No-Till Corn Productivity in a Southeastern United States Ultisol Amended with Poultry Litter

Dinku M. Endale,* Harry H. Schomberg, Dwight S. Fisher, Michael B. Jenkins,
Ron R. Sharpe, Miguel L. Cabrera

ABSTRACT

Corn (*Zea mays* L.) producers in the southeastern United States must overcome soil and water limitations to take advantage of the expanding corn market. In this 2001 to 2005 study on a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) near Watkinsville, GA, we compared dry land corn biomass and yield under conventional tillage (CT) vs. no-tillage (NT) with ammonium nitrate or sulfate (based on availability) as conventional fertilizer (CF) vs. poultry litter (PL). In a randomized complete block split plot design with three replications, main plots were under tillage and subplots under fertilizer treatments. The cover crop was rye (*Secale cereale* L.). Over 5 yr, NT and PL increased grain yield by 11 and 18%, respectively, compared with CT and CF. Combined, NT and PL increased grain yield by 31% compared with conventionally tilled and fertilized corn. Similarly, soil water was 18% greater in NT than CT in the 0- to 10-cm depth. In 2 yr of measurements, dry matter of stalks and leaves and leaf area index under PL were an average of 39 and 22% greater, respectively, than under CF during reproduction. Values were 21 and 6% greater, respectively, under NT than CT but during tasseling. Analysis of 70 yr of daily rainfall records showed that supplemental irrigation is needed to meet optimal water requirement. Our results indicate that corn growers can use rainfall more efficiently, reduce yield losses to drought, and expect increased corn yields with a combination of no-tillage management and long-term use of poultry litter.

DRYLAND CORN PRODUCTION is risky in the southeastern United States due to intermittent droughts and hot weather during the growing season. Until recently, profit margins limited use of irrigation because of low corn prices and higher production costs. In the past several decades, corn production declined in the southeastern United States as many producers curtailed production to avoid the risk of financial loss. This made the southeastern United States a corn deficit region. In Georgia for example, corn production declined from about 664,000 ha in the 1970s to <121,000 ha in 2006 with significant declines occurring in the 1980s (CAES, 2007a).

Renewable bioenergy production has substantially increased the price and demand for corn in the last few years. In response to the enactment of the Renewable Fuels Standard in 2005, mandating the use of 28.4 million m^3 (7.5 billion gallons) of renewable fuel in the United States by 2012 (from about 15.1 million m^3 or 4 billion gallons in 2006), the corn-based ethanol industry is expanding at an unprecedented rate (Renewable Fuels Association, 2006). As a result, future corn hectares in the United States are soon expected to be at their highest since 1944 (CTIC, 2007).

Corn producers in the southeastern United States must overcome the region's natural limitations of soil and climate to compete for this market. There is also concern that the rising demand for corn will result in converting marginal lands into corn fields with conventional tillage methods that have proven unsustainable and resulted in degrading natural resources. Many soils in the southeastern United States have low water holding capacity and/or root restrictive layers. Crusting is also a problem because the soils are low in organic matter and this increases runoff from fields. Cecil and related soils exhibit these characteristics and occupy more than half of the 16.7 million ha Southern Piedmont in the southeastern United States (Radcliffe and West, 2000). Conventional tillage methods, such as disking and harrowing, promote the development of these soil conditions and increase runoff.

High residue no-tillage systems have generally been shown to improve soil quality through increased organic matter and infiltration, and reduce runoff and soil loss compared with conventional tillage (Bradley, 1995; Endale et al., 2002b; Fawcett et al., 1994; Langdale et al., 1992; Reeves, 1997; Terra et al., 2005). However, data from peer-reviewed literature estimating the impact of high residue no-tillage management on corn grown in the Southern Piedmont are limited. Earlier studies in the Piedmont focused on no-tillage corn in sod or grass-based systems. Jones et al. (1968) and Bennett et al. (1973) reported no-tillage corn planted into orchardgrass (*Dactylis glomerata* L.) sod produced similar or greater yields than corn under conventional tillage. In Georgia, Adams et al. (1970) found that conventionally tilled corn following coastal bermudagrass [*Cynodon dactylon* (L.) Pers] or tall fescue (*Festuca arundinacea* Schreb.) yielded better than no-tillage

---

D.M. Endale, H.H. Schomberg, D.S. Fisher, M.B. Jenkins, and R.R. Sharpe, USDA-ARS, J. Phil Campbell Sr. Natural Resource Conserv. Center, 1420 Experiment Station Rd., Watkinsville, GA 30677; M.L. Cabrera, Crop and Soil Sciences Dep., Univ. of Georgia, Athens, GA 30602. Received 14 Dec. 2007. *Corresponding author (Dinku.Endale@ars.usda.gov).

Published in Agron. J. 100:1401–1408 (2008).
doi:10.2134/agronj2007.0401

Abbreviations: CF, conventional fertilizer; CT, conventional tillage; DAP, day after planting; LAI, leaf area index; NT, no-tillage; PL, poultry litter.

corn planted into sod with chemically suppressed vegetation. On the other hand, Wilkinson et al. (1987) found that following a hay harvest and completely killing tall fescue, no-tillage corn had equal or greater yields than did conventional tillage corn.

Poultry production is a significant source of income for many row crop and cattle producers in the southeastern United States. In 2005, 8.9 billion broilers were raised in the United States with a value of about \$20.9 billion (NASS, 2007). Four southeastern states (Alabama, Arkansas, Georgia, and North Carolina) produced about half of these broilers. In the process, more than 10 million Mg of poultry litter (a mixture of bedding material and manure) was produced nationally assuming a rate of 1.14 kg bird^{-1} yr^{-1} (Vest et al., 1994). Poultry litter can be a valuable resource that provides a wide range of plant nutrients and organic matter (Moore et al., 1995; CAES, 2007b). Research of poultry litter use in enhancing corn production on Piedmont soils is limited. Several recent studies have focused on N availability from fresh or composted poultry litter to regional commercially important crops like cotton (*Gossypium hirsutum* L.), or residual effect to succeeding crops like corn, but these have been more often on sandy Coastal Plain soils (Mitchell and Tu, 2005; Cooperband et al., 2002).

With the anticipated increase in corn production in the southeastern United States, and elsewhere, more research is required quantifying grain and biomass differentials arising from different choices of tillage and fertilizer sources across regions to help corn producers make informed decisions. The objective of this research was to quantify the agronomic effects of no-tillage and poultry litter in production of corn with a rye cover crop in comparison to a conventional tillage and conventional fertilizer production system on a typical Piedmont soil.

