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Poultry Litter Fertilization Impacts on Soil, Plant, and Water Characteristics in Loblolly Pine (*Pinus taeda* L.) Plantations and Silvopastures in the Mid-South USA

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1. Introduction

Increasing global human populations and wealth have resulted in increased demands for animal protein and widespread use of confined animal feeding operations to meet added animal protein consumptive demands. Disposal of animal wastes from these operations can be ecologically and environmentally problematic (Kellogg et al., 2000; Roberts et al., 2004; Shober & Sims, 2003). Poultry production is an important source of this protein and is a major agricultural industry in the United States. The United States is the world's largest producer and second largest exporter of poultry meat (UDSA Economic Research Service, 2009). Four-fifths of the United States poultry industry is comprised of broiler meat production. Broiler meat production is largely concentrated in Southeastern states (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas and Virginia), with 82% of U.S. broiler production occurring in these states (National Agricultural Statistic Service, 2008).

Broiler production results in the generation of massive amounts of litter, a mixture of feces, feed, feathers and bedding materials such as straw, peanut or rice hulls, and wood shavings (Gupta et al., 1997; Weaver, 1998). The U.S.A. poultry industry produces more than 11 million Mg of litter per year (Cabrera & Sims, 2000). Broiler poultry litter contains several plant macro- and micronutrients (Table 1), which makes it desirable as an agricultural fertilizer (Sistani et al., 2008). Following removal from poultry production facilities, litter is commonly applied to nearby pastures, hay meadows, and agricultural crops such as corn and cotton to increase crop production and quality (Harmel et al., 2004; Sims & Wolf, 1994). Applications of poultry litter ranging from 4.5 to 11.2 Mg ha^{-1} yr^{-1} are common to supplement or replace inorganic annual fertilizer additions to pastures (Adams et al., 1994). Thus, poultry litter application is an efficient and potentially cost-effective method for improving forage production within the vicinity of production facilities, which helps to sustain non-poultry related agriculture economies in poultry producing regions. Substitution of broiler litter for inorganic fertilizers continues to increase in the southeastern U.S.A. as prices of inorganic fertilizers escalate (Funderberg, 2009).

Element	Nutrient Concentration	
	(g kg^{-1})	(mg kg^{-1})
C	280-320	
N	31-49	
P	4-13	
K	2-28	
Ca	2-28	
Mg	0.4-6	
Fe		1950-2395
Mn		277-424
Cu		263-332
Zn		252-404
B		45-55

Table 1. Ranges of reported nutrient concentrations in broiler poultry litter on an oven-dry basis. Adapted from Eichhorn, 2001; Ekinci et al., 2000; Kingery et al., 1994; Mitchell & Donald, 1995; Pote et al., 2003; Sauer et al., 2000; Sims, 1986; Williams et al., 1999

Poorly planned, excessive, or long-term applications of broiler litter to pastures and other agroecosystems can result in excessive nutrient losses, reductions in surface water quality, and potential risks to human health. Poultry litter is typically applied as a nitrogen fertilizer, but N availability from litter is relatively difficult to predict because only one-third of the N in litter is in exchangeable forms such as NH_4-N and NO_3-N. Two-thirds of N in litter is in organic form, which must be mineralized before it is plant available. Mineralization of N in litter varies from 40 to 90% with edaphic and environmental conditions, particularly conditions at the time of litter application (Mitchell & Donald, 1995). Gaseous losses of N from litter via volatilization can vary from 5 to 20% of total N, which reduces the amount of N available for plant use (Mitchell & Donald, 1995). While the amounts and forms of N in litter can vary considerably, those of other nutrients, particularly P, are relatively stable. As a result, if litter is applied at rates that supply sufficient N to meet crop demand soils can become saturated with P as well as K, Ca, Mg, Cd, Cu, Mn, and Zn (Edmeades, 2003; Kingery et al., 1994). Surface water runoff or soil water leaching associated with these nutrient-saturated soils can reduce water quality in watersheds (Friend et al., 2006; Gallimore et al., 1999; Gaston et al., 2003; Kellogg et al., 2000; Sauer et al., 1999; Sims & Wolf, 1994). Excess nutrients are transported to surface waters via runoff either in particulate forms or sorbed to soil particles which are suspended in surface runoff. Soluble P and C, NO_3-N, NH_4-N, and some organic N species have been demonstrated to be transported by runoff as a solution. NH_4-N and P are often sorbed to soil particles and conveyed by runoff through erosion, and organic C, P, and N have been shown to be moved by runoff in particulate form (Edwards & Daniel, 1992). Repeated applications of poultry litter can lead to accumulations of N and P in soil as well as elevated levels of one or both of these nutrients in surface runoff and subsurface water (McLeod and Hegg, 1984; Sharpley and Menzel, 1987; Kingery et al., 1994). The potential for P saturation and leaching may be particularly high for highly-fertilized and sandy soils (Breeuwsma and Silva, 1992; Nair and Graetz, 2004). Large or chronic accumulations of N and P can contribute to accelerated eutrophication of water bodies, impairing their use and potentially leading to fish mortality and growth of algae (Schindler, 1978; Lemunyon and Gilbert, 1993). Elevated concentrations of N and P in surface water and eutrophication of water bodies have been found in areas with high levels of confined poultry and other animal production (Daniel et al., 1998; Sharpley, 1999; Fisher et al., 2000). State and federal environmental protection agencies have responded to these environmental concerns by implementing regulations requiring poultry operations to develop nutrient management plans, which will frequently reduce the allowable amounts of litter that can be applied (Friend et al., 2006). It is estimated that 50% of the litter produced from areas with high concentrations of poultry production facilities cannot be applied to grasslands and croplands in these same areas due to environmental or economic constraints, which has led to surpluses of manure N and P production in some parts of the southeastern U.S. (Kellogg et al., 2000).

The environmental impacts of poultry litter fertilization could be reduced by applying surplus litter to terrestrial ecosystems other than pasture and cropland where nutrient levels in soils are low and which have a low risk of nutrient transport. Disposal of poultry litter to these ecosystems could increase the area of litter dispersal, reduce the spatial concentration of poultry litter application, and decrease risks to water quality in watersheds. Forests may be a viable alternative to pastures and croplands for broiler litter application. Similar to agroecoystems, forests are often limited by soil N and P supplies (Elser et al., 2007). Forests also have a high potential for nutrient uptake (O'Neill & Gordon, 1994) and have been successfully used to mitigate environmental impacts of municipal waste, municipal effluent, and mill waste disposal (Henry et al., 1993; Polglase et al., 1995; Falkiner & Polglase, 1997; Jackson et al., 2000). In addition, infiltration rates are much higher in forested landscapes than many agricultural landscapes, which could increase potential retention of nutrients and reduce losses through surface runoff in comparison to agricultural crops.

