Nutr Cycl Agroecosyst
DOI 10.1007/s10705-009-9318-z

RESEARCH ARTICLE

Management implications of conservation tillage and poultry litter use for Southern Piedmont USA cropping systems

Dinku M. Endale · Harry H. Schomberg · Michael B. Jenkins · Dory H. Franklin · Dwight S. Fisher

Received: 23 May 2009 / Accepted: 8 September 2009

Abstract Conservation tillage and judicious use of animal manures as fertilizers can make significant contributions for sustainable food production in the twenty-first century. Identifying and understanding the many interactions occurring within agricultural systems is fundamental for accomplishing this feat. This paper synthesizes 14 years of research results from a study that began in the early 1990s in which researchers from USDA-ARS and the University of Georgia investigated cropping system influences on nutrient management under natural rainfall. Increases in C and N with no-till resulted in improved soil structure that increased infiltration rate and soil water availability. Biological activity as indicated by earthworms was greater with no-till and poultry litter (PL). In all but the very driest year, yields of cotton and corn increased on average 10–27% with no-till and 32–42% with combination of no-till and PL. On the other hand soil nutrient accumulation, particularly P and Zn from long-term use of poultry litter in corn production, reached excessive levels and could present environmental risks. Drainage increased in no-till raising the risk of leaching of nutrients into the soil profile. However, runoff decreased in no-till and the presence of a rye cover crop during the winter reduced the leaching losses of N compared to no cover crop. During cotton production under relative drought, no-till and poultry litter led to somewhat elevated dissolved phosphorus concentration in runoff, and fluometuron was detected in runoff and drainage while pendimethalin was not. Fecal indicator bacteria (*Escherichia coli* and fecal enterococci), and the hormones estradiol and testosterone were observed in drainage and runoff but concentrations were similar across all treatments. By conducting the study for an extended period under natural environmental conditions, we were able to highlight real risks and potentials of the contrasting cropping systems. While 6 out of 14 years of relative drought might have limited the water quality response of treatments, such droughts are common features of the weather pattern in the region. Even then, use of no-till as the predominant tillage system was supported by improved yields. Fertilizer management, especially crop N need-based use of PL, requires closer monitoring to insure that production advantages of no-till and poultry litter are not offset by concerns with environmental risks. Long-term research requires sustained resource inputs to answer critical questions of environmental risk and emerging unknown issues.

Keywords Conventional tillage · Corn · Cotton · No-till · Organic matter · Runoff · Soil quality · Water quality

D. M. Endale (✉) · H. H. Schomberg · M. B. Jenkins · D. H. Franklin · D. S. Fisher
USDA-ARS, J. Phil Campbell Sr. Natural Resource Conservation Center, 1420 Experiment Station Road, Watkinsville, GA 30677, USA
e-mail: Dinku.Endale@ars.usda.gov; dendale@uga.edu

Published online: 22 September 2009

Introduction

Mankind is challenged to provide adequate food and clean water for a burgeoning global population. Land and water resources are limited and we are uncertain of how climate change will impact crop production. Tillage methods using implements that unduly disturb the soil surface such as moldboard or disc plows, and harrows (conventional tillage) promote losses of organic matter that leads to diminished soil physical, chemical and biological properties. This reduction in soil quality often results in increased erosion and losses of nutrients along with reduced soil productivity (Langdale et al. 1992; Reeves 1997; CTIC 2001; Pieri et al. 2002; Lal 2002; FAO 2008). Over the past half century, research has focused on developing management practices that appropriately value soil resources for crop production and protecting soil and water quality. A key component associated with this focus has been improved conservation tillage systems. Successful conservation tillage systems, as defined by Schnepf and Cox (2006) and FAO (2008), among others, utilize four interlinked management practices: (1) minimum or no soil disturbance; (2) permanent residue cover on 30% or more of the surface; (3) direct sowing; and (4) sound crop rotation. According to FAO (2008), however, only 95 million ha approximately of the global cropland is under no-till (the ultimate form of conservation tillage), which represents less than 7% of the world's cropland. In the USA, 41% of the crop land is in conservation tillage while 57% of that is in no-till (CTIC 2009). Major improvements in soil quality from accumulation of surface organic matter with conservation tillage systems has a positive effect on infiltration, water availability, and nutrient cycling leading to increased yields (Langdale et al. 1992; Bruce and Langdale 1997; Reeves 1997; Allmaras et al. 2000; Endale et al. 2000, 2002a, b, 2008; CTIC 2001; Schomberg et al. 2003; Schnepf and Cox 2006; FAO 2008).

The Southern Piedmont of the USA covers 16.7 million ha from Alabama to Virginia along the east face of the Appalachian Mountains. Conventional tillage systems (plows and discs) were adopted by early settlers and are still common. These practices along with high intensity summer storms, rolling topography, low organic matter, and highly erodible soils resulted in severe erosion in the region (Trimble 1974). Low water holding capacity, root restrictive layers, and surface crusts due to low organic matter have further exacerbated the erosion. Cecil and related soils (USDA: Fine, kaolinitic, thermic, Typic Kanhapludults; FAO: Chromic-Alumic Acrisol; description given in "Materials and Methods") occupy more than half of the Southern Piedmont (Radcliffe and West 2000) and are typical of the highly eroded soils of the region.

Partly in response to concerns with land degradation under past land management practices, Piedmont agriculture has shifted to the present mix of 60% forest, 11% grassland (1.8 million ha), and 9% cropland (1.5 million ha) (NRCS 1998). Crops such as corn, cotton, soybeans, and small grains contribute to farm income along with beef cattle (*Bos taurus*) and poultry. In the US, annually over 50% of the 8.6 billion broilers come from this region (NASS 2009) creating at least 50% of the 10 million Mg of poultry litter (PL—a mixture of bedding material and manure) estimated to be produced by the poultry industry.

Poultry litter is a readily available source of nutrients. It contains N, P, and K along with Ca, Mg, S, Cu, Mn, and Zn (Stephenson et al. 1990; Moor et al. 1995; CAES 2007). Application of poultry litter to farmland has increasingly become a concern from both water quality and human health standpoints. Because of its low nutrient density, poultry litter is usually applied to agricultural land within a short distance of production facilities. Repeated application of poultry litter can result in the accumulation of P in surface soils (Sharpley et al. 1993; Kingery et al. 1994; Schomberg et al. 2009a) increasing the potential for loss as dissolved P in runoff or leachate (Moor et al. 1995; Sharpley et al. 1994). Poultry litter can also contain pathogenic bacteria such as Salmonella and Campylobacter (Kelley et al. 1994; Jeffrey et al. 1998) as well as fecal indicator bacteria such as total coliforms, *Escherichia coli* (*E. coli*) and fecal enterococci. Appreciable concentrations of the sex hormones 17β-estradiol and testosterone have also been found to naturally occur in broiler litter. The risk of contaminating surface waters with fecal bacteria and sex hormones could therefore be expected to increase with long-term applications of poultry litter.

The precise outcomes of management decisions are often difficult to estimate a priori because of the multifaceted interactions of biotic and abiotic factors. For example, increased water infiltration, often seen with conservation tillage systems, might be perceived as detrimental if nutrients leach below the root zone and eventually enter the ground water. Identifying and understanding the multiple interactions occurring within conservation tillage systems can help researchers and producers make informed decisions about how to better manage these tillage system.

In the early 1990s a water quality research program was initiated in cooperation with the University of Georgia at the USDA-ARS near Watkinsville, GA (McCracken et al. 1993, 1995). Initially, the objectives were to characterize hydrologic flow (preferential flow) through the soil and estimate nutrient and chemical losses associated with cover crops and conservation tillage. Data were used for calibrating and/or validating models of subsurface N losses. Over time the objectives shifted to quantifying the potential benefits of conservation tillage on crop productivity as well as describing fate and transport of water, nutrients, agricultural chemicals, pathogens and hormones in systems that included poultry litter as a nutrient source. This paper synthesizes results from 14 years of research providing a holistic look at productivity and environmental responses.