MATERIALS AND METHODS

Experimental Site

The research was conducted from 2001 to 2005 at the USDA-ARS J. Phil Campbell Sr. Natural Resource Conservation Center in Watkinsville, GA (83°24′ W, 33°54′ N) on 12 large (10 bt 30 m^2) nearly level (<1.5% slope) plots with drainage tiles set at about a meter depth from the surface. The soil is Cecil sandy loam with about a 20-cm thick brown sandy loam Ap-horizon, underlain by a 5- to 10-cm thick BA-horizon of a red sandy clay loam to clay loam texture (Bruce et al., 1983). This is followed by about a 100-cm thick red clay Bt-horizon underlain by about a 30-cm thick red loam to clay loam BC-horizon. The C-horizon is a loamy saprolite weathered from felsic igneous and metamorphic rocks.

Average daily air temperature is 6 to 8°C in winter and 23 to 27°C in summer. Frost-free days in the growing season typically range from 200 to 250. Mean annual precipitation is 1242 mm (for 1937–2006) with seasonal monthly variations: fall 76 to 89 mm, winter 103 to 119 mm, spring 96 to 137 mm, and summer 95 to 122 mm per month. Frequent short-term droughts are common in spring and summer and often suppress crop yield.

Experimental Procedures

The experiment was a randomized complete block split plot design with three replications. Conventional tillage and NT were main plots. Nitrogen fertilizer subplots were either CF applied as ammonium nitrate/sulfate vs. PL. Conventional tillage consisted of 30-cm deep chisel plowing followed by one to two diskings to 20-cm depth and a subsequent 8-cm deep disking with a tandem-disk to smooth the seed bed. The only soil disturbance in no-tillage was planting with a four-row no-tillage planter. The no-tillage treatment started in fall of 1991. From 1996 to 2000 cotton research was conducted under the same two tillage and fertilizer regimes (Endale et al., 2002a; Endale et al., 2002c).

The cropping regime consisted of cereal rye (cv. Hy-Gainer [2001 and 2002]; Penington WinterGrazer [2003 and 2004]; Wrens Abruzzi [2005]) grown in late-fall to early spring followed by corn (cv. Pioneer 3223 [2001 to 2003]; Pioneer 33V15 Poncho Treatment Em250 [2004 and 2005]) from mid-spring to mid-fall. Corn planting and harvest dates consecutively from 2001 were: 24 May and 9 October; 22 May and 4 October; 29 May and 22 October; 12 April and 9 September; and 11 May and 20 October. Corn was planted in 76-cm rows with density target of seven to eight plants per row meter.

Nitrogen fertilization for corn was at a rate of 168 kg available N ha^{-1} in all but the third year. In all but the third year, this meant a PL application of 11.25 Mg ha^{-1} at about 30% moisture assuming 50% mineralization (Vest et al., 1994; CAES, 2007b) during the corn season (i.e., the litter contained about 336 kg N ha^{-1} but only half of this became available). In the third year the N application rate was doubled in both tillage treatments (336 ka available N ha^{-1}; litter 22.5 Mg ha^{-1}) because of interest for detecting potential levels of the hormones estradiol and testosterone coming off the field in runoff or drainage from litter (Jenkins et al., 2004). Conventional N fertilizer was applied as ammonium nitrate or sulfate (depending on availability) in split applications (Gandy 10T series, pull behind drop fertilizer spreader, Gandy Company, Owatonna, MN)[1], one-third a day or two before planting, and two-thirds about 33 d later. The rye cover crop in the PL treatment was fertilized with litter at 124 kg N ha^{-1} in 2001, 67 kg N ha^{-1} in 2002 and 2003, and with ammonium nitrate or sulfate at 67 kg N ha^{-1} the rest of the period. Since litter application was based on assumption of 50% N mineralization in the current year, residual N mineralization could have increased the amount of N available to corn in subsequent years in the PL treatment. But we expect less and less N to become available each succeeding year from one litter application. Soil analysis was used to determine P and K needs in CF plots. All N, P, and K fertilizers were applied to the surface of plots 1 to 2 d before planting, and incorporated into the soil in CT plots only. Other agronomic activities followed routine regional practices.

Soil water content was measured at the center of each plot in 2001–2002 with the Moisture Point system (Environmental Sensors INC, Victoria, British Columbia, Canada), which uses time domain reflectometry technology to estimate soil water content in 15, 15, 30, 30, 30 cm segments down to 1.2 m. In 2003 to 2005 soil water content was measured with the Diviner 2000 system (Sentek Environmental Technologies, Stepney,

---

[1] The use of trade, firm, or corporation names in this publication is made 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, the Agricultural Research Service, or the University of Georgia of any product or service to the exclusion of others that may be suitable.

South Australia), which uses electrical capacitance methodology, to estimate soil water content at 10-cm intervals down to 1.2 m. A total of 14 readings in 2001 and 25 to 33 readings each season in 2002 to 2005 were taken at intervals of 2 to 4 d.

Dry matter for stalks and leaves, leaf area index, and root mass were estimated from four to six randomly selected plants per plot taken five times each in 2004 and 2005 at approximately 21 d intervals after planting. Leaf area index was determined from the first four and roots from the third and fifth samplings. Grain yield was determined by hand harvesting and weighing all whole corn ears from each plot. Twenty to 30 ears were then sampled from each plot to determine shelled corn weight. Grain yield was determined in proportion to the whole ear yield of each plot and expressed at moisture equivalent of 155 g kg^{-1}. Corn plants remaining after harvest were shredded with a rotary mower. Operations for the cover crop followed after that with same tillage regimes and a no-tillage drill used to plant the rye in both tillage treatments. In 2004 the rye was chemically killed early before the usual spring surge of biomass accumulation to make way for a rainfall simulation study on part of each plot, and the residue averaged only 0.36 Mg ha^{-1} across plots. Mean rye residue yield across all treatments for the remaining 4 yr varied in the narrow range of 3.45 to 3.97 Mg ha^{-1} with no difference among treatments.

Statistical Analysis

Data analyses were performed using Proc Mixed of SAS (Littell et al., 1996; SAS Institute, 2004) Tillage, fertilizer, and the interactions were analyzed with years as repeated measures and block and year as random variables. The BIC goodness of fit criterion was used to select the best fitting model and error structure for the analysis of variance. Day after planting (DAP) was included as a variable for analyses of dry matter and leaf area. Unless otherwise indicated, all significant differences are given at $P \leq 0.10$. To put the rainfall amount for critical periods during the research in perspective of long-term data, we used 70 yr (1937–2006) of daily rainfall records at the research location to develop rainfall exceedance probability tables and curves with the rank-order method referred to as Weibull plotting position formula (McCuen, 1998).

RESULTS AND DISCUSSION

Corn Grain Yield

Tillage and Fertilizer Effects

Tillage and fertilizer had significant effects on grain yield. The tillage × fertilizer interaction was not significant (P = 0.55). Over 5 yr, no-tillage increased grain yield by 11% compared with conventional tillage (Table 1; P = 0.032). Poultry litter increased yield by 18% compared with conventional mineral fertilizer (Table 1; P = 0.002). While there was no tillage × fertilizer interaction, the tillage and litter impacts combined proportionally in no-tillage plots that received litter since these had 31% more grain yield compared to the conventionally tilled and fertilized plots (8.3 vs. 6.3 Mg ha^{-1}) over 5 yr.