Loblolly pine (*Pinus taeda* L.) has been identified as a practical species to receive poultry litter application (Beem et al., 1998; Friend et al., 2006; Samuelson et al., 1999). Much of the poultry-producing regions of the southeastern U.S.A. are within the natural range of loblolly pine (*Pinus taeda* L.), so transportation of litter to land with loblolly pine is likely minimal (Friend et al., 2006). Loblolly pine is a prevalent and economically important species in the southeastern U.S.A.; it is used within the region to produce 18% of the world's supply of industrial timber (Allen et al., 2005; Prestemon and Abt, 2002). Loblolly pine growth is often limited by soil supplies of N and P (Binkley et al., 1999), and tree- and forest-level growth responses to N and P fertilization have been well demonstrated (Blazier et al. 2006; Colbert et al., 1990; Haywood et al., 1997; Murthy et al., 1997; Vose & Allen, 1988). Single applications of poultry litter, ranging between 2 to 23 Mg ha^{-1}, have been shown to increase loblolly pine growth rates (Dickens et al., 2004; Friend et al., 2006; Lynch and Tjaden, 2004; Roberts et al., 2006; Samuelson et al., 1999) and economic value (Dickens et al., 2004) of N- and P-deficient loblolly pine. Loblolly pine forests have a high capacity for fertilizer retention due to high plant biomass and soil organic matter. Will et al. (2006) reported that 90 to 100% of annually applied N and P was sequestered in aboveground biomass, soil organic matter, or the uppermost 10 cm of soil of a loblolly pine plantation. Due to this high fertilizer retention capacity, minimal offsite movement of nutrients associated with poultry litter application is expected. Furthermore, water runoff potential of forests is lower than that of grasslands and croplands due to their relatively higher infiltration (Zimmermann et al., 2006) and evapotranspiration rates (Farley et al., 2005). Friend et al. (2006) found that nutrients from an application of 4.6 Mg ha^{-1} of poultry litter (on a dry matter basis) was substantially contained within a loblolly pine forest and did not impair water quality.

The principal limitation to fertilizing loblolly pine with poultry litter is the relatively poor accessibility and maneuverability within dense plantations by ground-based fertilizer application equipment. Conventional manure-spreading equipment (manure trucks, tractor-drawn spreaders) cannot be driven through typical pine plantations due to close tree spacing, dense understory vegetation, and/or stumps high enough to cause equipment damage. These issues likely reduce the number of spreader contractors willing to operate within forests (Dickens et al., 2003).

Silvopasture is an alternative land management system that would allow the application of poultry litter to loblolly pine trees by largely circumventing maneuverability limitations of conventional loblolly pine plantations. Silvopasture management systems consist of forage grasses established and cultivated beneath trees in order to simultaneously produce timber and livestock (Clason & Robinson, 2000; Clason & Sharrow, 2000). Silvopasture regimes are currently the most popular form of agroforestry in the southeastern U.S. (Clason & Sharrow, 2000; Zinkhan & Mercer, 1996). Silvopastures are created by either planting trees in pastures (Robinson & Clason, 2002) or by establishing forage crops in forests (Clason & Robinson, 2000). Forage management in silvopastures is conducted similarly to conventional grasslands in the southeastern U.S.A.; herbicides and/or prescribed burning are used to reduce herbaceous and woody competition and fertilization is carried out to optimize forage yields. Due to land ownership and use patterns, there is high potential for conversion between agriculture and forestry in the southeastern U.S.A. (USDA SCS, 1989). Clason (1995) determined that loblolly pine was compatible with several forage crops in silvopasture systems. The relatively wide spacing of trees and forage understory in silvopastures make navigation of manure-spreading equipment possible (Figure 1).

Fig. 1. Applying broiler poultry litter to a silvopasture at the Louisiana State University Agricultural Center Hill Farm Research Station in northwest Louisiana, U.S.A. Picture by Terry Clason, USDA Natural Resource Conservation Service

A pine plantation in which straw is harvested is another management system where applications of poultry litter could increase commodity production. Pine straw mulch has emerged as a substantial commercial product for horticultural crops and landscaping in urban and suburban areas (Duryea and Edwards, 1989). Adding straw harvesting to conventional timber management regimes has been shown to markedly increase profits, with straw revenue potentially exceeding that of traditional forest products (Haywood et al., 1998; Lopez-Zamora et al. 2001; Roise et al,. 1991). These plantations are typically designed to allow access by conventional agronomic equipment to harvest the straw and are thus well suited for application of the poultry litter by small to mid-size manure or litter spreaders. Harvests of straw on large plantations are usually performed using a hay or pine straw rake, tractor, and mechanical baler (Mills and Robertson, 1991). Understory biomass is typically suppressed in straw harvesting management regimes to improve straw quality by eliminating woody and herbaceous debris (Mills and Robertson, 1991). Coarse and fine woody debris is also removed from the forest floor prior to baling to improve the economic value of baled pine straw (Minogue et al., 2007). This suppression of vegetation and woody debris removal between rows of trees fosters navigation of the plantations with tractor-drawn straw raking and baling equipment (Figure 2) as well as poultry litter application equipment.

Fig. 2. Mechanically baled straw in a 19-year-old loblolly pine plantation at the Louisiana State University Agricultural Center Calhoun Research Station in northeast Louisiana. Inset: Tractor-drawn straw baler used for mechanically baling straw in the plantation. Pictures by Keith Ellem, University of Arkansas Monticello

Poultry litter can be highly beneficial when applied to plantations in which straw is harvested because it can replenish nutrients lost in straw harvesting. The nutrient content in pine needles is substantial, and repetitive harvesting of pine straw removes significant amounts of nutrients from the soil. One metric ton of harvested straw contains approximately 21.3 kg nitrogen (N), 1.8 kg phosphorus (P), 4.5 kg potassium (K), 9.0 kg calcium (Ca), and 1.8 kg magnesium (Mg) (Pote & Daniel, 2008). Since fallen leaves are major sources of nutrient inputs to soils, repeated raking can reduce soil nutrient availability, particularly N, unless nutrients are replenished through management activities (Jorgenson & Wells, 1986; Lopez-Zamora et al., 2001). As such, periodic fertilization has been recommended to remedy nutrient removals that can occur with straw harvesting (Haywood et al., 1998; Lopez-Zamora et al., 2001).

Since poultry litter contains organic matter, it could potentially replenish some of the organic matter removed by pine straw raking. Fallen pine straw is a prominent source of organic matter in the soil organic horizon of pine forests, and it is the major reservoir of labile carbon used by soil microbes in the synthesis of new cells, a process that also mineralizes N (Pritchett & Fisher, 1987; Sanchez et al., 2006; Wagner & Wolf, 1999). Soil microbial biomass and activity are highly sensitive to changes in soil organic matter and are thus used as indicators of soil quality and sustainability (Fauci & Dick, 1994; Harris, 2003; Powlson & Brookes, 1987). Removal of the soil organic horizon decreased soil microbial biomass carbon (C_{mic}) due to reduced substrate availability in a study simulating organic matter removals associated with tree harvesting and site preparation in a boreal forest (Tan et al., 2005). Activities other than soil organic matter removal associated with straw harvesting may also impact soil biological properties. The suppression of understory vegetation prior to straw raking can reduce microbial biomass and activity because understory vegetation provides rhizodeposition important to soil microbes (Donegan et al., 2001; Gallardo and Schlesinger, 1994; Högberg et al., 2001). Inorganic fertilizers do not replenish organic matter essential as microbial substrates and may exacerbate soil microbial biomass and activity declines caused by organic matter removal (Blazier et al., 2005). In contrast, fertilization with poultry litter can increase soil microbial biomass and activity (Canali et al., 2004; Plaza et al., 2004). Soil organic matter also in part determines soil water availability and temperature (Attiwill & Adams, 1993), and poultry litter has been shown to increase soil water content and available water holding capacity and reduce soil temperature (Agbede et al., 2010; Warren & Fonteno, 1993).

Due to the potential influences of poultry litter on soil and tree nutrition, soil microbes, and tree growth, a series of experiments were conducted in the mid-South region of the U.S.A. This chapter will provide a review of the key results of these trials from 1996 through 2011. The focus of this chapter will be on the changes in soil nutrition, physical properties and microbes, tree nutrition and growth, and water nutrient contents in loblolly pine plantations and silvopastures in response to fertilization with conventional fertilizer and poultry litter.