Materials and methods

Experimental site

The research was conducted at the USDA-ARS, J. Phil Campbell, Sr. Natural Resource Conservation Center, Watkinsville, GA (83°24′W and 33°54′N). Average daily air temperature ranges from 6 to 8°C in winter and from 23 to 27°C in summer. Frost free days in the growing season range from 200 to 250. Mean annual precipitation is 1,240 mm with fall (September–November) seasonal precipitation typically less than the other seasons. Precipitation is typically greatest in March and least in October. Mean monthly potential evapotranspiration (PET) for 1997–2007 was greatest in May through August (140–150 mm) with a fairly uniform drop to ~40 mm by January followed by a uniform rise to May. Mean monthly precipitation was greater than PET from November to March (30–55 mm). The mean precipitation-PET deficit was greatest in August (−96 mm) followed by May (−59 mm) and April (−43 mm). The deficit for the remaining months varied from −8 mm (September) to −22 mm (June). Despite the high average annual precipitation, short and long term periods of drought are not uncommon. Short term droughts (5–10 days) are especially common during the summer growing season. The most recent long term droughts occurred from 1998 to 2002 and 2006–2008, with 2007 being the driest in nearly 70 years.

The facility consists of 12 tile-drained plots, each 10 m by 30 m, located on a nearly level (<2% slope) Cecil sandy loam soil. Cecil soil has a sandy loam surface lying over clayey argillic subsurface and is developed from residual saprolite weathered from felsic igneous and metamorphic rocks. This class of soils often has a low pH, low base saturation, low cation exchange capacity, and has abundant iron and aluminum oxides in the Bt horizon. The soil at the research site has a 20-cm thick Ap horizon of brown sandy loam with 75% sand and 6% clay, and is underlain by a 5- to 10-cm thick BA horizon of red sandy clay loam to clay loam texture (Bruce et al. 1983). The Bt horizon consists of about 100-cm thick red clay followed by about 30-cm thick red loam to clay loam BC horizon. The C horizon is a loamy saprolite.

Each plot is underlain by five 30-m long drain lines spaced 2.5 m apart. Drain lines consist of 10-cm diameter, flexible, slotted PVC pipe installed on a 1% grade. At the lower plot edge, the depth of each drain line is 1 m from the soil surface. To exclude subsurface lateral flow, plot borders are enclosed with polyethylene sheeting that extends from the soil surface to the depth of the drain lines. A surface runoff collector (14 gauge galvanized steel) spans the plot width at the lower end of each plot. Each collector channels the surface runoff from a single plot to an HS flume, where water height is measured and recorded continuously (during an event) to provide runoff volume. Six CR10X data loggers (Campbell Scientific Inc, Logan, Utah), each serving a pair of plots, log runoff and drainage quantities as well as triggering automatic samplers for collection of runoff and drainage samples. When first established a single CR7 data logger was used to perform all data logging and triggering of sample collection. This proved to be less desirable than multiple data loggers because of electrical surges from storms. Even with the more robust use of multiple data loggers, runoff measurement sensors continue to be particularly vulnerable to storm electrical surge damage resulting in periodic loss of data.

Table 1 Mean percent pore areas of pore size distributions separated for dye-stained and undyed soil in the Ap horizon

	Pore size class (mm)				
Stain status	0.05–0.10	0.10–0.25	0.25–0.50	0.50–1.0	1.0–2.0
	Distribution (%)				
Dye stained	0.61	2.48	3.60	4.68	4.16
Undyed	0.51	1.12	0.75	0.55	0.23

Percent pore areas for each pore-size class was determined using image analysis of cross-sectional surfaces

In 1992, preferential flow paths were evaluated in the upper horizons from forty soil columns, each 15-cm diameter and 30–60 cm length, collected from one of two similarly established plots adjacent to the 12 plot instrumented facility (Gupte et al. 1996; Radcliffe et al. 1996; Franklin et al. 2007). The area containing the plots had been in conventionally tilled row crops for at least 10 years. Saturated hydraulic conductivity ranged from 7.7 to 20.2 cm h^{-1}. Preferential flow paths identified with methylene blue indicated abundant water transmission through the Ap and BA horizons (dye-stained area was greater than 95%; Franklin et al. 2007). The Bt horizon had lower flow (60–80% staining) and preferential flow began just above the Bt and BA interface (Gupte et al. 1996). The Ap horizon had a sandy loam texture, weak structure, and pores that were predominantly coarse packing voids. Few coarse pores or open channels were observed (Table 1) in the Ap horizon. Photographic image analysis showed a significantly greater percentage of pores (14.9%) >10 mm equivalent diameter in dyed areas than undyed areas (2.7%) and similar results for pores >25 mm (12 vs. 2%). The lack of macropores in undyed areas restricted movement of water and associated dye. The gross morphology analysis indicated that both tree roots and soil fauna appear to be major factors influencing preferential movement of water and solutes through these soils.

Cropping

From 1991 to 1994, the influences of tillage [conventional (CT) or no-tillage (NT)], and winter cover crop [fallow or cereal rye (*Secale cereale* L.)] on N leaching were evaluated under natural rainfall. During summer of 1991, conventional tillage corn (*Zea mays* L.) was grown on the entire 12 plot area. In mid October 1991, six plots were no-till planted to rye and the remaining six plots were left in fallow. The experimental design was a split plot with three blocks (replications). A tillage treatment (whole plot) was applied on two adjacent instrumented plots; one with and one without a rye cover crop (split plots). The no-till plots have remained in place since 1991. In years 1992, 1993, and 1994 corn, fertilized with 168 kg N ha^{-1} (NH_4NO_3), was grown on both the no-till and conventional tillage plots. Conventional tillage, conducted in the spring and fall, consisted of a 30-cm deep chisel plowing, to break possible hard pans, 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. Soil disturbance in no-till was limited to that caused by a coulter and double disc opener on the no-till planter.

The cropping system was changed in fall 1994. The two tillage practices remained in place but the summer cropping was changed from corn to cotton (*Gossipium hirsutum* L.) and subplot treatments were changed from a comparison of fall cover versus fallow to a comparison of spring applied commercial fertilizer (CF—NH_4NO_3) and poultry litter in a factorial combination of treatments: CT-CF, CT-PL, NT-CF, and NT-PL. The winter rye cover crop was now grown on all plots. There was a transition year in 1995 when instrumentation for surface runoff or drainage collection and sampling was upgraded and no data were collected. The upgrading included better protection of sensors and samplers from storm damage, replacement of damaged sensors, improved data logging and programming for better logging and sampling schedules.

For the next 10 years, combinations of the two tillage (mainplot) and two fertilizer sources (subplots) were evaluated for cotton and corn production as well as influence on hydrology and water quality under natural rainfall. In 1996–2000 cotton and a winter rye cover crop were grown. The main crop was switched to corn from 2001 through 2005. Fertilizer application rates from 1996 to 2005 were based on agronomic recommendations for each crop and are presented in Table 2. The poultry litter consisted of manure and pine (*Pinus palustris* P. Miller and *Pinus elliottii* Englem.) wood shavings. Each batch of poultry litter was analyzed at the Soil, Plant and Water Analysis Laboratory at the University of Georgia, Athens, Georgia. Poultry litter was applied based on crop N requirement, and the assumption that 50% of the N would be mineralized during the main cropping season (Ritz and Merka 2004) meaning the N content of the litter was twice the N requirement of the crop. The poultry litter application rate was doubled in 2003 to test for losses of estradiol and testosterone. From 2006, the plots continue to be managed under conventional tillage and no-till with pearl millet [*Pennisetum glaucum* (L.) R.Br.] as the summer crop and fertilized with conventional fertilizer only; i.e. the last poultry litter application in the plots was in spring 2005. The millet phase is not covered in this paper.