A factor likely to have contributed to the superior performance of no-tillage treatment is soil water content (Fig. 1 for 0- to 15-cm depth in 2001–2002; Fig. 2 for 0- to 10-cm depth in 2003–2005). The difference in the measurement depths arose because of the different sensors used for soil water measurement. In summary of the 5-yr data (not shown), at 0 to 10 cm (taking the 0- to 15-cm data of 2001–2002 as part of this set) the no-tillage treatment showed greater soil water content (mean 20.9%) over the course of the year than the conventional tillage (mean 17.7%; P = 0.02; a difference of 18%). The fertilizer source had no effect (P = 0.66) on soil water content and there was no tillage × fertilizer interaction (P = 0.86). Over 5 yr there was no effect on soil water content at 10- to 20-cm depth associated with tillage (P = 0.26), fertilizer sources (P = 0.63), or the interaction of these effects (P = 0.33). There was also no difference between treatments in the other depths. The significant effect at 0- to 10-cm depth is likely the result of both increased infiltration rates and increased water holding capacity associated with higher organic matter accumulation under no-tillage management (Endale et al., 2002a, 2002b; Reeves, 1997; Soil and Water Conservation Society, 2006). At other depths, likely greater soil water use by NT corn (more biomass) might have masked soil water content differences.

Table 1. Mean corn grain yield with standard error by tillage and fertilizer treatments for 2001to 2005.†

Year	Tillage CT	Tillage NT	Fertilizer CF	Fertilizer PL
	Mg ha^{-1}			
2001	7.61 ± 0.32	9.22 ± 0.14	8.05 ± 0.48	8.78 ± 0.31
2002	1.81 ± 0.23	2.48 ± 0.10	2.24 ± 0.23	2.06 ± 0.23
2003	5.96 ± 0.37	5.28 ± 0.47	4.92 ± 0.27	6.32 ± 0.36
2004	8.01 ± 0.61	9.47 ± 0.41	8.10 ± 0.61	9.38 ± 0.46
2005	10.54 ± 0.47	11.35 ± 1.07	9.56 ± 0.55	12.33 ± 0.60
2001–2005*	6.79 ± 0.56a	7.56 ± 0.64b	6.57 ± 0.53a	7.77 ± 0.66b

* Means followed by different letters are significantly different at P = 0.10 for contrasts between tillage or fertilizer treatment pairs (CT vs. NT or CF vs. PL).

† CT = conventional tillage; NT = no-tillage; CF = conventional fertilizer; PL = poultry litter.

To check for possible differences in N availability between the fertilizer treatments, we compared N content of stalks and leaves between the two treatments from 12 samplings from 21 June 2001 to 26 July 2004. Mean N content was 2.23% for the conventional fertilizer and 2.24% for the litter treatment. Moreover, the regression of N content of stalks and leaves between litter and conventional fertilizer treatments had R^2 of 0.97, a slope of 0.98 and an intercept of 0.05. We conclude, therefore, that there was no difference in N availability between CF and PL. However, with larger plants or biomass of PL corn there may have been differences.

Amounts of P and K added to CF and PL plots were compared based on the litter rate and its nutrient content from each application (Schomberg et al., 2008). In the 5 yr before the start of this research (cotton-rye), the PL plots had received 2.8 times more P and 2.3 times more K than CF plots (P: 71 vs. 25 and K: 163 vs. 71 kg ha^{-1} yr^{-1}). During this research, before the N application was doubled in 2003, the litter plots received 276 kg P ha^{-1} yr^{-1} and 511 kg K ha^{-1} yr^{-1} compared with 15 kg P ha^{-1} yr^{-1} and 37 kg K ha^{-1} yr^{-1} for CF plots (18.4 and 13.8 times, respectively). Subsequently, the litter plots received 249 kg P ha^{-1} yr^{-1} and 460 kg K ha^{-1} yr^{-1} compared with 23 kg P ha^{-1} yr^{-1} and 50 kg K ha^{-1} yr^{-1} for CF plots (10.8 and 9.2 times, respectively). Since P and K rates for CF treatment plots were based on soil test recommendations by crop by plot, P and K need would have been met in both fertilizer treatments.

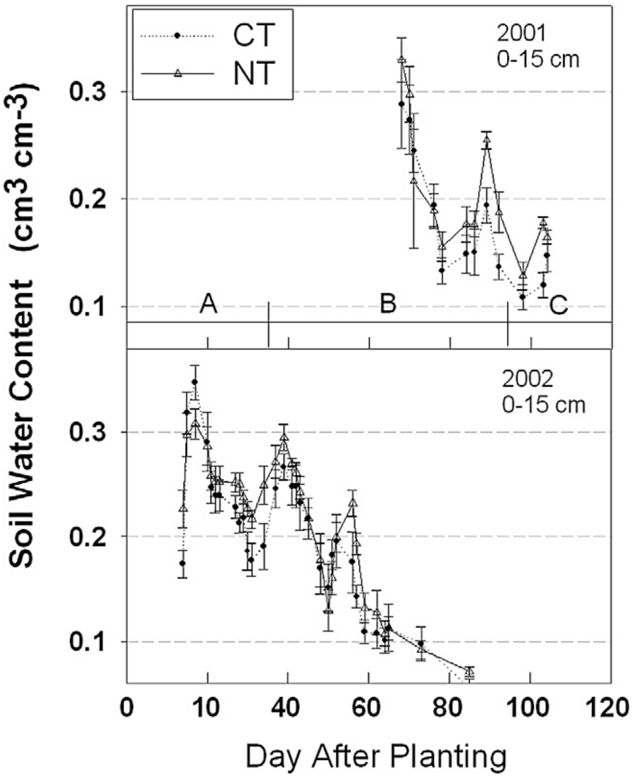

Fig. 1. Mean soil water content with standard error bars for no-tillage (NT) and conventional tillage (CT) for 2001–2002 for 0- to 15-cm depth. The letters A, B, and C signify approximate periods for vegetative, reproductive, including early dough, and dough to beginning of black layer stages, respectively.