2. Study descriptions

Results of five studies conducted in the mid-South U.S.A are described in this chapter. At least one treatment in each study received surface application of broiler litter as fertilizer, and loblolly pine was the tree component of each study. All studies occurred in the Western Gulf Coastal Region within areas identified by Friend et al. (2006) as having high occurrence of poultry production and southern pine forests. Two of the studies (SILVO, SWITCH) included poultry litter applied to silvopastures. The silvopasture in the SILVO study consisted as bahiagrass (Paspalum notatum Flüggé) established under thinned loblolly pine, and the silvopasture in the SWITCH study was comprised of switchgrass (Panicum virgatum L.) established under thinned loblolly pine. Two of the studies (AR-FORvsPAST, LA-FORvsPAST) included a comparison of broiler litter in loblolly pine and pastures. The STRAW study included poultry litter applied to a loblolly pine plantation in which straw was annually harvested.

The SILVO and SWITCH studies were conducted at the Louisiana State University Agricultural Center Hill Farm Research Station in Homer, Louisiana, U.S.A. The STRAW and LA-FORvsPAST trials were carried out at the Louisiana State University Agricultural Center Calhoun Research Station in Calhoun, Louisiana, U.S.A. The AR-FORvsPAST study was conducted at the University of Arkansas Southwest Research and Extension Center near Hope, Arkansas, U.S.A. Average annual precipitation of the region in which the studies were carried out is 120 cm, and average temperature is 18°C (Bailey, 1995). Primary study site characteristics are described in Table 2.

Study	Geographical Coordinates	Vegetation	Tree Age (years)	Tree Density (trees ha^{-1})	Soil Classification
SILVO	32°44′N, 93°03′W	loblolly pine-bahiagrass silvopasture	12	247	Loamy, siliceous, thermic Arenic Paleudults
SWITCH	32°44′N, 93°03′W	loblolly pine-switchgrass silvopasture	17	124	Loamy, siliceous, thermic Arenic Paleudults
STRAW	32°31′N, 92°21′W	loblolly pine plantation	10	618	Fine-loamy siliceous thermic Typic Fragiudults
LA-FORvsPAST	32°31′N, 92°21′W	loblolly pine, bermudagrass as vegetation type treatments	5	1586	Fine-loamy siliceous thermic Typic Fragiudults
AR-FORvsPAST	33°42′N, 93°32′W	loblolly pine, bahiagrass as vegetation type treatments	26	201	Fine-loamy, siliceous thermic Typic Fraigudults; Clayey, mixed, thermic Aquic Hapludults

Table 2. Location, vegetation, tree and density at study initiation, and soil characteristics for studies of poultry litter fertilization of loblolly pine in the mid-South U.S.A.

Treatments (Table 3) were replicated four times each in the STRAW, LA-FORvsPAST studies, three times in the SILVO and AR-FORvsPAST studies, and six times in the SWITCH study. Treatments were applied as a one-way treatment structure in the STRAW, LA-FORvsPAST, SWITCH, and SILVO studies. Treatments were applied as a split-plot treatment structure in the AR-FORvsPAST study, with vegetation type (pasture, forest) as a whole-plot treatment and fertilization as a sub-plot treatment. The experimental design was a randomized complete block design for all studies. In statistical analyses of all variables assessed in these treatments, differences among treatments were determined by analysis of variance at $\alpha = 0.05$; correlation among variables was assessed at $\alpha = 0.05$ as well.

Study	Treatment[1]	Treatment Description
SILVO	CONTROL	No treatment
	IF	Inorganic fertilizer mixture (diammonium phosphate, ammonium nitrate, muriate of potash to annually supply 114 kg N ha^{-1}, 39 kg P ha^{-1}, 20 kg K ha^{-1})
	PL5	Poultry litter applied at 5 Mg ha^{-1} that supplied N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, B at 112, 36, 78, 106, 23, 9, 2, 1, 1.5, 0.2 kg ha^{-1}, respectively
	PL10	Poultry litter applied at 10 Mg ha^{-1} that supplied N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, B at 224, 73, 157, 211, 45, 18, 3, 2, 3, 0.3 kg ha^{-1}, respectively
SWITCH	CONTROL	No treatment
	IF80	Ammonium nitrate applied that supplied 80 kg N ha^{-1}
	IF160	Ammonium nitrate applied that supplied 160 kg N ha^{-1}
	PL1.5	Poultry litter applied at 1.5 Mg ha^{-1} to supply N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, and B at 80, 42, 90, 54, 15, 2, 1.5, 0.15, 1, and 0.1 kg ha^{-1}, respectively.
	PL3	Poultry litter applied at 3 Mg ha^{-1} to supply N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, and B at 160, 84, 180, 108, 30, 4, 3, 0.3, 2, and 0.2 kg ha^{-1}, respectively.
STRAW	CONTROL	No treatment
	RAKE	Straw harvesting
	RAKE-IF	Straw harvesting, diammonium phosphate and urea inorganic fertilizers that supplied N and P at 193 and 102 kg ha^{-1}, respectively
	RAKE-PL	Straw harvesting, poultry litter applied at 8 Mg ha^{-1} that supplied N and P at 193 and 102 kg ha^{-1}, respectively. Other nutrients added by poultry litter not tested due to budget constraints.
LA-FORvsPAST	CONTROL	No treatment
	PL5	Poultry litter applied at 5 Mg ha^{-1} that supplied N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, B at 112, 109, 92, 159, 34, 9, 2, 3, 2, 0.2 kg ha^{-1}, respectively
	PL10	Poultry litter applied at 10 Mg ha^{-1} that supplied N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, B at 224, 218, 184, 318, 68, 18, 3, 6, 3, 0.3 kg ha^{-1}, respectively
	PL20	Poultry litter applied at 20 Mg ha^{-1} that supplied N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, B at 448, 436, 368, 636, 136, 36, 6, 12, 6, 0.6 kg ha^{-1}, respectively
	FOREST	Loblolly pine plantation
	PASTURE	Bermudagrass pasture
AR-FORvsPAST	FOREST	Loblolly pine plantation
	PASTURE	Bahiagrass pasture
	CONTROL	No treatment
	PL9	Poultry litter at 9 Mg ha^{-1} that supplied N, P, K at 30, 14, 22 kg ha^{-1}. Other nutrients added by poultry litter not tested due to budget constraints.

Table 3. Treatments conducted in studies of poultry litter fertilization of loblolly pine conducted in the mid-South U.S.A. [1]Italicized treatments were applied as sub-plot treatments, underlined treatments were applied in all possible combinations to whole plots, all other treatments were applied as whole-plot treatments