In both the conventional tillage and no-till treatments, the cover crop was chemically killed by applying glyphosate (2.3 l ha^{-1}) 2–3 weeks before planting of the spring crop. Crop residues were incorporated only in the conventional tillage treatment while in the no-till treatment residues were left on the surface. Nutrients were applied 1–2 days before planting and incorporated in the conventional tillage treatment during the final disking operation. Standard recommended practices were followed for controlling weeds and pests and in the application of cotton harvest aids. Additional details can be found in Endale et al. (2002a, b), Jenkins et al. (2008), and Schomberg et al. (2009a).

Results

Crop productivity

Cotton

No-till management with poultry litter as a nutrient source produced superior lint yields compared to conventional tillage management with ammonium nitrate fertilizer (Endale et al. 2002b, c). During the first 3 years sub-optimal rainfall limited growth but there were no serious deficits during the critical blooming period. Cotton yields were 43, 35, and 50% greater from no-till fertilized with poultry litter compared to conventional tillage with conventional fertilizer (0.87, 1.01, 0.81 Mg ha^{-1}, respectively, for CT-CF). In the fourth year, a 35-day drought occurred during blooming resulting in the least yield of the 5 years and no yield difference between tillage or fertilizer treatments. In the fifth year, drought during establishment caused severe stress in the conventional tillage cotton, but the no-till cotton showed less stress and reached bloom stage in better condition. A mild drought during blooming exerted additional stress, which was more apparent on the conventional tillage cotton. No-till cotton made better use of limited rainfall. As a result, no-till average cotton yield for the 2 dry years surpassed that from conventionally tilled cotton by 41% (CT: 0.56 Mg year^{-1}). The combination of no-till and poultry litter produced more lint in 4 of 5 years compared to conventional tillage with commercial fertilizer. Over the 5 years no-till enhanced lint yield by 31% (CT: 0.81 Mg ha^{-1}) while no-till fertilized with poultry litter increased lint yield by 42% (CT-CF: 0.77 Mg ha^{-1}).

Corn

Corn production in 2001–2005 showed that growers can conserve and use rainfall more efficiently, reduce the severity of yield-limiting droughts, and expect increased corn yields with no-till and poultry litter (Endale et al. 2008). Over 5 years, no-till enhanced grain yield by 11% (CT: 6.79 Mg ha^{-1}) while poultry litter enhanced grain yield by 18% (CF: 6.57 Mg

Table 2 Cropping sequence and fertilizer application rates from 1996 to 2005 for the study plots

Phase	Years	Crop	PL rate (Mg ha^{-1})	Conventional fertilizer (N kg ha^{-1})
1	1996–2000	Cotton	4.5[a]	67
2	2001, 2002	Corn	11.2 + 4.5[b]	168
3	2003	Corn	22.4 + 4.5	336
4	2004, 2005	Corn	11.2[a]	168

[a] In phase 1 and 4, the rye cover crop in both the poultry litter (PL) and conventional fertilizer treatments received 56 kg N ha^{-1} from inorganic fertilizer

[b] The rye cover crop was fertilized with 4.5 Mg ha^{-1} PL in the poultry litter treatment during 2001, 2002 and 2003 and received 56 kg N ha^{-1} in the conventional fertilizer treatment from inorganic fertilizer

ha^{-1}). Over 5 years, no-till combined with poultry litter enhanced grain yield by 31% compared with conventionally tilled and fertilized corn (CT-CF: 6.29 Mg ha^{-1}). In the year with driest corn season (2002) no-till increased corn grain yield by 37% compared to conventional tillage (CT 1.85 Mg ha^{-1}). Soil water in the 0- to 10-cm depth was 18% greater with no-till compared with conventional tillage over the 5 years. Analysis of 70-year of historical rainfall data indicated that less than optimum rainfall before initiation of tasseling occurs about 33% of the time, from initiation of tasseling to early dough stage about 95% of the time, and from dough stage to beginning of black layer about 90% of the time. However, no-till and poultry litter improved corn grain yield over 5 years in which 1 year received only 20%, three received about 62%, and the fifth about 95% of the optimum rainfall required during the critical tasseling to early dough. These corn production and weather data analyses suggest that corn production in the region is risky without supplemental irrigation targeted at those periods where corn is most vulnerable from drought. With targeted irrigation, no-till with or without poultry litter would provide increased efficiency of water use from rain and/or irrigation.

Soil C, N

Initial C and N contents for the 0–15 cm depth in 1991 prior to the initiation of the conservation tillage treatments were 8.4 and 0.80 g kg^{-1}, respectively, (Johnson et al. 1999). In winter 2005, soil C had increased to 13.3 and 16.2 g kg^{-1} and N had increased to 1.24 and 1.45 g kg^{-1} for the conventional tillage and no-toll treatments, respectively, for plots receiving poultry litter (Schomberg et al. 2009b). Increases were also seen in the conventional fertilizer treatment for no-till and conventional tillage where C had increased to 10.2 and 13.6 g kg^{-1} and N had increased to 0.84 and 1.05 g kg^{-1}, respectively. Various N fractions and particulate organic matter C (POMC) also showed response to the tillage and poultry litter treatments (Table 3). Some of the increase in C and N was the result of intensive crop production that included a rye cover crop on both conservation and conventional tillage. Inputs of organic matter as part of the poultry litter treatment also contributed to increasing soil C and N. The response to both the poultry litter and rye cover crop was much greater in the no-till than in the conventional tillage treatment.

Soil nutrient changes

Initial nutrient contents in the fall of 1991 prior to the initiation of the conservation tillage treatments were 1.8, 125, 33, 777, 111, 33, and 3.2 kg ha^{-1} for N, P, K, Ca, Mg, Mn, and Zn, respectively, and the pH was 6.0. Long-term poultry litter addition effects on soil nutrients was assessed from soil samples collected annually during the cotton and corn phases (Schomberg et al. 2009a). Because poultry litter application was based on N requirements of cotton and corn (assuming 50% availability), P and K applications from poultry litter were 2.8 and 2 times greater than in the conventional fertilizer treatment, respectively, during the cotton phase, and averaged 14.1 and

Table 3 Particulate organic matter and various N fractions determined on soil samples collected in spring 2005 for the 0–15 cm depth (after Schomberg et al. 2009b)

Treatment	POMC (g kg^{-1})	POMN (mg kg^{-1})	NaOH (mg kg^{-1})	Anaerobic (mg kg^{-1})	Phosphate Borate (mg kg^{-1})	Hot KCl (mg kg^{-1})	Hydro-lyzable (mg kg^{-1})	Cold KCl (mg kg^{-1})	24 day N mineralization (mg kg^{-1})
CT-PL	4.7	340	150.8	72.2	34.1	19.6	16.2	6.8	32.0
NT-PL	6.9	430	175.0	56.6	33.0	21.8	16.6	9.5	41.0
CT-CF	3.4	183	158.5	23.7	29.8	13.3	10.0	1.1	14.1
NT-CF	6.2	379	168.1	31.7	30.4	16.0	13.0	1.3	21.8
STD	1.4	95	9.5	20.4	1.9	3.4	2.8	3.8	10.8

CT conventional tillage, *NT* no-till, *CF* conventional fertilizer, *PL* poultry litter, *STD* standard deviation, *POMC* particulate organic matter C, *POMN* particulate organic matter N, *NaOH* NaOH distillable N, *Anaerobic* N released during 7 day anaerobic incubation, *Phosphate borate* phosphate borate distillable N, *Hot KCl* NO_3 extractable with hot KCl, *Hydrolyzable* Hydrolyzable organic N, *Cold KCl* NO_3 extractable with room temperature KCl, *24 day N mineralization* the amount of N mineralized during a 24 day incubation

9.2 times greater, respectively, during the corn phase. Temporal changes in nutrient contents and soil pH were expected to be greater with poultry litter compared to conventional fertilizer and during the corn phase than in the cotton phase.