Soil test results for pH, P, Ca, K, Mg, and Zn averaged across cropping phases are presented in Fig. 3. Soil test results are discussed in detail within and across cropping phases in Schomberg et al. (2008). The cropping phases are made up of: Phase 1, cotton with litter application of 4.45 Mg ha^{-1}; Phase 2, corn with litter application of 11.25 Mg ha^{-1}; Phase 3, corn with litter application of 22.5 Mg ha^{-1}; Phase 4, corn with litter application again of 11.25 Mg ha^{-1}; and Phase 5, which is not discussed in this paper, but is the start of pearl millet study with only inorganic fertilization in all plots. During the cotton phase, differences in soil test values between CF and PL treatments were minor. Differences widened during Phase 2 and increased several fold during Phase 3 and thereafter. As shown in Fig. 3(a), pH remained above 6 for the litter treatment, whereas there was a decline for the CF treatments from phase 1 to 4. Similar declines were observed for Ca, K, and Mg (Fig. 3b, 3d, 3e). On the other hand, soil test P varied in the narrow range of 44 to 59 kg ha^{-1}, while Zn varied from 3.7 to 7.0 kg ha^{-1} in CF treatments from phase 1 to 4 (Fig. 3c and 3f).

The observed advantages of the litter in enhancing crop performance may have been partly due to differences in soil test values discussed above. It is also possible that residual effects of nutrients from PL (especially N) under continuous litter application may have positively impacted crop performance in subsequent years as well. For example, N mineralization from PL may have been more than the assumed 50% at times, which might have had a positive impact on crop performance.

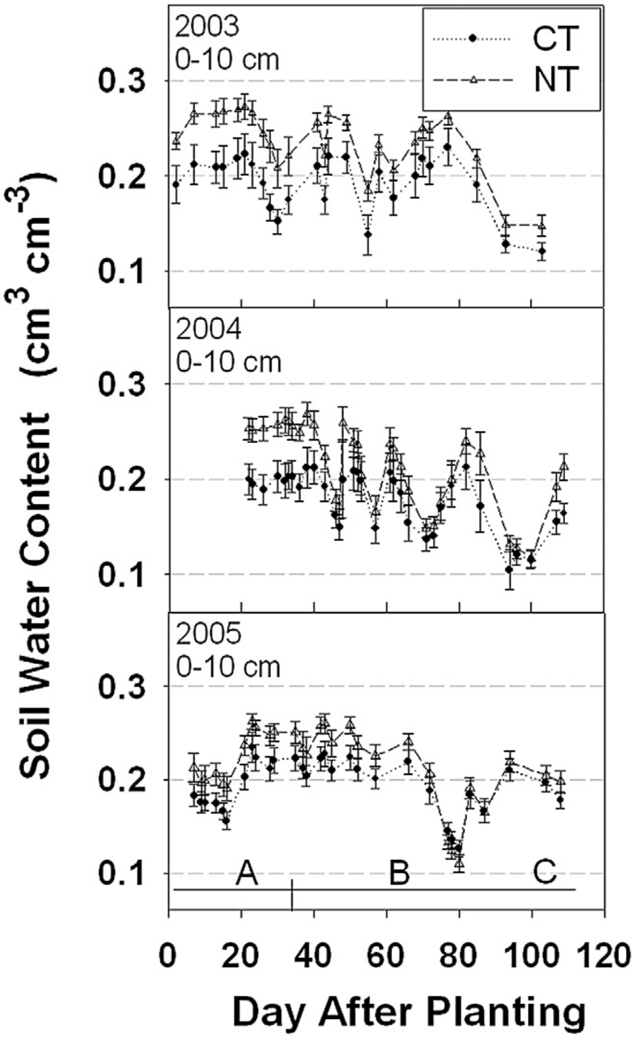

Fig. 2. Mean soil water content with standard error bars for no-tillage (NT) and conventional tillage (CT) for 2003–2005 for 0- to 10-cm depth. The letters A, B, and C signify approximate periods for vegetative, reproductive, including early dough, and dough to beginning of black layer stages, respectively.

Variability by Year

Mean grain yield across treatments varied by year with a fivefold difference between the least and greatest mean yields (Table 1). Sequentially from 2001, mean yield across treatments was 8.4, 2.2, 5.6, 8.7, and 11.0 Mg ha^{-1} (SE = 0.46). Likely causes for variability were high temperature stress, pest pressure, and rainfall variability limiting water availability. In 2002, average weekly maximum temperature was above 32.2°C (90°F) and the minimum close to 21°C (70°F) during the reproductive growth stage, which caused stress in the 2002 corn. Insect damage was a primary cause of stress in 2003. Four of the six no-tillage plots had severe damage to the young shoots in several rows soon after germination, due to corn rootworm attack, and other insect damage later in the crop season, which reduced plant stand and subsequent grain yield.

Rainfall varied during critical growth periods (Fig. 4). Corn is particularly sensitive to water stress during its reproductive period (tasseling, pollination, kernel development, and grain filling). Water requirement for corn production starts to increase from about V6 to V8 stage about 37 d after planting (DAP), with daily water requirement increasing and peaking during early dough stage at 90 to 94 DAP (CAES, 2007a). Beginning of black layer (physiological maturity) is taken as 110 DAP. In assessing adequacy of rainfall with respect to the optimal water requirement in this research, we compared actual water supply with the optimal requirement for the three critical periods of early vegetative stage (1–36 DAP), V6 to V8 stage through early dough (37–94 DAP), and dough to beginning of black layer stage (95–109 DAP) (Fig. 4; Table 2).

Actual water supply was severely limited in 2002 and conditions for seed germination and early development were particularly unfavorable, and some replanting was necessary to establish good stands. In 2002, all plots received 56 and 66 mm of irrigation on Days 13 and 14 after planting, respectively. The need to induce runoff to monitor hormone levels partially contributed to the high level of irrigation. No other irrigation occurred during the research. Rainfall was closest to the optimal requirement in 2005 (Table 2).

Regression analysis revealed that the strongest yield-rainfall correlation was for that between grain yield and rainfall during the reproductive stage including soft dough (Table 3). For the tillage treatments the coefficient of determination (R^2) was 0.75 with no difference in intercepts and slopes ($P = 0.58$). One equation was developed to describe the relationship in both tillage treatments (Table 3). For the fertilizer treatments, intercepts were not different ($P = 0.31$) but slopes were ($P = 0.03$). Two equations were developed, one for CF and the second for PL (Table 3). Using this model, rainfall during the reproductive stage including soft dough explained 67% of the yield variability in the CF and 84% in the PL treatments.

The correlation improved with regression that included rainfall during the reproductive stage through soft dough as one independent variable, and rainfall and irrigation during vegetative stage as a second independent variable. For the tillage treatments, R^2 was 0.81 with no difference in intercepts or slopes ($P = 0.13$ for each). One equation describing the relationship was developed for both tillage treatments (Table 3). For the fertilizer treatments, intercepts were not different ($P = 0.42$), nor was the second slope associated with the second independent variable ($P = 0.93$), but the first slopes were ($P = 0.01$). Two equations were developed, one for CF and the second for PL (Table 3). Using this model, water supply during the vegetative and reproductive stage including soft dough explained 79% of the yield variability in the CF and 91% in the PL treatments.

Table 2. Optimal water requirement for corn during three critical growth stages (College of Agriculture and Environmental Sciences, 2007a) compared with actual water supply during 2001 to 2005.