Soil and/or plant responses to treatments were observed in the studies (Table 4). In the SILVO, SWITCH, and LA-FORvsPAST studies, grass clippings were randomly collected within quadrats either at the end of growing seasons (in the SWITCH study) or multiple times during the season and averaged (in the SILVO and LA-FORvsPAST studies) to determine forage yields. In the SILVO, STRAW, and LA-FORvsPAST studies loblolly pine basal area was measured by converting diameter at breast height measurements into basal area for all trees in measurement plots; basal area measures were summed for each plot to estimate stand level basal area. In the SILVO study soil was sampled by a tractor-mounted auger to the bottom of the B_t horizon and separated into A, E, and B_t horizons, which had average depths of 0.15, 0.48, and 0.59 m, respectively. In the SWITCH study, soil was sampled with punch augers to a 15-cm depth for labile C determination and 30 cm for nutrient analyses. Soil in the STRAW study was sampled with punch augers to a 15-cm depth. In the LA-FORvsPAST study, soil was sampled to a 15-cm depth with punch augers pre-treatment and sampled to 0-15, 15-30, 30-45, 60-80, and 80-100 cm depths post-treatment. Soil was sampled to a 15 cm depth in the AR-FORvsPAST study using punch augers. In the SILVO and STRAW studies, loblolly pine foliage was sampled from the upper third of crowns.
Organic matter in soil samples was quantified by the Walkley-Black method (Walkley, 1947) in the SILVO, LA-FORvsPAST, and SWITCH studies and by the loss on ignition method (Ball, 1964) in the STRAW and AR-FORvsPAST studies. Soil pH was determined by pH meters in a 2:1 mixture of deionized water to soil in the SILVO and SWITCH studies. Phosphorus in the samples was extracted by Bray 2 P (Bray & Kurtz, 1945) in the SILVO and LA-FORvsPAST studies and by Mehlich 3 (Mehlich, 1984) in the AR-FORvsPAST and SWITCH studies. Nutrients other than P were extracted by ammonium acetate (K, Ca, Mg, Na) and DTPA (Cu, Fe, Mn, Zn) in the SILVO and LA-FORvsPAST studies (Gambrell, 1996; Helmke & Sparks, 1996). Mehlich 3 was used to extract K, Ca, Mg, S, Cu, and Zn in the SWITCH study (Mehlich, 1984). All nutrients from soil samples were quantified via ICP spectrometry (Jones & Case, 1990) in all studies in which soil was analyzed for nutrient concentration. Exchangeable N (NH_4-N, NO_3-N) was extracted by KCl extraction (Mulvaney, 1996) in the SILVO and AR-FORvsPAST studies and measured colorimetrically on Bran Luebbe (Bran-Luebbe, Inc, Delavan, WI) and Lachat autoanalyzers (Lachat Instruments, Loveland, CO, U.S.A.) in the SILVO and AR-FORvsPAST studies, respectively. In the STRAW and SWITCH studies soil labile C was measured by sequential fumigation incubation (Zou et al., 2005). In the STRAW and SWITCH studies microbial biomass C was measured by fumigation incubation (Jenkinson and Powlson, 1976*a,b*) and microbial activity was measured by an assay of dehydrogenase activity (Lenhard, 1956; Alef, 1995). In the STRAW study N mineralization and nitrification was measured using the buried bag method (Eno, 1960). In the AR-FORvsPAST study, potential N mineralization and nitrification (Hart et al., 1994) were assessed in samples aerobically incubated in the laboratory for 28 days; NH_4-N and NO_3-N used to determine mineralization and nitrification in this procedure were measured by the cadmium reduction method (Mulvaney, 1996) using a Lachat autoanalyzer. Total N in soil samples from the AR-FORvsPAST study was determined by dry combustion using an Elementar Vario MAX CN analyzer (Elementar Analysesysteme GmbH, Hanau, Germany).
All nutrients except N in foliage were analyzed by nitric acid digestion and ICP spectrometry; N in these samples was measured by Dumas combustion and thermal conductivity detection using a Leco N/protein analyzer (Leco Inc., St. Joseph, MI, U.S.A) (Helmke & Sparks, 1996; Tate, 1994; Zarcinas et al., 1987). In the SILVO study, N concentrations of bahiagrass samples

Study	Treatment or Measurement[1]	Year 1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
SILVO	Fertilization			■	■	■	■				
	Forage yield				■						
	Soil pH, OM, nutrients		■		■	■		■			
	Soil NH_4-N, NO_3-N		■					■			
	Pine foliage nutrients				■					■	
	Pine basal area		■	■	■	■		■			
SWITCH	Fertilization										
	Forage yield										
	Soil pH, OM, nutrients										
	Soil LABC, CMIC, ACT										
STRAW	Straw raking					■	■	■	■	■	■
	Fertilization								■	■	■
	Soil STR, P, BD, WHC										
	Soil OM, LABC, NMIN, exchangeable N										
	Soil CMIC, ACT										■
	Pine foliage nutrients										
	Pine basal area							■			■
LA-FORvsPAST	Fertilization		■	■	■	■	■				
	Forage yield		■	■	■	■	■				
	Soil pH, OM, nutrients	■	■	■	■	■	■				
	Pine basal area	■	■	■	■	■	■	■			
	Runoff nutrients						■				
AR-FORvsPAST	Fertilization									■	■
	Forage yield									■	■
	Soil NH_4-N, NO_3-N									■	■
	Soil potential NMIN										■
	Soil OM, N, P									■	■

Table 4. Timeline of treatments and measurements in studies of fertilization of loblolly pine with poultry litter in the mid-South U.S.A. Shaded cells designate years in which treatments or measurements occurred. [1]OM = organic matter, STR = strength, BD = bulk density, WHC = water holding capacity, LABC = labile C, NMIN = N mineralization, CMIC = microbial biomass C, ACT = microbial dehydrogenase activity

were ascertained by Kjeldahl method; other nutrients in the samples were determined by Dumas combustion and nitric acid digestion and ICP spectrometry (Helmke & Sparks, 1996; Horneck & Miller, 1998; Tate, 1994; Zarcinas et al., 1987).

Bulk density, porosity, soil moisture content, and air-filled porosity of soil samples collected in the STRAW study were analyzed using procedures of Blake & Hartge (1986) and Danielson & Sutherland (1986). Available water holding capacity was determined in the STRAW study using soil moisture retention curves (Brye, 2003; Gee et al., 1992). Soil strength in the STRAW study to 15- and 30-cm depths was measured with a Scout SCT compaction meter (Spectrum Technologies, Inc., Plainfield, IL, USA) (Bradford, 1986).

Soil water was collected to a 30-cm depth using tension lysimeters in the AR-FORvsPAST study; NO_3-N and PO_4-P in the water samples was analyzed by ion chromatography and NH_4-N was measured with a Lachat autoanalyzer. Water samples were also digested using a Kjeldahl digestion procedure and analyzed for total Kjeldahl nitrogen (TKN) and total Kjeldahl phosphorus (TKP) using the Lachat spectrophotometer. In the LA-FORvsPAST study, water was collected from runoff troughs after every rain event. Water samples were analyzed for total P by acid persulfate digestion and ICP spectrometry and for dissolved P by ICP spectrometry (Clesceri et al., 1998; Pote & Daniel, 2000).

3. Plant biomass and nutrition

Increases in forage yields were observed in response to poultry litter in the SILVO, LA-FORvsPAST, AR-FORvsPAST, and SWITCH studies. In the SILVO study poultry litter increased bahiagrass yields, but the magnitude of response was rate-dependent. The PL10 treatment had greater bahiagrass yields than all other treatments, and the PL5 and IF treatments had greater bahiagrass yields than the CONTROL treatment (Evans, 2000). The PL10 treatment also led to greater P, Zn, and Cu concentrations in bahiagrass relative to the CONTROL and IF treatments (Evans, 2000). These results indicated that poultry litter increased yields and nutritional quality of bahiagrass. Gaston et al. (2003) similarly found in the LA-FORvsPAST study that bermudagrass yields increased with increasing litter application rate. In the AR-FORvsPAST study, bahiagrass yields of the PL9 treatment were ~1.5 times greater than those of the CONTROL treatment in the first two years of fertilization. Switchgrass yield response to poultry litter in the SWITCH study was not rate-dependent as in the SILVO and LA-FORvsPAST studies, because both application rates led to comparable yields.

