. 2B). This was attributed to 5 weeks of dry weather coinciding with flowering and boll formation and causing serious water stress at the most critical period of growth. Most of the complications of interactions between tillage, fertilizer, and year arose because of yield suppression arising from this drought.

3.2. Establishment and biomass

Low precipitation during the first 3 weeks of the season in 1998 and 1999 led to emergence and establishment problems in some spots within some CT plots (data not shown). The problem was more pronounced in 1999. Plant population per hectare in CT near harvest time was 86,000 in 1996, 79,000 in 1998, and 53,000 in 1999. For NT it was 116,000, 86,000 and

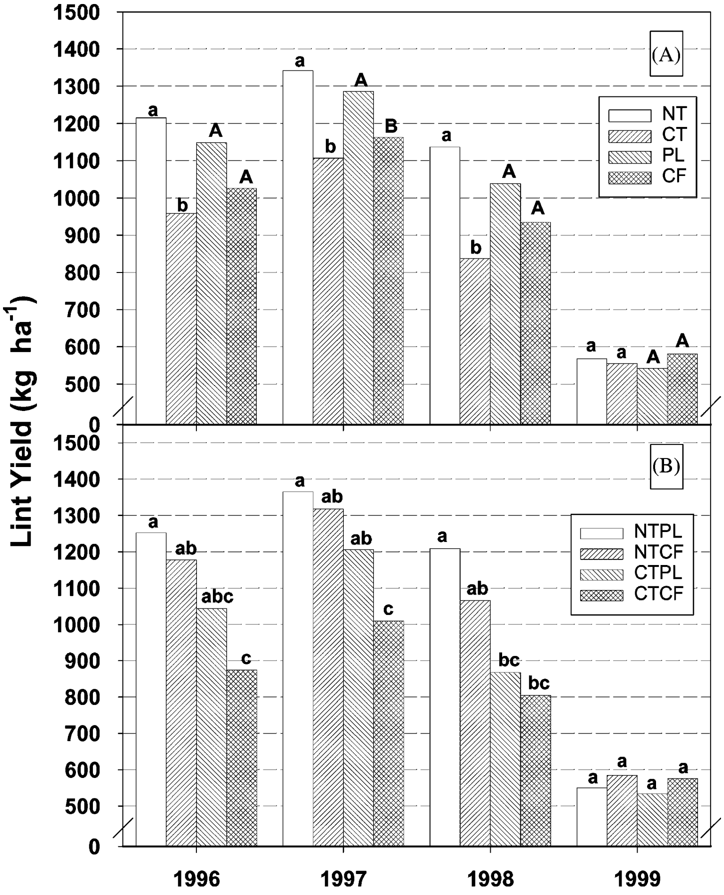

Fig. 2. Average lint yield (kg ha^{-1}) per year from 1996 to 1999: (A) NT, CT, PL, and CF; (B) NTPL, NTCF, CTPL and CTCF. Treatments with the same letters above the bars are not significantly different (in (A) small letters are used for NT vs CT, and capital letters for PL vs CF).

59,000, respectively. We have no data for 1997 but values were more similar to 1996 and 1998.

Treatment effects were also observed on overall vigor and growth of cotton throughout the 4 years of experiment. In general, cotton was taller and had more biomass by first bloom in NT than CT. Results from a 1998 sampling, done 2 weeks before harvest, are given in Tables 1 and 2. Plant height and dry weights for leaf,

Table 1
Average plant height, leaf area, and biomass dry weight per plant in 1998, determined from six plants from each plot, 2 weeks before harvest, from the CT, NT, CF, and PL treatments[a]

Treatment	Plant height (cm)	Leaf area (cm^2)	Average dry weight per plant (g)			
			Petiole	Leaf	Stem	Boll
CT	58.3 a	8615 a	6.9 a	59.9 a	124 a	281 a
NT	74.8 b	10453 a	8.1 a	72.6 b	198 b	444 b
CF	64.7 A	9000 A	6.8 A	61.5 A	146 A	338 A
PL	68.4 B	10000 B	8.2 B	70.7 A	176 B	383 A

[a] Values followed by the same letters within a column are not significantly different. Comparisons are between CT vs NT (small letters) and CF vs PL (capital letters).