Water supply	Vegetative stage	Reproductive stage through soft dough	Dough to beginning of black layer stage
		mm	
Optimal requirement	82	421	114
Rainfall for year			
2001	208	262	10
2002	70†	83	8
2003	266	260	15
2004	61	255	44
2005	172	398	45

† There was an additional 122 mm of irrigation.

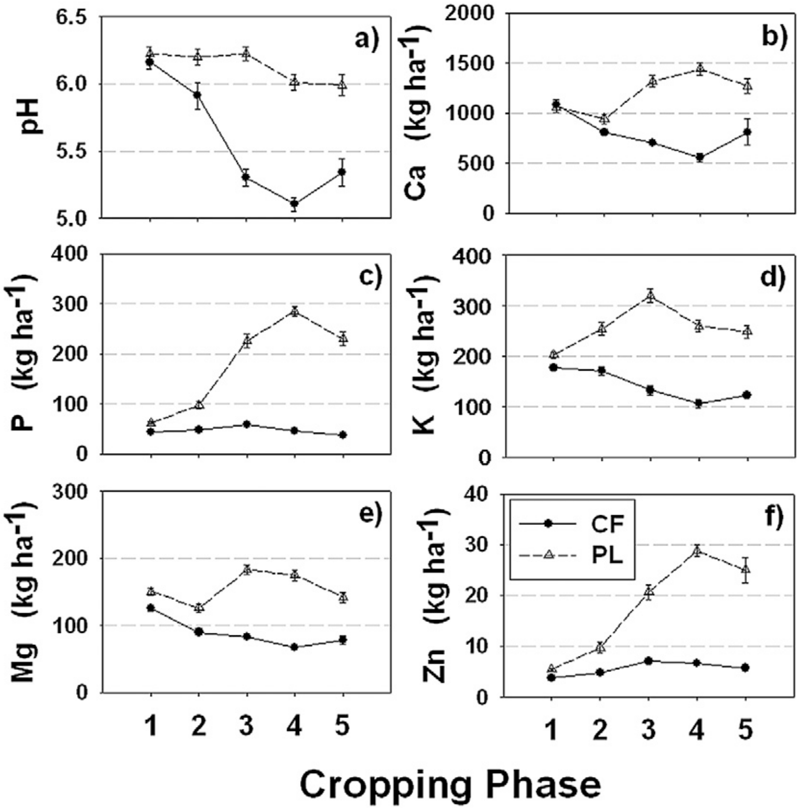

Fig. 3. Mean soil test values with standard error bars for conventional fertilizer (CF) and litter (PL) treatment plots averaged by cropping phases as: Phase 1, cotton with litter application of 4.45 Mg ha^{-1}; Phase 2, corn with litter application of 11.25 Mg ha^{-1}; Phase 3, corn with litter application of 22.5 Mg ha^{-1}; Phase 4, corn with litter application again of 11.25 Mg ha^{-1}; and Phase 5, the start of a pearl millet phase with only inorganic fertilization in all plots.

We studied probabilities of rainfall amounts likely to occur during the development stages discussed above using rainfall exceedance tables and curves developed from 70 yr (1937–2006) of daily rainfall records (Fig. 5). These data show, for example, that the 50% rainfall exceedance probabilities for the vegetative, reproductive through soft dough, and dough to beginning of black layer stages for April and May planting

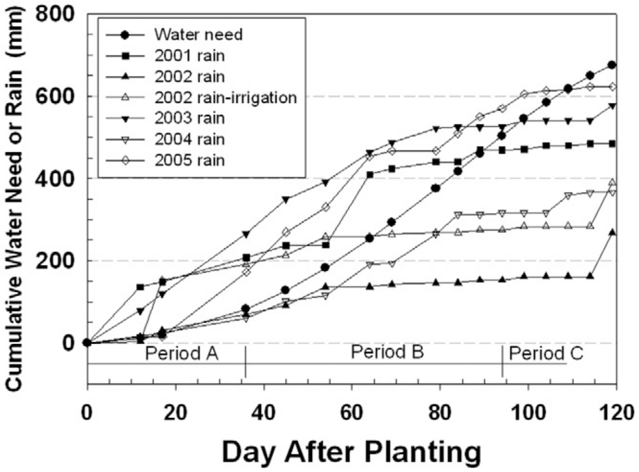

Fig. 4. Cumulative water need (College of Agriculture and Environmental Sciences, 2007a) and rainfall for 120 d of corn production with three critical periods indicated as: early vegetative stage (Period A, 1–36 DAP); V6 to V8 stage through early dough (Period B, 37–94 DAP); and the dough to beginning of black layer stage (Period C, 95–109 DAP).

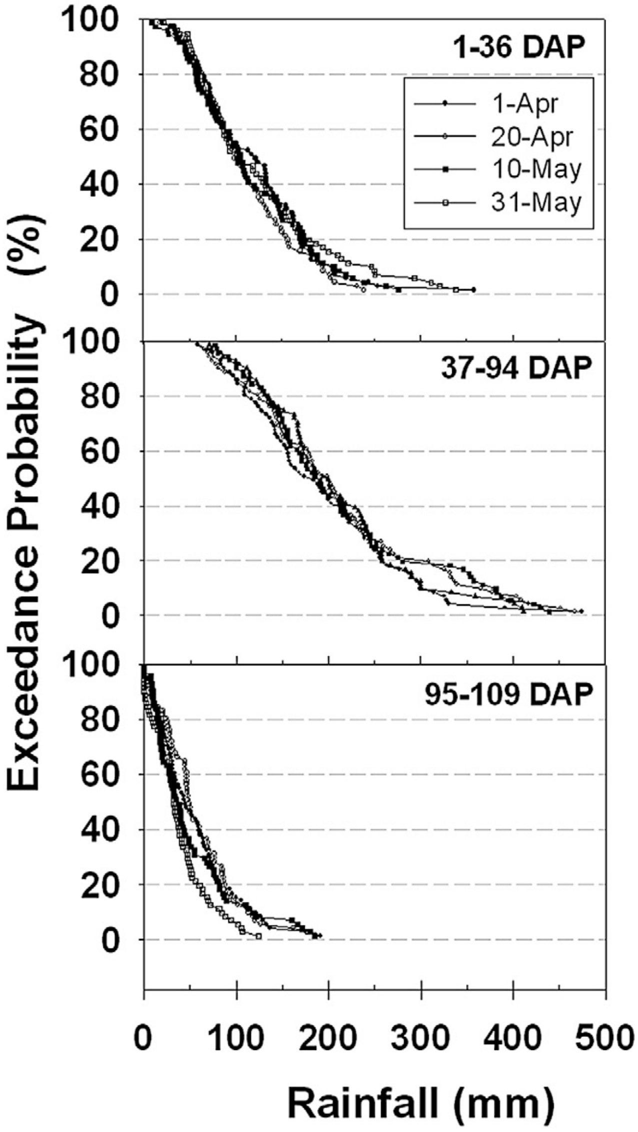

Fig. 5. Exceedance probability for rainfall on 1April, 20 April, 10 and 31 May during early vegetative stage (1–36 DAP), V6 to V8 stage through soft dough (37–94 DAP), and dough to beginning of black layer stage (95–109 DAP) for corn. The curves indicate the range of one variable against a value of the other based on the 4 selected dates from April and May. Curves for other dates in April and May are not shown.