Loblolly pine growth was also improved by poultry litter in the SILVO and AR-FORvsPAST studies. In the SILVO study, tree- and stand-level basal area growth was increased by poultry litter at the 10 Mg ha^{-1} rate (Blazier et al., 2008a). As with forage yields, litter application rate affected the level of growth response. After four annual litter applications, the 10PL treatment had greater annual basal area growth per tree than that of all other treatments, and the 5PL treatment had greater annual basal area growth than the CONTROL treatment. Stand-level basal area growth of the 10PL treatment was greater than that of the CONTROL and IF treatments. All fertilizer treatments led to greater foliage N concentrations than the CONTROL treatment, and both poultry litter treatments had greater foliage P concentrations than the CONTROL treatment. These results, which are consistent with other studies (Dickens et al., 2004; Friend et al., 2006; Roberts et al., 2006), show that loblolly pine growth can be increased with poultry litter amendments. The levels of growth responses were somewhat surprising, because all foliage nutrient concentrations were above critical levels (Allen, 1987; Blazier et al., 2008a; Jokela, 2004). Due to the relatively low density of trees in silvopastures, trees may have more readily responded to fertilization by virtue of larger crown mass (which provides a larger nutrient sink per tree) and less competition for applied nutrients compared to that in typical pine plantations. The similarities in growth responses and N and P application rates of the 5LIT and INO treatments suggests that although the 5LIT treatment supplied more K and a wider array of nutrients than the INO treatment, N and P were likely the primary limiting nutrients in the stand (Blazier et al., 2008*a*). In the AR-FORvsPAST study, annual loblolly pine basal area growth in response to the PL9 treatment was 10.9% greater than that of the CONTROL treatment.

In the STRAW and LA-FORvsPAST studies, no significant loblolly pine growth responses to treatments were observed (Gaston et al., 2003). Before the studies were established, the land was intensively managed for forage production. As such, the decades of fertilization application at these locations had resulted in high nutrient availability. Foliage P and S concentrations were increased by the RAKE-PL treatment relative to the other treatments in the STRAW study, but these increases appeared to have been luxury consumption since these nutrient increases were not accompanied by increased loblolly pine growth.

4. Soil physical properties and organic matter

In the STRAW study, all treatments that included straw harvesting induced evidence of soil compaction by significantly increasing bulk densities (Table 5) to levels 0.6 to 3.3% greater than the 1.75 g cm^{-3} bulk density defined as a growth-limiting threshold for forests grown on loamy soils (Daddow and Warrington, 1983), whereas soil in the CONTROL treatment remained below this threshold. These bulk density increases were also associated with significant declines in porosity in all treatments that included straw harvesting (Table 5). These findings suggest that annual straw harvesting had potential to reduce tree growth through reduced rooting volume and aeration. Nevertheless, no decreases in loblolly pine growth were observed in response to raking, as described above. It is likely that equipment traffic and increased exposure of mineral soil to rainfall associated with straw harvesting led to these increases in bulk density. Similarities in bulk density and porosity among the RAKE treatment and treatments that included raking and fertilization suggest that the additional trafficking from fertilization equipment each season did not appreciably compact the soil and that straw harvesting was the predominant cause of soil compaction (Blazier et al, 2008*b*).

Treatment	Bulk Density (g cm^{-3})	Porosity (g kg^{-1})	Air-filled Porosity	Moisture (g kg^{-1})	Soil Strength (MPa)	Organic Matter (g kg^{-1})	Available Water Holding Capacity (g kg^{-1})
CONTROL	1.67 b	369 a	99 a	270 a	1.25 b	27.8 a	427 a
RAKE	1.81 a	318 b	51 b	268 ab	2.31 a	25.8 ab	367 b
RAKE-IF	1.76 a	334 b	86 a	248 b	2.45 a	19.0 b	353 b
RAKE-PL	1.78 a	329 b	48 b	281 a	0.99 b	25.8 ab	384 ab

Table 5. Soil physical properties and organic matter in response to pine straw harvesting and fertilization with inorganic fertilizer and poultry litter in a loblolly pine plantation in north central Louisiana, U.S.A. Means within columns followed by different letters differ at $P < 0.05$. Adapted from Blazier et al. (2008b)

The RAKE-PL treatment appeared to have ameliorated some of the soil physical impacts of the raking since soil strength, organic matter, and moisture in the RAKE-PL treatment were similar to that in the CONTROL treatment (Table 5). However, the RAKE-PL treatment was characterized by lower air-filled porosity than the CONTROL treatment (Table 5), so there may have been a compaction potential associated with the application of the poultry litter (Tekeste et al., 2007). Poultry litter did not alter soil physical properties in a manner similar to inorganic fertilizers. The RAKE-PL treatment was characterized by soil moisture content, strength, organic matter concentrations, and available water holding capacity similar to the CONTROL treatment (Table 5). The RAKE-PL treatment may have replenished some organic matter lost through straw harvesting and accelerated decomposition associated with increased nutrient levels, because broiler poultry litter typically consists of 44% organic matter (Adeli et al., 2006; Dick et al., 1998). These results suggest that use of poultry litter as a fertilizer source in an annual straw harvest regime was superior to inorganic fertilizers in sustaining soil physical quality.

In contrast with the RAKE-PL treatment, the RAKE and RAKE-IF treatments had detrimental effects on some soil physical properties. The RAKE and RAKE-IF treatments both had soil strengths 46% greater than the CONTROL treatment. Soil strengths of the RAKE and RAKE-IF treatments also exceeded the 2 MPa soil strength threshold defined as highly compacted because of demonstrated root growth restrictions (Taylor & Gardner, 1963; Tiarks & Haywood, 1996). Available water holding capacity was also reduced by the RAKE and RAKE-IF treatments relative to the CONTROL treatment. These findings suggest that the RAKE and RAKE-IF treatments made soil less amenable for root growth in the uppermost 5 cm of soil, which is the predominant zone in which tree roots, particularly fine roots, grow (Gilman, 1987). Relative to the CONTROL treatment, only the RAKE-IF treatment had greater soil strength, reduced moisture content, and reduced soil organic matter concentrations (Table 5). Repeated fertilization with inorganic nitrogen has been shown to reduce soil organic matter concentrations by increasing decomposition rates (Khan et al., 2007). Increased soil strength in response to the RAKE-IF treatment may have been due to the reductions in soil organic matter concentrations caused by this treatment. Soil strength tends to increase with decreasing soil organic matter concentrations because soil organic matter serves as an organic aggregate binding and bonding material (Munkholm et al., 2002). The relatively lower moisture content and available water holding capacity of the RAKE-IF treatment is consistent with its lower soil organic matter content because organic matter fosters soil moisture retention (Plaza et al., 2004; Powers et al., 2005).

There were no differences in soil organic matter among treatments in the SILVO, SWITCH, LA-FORvsPAST, and AR-FORvsPAST studies (Blazier et al., 2008a; Liechty et al., 2009), in which litter was not removed. As such, increases in forage and/or tree yields from fertilization in these studies were not associated with concomitant increases in soil organic matter. In the SILVO and SWITCH studies, the lack of declines in organic matter in response to inorganic fertilizer application as seen in the STRAW study was likely due to the straw raking done in tandem with fertilization in the STRAW study. As organic matter supply was drastically reduced by annual straw harvesting, stimulating decomposition with inorganic fertilizer led to significant declines in soil organic matter. Additionally, the increases in forage understory biomass of the SILVO and SWITCH studies may have been less prone to lead to increases in organic matter, as evidenced in the LA-FORvsPAST study. In that study no differences in organic matter were found among treatments in the pasture despite the increases in bermudagrass yields described above, whereas organic matter in the loblolly pine plantation differed among treatments as PL20 > PL10, PL5 > CONTROL.