During the cotton phase, some soil nutrient contents (Ca, Mg, and K) were different between the poultry litter and conventional fertilizer treatments due to the different rates of application and different rates of leaching between tillage treatments. The amount of Ca, Mg, Mn and K was lower with no-till compared to conventional tillage probably due to greater infiltration and water movement with no-till as noted above (Endale et al. 2002a). Soil P was not influenced by tillage but was different between conventional fertilizer and poultry litter. In the conventional fertilizer treatment P decreased at the rate of 0.67 kg ha^{-1} $year^{-1}$ while in the poultry litter treatment P increased at the rate of 3.1 kg ha^{-1} $year^{-1}$ reflecting differences in nutrient inputs between the two sources (Schomberg et al. 2009a).

During the corn cropping phase annual nutrient inputs from poultry litter were about 3 times greater than in the cotton cropping phase and exceeded the crop nutrient demand. This resulted in significant nutrient accumulation in the soil (Table 4). For most nutrients found in poultry litter the accumulation was greater than what we saw for the conventional fertilizer treatment. Some crop uptake, movement deeper into the soil profile, and other reductions in availability are apparent from the data as indicated by the change in nutrient content relative to that input as poultry litter (Table 4). Comparing soil test nutrient contents from fall 2005 to those in fall 1996 indicated that Ca, K, Mg, P, and Zn increased by 1.6, 1.6, 1.4, 5.3, and 6.4 fold, respectively. The large increases for P and Zn may be of concern due to the agronomic and environmental implications of excess accumulation of these two elements (Sharpley et al. 1994; Jackson et al. 2003). Differences between tillage treatments were small during both the cotton and corn phases.

Table 4 Rate of accumulation of nutrients and change in soil nutrients relative to poultry litter nutrient input during the corn phase of research (after Schomberg et al. 2009a)

Soil nutrient/pH	CF (kg ha^{-1} $year^{-1}$)	PL (kg ha^{-1} $year^{-1}$)	Change relative to PL nutrient input (kg kg^{-1})[a]
Ca	50.9	182.6	0.44
K	12.3	17.4	0.04
Mg	4.0	21.4	0.26
P	2.5	65.7	0.23
Zn	0.7	6.2	0.89
pH	−0.2	0.04	

CF commercial fertilizer, *PL* poultry litter treatments

[a] There was no difference in response between tillage treatments so the data are averaged across tillage treatments

Changes in nutrient content below 15 cm were evaluated with soil samples from fall of 1997, 2000, and 2005 (Table 5). The 1997 samples were the earliest available for depths below 15 cm and were collected after 3 applications of poultry litter (totaling 13.4 Mg ha^{-1}). Samples from 2000 were collected at the end of the cotton phase after 6 applications of poultry litter (totaling 26.8 Mg ha^{-1}). Samples from 2005 were collected at the end of the corn phase after more than 110 Mg PL ha^{-1}. Differences in nutrient contents among sampling dates were present primarily for the 0- to 15-cm depth (previously discussed), but differences were also observed for some nutrients at lower depths.

In the 15- to 30-cm depth there were large differences among years for K, P and Zn with amounts being greater in 2005 following long-term poultry litter application. Similar changes were noted in the 30- to 45-cm depth. In CT, movement of K, P, and Zn was limited to the top 30 cm while in the no-till there was an indication of a potential for movement of P and K to greater depths. It is not surprising to find greater movement of K in these low CEC soils. Movement of P deeper into the profile is most likely through macropore flow in the no-till plots. Although concerns about losses of crop nutrients are often raised about use of poultry litter, reducing runoff losses appears to be the most effective area to target for protecting the environment (Jackson et al. 2003; EPA 2004).

Earthworm density and population

Lachnicht et al. (2008) tested a custom built electrical device for extracting and sampling earthworms without soil disturbance. They found greater numbers of earthworms during October (2002) and March (2003) when soil moisture was near optimal for earthworm activity. Generally earthworm populations showed a trend of NT-PL > NT-CF > CT-PL > CT-CF. The

Table 5 Soil nutrient content measured for 3 years at 15–30 and 30–45 cm in response to poultry litter inputs on the study plots under conventional tillage (CT) and no-till (NT) (after Schomberg et al. 2009a)

Depth/nutrient	CT (kg ha^{-1})			NT (kg ha^{-1})			MSD (kg ha^{-1})
	1997	2000	2005	1997	2000	2005	
15–30 cm							
Ca	953	770	782	678	620	674	276
K	174	183	347	165	200	277	76
Mg	171	145	153	113	114	125	41
Mn	113	84	121	81.6	63.3	95.2	49.5
P	10.1	9.2	30.4	10.2	11.7	75.7	22.3
Zn	3.3	3.3	4.8	3.5	3	5.9	2.6
30–45 cm							
Ca	792	527	571	697	576	595	NS
K	118	88	260	101	110	286	59.2
Mg	153	107	125	124	111	132	NS
Mn	22.5	14.9	23	22.9	12.7	15.5	NS
P	5.2	4.1	4.6	4.9	4.8	8.5	3.8
Zn	2.2	1.9	2.4	2.3	1.9	2.6	NS

MSD minimum significant difference based on 95% confidence limit, *NS* not significant

majority of earthworms sampled in no-till were *Lumbricus rubellus* and *Aporrectodea* spp. while in conventional tillage they were *Microscolex* spp. suggesting greater biomass and abundance under no-till. These findings, while limited in extent, are comparable to other investigations of earthworm populations and/or abundances in no-till and/or conventional tillage with organic or inorganic fertilizer source (Hendrix et al. 1992; Brown et al. 2003; Jordan et al. 2004; Reeleder et al. 2006).

Hydrology

Early data from the facility (1991–1994) demonstrated the time lag needed to establish effects of conservation tillage (McCracken et al. 1995). From summer 1992 to winter 1993, drainage from the plots showed no effect of the tillage treatments perhaps due to below normal rainfall and little to no tile drainage. Cover cropping did not influence total drainage but the impact of no-till on drainage was observed for the first time in winter 1993 (NT/CT $\sim$ 1.6). Summer of 1994 had above average rainfall and total drainage was significantly affected by tillage (NT/CT $\sim$ 1.5).

After 6 years of no-till and conventional tillage, subsurface drainage characteristics were quantified with data collected from 3 May 1997 to 9 May 1998 (Table 6; Endale et al. 2002a). The 67 rainfall events of approximately 6–120 mm and 30 drainage events produced 41 distinguishable drainage hydrographs (occasionally more than one per event due to varying rainfall intensities during an event). No-till plots regularly had two to three times more total drainage and mean and peak drainage rates, and approximately 1.3 times greater total drainage time, compared to conventional tillage plots. The ratio NT/CT for total drainage and mean and peak drainage rate was greater than 1.0 for >85% of the events. The amount of total rainfall partitioned into drainage was 12.5% in conventional tillage and 27.6% in no-till. Drainage period varied from 4 to 80 h in conventional tillage and 16–87 h in no-till. The recession time constant (RTC) of the hydrographs, an index of the structural macropore development in the soil above the tile drains (Young 1985), was significantly less in no-till than conventional tillage, indicating no-till had less tortuous water flow paths. The RTC NT/CT ratio was less than 1.0 in about 80% of the events analyzed. No-till, therefore, enhanced water movement into deeper profiles. This means on one hand that soil water conservation and plant water availability is enhanced but on the other hand nutrient leaching to

Table 6 Descriptive statistics for rainfall and drainage characteristics given as ratio of no-till (NT) to conventional tillage (CT) for events that occurred 3 May 1997 to 9 May 1998 (after Endale et al. 2002a)

Parameter	Descriptive statistics					
	Mean	SE	Median	Min	Max	*n*
Rainfall						
Amount (mm)	32.5	3.8	23.4	4.5	121.3	41
Duration (h)	13.5	1.8	10.0	2.0	49.0	41
Average intensity (mm/h)	3.5	0.5	2.6	0.5	14.3	41
Maximum intensity (mm/h)	10.5	0.9	8.5	1.9	29.3	41
Drainage (NT/CT ratio)						
Total drainage	2.8	0.3	2.5	0.6	6.9	30
Total hour of drainage	1.3	0.1	1.1	1.0	4.0	30
Mean drainage rate (mm/h)	2.2	0.1	2.2	0.3	4.1	49
Peak drainage rate (mm/h)	3.0	0.3	3.0	0.3	7.5	40
Recession time constant	0.9	0.04	0.8	0.6	1.6	31

lower soil profile is a possibility. Tile drainage is not a normal practice in this area and water that exited the plots through tile drainage probably would have been available for crops in soils where there was not tile drainage.