Table 2
Average plant height, leaf area, and biomass dry weight per plant in 1998, determined from six plants from each plot, 2 weeks before harvest, for CTCF, CTPL, NTCF, and NTPL treatments[a]

Treatment	Plant height (cm)	Leaf area (cm^2)	Average dry weight per plant (g)			
			Petiole	Leaf	Stem	Boll
CTCF	57.0 a	7378 a	6.3 a	54.7 a	107 a	253 a
CTPL	59.5 a	9847 b	7.5 ab	64.8 ab	141 b	309 ab
NTCF	72.4 b	10077 ab	7.3 ab	68.3 b	184 c	423 bc
NTPL	77.3 b	10830 ab	8.9 b	76.7 b	211 c	457 c

[a] Values followed by the same letters within a column are not significantly different.

stem and boll were significantly higher by 21–60% in NT than CT (Table 1). Similar significant differences of 6–21% were observed for PL over CF for plant height, leaf area, and dry weights for petiole and stem (Table 1). Table 2 shows treatment differences between CTCF, CTPL, NTCF and NTPL. There were significant differences of 36–98% for all measured variables except leaf area between NTPL and CTCF. Significant differences of 27–72% were also observed for all variables but leaf area and petiole dry weight between NTCF and CTCF. Plant height, stem dry weight and boll dry weight were significantly higher in NTPL than CTPL. Leaf area and stem dry weight were significantly different between CTPL and CTCF. No significant differences were observed between NTPL and NTCF for any measured variable.

3.3. Water deficit

In order to put the marked yield reduction across all treatments in 1999 in the context of water stress, we used the daily precipitation data to see where water supply deficit might have occurred. Cotton is very susceptible to yield reduction if water stress occurs during the time of squaring, flowering approaching peak bloom and boll development. From 14 July to 17 August 1999, a period of 35 days coinciding with this very critical period for water need, only 20 mm of precipitation was recorded at the site. As indicated in Section 1, such dry periods are not uncommon in Georgia, and the Southeast generally, and are of great concern as far as their impact on crop production. In contrast, the precipitation in 1996, 1997, and 1998 during the equivalent 35 days period was 126, 198, and 144 mm, respectively. Regression analysis between average yearly yield and precipitation during this critical 35 days period of that year showed a close correlation (R^2: 0.93, CTCF; 0.88, CTPL; 0.93, NTCF; 0.92, NTPL). It is generally accepted that dry matter production is curtailed in proportion to this water stress factor.

3.4. Soil water

Change in soil water occurs as a result of the difference between inputs such as precipitation and outputs such as evapotranspiration, runoff, and drainage in the root zone. There was hardly any runoff or drainage in the cotton growth period in 1998 and 1999 (data not reported). The change in soil water was, therefore, generally in response to precipitation and evapotranspiration. Soil water data from 1998 to 1999 are presented in Figs. 3–5, and Table 3. The figures are for one CTCF and one NTPL plot. These two treatments produced the lowest and highest average yields, respectively, for each of the first 3 years. Differences in soil water pattern and use were, however, evident between all four treatments, especially between tillage treatments.

The soil water contents in 1998 for one CTCF and one NTPL plot are shown in Fig. 3. Changes were more dynamic in the NTPL than CTCF plot. For the first 3 weeks in June the NTPL showed diminishing but higher soil water content in the 0–15 cm depth than the CTCF which had a steady 0.15 $cm^3\ cm^{-3}$. The soil profile in both plots recharged fairly fast following precipitation. The NTPL showed higher recharge rate from the 26 June precipitation of 30 mm. Until the next recharge by the precipitation of 25 mm of 17 July, water content decreased by about 0.1 $cm^3\ cm^{-3}$ in the NTPL in the top 30 cm of the soil profile whereas in the CTCF it decreased by less than