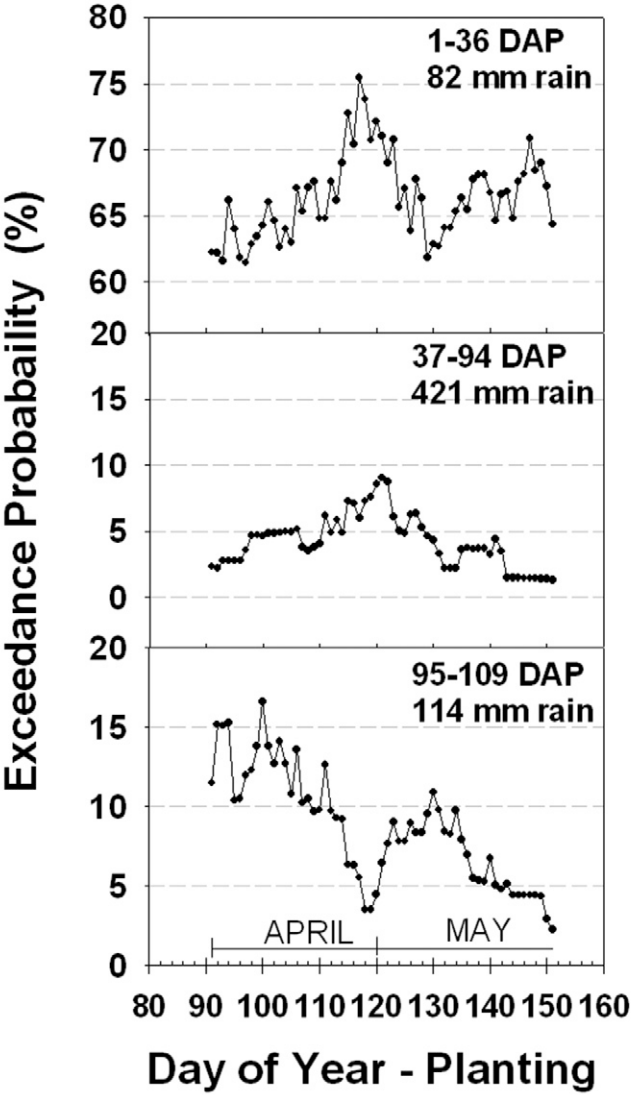

Fig. 6. Exceedance probabilities for optimal rainfall of 82 mm for early vegetative stage (1–36 DAP), 421 mm for V6 to V8 stage through soft dough (37–94 DAP), and 114 mm for the dough to beginning of black layer stage (95–109 DAP).

of corn range from 100 to 110, 173 to 200, and 30 to 60 mm, respectively (Fig. 5). The exceedance probabilities for the optimum rainfalls of 82, 421, and 114 mm (Table 3) for these three stages, respectively, are presented in Fig. 6.

Table 3. Coefficients for one and two parameter models for regression of yield vs. water supply as rain or rain and irrigation during critical growth periods of corn in 2001–2005.

			Intercept§		Slope 1§		Slope 2§	
Equation†	Treat.‡	R^2	SE	*P* value	SE	*P* value	SE	*P* value
One parameter model								
$Y = 0.110 + 0.028 \times X_1$	CT & NT	0.75	0.598	0.855	0.002	<0.0001	–	–
$Y = 0.668 + 0.023 \times X_1$	CF	0.67	0.769	0.389	0.003	<0.0001	–	–
$Y = 0.033 \times X_1 – 0.447$	PL	0.84	0.769	0.563	0.003	<0.0001	–	–
Two parameter model								
$Y = 2.717 + 0.027 \times X_1 – 0.014 \times X_2$	CT and NT	0.81	0.742	0.0006	0.002	<0.0001	0.003	<0.0001
$Y = 3.233 + 0.023 \times X_1 – 0.013 \times X_2$	CF	0.79	0.913	0.0008	0.002	<0.0001	0.003	0.0003
$Y = 2.201 + 0.032 \times X_1 – 0.014 \times X_2$	PL	0.91	0.913	0.019	0.002	<0.0001	0.003	0.0002

† Y = grain yield in Mg ha^{-1}; X_1 = rain in mm from tasseling through early dough; X_2 = rain and irrigation in mm for vegetative stage.

‡ Treat. = treatment; CT = conventional tillage; NT = no-tillage; CF = conventional fertilizer; PL = poultry litter.

§ SE = standard error; Slope 1 associated with X_1; Slope 2 associated with X_2.

For the vegetative stage, mean exceedance probability for the optimum rainfall is about 66%, which means about 33% of the time (3 to 4 of every 10 yr) it is possible to get less rainfall. In the current experiment, this occurred in 2002 and 2004 (Table 2). For the reproductive stage through soft dough, exceedance probabilities for optimum rainfall are low with mean of 4.8% for April and 3.6% for May. This means about 95% of the time rainfall amount for this period is not optimal. In this research, only in 2005 was rainfall close to optimal. The 2001, 2003, and 2004 rainfalls (255–262 mm) have exceedance probabilities of approximately 20 to 30%, which means about 70 to 80% of the time less rainfall is expected in April and May. Exceedance probabilities are again low for the dough to beginning of black layer stage with mean of 10.7% for April and 6.6% for May. About 90% of the time optimal water need from rain is not met for this period. Within these ranges, exceedance probabilities are maximized for 25 April to 3 May planting for the first two stages (Fig. 6), which as shown correlate well with grain yield. These findings highlight the risk associated with dry land corn production in the area and suggest the need for supplemental irrigation.

Use of no-tillage management would help maximize water use efficiency through increased infiltration and water holding capacity compared with conventional tillage under these often non-optimal rainfall periods during corn seasons. The yield advantage of no-tillage is enhanced with long-term use of litter as an alternative N source. Droughts like that in 2002 severely limit water supply to the extent that even no-tillage crops suffer water stress but maximizing the rainfall retained in the root zone can minimize the negative impacts.