Water quality

Leached NO_3-N measurements from 1991 through 1994 illustrate two important issues for good N management (McCracken et al. 1995). First, cover crops are effective in reducing NO_3-N losses to subsurface drainage. In winter 1991, tile drainage concentrations and total loads were lower under rye (8.7 mg l^{-1} and 3.4 kg ha^{-1}) compared to fallow (22.7 mg l^{-1} and 12.2 kg ha^{-1}). Overall during 1991–1994, rye cover crop consistently limited NO_3-N leaching losses during winter. Second, summer crop growth and associated N uptake directly impacts N availability during the subsequent winter period. For example, winter of 1992 leachate had lower NO_3-N concentrations than winter 1991 attributed to better corn growth and associated greater N uptake in summer 1991 than in summer 1990. Additionally, no-till had less NO_3-N leaving the plots than conventional tillage (NT 4.5 mg l^{-1} and 14.6 kg ha^{-1}; CT 6.2 mg l^{-1} and 18.0 kg ha^{-1}) which correlated with the greater growth and yield of previous corn in the no-till plots. In 1993, a very dry year, corn productivity was poor and N uptake was reduced, which resulted in higher NO_3-N concentrations in subsurface water the following winter (1993–1994). Even with the poor corn growth, NO_3-N concentration was less in no-till than conventional tillage while N load was similar between no-till and conventional tillage (NT 13.6 mg l^{-1} and 15.2 kg ha^{-1}; CT 20.3 mg l^{-1} and 14.3 kg ha^{-1}).

Losses of NH_4-N, NO_3-N, PO_4-P, and sediment in runoff and drainage quantified from 29 storms from April 1997 to July 1998 showed a high degree of variability within treatments which reduced our ability to detect differences among treatments (Endale et al. 2001, 2004; Table 7). Storm characteristics, antecedent moisture and crop stage contributed to the variability. Neither no-till nor poultry litter appear to have influenced inorganic N concentrations in runoff during this period (Table 7). Runoff with conventional tillage averaged 2.6 times greater than with no-till during this period leading to a greater NH_4-N load for conventional tillage compared to NT. The NO_3-N load was lowest for NT-PL (Table 7). The concentration of PO_4-P in runoff was elevated for no-till (NT: 0.97–1.75 mg l^{-1}; CT: $<$0.51 mg l^{-1}) but the mean load was variable across treatments. Subsurface drainage (reported above) was greater with no-till (2.6 times CT). In drainage during this period, neither no-till nor poultry litter appeared to have influenced average inorganic N concentrations or loads and NO_3-N concentration in drainage was close to the accepted maximum drinking water standard of 10 mg l^{-1} in all treatments (Table 7). Mean load of NH_4-N, NO_3-N, and PO_4-P in drainage was similar across the treatments.

Vencill et al. (1999) reported herbicide runoff and leaching from cotton for 1997. Fluometuron, a commonly substituted-urea broadleaf herbicide in cotton with moderate solubility, was detected in surface runoff and leachate for approximately 40 days after application. In runoff, no-till and poultry litter treatments generally had greater concentration than conventional tillage and conventional fertilizer, respectively. No difference was detected in leachate among treatments. The desmethyl metabolite was identified in all water

Table 7 Losses of ammonium, nitrate and ortho-P in runoff and drainage from 29 storms during April 1997 to July 1998

Parameter	Treatment	Runoff		Drainage	
		Concentration (mg l^{-1})	Load (kg ha^{-1})	Concentration (mg l^{-1})	Load (kg ha^{-1})
NH_4-N					
	CT-CF	0.63 ± 0.12	0.042 ± 0.011	0.15 ± 0.03	0.004 ± 0.001
	CT-PL	0.67 ± 0.09	0.031 ± 0.007	0.27 ± 0.12	0.008 ± 0.004
	NT-CF	0.52 ± 0.08	0.009 ± 0.003	0.26 ± 0.12	0.008 ± 0.002
	NT-PL	0.78 ± 0.11	0.015 ± 0.004	0.25 ± 0.09	0.008 ± 0.002
NO_3-N					
	CT-CF	1.75 ± 0.35	0.064 ± 0.013	10.38 ± 1.31	0.772 ± 0.146
	CT-PL	1.95 ± 0.30	0.064 ± 0.012	11.82 ± 1.30	1.236 ± 0.269
	NT-CF	2.17 ± 0.42	0.051 ± 0.020	8.44 ± 0.80	1.305 ± 0.312
	NT-PL	2.19 ± 0.30	0.027 ± 0.006	9.09 ± 0.85	1.283 ± 0.201
PO_4-P					
	CT-CF	0.27 ± 0.05	0.010 ± 0.002	0.08 ± 0.01	0.012 ± 0.004
	CT-PL	0.50 ± 0.16	0.038 ± 0.027	0.11 ± 0.02	0.016 ± 0.004
	NT-CF	0.97 ± 0.19	0.021 ± 0.010	0.11 ± 0.02	0.020 ± 0.006
	NT-PL	1.75 ± 0.32	0.018 ± 0.004	0.11 ± 0.02	0.020 ± 0.005

Values are means followed by standard errors (after Endale et al. 2004)

CT conventional tillage, *NT* no-till, *CF* conventional fertilizer, *PL* poultry litter

samples containing fluometuron. Pendimethalin, a dinitroaniline herbicide of low solubility soil applied for control of annual grass and broadleaf weeds on about 30% of cotton in the US was not detected in surface runoff or leachate. Due to the dry conditions no additional analyses were performed.

A growing concern about the presence of the naturally occurring gender regulating hormones 17β-estradiol and testosterone in poultry feces and poultry litter led to an evaluation of presence in the soils and runoff from the research area in the fall of 2001 and spring of 2002 (Jenkins et al. 2009).These hormones have endocrine disrupting properties which could have a potential negative impact on ecological and public health. Concentrations of these hormones in poultry litter range between 14 and 65 µg kg^{-1} and 0.1 and 133 µg kg^{-1} dry weight litter, respectively, (Jenkins et al. 2008). Sprinkler irrigation was applied to the plots to create sufficient runoff and drainage. Both estradiol and testosterone were detected in subsurface drainage and overland runoff in 2001 and 2002 but there were no differences in flow-weighted concentrations between fertilizer and tillage treatments. Flow-weighted concentrations of estradiol ranged between 12.8 and 78.5 ng l^{-1} in 2001 and between 8.0 and 18.0 ng l^{-1} in 2002. Flow-weighted concentrations of testosterone ranged between 7.4 and 9.9 ng l^{-1} in 2001 and between 6.0 and 12.3 ng l^{-1} in 2002. In 2001 the loads of estradiol and testosterone in runoff were significantly less for the no-till treatments than the conventional tillage treatments reflecting the difference in runoff volume between the tillage treatments. No difference in runoff load, however, was observed between fertilizer treatments.