5. Soil labile C, microbial biomass C, and microbial activity

Annual application of inorganic fertilizer had a profound effect on microbial biomass and activity in the STRAW study (Table 6). Microbial biomass C of the RAKE-IF treatment was lower than that of the CONTROL and RAKE treatments, and dehydrogenase activity of the RAKE-IF treatment was lower than all other treatments. The reductions in microbial biomass C and activity were apparently not a result of lower substrate supply, because labile C was similar among treatments (Table 6). Consequently, the higher potential turnover rate of the RAKE-IF treatment relative to all others is likely a result of reduced microbial biomass and activity rather than relatively high recalcitrance of organic matter.

The reductions in microbial biomass C and activity in the RAKE-IF treatment were likely associated with the lower pH of this treatment relative to all others. It has been well-demonstrated that intensive fertilization with inorganic N reduces soil pH and that declining pH is associated with reductions in soil microbial biomass and activity (Anderson and Domsch, 1993; Baath et al., 1995; Blazier et al., 2005). These results thus showed that microbial biomass and activity were reduced by declines in pH from inorganic fertilizer, whereas annual raking and fertilization with poultry litter had no such effects. In contrast to inorganic fertilizer, poultry litter tends to increase soil pH because litter contains calcium carbonate originating from poultry rations (Hue, 1992; Kingery et al., 1993). Although litter did not significantly increase pH in the STRAW study, litter sustained pH at levels comparable to the CONTROL treatment, which fostered microbial biomass C and activity levels comparable to the CONTROL treatment as well.

As in the STRAW study, inorganic fertilizer led to declines in microbial biomass C relative to the CONTROL treatment (Table 6) in the SWITCH study. Fertilization has been shown to reduce soil microbial biomass C in forest soils (Rifai et al., 2010; Wallenstein et al., 2006). Rifai et al. (2010) identified several possible mechanisms for soil microbial biomass declines in response to fertilization, including (1) pH reduction caused by nitrate leaching induced by application of high rates of NH_4NO_3, and (2) inhibition of organic compound decomposition from excess N that reduces organic matter available to soil microbes. In the SWITCH study there were no declines in pH among treatments consistent with declines in soil microbial biomass C, although pH of the inorganic fertilizer treatments were lower than those of the poultry litter treatments. Dehydrogenase activity decreased as fertilizer application rates increased for both fertilizer types. Since N was the sole nutrient added by inorganic fertilizer treatments in this study, these dehydrogenase activity trends suggest that excess N perturbed microbial decomposition of organic matter in this loblolly pine and switchgrass system. However, potential C turnover rate was shorter for the lower rate of inorganic fertilizer (IF80) relative to the lower rate of poultry litter (PL1.5) despite the equivalent N rate of the two treatments. Since labile C supply, microbial biomass C, and dehydrogenase activity were similar for the IF80 and PL1.5 treatments, the reason for the higher potential C turnover rate of the PL1.5 treatment was unclear and merited further study.

	Treatment				
STRAW	**CONTROL**	**RAKE**	**RAKE-IF**	**RAKE-PL**	
Labile C (mg kg^{-1})	475.1 a	522.3 a	457.0 a	582.5 a	
Potential C turnover rate (days)	46.0 b	53.2 b	92.9 a	62.8 ab	
Microbial biomass C (mg kg^{-1})	169.2 a	157.2 a	75.3 b	143.5 ab	
Dehydrogenase activity (µg g^{-1})	50.6 a	71.0 a	25.8 b	44.5 a	
pH	4.9 a	4.9 a	4.3 b	5.1 a	
SWITCH	**CONTROL**	**IF80**	**IF160**	**PL1.5**	**PL3**
Labile C (mg kg^{-1})	835.6 a	585.2 a	718.1 a	878.7 a	836.7 a
Potential C turnover rate (days)	29.7 ab	24.7 b	30.4 ab	43.8 a	37.3 ab
Microbial biomass C (mg kg^{-1})	410.9 a	341.6 b	348.4 b	320.4 ab	377.4 ab
Dehydrogenase activity (µg g^{-1})	11.0 ab	24.2 a	9.9 b	24.3 a	5.9 b
pH	5.5 bc	5.4 c	5.4 c	5.6 ab	5.7 a

Table 6. Soil labile C, microbial, and pH responses to fertilization in an annually raked loblolly pine plantation (STRAW) and a loblolly pine and switchgrass silvopasture (SILVO) in the mid-South U.S.A. For each study, means within columns followed by different letters differ at $P < 0.05$. Adapted in part from Blazier et al. (2008b)

6. Soil nutrients

6.1 Nitrogen

In all studies in which exchangeable soil N was measured, NO_3-N amounts or proportions of in soil increased in response to poultry litter application (Table 7). In the AR-FORvsPAST study, NO_3-N significantly increased in the loblolly pine plantation and in pasture relative to the CONTROL treatment following two years of poultry litter application. The proportion of NO_3-N to total exchangeable N was also greater in response to poultry litter than without litter application (Liechty et al., 2009). There was no difference in NO_3-N concentrations among treatments in the SILVO study, but as in the AR-FORvsPAST study the ratio of NO_3-N to total exchangeable N increased in response to poultry litter additions. This increase in the proportion of NO_3-N in the SILVO study occurred in response to both rates of broiler litter tested; no such increase was observed in response to the inorganic fertilizer mixture (Blazier et al., 2008a). Results similar to the SILVO study were also found in the STRAW study; NO_3-N increased in response to the treatment regime that included poultry litter, whereas no such increase was observed in response to non-fertilized treatments and the treatment regime that included a mixture of inorganic fertilizers (Liechty et al., 2009).
Increases in soil NO_3-N in response to poultry litter were attributable to greater nitrification rates (Table 7). Soil in plots treated with broiler litter had greater N mineralization rates in the AR-FORvsPAST study, and a greater proportion of mineralized N was nitrified. There was also a significant positive correlation between NO_3-N in soil and nitrification rates (Liechty et al., 2009). Similar results were observed in the STRAW study, in which both rates of poultry litter had greater N mineralization and nitrification than CONTROL and IF treatments (Blazier et al, 2008b). The greater nitrification and NO_3-N of poultry litter treatments relative to CONTROL treatments in both studies was likely predominately a function of the addition of N to soil by litter. Relatively high NO_3-N in soil after fertilization is in part indicative of low plant sequestration of applied N (Adeli et al., 2006), so

consecutive applications of litter at the rates in these studies likely exceeded loblolly pine, bermudagrass, and bahiagrass N demand. The higher nitrification rates seen in response to poultry litter in these studies relative to inorganic fertilizer, even when both fertilizer sources were applied to provide the same N rates, was likely due to the differences in the effects of the fertilizer sources on soil pH. In the SILVO and STRAW studies, soil pH declined in response to inorganic fertilization applications relative to all other treatments (Tables 6 and 7). Likewise, soil pH of the poultry litter treatments in the SWITCH study was greater in response to broiler litter than to CONTROL and inorganic fertilizer treatments (data not shown). Ellum (2010) found in the STRAW study that nitrification was significantly and positively correlated with pH. Nitrification rates have been shown to decline with decreasing pH due to reductions in populations and activity of nitrifying bacteria (Aune & Lal, 1997).