Dry Matter Production

Analysis of 2 yr (2004 and 2005) of dry matter in stalks and leaves from five dates each year at intervals of approximately 21 d, showed a large fertilizer and DAP effect and fertilizer × DAP interaction ($P < 0.001$ for both). There was a small tillage effect and tillage × DAP interaction ($P = 0.075$ for both). No-tillage had about 21% more dry matter accumulation than conventional tillage at the third sampling, 66 DAP (Table 4). The litter treatment had 58% more dry matter accumulation at 45 DAP, 41% at 66 DAP, 29% at 87 DAP, and 26% at 108 DAP than the conventional fertilizer treatment. These data indicate the season-long benefit of litter, beginning early in the corn growth period, resulting in relatively greater accumulation of dry matter compared with the conventional fertilizers used in this experiment. It appears growers who wish to harvest a corn crop for biomass would maximize production with no-tillage and litter.

Analysis of leaf area index (LAI) measurements from the first four dates combined for 2004 and 2005 showed a tillage effect ($P = 0.047$), a fairly large fertilizer and DAP effect ($P \leq 0.001$) and a fertilizer × DAP interaction ($P = 0.002$). The litter treatment had 30, 21, and 15% more LAI than conventional tillage treatment at 45, 66, and 87 DAP (Table 5). No-tillage produced slightly more leaf area than conventional tillage at 66 DAP.

Analysis of root dry matter measurements from samples taken 66 and 108 DAP combined for 2004 and 2005 showed only a DAP and fertilizer × DAP interaction effect ($P = 0.037$). The litter treatment had 55% more root mass at 66 DAP (Table 6). However, the conventional tillage treatment had developed 25% greater root mass at 108 DAP. These data suggest that the litter enabled the corn to develop close to maximum root mass by 66 DAP (about half way through reproductive period). In contrast, root mass under conventional tillage was 72% more at 108 DAP than at 66 DAP.

Table 4. Mean dry matter for stalks and leaves for 2004 and 2005 by sampling date.†

	Stalks and leaves mean dry matter				
Treatment	**24 DAP**	**45 DAP**	**66 DAP**	**87 DAP**	**108 DAP**
	$\mathrm{Mg\ ha^{-1}}$				
Tillage					
CT	0.11a‡	1.49b	6.61c	8.40d	8.67d
NT	0.10a	1.51b	8.02c	8.76d	9.06d
	NS§	NS	*	NS	NS
Fertilizer					
CF	0.08a	1.16b	6.04c	7.48d	7.84d
PL	0.13a	1.83b	8.58c	9.67d	9.89d
	NS	*	*	*	*

* Significant at $P = 0.1$ for contrasts between tillage treatment pairs (conventional tillage [CT] vs. no-tillage [NT]) and fertilizer treatment pairs (conventional fertilizer [CF] vs. poultry litter [PL]) by each date.

† DAP = day after planting.

‡ Means followed by the same lower case letters in each row are not significantly different at $P = 0.1$.

§ NS indicates nonsignificance at $P = 0.1$ for contrasts between tillage treatment pairs (CT vs. NT) and fertilizer treatment pairs (CF vs. PL) by each date.

Table 5. Mean leaf area index for 2004 and 2005 by sampling date.†

	Mean leaf area index			
Treatment	**24 DAP**	**45 DAP**	**66 DAP**	**87 DAP**
	$\mathrm{m^2\ m^{-2}}$			
Tillage				
CT	0.24a‡	2.65b	4.51c	4.15d
NT	0.22a	2.76b	4.77c	4.31d
	NS§	NS	*	NS
Fertilizer				
CF	0.20a	2.35b	4.19c	3.93d
PL	0.27a	3.06b	5.08c	4.53d
	NS	*	*	*

* Significant at $P = 0.1$ for contrasts between tillage treatment pairs (conventional tillage [CT] vs. no-tillage [NT]) and fertilizer treatment pairs (conventional fertilizer [CF] vs. poultry litter [PL]) by each date.

† DAP = day after planting.

‡ Means followed by the same lower case letters in each row are not significantly different at $P = 0.1$.

§ NS indicates nonsignificance at $P = 0.1$ for contrasts between tillage treatment pairs (CT vs. NT) and fertilizer treatment pairs (CF vs. PL) by each date.

Table 6. Mean dry matter for roots for 2004 and 2005 by sampling date.†

	Root mean dry matter	
Treatment	**66 DAP**	**108 DAP**
	$\mathrm{Mg\ ha^{-1}}$	
Tillage		
CT	2.70a‡	3.52a
NT	3.09a	3.90a
	NS§	NS
Fertilizer		
CF	2.27a	3.90b
PL	3.51a	3.53a
	*	*

* Significant at $P = 0.1$ for contrasts between tillage treatment pairs (conventional tillage [CT] vs. no-tillage [NT]) and fertilizer treatment pairs (conventional fertilizer [CF] vs. poultry litter [PL]) by each date.

† DAP = day after planting.

‡ Means followed by the same lower case letters in each row are not significantly different at $P = 0.1$.

§ NS indicates nonsignificance at $P = 0.1$ for contrasts between tillage treatment pairs (CT vs. NT) and fertilizer treatment pairs (CF vs. PL) by each date.

CONCLUSIONS

This 5-yr study in the southeastern United States on a typical Piedmont soil showed that growers can conserve and use rainfall more efficiently, reduce the severity of yield-limiting droughts, and expect increased corn yields with no-tillage and poultry litter. In the study, both no-tillage and poultry litter enhanced corn grain yield compared with conventionally tilled and fertilized corn. No-tillage management enhanced grain yield by 11%. Poultry litter enhanced grain yield by 18%. No-tillage and litter combined enhanced grain yield by 31% over 5 yr compared with conventionally tilled and fertilized corn. Over the course of the study, soil water in no-tillage in the 0- to 10-cm depth was greater by 18% compared with conventional tillage. Litter and no-tillage also increased corn dry matter during the whole reproductive stage (litter) or around the middle of the reproductive stage (tillage) compared with conventional tillage and fertilizer. This would give growers additional market options in the bio-energy production industry.

Analysis of 70 yr of daily rainfall records showed that the location receives less than optimum rainfall for corn production about 33% of the time before initiation of tasseling, 95% of the time from initiation of tasseling to early dough stage, and 90% of the time from dough stage to beginning of black layer. However, no-tillage and poultry litter increased corn grain yield over 5 yr in which 1 yr received only 20%, three received about 62%, and the fifth about 95% of the optimum rainfall required during the critical tasseling to early dough period. This suggests that in areas with targeted supplemental irrigation, the advantage of superior infiltration and water holding capacity under no-tillage can be used to increase corn biomass and yield in years receiving less than optimal rainfall and increase efficiency of water use from rain and/or irrigation.

ACKNOWLEDGMENTS

This research was supported in part by grants from USDA-CSREES NRI and US Egg and Poultry Association. We are grateful for many technicians and students for their expert assistance, including, Stephen Norris, Robin Woodroof, Burt Schutza, Stephanie Steed, Shaheen Humayoun, Mike Thornton, Eric Elsner, Ronald Phillips, Robert Sheats, Fred Hale, Debbie Beese, Beth Barton, Steve Knapp, Tony Dillard, Robert Martin, Clara Parker, Terrel Gibson, Willie Horan, Devin Berry, Heather Hart, Drew Kitchens, Becca Styles, Ryan Talton, and Nathan Tyson.