In the spring of 2004 and 2005 rainfall simulation experiments were undertaken on a portion of each plots to quantify under more controlled conditions the impact of tillage systems on the transport of bacterial pathogens and hormones from poultry litter (Jenkins et al. 2008). The simulations applied a constant rain intensity in 2004 and variable rain intensity in 2005 that simulated natural spring rain events in the Southern Piedmont. The total rainfall volume for each rainfall simulation was similar. The rates of litter application and loads of fecal indicator bacteria (*E. coli* and fecal enterococci), pathogens [*Salmonella*, *Campylobacter*, and *Clostricium perfringens*(*C. perfringens*)], and the hormones estradiol and testosterone are listed in Table 8. Neither *Salmonella*, *Campylobacter*, nor antimicrobial residues of

Table 8 Rates of poultry litter (PL) (dry weight basis), total load of *E. coli* (Ec), fecal enterococci (FE), *Salmonella* (Salmon), *Campylobacter* (Campy), *C. perfringens* (Cp), estradiol, testosterone applied to experimental plots for the 2004 constant intensity rainfall experiment and the 2005 variable intensity rainfall experiment (after Jenkins et al. 2008)

Experiment	Litter (kg ha^{-1})	Ec (log_{10} MPN ha^{-1})	FE (log_{10} MPN ha^{-1})	Salmon (log_{10} cells ha^{-1})	Campy (log_{10} cells ha^{-1})	Cp (log_{10} cells ha^{-1})	Estradiol (mg ha^{-1})	Testosterone (mg ha^{-1})
2004	11.2	11.6	12.4	ND	ND	10.8	21.0	8.4
2005	11.2	10.7	11.8	ND	ND	9.4	9.1	1.4

ND not detected

β-Lactams, Tetracyclines, Sulfonamides, and Macrolides were detected in either batch of broiler litter.

Runoff volume was greater in conventional tillage than in no-till for the constant intensity rainfall simulation (176.3 vs. 35.6 l, respectively; a ratio of $\sim$5), but was not different for the variable intensity rainfall simulation. Application of poultry litter increased the soil concentrations of the indicator bacterium *E. coli* only during the constant intensity rainfall simulation. Mean concentration for conventional fertilizer was 3 log_{10} most probable number (MPN) kg^{-1} soil, and for poultry litter the mean concentration was between 7 and 8 log_{10} MPN kg^{-1} soil. No differences were observed between tillage and fertilizer treatments in flow-weighted concentrations of *E. coli*, fecal enterococci, *C. perfringens*, and estradiol for either of the rainfall simulations. Flow-weighted concentrations of *E. coli* ranged between −0.3 and 3.7 log_{10} MPN 100 ml^{-1}; for fecal enterococci the range was between 2.3 and 5.5 log_{10} MPN 100 ml^{-1}; for *C. perfringens* the range was between 2.7 and 3.1 cfu l^{-1}; and for estradiol the range was between 6.0 and 145 ng l^{-1}.

Although the flow-weighted concentrations of testosterone from the constant intensity rainfall simulation were just above detection limits, no-till with poultry litter (NT-PL) had significantly greater concentration than the other tillage and fertilization treatments at 8.3 ng l^{-1}. Flow-weighted concentrations of testosterone from the variable intensity rainfall simulation were significantly greater for NT-PL (126.6 ng l^{-1}) than for CT-PL (20.4 ng l^{-1}). Background concentrations in the inorganic fertilizer plots for both rainfall simulations ranged between 4 and 10.9 ng l^{-1}. Results for total load of testosterone in the runoff for the variable intensity rainfall simulation paralleled the results of the flow-weighted concentrations (NT-PL 39.3 vs. CT-PL 7.7 mg ha^{-1}). Background runoff loads of testosterone for the inorganic fertilizer plots ranged between 1.1 and 1.2 mg ha^{-1}.

Significant correlation coefficients were observed between the total runoff load of estradiol and testosterone and the total volume of runoff for the constant intensity rainfall simulation (Jenkins et al. 2008) perhaps due to the 2- and 6-times, respectively, greater total load of estradiol and testosterone for the constant rainfall simulation compared to the variable rainfall simulation. A significant correlation coefficient was observed between the total runoff load of fecal enterococci and the total runoff volume for the variable intensity rainfall simulation. Since the total load of fecal enterococci was similar for each rainfall simulation, the difference in correlation results may reflect a fundamental difference in characteristics between the two types of rainfall simulations.

Soil microbial community structure

Phospholipid fatty acid (PLFA) analysis and sequence analysis of 16S rRNA gene libraries indicated soil microbial communities had responded differently to long-term (14 years) applications of poultry litter and inorganic fertilizer (Jangid et al. 2008). Based on the PLFA analysis, soils receiving poultry litter had a greater soil microbial biomass C and a greater mass of phospholipid fatty acids than soil amended with inorganic fertilizer. The PLFA composition of the soil microbial community differed between the two treatments. The sequenced 16S rRNA genes also indicated greater diversity and species richness in soil amended with the poultry litter treatment compared to the inorganic fertilizer. The composition of *Acidobacteria*, *Bacteroidetes*, and α-, β-, δ-, γ-*Proteobacteria* differed significantly between the two nutrient sources, while no differences were observed for the composition of the *Firmicutes* and *Planctomycetes*. The abundance of the *Acidobacteria* and *γ-Proteobacteria* were lower with poultry litter compared to CF. Seasonal (summer, winter) differences in community composition were observed only in the soil amended with inorganic fertilizer, and microbial diversity was lower in summer than in winter. None of the operational taxonomic units identified were closely related to poultry litter-associated bacteria. These findings help improve our understanding of specific changes in soil microbial communities in response to long-term agricultural management practices.

Discussion and conclusions

Crop productivity and environmental benefits of adopting conservation tillage have been well established on many soil types and for many cropping systems over the past three to four decades (CTIC 2001; Schnepf and Cox 2006; FAO 2008). Our research has provided additional insight about changes in physical, chemical and biological soil properties as the result of tillage, cover crop, and fertilizer management. We observed that changes in physical and/or biological properties influencing hydrologic properties required 2–3 years of conservation tillage to became evident (i.e. fall 1991 to winter 1993 for drainage characteristics). Hargrove et al. (1982) reported similar results for a hapludult soil similar to this one in the southeastern USA. Some of this change is related to development of additional flow paths or the absence of crusting as the result of addition of surface residue and of the absence of soil disturbance in conservation tillage systems.

Macropore development after 6 years of no-till was evident at our site as indicated by significantly lower recession time constants compared to conventional tillage in observed drainage hydrographs. These drainage recession time constants give an index of the structural macropore development in the soil above the tile drains (Young 1985). In addition, we documented evidence of earthworm activity in the no-till plots. Over time, establishment of macropores in the Ap and BA horizons with no-till enhances water movement (Golabi et al. 1995). Increasing water availability is the key to enhancing crop productivity in Cecil soils (Bruce et al. 1997). Addition of crop residues with a cover crop is critical for increasing organic matter at the soil surface and use of no-till is critical for development of macropores in upper soil layers thus allowing more water to infiltrate during intense rain storms.

Poultry litter alone and in combination with no-till greatly enhanced corn and cotton production. Some of this effect is due to the slow release of nutrients from poultry litter creating greater synchrony with crop nutrient needs. Application of poultry litter based on N requirements resulted in significant accumulation of nutrients compared to the conventional fertilizer treatment. During the 5 years of the cotton phase, excess accumulation of nutrients was avoided. However, levels of P, Zn, and Cu, from poultry litter became unacceptable during the corn cropping phase due to the long history of application along with the greater rates of application. Since the late 1990s, most southeastern states have adopted P-based nutrient management for animal manures on agricultural lands. Our results support this approach to limit environmental risk from P and other nutrients added to the soil. Proper P management with poultry litter use is critical to retain use of this valuable nutrient source on the more than 22.4 million ha of crop and forage land in the southeast.

Nutrient source had a greater effect on microbial community diversity and abundance over time than tillage management. Greater microbial diversity and abundance with poultry litter compared to conventional fertilizer most likely reflects increases in labile C and inorganic N (Franzluebbers et al. 2004). As noted above, poultry litter increased crop productivity which, in turn, would increase the organic matter returned to the soil compared to the conventional fertilizer applications. Greater microbial diversity and abundance (biomass) is indicative of soil quality factors important to nutrient cycling and disease reduction in agricultural systems (Doran and Parkin 1994).

Frequent short term (few weeks or more) and less frequent longer term drought is part of the weather cycle in the southeastern USA. This weather variability has to be taken into account in environmental risk assessment. Although drought at times limited our ability to meet immediate research objectives, the data collected under ambient environmental conditions provides realistic data for calibration and testing of agrohydrologic models. The data can also be coupled with other studies investigating temporal and spatial ecosystem dynamics across regions. Data generated from the Watkinsville facility were used to evaluate the LEACHN (Johnson et al. 1999) and RZWQM (Abrahamson et al. 2006) models for estimating tile drainage and nitrate leaching from Cecil soils.