	Treatment			
SILVO – 5 years post-treatment	**CONTROL**	**IF**	**PL5**	**PL10**
NO_3-N (mg kg^{-1})	7.2 a	0.1 a	4.8 a	16.2 a
Total exchangeable N (mg kg^{-1})	34.8 a	18.6 a	29.6 a	71.0 a
% NO_3-N	31.0 b	11.1 c	51.7 a	55.6 a
pH	4.9 a	4.5 a	5.0 a	5.0 a
STRAW – 5 years post-treatment	**CONTROL**	**RAKE**	**RAKE-IF**	**RAKE-PL**
NO_3-N (mg kg^{-1})	0.6 c	0.8 c	1.4 b	10.0 a
Total exchangeable N (mg kg^{-1})	6.5 b	5.1 c	6.3 b	14.4 a
% NO_3-N	15.9 c	17.8 c	25.2 b	65.6 a
N mineralization (mg kg^{-1})	23.6 b	18.5 b	13.7 b	51.2 a
N nitrification (mg kg^{-1})	23.2 b	17.4 b	17.3 b	48.2 a
% N nitrified	98.3 a	94.1 a	126.3 a	94.1 a
AR-FORvsPAST – 2 years post-treatment	**PASTURE-CONTROL**	**PASTURE-PL9**	**FOREST-CONTROL**	**FOREST-PL9**
NO_3-N (mg kg^{-1})	2.1 b	4.1 a	0.1 b	15.3 a
Total exchangeable N (mg kg^{-1})	8.9 b	11.0 b	6.2 b	24.4 a
% NO_3-N	21.4 bc	37.6 ab	1.1 c	57.1 a
N mineralization (mg kg^{-1})	14.3 b	23.6 a	7.3 c	14.3 b
N nitrification (mg kg^{-1})	15.6 b	26.3 a	3.4 d	13.3 c
% N nitrified	109.0 b	111.4 a	46.5 d	93.3 c

Table 7. Soil exchangeable N, mineralization, nitrification, and pH in response to fertilization in loblolly pine plantations, silvopasture, and bahiagrass pasture in a series of trials conducted in the mid-South U.S.A. Means within rows followed by different letters differ at $P < 0.05$. Adapted in part from Liechty et al. (2009)

Although differences in soil NO_3-N and nitrification between loblolly pine and bahiagrass pasture in the AR-FORvsPAST study in part reflected the differences in pH and C:N ratios of the soils in these two land uses (Richardson 2006), they also reflected the differences in uptake and use of available N forms by the loblolly pine and pastures. Although N mineralization and nitrification was greater in pasture when fertilized with poultry litter, the increase in NO_3-N remaining in soil per unit increase in potential net nitrification was greater in loblolly pine plantation than in pasture by the second application of poultry litter (Liechty et al., 2009). Conifer tree roots have been shown to preferentially absorb NH_4-N rather than NO_3-N (Kronzucker et al., 1997), whereas NO_3-N is preferentially taken up by forage (Blevins and Barker, 2007). Thus, loblolly pine plantation had a greater propensity to retain a higher proportion of NO_3-N than pasture. Given this tendency of loblolly pine to retain proportionally greater NO_3-N, it is likely that less poultry litter should be applied to such plantations than to pastures to minimize NO_3-N pollution in surface and subsurface water.

Annual raking in the STRAW study reduced total exchangeable N, and fertilization, regardless of source, replaced at least a portion of the lost N and increased total exchangeable N (Table 7). Interestingly, although both fertilizers increased exchangeable N, poultry litter increased exchangeable N to a greater extent than the inorganic fertilizer, although both fertilizers were applied at the same N rate (Ellum, 2010). The higher exchangeable N concentrations in the RAKE-PL reflected the increases in NO_3-N levels in the RAKE-PL treatment. The NO_3-N concentrations were nearly 7 and 17 times greater in this treatment than those in the RAKE-IF and CONTROL treatments, respectively. This result provides evidence of the propensity of loblolly pine plantations to accumulate NO_3-N in response to annual applications of broiler litter, even when exchangeable N is reduced by annual straw raking. To safeguard against such NO_3-N accumulation, it is likely necessary to fertilize a raked loblolly pine plantation with broiler litter less frequently and at lower rates than in the STRAW study.

6.2 Phosphorus

Soil test P accumulation, determined as the annual difference in soil test P concentrations from pre-treatment concentrations, increased in the uppermost soil horizon in all studies in which soil test P was measured (Table 8). In the SILVO study, both litter treatments had significantly greater soil test P accumulation in the uppermost soil horizon than the CONTROL and IF treatments. After the first application, soil test P accumulation was similarly increased by both litter rates. After four annual applications, the PL10 treatment had greater soil test P accumulation than all other treatments. The IF treatment did not result in a significant accumulation of soil test P at any point in the study (Liechty et al, 2009). Soil test P accumulation also increased in the SWITCH study in response to a single application of litter at both rates. In the LA-FORvsPAST and AR-FORvsPAST studies, soil test P accumulation increased in response to broiler litter in loblolly pine plantation and in pasture (Liechty et al., 2009). Increases in soil test P in surface soil in response to litter application have been similarly found in agricultural (Mitchell & Tu, 2006; Sharpley et al., 1993; Sistani et al., 2004) and forest (Friend et al., 2006) soils. In addition to these increases in upper soil horizons, soil test P accumulation was increased to the B_t horizon (an average depth of 0.59 m) by the 10PL treatment after four applications in the SILVO study (Blazier et al., 2008*a*). Additional evidence of increasing soil test P in lower soil profile was found in the LA-FORvsPAST study, in which soil test P concentrations of the 20PL treatment exceeded that of all others in the 30 to 45 cm depth in loblolly pine and bermudagrass soil in the seventh year of the study (data not shown). These increases in soil test P in surface and subsurface soil in response to annual litter applications suggest that vegetation P demands and soil P sorption capacity were exceeded at all sites irrespective of vegetation type and stand conditions.

			Year after treatment						
Study	**Treatment**	**Depth (cm)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
SILVO	CONTROL	0–15[a]	13.0 *b*	------	16.9 *b*	10.5 *c*	------	------	------
	IF		19.0 *b*	------	22.1 *b*	24.1 *c*	------	------	------
	PL5		36.7 *a*	------	68.5 *a*	87.2 *b*	------	------	------
	PL10		48.8 *a*	------	84.2 *a*	146.5 *a*	------	------	------
	CONTROL	15-48[b]	3.8 *a*	------	-0.4 *a*	-5.2 *b*	------	------	------
	IF		0.9 *a*	------	-2.0 *a*	-5.8 *b*	------	------	------
	PL5		3.3 *a*	------	1.1 *a*	0.9 *b*	------	------	------
	PL10		2.8 *a*	------	4.4 *a*	80.2 *a*	------	------	------
	CONTROL	48-59[c]	2.2 *a*	------	-1.4 *a*	-4.0 *b*	------	------	------
	IF		-0.4 *a*	------	-4.5 *a*	-6.6 *b*	------	------	------
	PL5		-0.5 *a*	------	-3.5 *a*	-5.7 *b*	------	------	------
	PL10		-1.8 *a*	------	-3.5 *a*	44.6 *a*	------	------	------
SWITCH	CONTROL	0-15	0.2 *c*	------	------	------	------	------	------
	IF80		0.1 *b*	------	------	------	------	------	------
	IF160		0.1 *b*	------	------	------	------	------	------
	PL90		0.5 *a*	------	------	------	------	------	------
	PL180		0.5 *a*	------	------	------	------	------	
LA-FORvsPAST[d]	CONTROL	0-15	-19.9 *b*	-8.67 *a*	-24.1 *b*	-11.9 *c*	------	-11.0 *c*	-19.6 *c*
	PL5		3.2 *b*	9.3 *a*	-14.2 *b*	26.4 *bc*	------	162.5 *bc*	82.9 *bc*
	PL10		32.2 *ab*	29.7 *a*	65.3 *a*	103.2 *b*	------	328.2 *b*	210.0 *b*
	PL20		71.2 *a*	43.5 *a*	80.8 *a*	243.4 *a*	------	760.0 *a*	447.6 *a*
AR-FORvsPAST[d]	CONTROL	0-15	------	10.1 *b*	------	------	------	------	------
	PL9		------	47.2 *a*	------	------	------	------	------