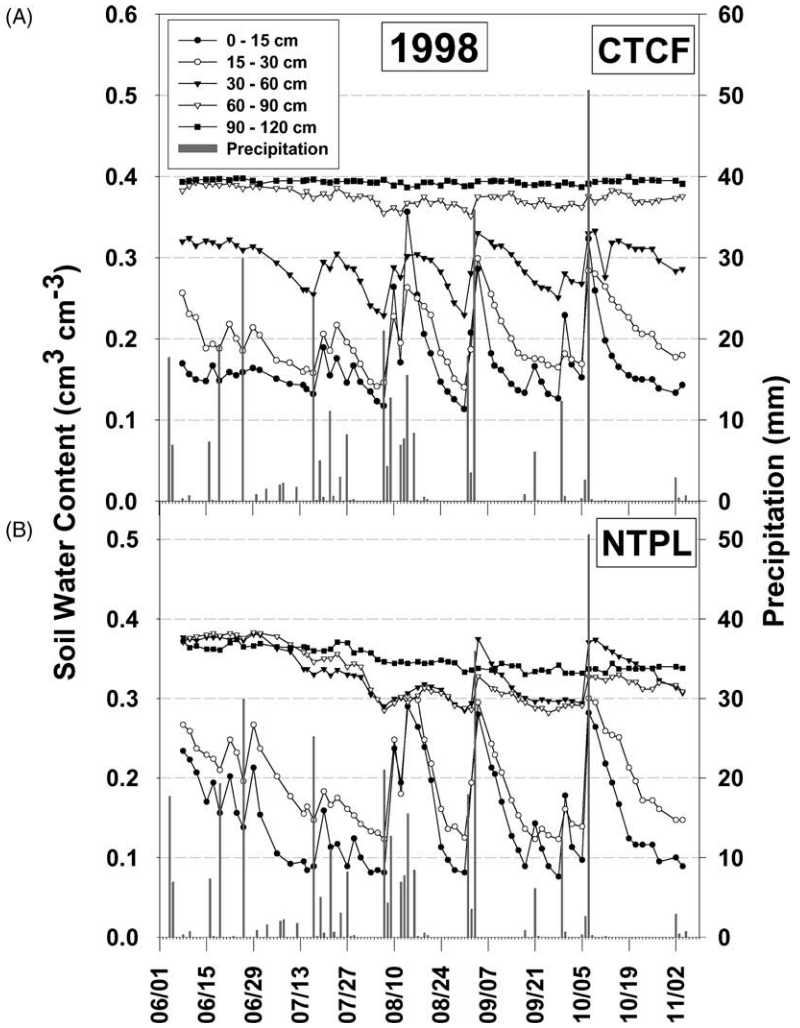

Fig. 3. Volumetric soil water content from 6 June to 12 November, 1998: (A) plot 12 under CTCF treatment; (B) plot 7 under NT and poultry litter treatment (NTPL).

Table 3
Average net soil water content change in cm^3 cm^{-3} and mm from 14 July to 17 August, 1999 for CTCF, CTPL, NTCF, and NTPL treatments

Depth (cm)	CTCF		CTPL		NTCF		NTPL	
	cm^3 cm^{-3}	mm	cm^3 cm^{-3}	mm	cm^3 cm^{-3}	mm	cm^3 cm^{-3}	mm
0–15	−0.17	−25	−0.19	−29	−0.17	−25	−0.20	−30
15–30	−0.15	−22	−0.12	−17	−0.13	−20	−0.17	−25
30–60	−0.12	−37	−0.11	−33	−0.13	−38	−0.15	−44
60–90	−0.10	−29	−0.05	−15	−0.08	−24	−0.09	−26
90–120	−0.04	−12	−0.01	−3	−0.05	−14	−0.04	−12
Total		−126		−97		−121		−137

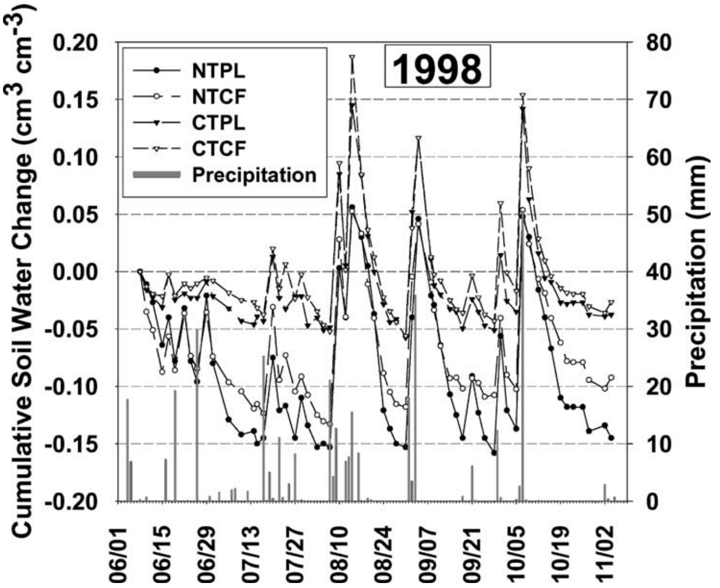

Fig. 4. Temporal net volumetric soil water content change in the top 0.15 m of soil profile from 4 June to 15 November, 1998 for NTPL, NTCF, CTPL, and CTCF treatments.