Water quality studies often rely on artificially generated high intensity rain applied to small plots over a short period (±1 h for example). This has been justified based on a few (extreme) rain storms generally accounting for large amounts of off site pollutant loads (generally true for sediments). Processes like fate and transport of pollutants are often scale dependent and results from small plots are difficult to scale up to larger areas. Our two different scale studies [irrigation (Jenkins et al. 2009) and rain simulation (Jenkins et al. 2008)] both indicated that poultry litter applications at rates commensurate with the nutrient requirement of rye and corn had minimal impact on the quality of drainage and runoff and surface waters in general for the assessed parameters. The soil and flow-weighted concentrations of estradiol, testosterone, and fecal indicator bacteria were not above background concentrations (in both irrigation and rain-simulation experiments) and were comparable to background concentrations that Jenkins et al. (2006), Finlay-Moore et al. (2000), and Nichols et al. (1997) have reported. Results of these two different plot-scale hydrologic transport experiments were similar to results from a-close-by catchment-scale study under actual rainfall conditions (Jenkins et al. 2006) demonstrating that the two approaches were appropriate to evaluate the risk of contaminant transport in agricultural systems.

Results from these several studies taken as a whole demonstrate the considerable value of conducting long-term research on plots instrumented for monitoring hydrologic variables. Future results on fate and transport of microorganisms from poultry litter or changes in microbial diversity with different sources of nutrients were not envisioned as outcomes when the plots were first established to quantify tillage and cover crop effects on N losses. Long-term facilities must be maintained to help answer emerging questions about the role of agriculture in C sequestration, global warming, and questions not even asked at this point.

Acknowledgments This type of experimental facility requires a significant investment of time and funds to meet the research and maintenance demands. A dedicated team of technical support is critical for maintaining instrumentation as well as data collection, processing and checking. Over the years several scientists technical support staff and students have contributed time, effort, and talent toward the various studies carried out at this research facility. While too many to list here, they should know that we are grateful to all of them. We also acknowledge the generous financial support from CSREES-NRI sources as well as base funding from USDA and University of Georgia. Mention of trademark, proprietary product or vendor does not constitute a guarantee or warranty of the product by the USDA and does not imply approval to the exclusion of other products or vendors that also may be suitable.

References

Abrahamson DA, Radcliffe DE, Steiner JL, Cabrera ML, Endale DM, Hoogenboom G (2006) Evaluation of the RZWQM for simulating tile drainage and leached nitrate in the Georgia Piedmont. Agron J 98:644–654

Allmaras RR, Schomberg HH, Douglas CL Jr, Dao TH (2000) Soil organic carbon sequestration potential of adopting conservation tillage in U.S croplands. J Soil Water Conserv 55:365–373

Brown GG, Benito NP, Pasini A, Sautter KD, Guimaraes MDF, Torres E (2003) No-tillage greatly increases earthworm populations in Parana state, Brazil. Pedobiologia 47(5–6): 764–771

Bruce RR, Langdale GW (1997) Soil carbon level dependence upon crop cultural variables in a Themic-Udic region. In: Paul EA, Paustian K, Elliot ET, Cole CV (eds) Soil organic matter in temperate agroecosystems. Long term experiments in North America. Lewis, Ann Arbor, MI

Bruce RR, Dane JH, Quisenberry VL, Powell NL, Thomas AW (1983) Physical characteristic of soils in the southern region: Cecil. Southern Coop Series Bull No 267. University of Georgia, Athens, GA

CAES (College of Agriculture and Environmental Sciences) (2007) Poultry litter application on pastures and hayfields. Bull 1330. University of Georgia, College of Agric and Environ Sci, Coop Ext Serv, Athens, GA

CTIC (Conservation Technology Information Center) (2001) Better soil better yields. A guide to improving soil organic matter and infiltration with continuous no-till. Conservation Technology Information Center, Purdue University, West Lafayette, IN

CTIC (Conservation Technology Information Center) (2009) 2008 National crop residue management survey. Conservation Technology Information Center, Purdue University, West Lafayette, IN. http://www.crmsurvey.org (validated 4 Sep 2009)

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA (eds) Defining soil quality for a sustainable environment. SSSA Spec. Pub. No. 35. Soil Science Society of America, Madison, WI, pp 3–21

Endale DM, Schomberg HH, Steiner JL (2000) Long term sediment yield and mitigation in a small Southern Piedmont watershed. Intern J Sediment Res 15(1):60–68

Endale DM, Cabrera ML, Radcliffe DE, Steiner JL (2001) Nitrogen and phosphorus losses from no-till cotton fertilized with poultry litter in the Southern Piedmont. In: Hatcher KJ (ed) Proceedings of the 2001 Georgia Water Resources Conference, 26–27 March 2001, Athens, Georgia. Institute of Ecology, University of Georgia, Athens, GA, pp 408–411

Endale DM, Radcliffe DE, Steiner JL, Cabrera ML (2002a) 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 DM, Cabrera ML, Steiner JL, Radcliffe DE, Vencill WK, Schomberg HH, Lohr L (2002b) 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 DM, Schomberg HH, Cabrera ML, Steiner JL, Radcliffe DE, Vencill WK, Lohr L (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. In: van Santen E (ed) Making conservation tillage conventional: building a future on 25 years of research. Proceedings of 25th annual Southern conservation tillage conference for sustainable agriculture, Auburn, AL, 24–26 June 2002, pp 115–122

Endale DM, Schomberg HH, Radcliffe DE, Jenkins M, Cabrera ML (2004) No-till on Cecil soil: Hydrologic and water quality impacts. Agronomy Abstracts 2004. American Society of Agronomy, Madison, WI

Endale DM, Schomberg HH, Fisher DS, Jenkins MB, Cabrera ML (2008) Corn production in no-till amended with poultry litter in an Ultisol of southeastern USA. Agron J 100:1401–1408

EPA (2004) Managing manure nutrients at concentrated animal feeding operations. EPA 821-F-04–011. Office of Water (4503-T). U.S. Environmental Protection Agency, Washington, DC

FAO (2008) Conservation agriculture. Food and Agricultural Organization of the United States. http://www.fao.org/ag/ca/index.html (validated 4 Sep 2009)

Finlay-Moore O, Hartel PG, Cabrera ML (2000) 17β-estradiol and testosterone in soil and runoff from grasslands amended with broiler litter. J Environ Qual 29:1604–1611

Franklin DH, West LT, Radcliffe DE, Hendrix PF (2007) Characteristics and genesis of preferential flow paths in a Piedmont Ultisol. Soil Sci Soc Am J 71(3):752–758

Franzluebbers AJ, Wilkinson SR, Stuedemann JA (2004) Bermudagrass management in the Southern Piedmont, USA: IX. Trace elements in soil with broiler litter application. J Environ Qual 33:778–784

Golabi MH, Radcliffe DE, Hargrove WL, Tollner EW (1995) Macropore effects in conventional tillage and no-tillage soils. J Soil Water Conserv 50(2):205–210

Gupte SM, Radcliffe DE, Franklin DH, West LT, Tollner EW, Hendrix PE (1996) Anion transport in a Piedmont Ultisol: II. Local-scale parameters. Soil Sci Soc Am J 60:755–761

Hargrove WL, Reid JT, Touchton JT, Gallaher RN (1982) Influences of tillage practices on the fertility status of an acid soil double-cropped to wheat and soybean. Agron J 74:684–687

Hendrix PF, Mueller BR, Bruce RR, Langdale GW, Parmelee RW (1992) Abundance and distribution of earthworms in relation to landscape factors on the Georgia Piedmont. U S A Soil Biol Biochem 24:1357–1361