REFERENCES

Adams, W.E., J.E. Pallas, Jr., and R.N. Dawson. 1970. Tillage methods for sod systems in the southern Piedmont. Agron. J. 62:646–649.

Bennett, O.L., E.L. Mathias, and P.L. Lundberg. 1973. Crop response to no-till management practices on hilly terrain. Agron. J. 65:488–491.

Bradley, J.F. 1995. Success with no-till cotton. p. 31–38. *In* M.R. McClelland, T.D. Valco, and F.E. Frans (ed.) Conservation-tillage systems for cotton: A review of research and demonstration results from across the cotton belt. Arkansas Agric. Exp. Stn., Fayetteville, AR.

Bruce, R.R., J.H. Dane, V.L. Quisenberry, N.L. Powell, and A.W. Thomas. 1983. Physical characterization of soils in the southern region: Cecil. Southern Coop. Series Bull. No. 267. University of Georgia, Athens.

College of Agriculture and Environmental Sciences. 2007a. A guide to corn production in Georgia 2007. Lee D (ed.). The Univ. of Georgia, College of Agric. and Environ. Sci., Coop. Ext. Serv., Athens.

College of Agriculture and Environmental Sciences. 2007b. Poultry litter application on pastures and hayfields. Bull.1330. The Univ. of Georgia, College of Agric. and Environ. Sci., Coop. Ext. Serv., Athens.

Cooperband, L., G. Bollero, and F. Coale. 2002. Effect of poultry litter and composts on soil nitrogen and phosphorus availability and corn production. Nutr. Cycling Agroecosyst. 62:185–194.

Conservation Tillage Information Center. 2007. More corn: Is conservation tillage at risk. Partners 25(2). Conserv. Tillage Info. Ctr., Lafayette, IN.

Endale, D.M., M.L. Cabrera, J.L. Steiner, D.E. Radcliffe, W.K. Vencill, H.H. Schomberg, and L. Lohr. 2002a. 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. Soil Tillage Res. 66:55–86.

Endale, D.M., D.E. Radcliffe, J.L. Steiner, and M.L. Cabrera. 2002b. Drainage characteristics of a Southern Piedmont soil following six years of conventionally tilled or no-till cropping systems. Trans. ASAE 45(5):1423–1432.

Endale, D.M., H.H. Schomberg, M.L. Cabrera, J.L. Steiner, D.E. Radcliffe, W.K. Vencill, and L. Lohr. 2002c. Lint yield advantages of no-till and poultry litter-based cotton/rye cropping system in a Southern Piedmont soil: A five-year data set. p. 115–122. *In* E. van Santen (ed.) Making conservation tillage conventional: Building a future on 25 years of research. Proc. of 25th Annual Southern Conservation Tillage Conf. for Sustainable Agriculture, Auburn, AL. 24–26 June 2002. Univ. of Auburn, Auburn, AL.

Fawcett, R.S., B.R. Christensen, and D.P. Tierney. 1994. The impact of conservation tillage on pesticide runoff into surface water: A review and analysis. J. Soil Water Conserv. 49(2):126–135.

Jenkins, M., D.M. Endale, H.H. Schomberg, H.A. Sangsupan, D.R. Radcliffe, P.G. Hartel, M.L. Cabrera, W.K. Vencill, and N.W. Shappell. 2004. Fate and transport of sex hormones from poultry litter applied to till- and no-till cropping systems. Agron. Abstr. p. 339. ASA, Madison, WI.

Jones, J.N., J.E. Moody, G.M. Shear, W.W. Moschler, and J.H. Lillard. 1968. The no-tillage system for corn (*Zea mays* L.). Agron. J. 60:17–20.

Langdale, G.W., L.T. West, R.R. Bruce, W.P. Miller, and A.W. Thomas. 1992. Restoration of eroded soil with conservation tillage. Soil Technol. 5(1):81–90.

Littell, R.C., G.A. Milliken, W.W. Stroup, and W.R. Wolfinger. 1996. SAS systems for mixed models. SAS Inst., Cary, NC.

McCuen, R.H. 1998. Hydrologic analysis and design. Prentice Hall, Englewood Cliffs, NJ.

Mitchell, C.C., and S. Tu. 2005. Long-term evaluation of poultry litter as a source of nitrogen for cotton and corn. Agron. J. 97:399–407.

Moore, P.A., Jr., T.C. Daniel, A.N. Sharpley, and C.W. Wood. 1995. Poultry manure management: Environmentally sound options. J. Soil Water Conserv. 50(3):321–327.

National Agricultural Statistics Service. 2007. Poultry– Production and value 2006 Summary. NASS, Agric. Statistics Board, USDA, Washington, DC.

Radcliffe, D.E., and L.T. West. 2000. MLRA 136: Southern Piedmont. Southern Coop. Ser. Bull. 395. Univ. of Georgia, Athens.

Reeves, D.W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping system. Soil Tillage Res. 43:131–167.

Renewable Fuels Association. 2006. From niche to nation. Ethanol industry outlook 2006. Available http://www.ethanolrfa.org/objects/pdf/outlook/outlook_2006.pdf (accessed 14 Dec. 2007, verified 16 June 2008).

SAS Institute. 2004. SAS/STAT. Statistical analysis system for Windows. v. 9.1. SAS Inst., Cary, NC.

Schomberg, H.H., D.M. Endale, M.B. Jenkins, R.R. Sharpe, D.S. Fisher, M.L. Cabrera, and D.V. McCracken. 2008. Poultry litter induced changes in soil test nutrients of a Cecil soil under conventional tillage and no-tillage. Soil Sci. Soc. Am. J. (in press).

Soil and Water Conservation Society. 2006. Environmental benefits of conservation on cropland. The status of our knowledge. Max Schnepf and Craig Cox (ed.) SWCS, Ankeny, IA.

Terra, J.A., D.W. Reeves, J.N. Shaw, and R.L. Raper. 2005. Impacts of landscape attributes on carbon sequestration during the transition from conventional to conservation management practices on a Coastal Plain filed. J. Soil Water Conserv. 60(6):437–446.

Vest, L., B. Merka, and W.I. Segars. 1994. Poultry waste: Georgia's 50 million dollar forgotten crop. Leaflet no. 206(July) 1994. The Univ. of Georgia, College of Agric. and Environ. Sci., Coop. Ext. Serv., Athens.

Wilkinson, S.R., O.J. Devine, D.P. Belesky, J.W. Dobson, Jr., and R.N. Dawson. 1987. No-tillage intercropping corn production in tall fescue sod as affected by sod-control and nitrogen fertilization. Agron. J. 79:685–690.