0.05 cm^3 cm^{-3}. These recharge and water use patterns generally repeated themselves after significant precipitation events. The 0–15 cm profile dried to below 0.1 cm^3 cm^{-3} soil water content in the NTPL compared to 0.12–0.15 cm^3 cm^{-3} in the CTCF, indicating more extraction of soil water by NTPL. The 30–60 cm depth of the NTPL generally remained at about 0.05 cm^3 cm^{-3} higher soil water content than that of the CTCF and showed less variation. There was hardly any soil water change in the CTCF below 60 cm, whereas the NTPL showed distinct changes over time. This could be an indication of deeper rooting and water extraction from NTPL. Note that between 14 July and 17 August of 1998 (flowering and boll formation period), crop water use was partially compensated by a series of precipitation recharges.

The temporal soil water pattern for CTPL closely resembled that of CTCF (data not shown) but CTPL was generally 0.01–0.02 cm^3 cm^{-3} drier in all but the 30–60 cm profile, where it was 0.02–0.05 cm^3 cm^{-3} drier. While the temporal soil water pattern between NTPL and NTCF was also similar (data not shown), there were more differences in content than between CTPL and CTCF. First, soil water contents of the 0–15 and 15–30 cm profiles in the NTCF were virtually the same, whereas in the NTPL the 15–30 cm profile was 0.02–0.05 cm^3 cm^{-3} wetter than the overlying 0–15 cm profile. Both had very similar water contents for the 0–15 cm profiles. Then the 30–60 cm profile was 0.05–0.1 cm^3 cm^{-3} drier in NTCF. Soil water content in the 60–90 cm profile was about 0.03 cm^3 cm^{-3} drier in the NTPL.

Temporal net soil water content change in 1998 in the 0–15 cm depth for plots under the four treatments is shown in Fig. 4. Changes in soil water content between two consecutive readings (positive or negative) were cumulatively added to produce this figure. It shows the balance of soil water at any day beginning on 8 June until the end of October. Net soil water change generally was in the order NTPL > NTCF > CTPL > CTCF. The change at any one period remained within 0 to -0.10 cm^3 cm^{-3} for the CT but was in the -0.10 to -0.15 cm^3 cm^{-3} range for the NT. Changes were similar but to a lesser extent in the lower profiles. Total net soil water change from 8 June to 4 November in the 0–90 cm depth was -0.14, -0.16, -0.24, and -0.4 cm^3 cm^{-3} in the CTCF, CTPL, NTCF and NTPL plots, respectively. The NT showed more crop water use, which translated to more crop biomass and yield (Table 2; Fig. 2).

The soil water contents in the CTCF and NTPL plots in 1999 (the same plots as in 1998) are shown in