Jackson BP, Bertsch PM, Cabrera ML, Camberato JJ, Seaman JC, Wood CW (2003) Trace element speciation in poultry litter. J Environ Qual 32:535–540

Jangid K, Williams MA, Franzluebbers AJ, Sanderlin JS, Reeves JH, Jenkins MB, Endale DM, Coleman DC, Whitman WB (2008) Relative impacts of land-use, management intensity and fertilization upon soil microbial community structure in agricultural systems. Soil Biol Biochem 40:2843–2853

Jeffrey JS, Kirk JH, Atwill ER, Cullor JS (1998) Prevalence of selected microbial pathogens in processed poultry waste used as dairy cattle feed. Poult Sci 77:808–811

Jenkins MB, Endale DM, Schomberg HH, Sharpe RR (2006) Fecal bacteria and sex hormones in soil and runoff from cropped watersheds amended with poultry litter. Sci Total Environ 358:164–177

Jenkins MB, Truman CC, Siragusa G, Line E, Bailey JS, Frye J, Endale DM, Franklin DH, Schomberg HH, Fisher DS, Sharpe RR (2008) Rainfall and tillage effects on transport of fecal bacteria and sex hormones 17β-estradiol and testosterone from broiler litter applications to a Georgia Piedmont Ultisol. Sci Total Environ 403:154–163

Jenkins MB, Endale DM, Schomberg HH, Hartel PG, Cabrera ML (2009) 17β-estradiol and testosterone in drainage and runoff from poultry litter applications to tilled and no-till crop land under irrigation. J Environ Manage 90:2659–2664

Johnson AD, Cabrera ML, McCracken DV, Radcliffe DE (1999) LEACHN simulations of nitrogen dynamics and water drainage in an Ultisol. Agron J 91:595–606

Jordan D, Miles RJ, Hubbard VC, Lrenz T (2004) Effect of management practices and cropping systems on earthworm abundance and microbial activity in Sanborn Field: a 115-year-old agricultural field. Pedobiologia 48:99–110

Kelley TR, Pancorbo OC, Merka WC, Thompson SA, Cabrera ML, Barnhart HM (1994) Fate of selected bacterial pathogens and indicators in fractionated poultry litter during storage. J Appl Poult Res 3:279–288

Kingery WL, Wood CW, Delaney DP, Williams JC, Mullins GL (1994) Impact of long-term land application of broiler litter on environmentally related soil properties. J Environ Qual 23:139–147

Lachnicht WS, Schomberg HH, Hendrix PF, Spokas KA, Endale DM (2008) Construction of and electrical device for sampling earthworm populations in the field. Appl Eng Agric 24:391–397

Lal R (2002) Carbon sequestration in dryland ecosystems of West Asia and North Africa. Land Degrad Dev 13:45–59. doi:10.1002/ldr.477

Langdale GW, West LT, Bruce RR, Miller WP, Thomas AW (1992) Restoration of eroded soil with conservation tillage. Soil Technol 5(1):81–90

McCracken DV, Hargrove WL, Box Jr JE, Cabrera ML, Johnson JW, Reymer PL, Harbers GW, Johnson AD (1993) Influence of tillage and cover cropping on nitrate

leaching. In: Bollich PK (ed) Proceedings of Southern conservation tillage conference for sustainable agriculture, Monroe Louisiana 15–17 June 1993. Louisiana Agric Exp Stn 93-86-7122, Louisiana State University, Baton Rouge, LA, pp 11–15
McCracken DV, Box JE Jr, Hargrove WL, Cabrera ML, Johnson JW, Reymer PL, Johnson AD, Harbers GW (1995) Nitrate leaching as affected by tillage and winter cover crop. In: Kingrey WL, Buehring N (eds) Proc Southern Conserv Tillage Conf for Sustainable Agric, Jackson Mississippi 26–28 June 1995. Mississippi Agric and Forest Exp Stn Spec Bull 88–7. Mississippi State University, MS, pp 26–31
Moor PA Jr, Daniel TC, Sharpley AN, Wood CW (1995) Poultry manure management: environmentally sound options. J Soil Water Conserv 50:321–327
NASS (National Agricultural Statistics Service) (2009) Poultry. Production and value. 2008 summary. NASS, Washington, DC
Nichols DJ, Daniel TC, Moore PA, Edwards DR, Pote PH (1997) Runoff of estrogen hormone 17β-estradiol from poultry litter applied to pasture. J Environ Qual 26:1002–1006
NRCS (National Resource Conservation Service) (1998) MLRA 136—Southern Piedmont. USDA-NRCS MO15, Washington, DC
Pieri C, Evers G, Landers J, O'Connell P, Terry E (2002) No-till farming for sustainable rural farming. Agriculture and rural development working paper. The International Bank for Reconstruction and Development, Washington, DC
Radcliffe DE, West LT (2000) MLRA 136: Southern Piedmont, Southern Coop Series Bulletin #395. University of Georgia, Athens, GA
Radcliffe DE, Tillotson PM, Hendrix PE, West LT, Box JE Jr, Tollner EW (1996) Anion transport in a Piedmont Ultisol: I. Field-scale parameters. Soil Sci Soc Am J 60(3):755–761
Reeleder RD, Miller JJ, Coelho BRB, Roy RC (2006) Impacts of tillage, cover crop, and nitrogen on populations of earthworms, microarthropods, and soil fungi in a cultivated fragile soil. Appl Soil Ecol 33(3):243–257
Reeves DW (1997) The role of soil organic matter in maintaining soil quality in continuous cropping system. Soil Tillage Res 43:131–167
Ritz CW, Merka WC (2004) Maximizing poultry manure use through nutrient management planning. Bulletin 1245, Georgia Coop Ext Service, College of Agriculture and Environ Sci. University of Georgia, Athens, GA
Schomberg HH, Lewis L, Tillman G, Olson D, Timper P, Wauchope D, Phatak S, Jay M (2003) Conceptual model for sustainable cropping systems in the Southeast: cotton systems. J Crop Prod 8:307–327
Schomberg HH, Endale DM, Jenkins MB, Sharpe RR, Fisher DS, Cabrera ML, McCracken DV (2009a) Soil test nutrient changes induced by poultry litter under conventional tillage and no-tillage. Soil Sci Soc Am J 73:154–163
Schomberg HH, Wietholter S, Griffin TS, Reeves DW, Cabrera ML, Fisher DS, Endale DM, Novak JM, Balkcom KS, Raper RL, Kitchen NR, Locke MA, Potter KN, Schwartz RC, Truman CC, Tyler DD (2009b) Assessing indices for predicting potential nitrogen mineralization in soils under different management systems. Soil Sci Soc Am J 73:1575–1586
Schnepf M, Cox C (eds) (2006) Environmental benefits of conservation on cropland. The status of our knowledge. Soil and Water Conservation Society, Ankeny, IA
Sharpley AN, Smith SJ, Bain WR (1993) Nitrogen and phosphorus fate from long-term poultry litter application to Oklahoma soils. Soil Sci Soc Am J 57:1131–1137
Sharpley AN, Chupru SC, Wedenphol R, Sims JT, Daniel TC, Reddy KR (1994) Managing agricultural phosphorus for protection of surface water issues and options. J Environ Qual 23:437–451
Stephenson AH, McCaskey TA, Ruffin BG (1990) A survey of broiler litter composition and value as a potential nutrient resource. Biol Waste 34:1–9
Trimble SW (1974) Man induced soil erosion on the Southern Piedmont, 1770–1970. Soil and Water Conservation Society of America, Ankeny, IA
Vencill WK, Radcliffe DE, Cabrera ML, Endale DM, Steiner JL, Schomberg HH, Lohr L (1999) Herbicide surface runoff and leaching from a cotton-rye cropping system under contrasting tillage and nutrient management levels. In: The 1999 Brighton conference—weeds. Proceedings of international conference held at the Brighton, Metropole Hotel, Brighton, UK, 15–18 Nov 1999. British Crop Protection Council, pp 663–668
Young EG (1985) Characterization of hydrograph recession of land drains. J Hydrol 82(1–2):17–25