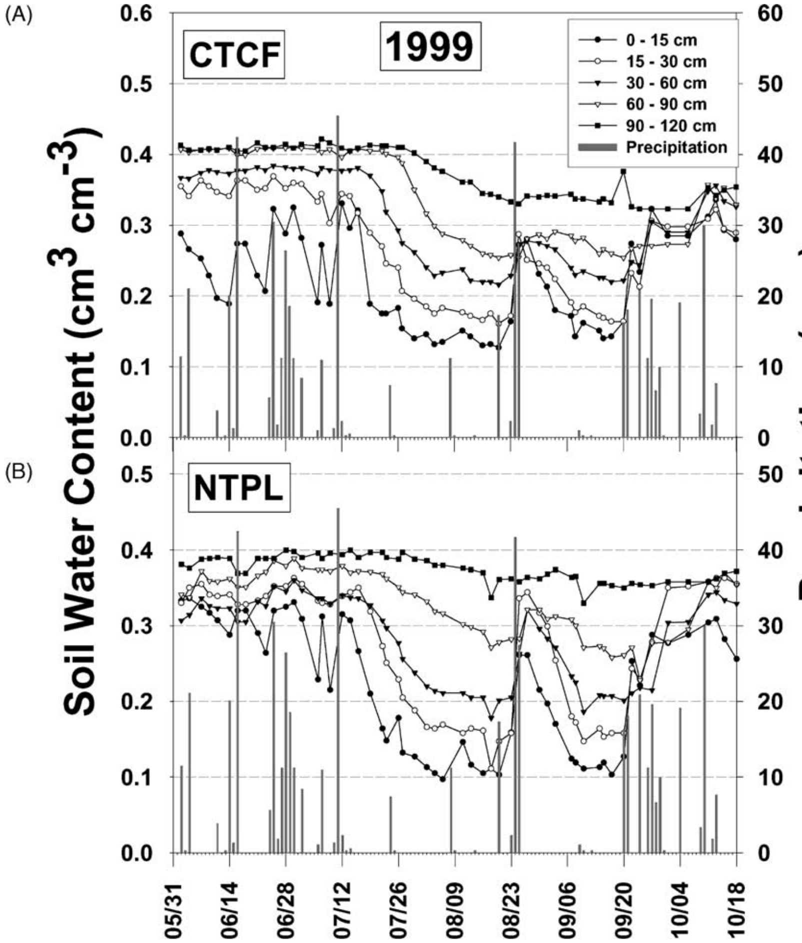

Fig. 5. Volumetric soil water content from 1 June to 18 October, 1999: (A) plot 12 under CTCF treatment; (B) plot 7 under no-till and poultry litter treatment (NTPL).

Fig. 5. A series of precipitation events kept the soil water partially charged until 14 July. During this period, soil water in the two plots in Fig. 5 showed differences. The average soil water content of the 0–15 cm profile was 0.30 and 0.26 cm^3 cm^{-3} for NTPL and CTCF, respectively. It was about the same for both in the 15–30 cm profile. In the 30–60 cm profile average water content was 0.33 cm^3 cm^{-3} for NTPL and 0.38 cm^3 cm^{-3} for CTCF. Below 60 cm, CTCF was 0.02–0.03 cm^3 cm^{-3} wetter.

The effect of the dry period from 14 July to 17 August, discussed in the previous section, on soil water is clearly shown in Fig. 5. There were only two precipitation events of 7.6 and 11.6 mm in a 37 days period beginning 14 July. Consequently, the full water requirement of the cotton was not met by the diminishing water stored in the soil profile. Soil water was extracted even from the deepest profiles, especially from CTCF. Generally, the NT treatment dried to between 0.05 and 0.1 cm^3 cm^{-3} soil water content, with NTPL slightly drier than NTCF, whereas the CT treatment dried to between 0.1 and 0.15 cm^3 cm^{-3} soil water content with CTPL slightly drier than CTCF, indicating slightly more soil water extraction by NT. Mean net soil water change in this period from the four treatments is presented in Table 3. The total change showed only small differences between CT (average −112 mm) and NT (average −129 mm). As already discussed, the yield in 1999 was low and similar among treatments in response to stressed conditions.

4. Discussion

4.1. Yield differences

We chose to consider yield differences over 4 years (as well as in individual years) even though water deficit in 1999 clearly reduced yield and negated treatment effects. The statistical significance for year, tillage × year and fertilizer × year interactions arose because of the depressed yields in 1999. Analysis of yield over the first 3 years only removes the significance of interactions and year. Reported yield differences would be greater if the analysis is limited to the first 3 years only. Including the fourth year strengthens the analysis, however, because it adds the element of risk, which is always associated with real world farming, especially in view of the common short-term summer droughts in the region. It appears that for NT and PL to have significant effect on yield in the southeastern United States, growing seasons have to have adequate precipitation. Otherwise water will become the dominating growth limiting factor.

4.2. Water stress

The southeastern United States is generally well supplied with precipitation throughout the year. Water stress related problems are normally not due to lack of gross precipitation but inadequate frequency and distribution during the growing season. Analysis of weather records indicates that a drought period of 14 or more days with not more that 6 mm of precipitation in any 24 h period is expected at frequencies of 1 in the spring, 1.5 in the summer and about 2 in the fall (autumn). Cotton is generally considered as one of the most drought tolerant field crops grown in the Southeast. However, large yield reductions occur when water deficits occur during peak flowering period (Sweeten and Jordan, 1987), and loss of yield cannot be recovered even if the deficit is lifted at a later date. Drought is rated by far the greatest cause of disasters of cotton and other crops in the Southeast by the Federal Crop Insurance Corporation (Edmisten et al., 1994). The 35 days drought of 1999 demonstrated the typical risk associated with such events in this region.

The net soil water content change in 1998, an indicator of cotton water uptake, was highest in NTPL followed by NTCF, CTPL, and CTCF in that order. As a result of limited water supply, no such differences were observed during the dry period of the 1999 cotton season. During the 3 years of adequate precipitation, yields followed the water use pattern of 1998 among treatments, developing a link of favorable soil water regimes and improved yields under NT. The NT and PL combination provided a far more favorable environment for higher yields than the CT combination with either PL or CF, as did the NT and CF combination over CT with CF. The one in 4 year drought only reduced the degree of this advantage and not the advantage. Although short-term drought occurs in the Southeast, the net long-term advantage of adopting NT and fertilizing with PL in cotton production appears to be clear from this research.

4.3. Use of PL

Although PL provides advantages for cotton production under NT, one should also be concerned about sustainability of any farming system. In this regard, a nutrient management strategy, with respect to PL, should be included as part of the farming system. There is concern that repeated application of PL can result in a build up of nutrients such as N, P and K, with N and P being of particular environmental significance. PL varies widely in nutrient content due to several reasons. These include moisture, temperature, feed rations, number and batches before clean-out, storage and handling. Predicting N availability is difficult due to unknown losses (ammonia volatilization, denitrification) and rates of N mineralization. Data are variable and sometimes conflicting. In Georgia, PL application in cotton has historically been based on the desired N application rate assuming 50–60% of the N in the litter becoming available during the growing season (GCES, 1997). Some of the inorganic N (as ammonia) is lost when surface applied. Some becomes residual N and is utilized in the following crop. The soil nutrient data from these research plots show no incremental trend for P and K although the levels of P in the PL treatment plots fall in the medium to high range of the University of Georgia Cooperative Extension Service ratings for P, compared to mostly medium in the CF treatment plots. The ratings also indicate generally medium levels of K in all plots. An earlier study at the same plots found that winter rye cover crop helps sequester N in above ground biomass (McCracken et al., 1995).

From a practical crop management stand point, nutrient management should incorporate a rigid litter, soil and cotton petiole sampling and analysis to determine long-term sustainable levels of N, P, and K applications. Cotton petiole analysis has become a popular tool for determining N excess or deficiency in cotton. Other strategies such as crop rotation should also be considered to limit environmental degradation.

5. Conclusions

Our data indicate that adoption of NT, as alternative to CT, and use of PL, as alternative to inorganic fertilizers, such as ammonium nitrate, in cotton production can increase lint yield in southeastern United States. NT cotton fertilized with PL can produce up to 50% more lint compared to conventionally tilled cotton fertilized with ammonium nitrate, except in a year of drought when soil water becomes limiting. Similarly, NT cotton can be produced up to 30% more lint than CT cotton in non-drought years when both are fertilized with ammonium nitrate. Over the long-term, the yield advantage in normal years more than compensates for the yield suppression in dry years. This primary yield advantage is associated with NT, which is attributed to favorable surface soil physical conditions leading to better soil water characteristics (better infiltration and available water in the soil profile). The statistical yield advantage of PL alone over ammonium nitrate is limited.

Adoption of NT and PL application in cotton production in the southeastern United States would not only improve cotton production, but also create a useful outlet for the large amount of litter produced from the poultry industry in this region. Adoption of such farming methods should, however, include a good nutrient management plan to avoid excess nutrient accumulation in the soil and subsequent environmental degradation.

Acknowledgements

Funding for the research was provided by the USDA Cooperative State Research Service NRICGP Water Resources Assessment Protection Program and by the Southeast Egg and Poultry Association. The leadership of Dan McCracken as the first Principal Investigator is appreciated as is the help from many technicians and students throughout the research period. We are grateful to Dwight Seman (USDA-ARS, Watkinsville, GA), and Larry Douglass (University of Maryland, College Park, MD) for their help with statistical analysis.

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