Table 8. Soil test P accumulation ($mg\ kg^{-1}$) in response to fertilization with poultry litter and inorganic fertilizer in the mid-South U.S.A. For each study site and soil depth, means within columns followed by different letters differ at $P < 0.05$. [a]Average depth of soil samples subdivided into the A horizon, [b]average depth of soil samples subdivided into the E horizon, [c]average depth of soil samples subdivided into the B_t horizon, [d]soil test P accumulation reported for study is an average of loblolly pine plantation and pasture soils because analyses did not reveal a treatment x land use type interaction. Adapted in part from Blazier et al. (2008*a*) and Liechty et al. (2009)

Land use type and rate affected soil test P trends in response to broiler litter in the LA-FORvsPAST study. Soil test P accumulation in the loblolly pine plantation averaged over all treatments exceeded that of the pasture for six years of the study (Figure 3). Initial soil test P concentrations of the pasture were 1.5 times greater than that of the loblolly pine plantation (data not shown), but in the first three years of treatment soil test P accumulation of the pasture was negative whereas soil test P accumulation of the loblolly pine plantation ranged from 51 to 76 $mg\ kg^{-1}\ year^{-1}$ over the same period. Until the final fertilization, soil test P increased more markedly in the loblolly pine plantation than in the pasture. These differences in soil test P accumulation trends between land use types may have been indicative of lower P demand by loblolly pine than bermudagrass, which led to a greater P accumulation in the soils of the loblolly pine plantations than pastures. Litter application rate also influenced soil P accumulation in both land use types in the LA-FORvsPAST study

(Table 8). Annual applications of litter at 5 Mg ha^{-1} did not significantly increase soil test P relative to the CONTROL treatment during the study. Soil test P accumulation was greater in response to the 20 Mg ha^{-1} litter application rate relative to the CONTROL and PL5 treatments throughout the study and greater relative to the 10 Mg ha^{-1} rate by the fourth annual fertilization.

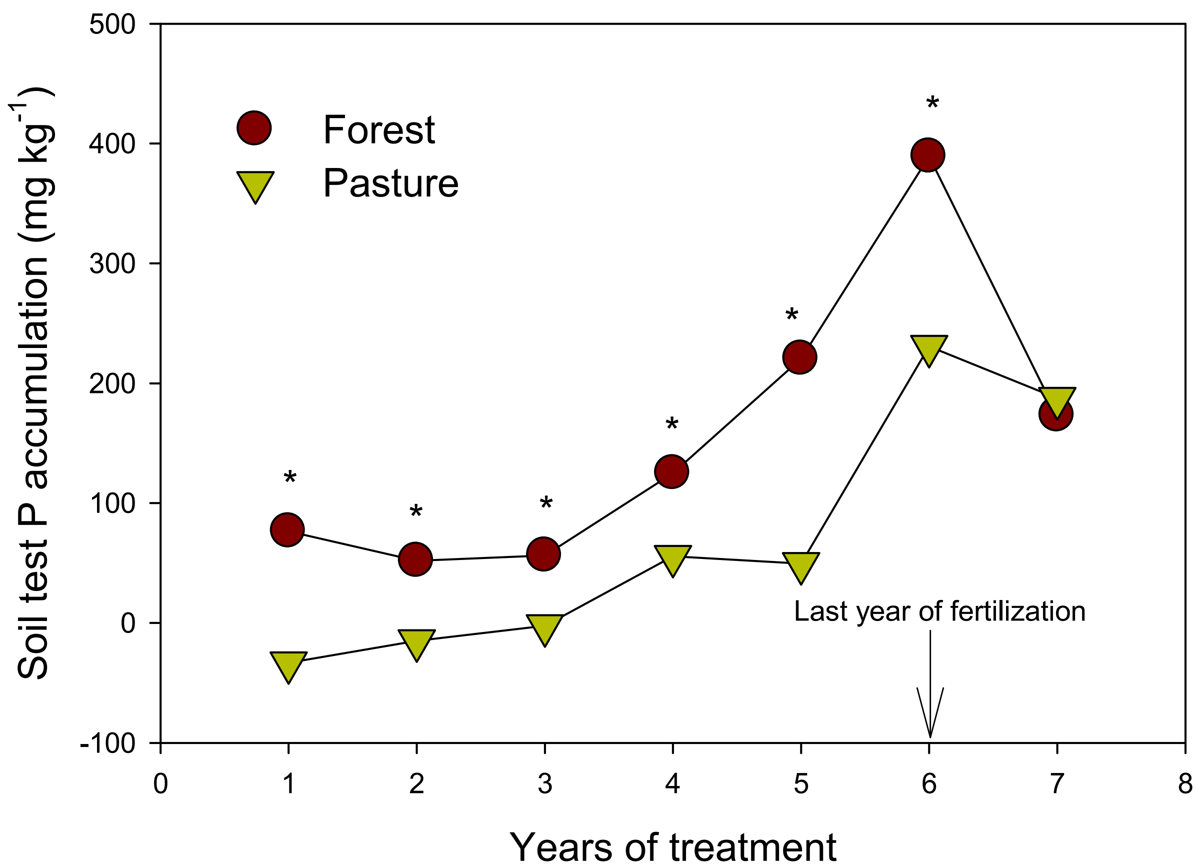

Fig. 3. Soil test P accumulation (0 to 15 cm) as affected by annual fertilization with poultry litter in a loblolly pine plantation and a bermudagrass pasture in the mid-South U.S.A. Asterisks denote years in which soil test P accumulation differed among land use types at $P < 0.05$

6.3 Other nutrients

Soil K concentrations were increased by broiler litter in the SILVO study (Table 9). A single application of the 10PL treatment increased K concentrations in the A horizon, and subsequent applications led to increases in K concentrations in the E horizon. Increases in K concentrations in lower soil depths have also been observed in response to annual litter fertilization of pastures and agricultural crops on sandy soils (Kingery et al., 1994; Mitchell & Tu, 2006). A similar increase in soil K concentrations in the uppermost 15 cm of soil in response to a single application of broiler litter was found in the SWITCH study (data not shown). In that study soil K increased more in response to the PL3 treatment than all others, and K concentrations of all other fertilizer treatments exceeded that of the CONTROL treatment. Results of both studies indicate that poultry litter can lead to increases in soil K concentrations in these silvopastures, even after a single application.

Although soil K concentrations increased in both the SILVO and SWITCH studies, the amount of poultry litter required to increase the concentrations differed between the two types of silvopastures. An application of only 1.5 Mg ha^{-1} of litter was needed to increase K concentrations in the loblolly pine-switchgrass silvopasture while in the loblolly pine-bahiagrass silvopasture K concentrations were observed only after two annual applications of 10 Mg ha^{-1} of poultry litter. Since the soil type was identical for these two studies, these results suggest that loblolly pine-bahiagrass silvopasture had a greater K demand than the loblolly pine-switchgrass silvopasture. The higher demand of the loblolly pine and bahiagrass pasture was likely due in part to loblolly pine density that was nearly double that in the loblolly pine and switchgrass silvopasture. The switchgrass also likely had a lower K demand than bahaiagrass , because switchgrass is characterized by relatively low nutrient demand despite its relatively high biomass growth potential (Tilman et al., 2006). Nevertheless, annual broiler application at 10 Mg ha^{-1} apparently exceeded vegetation K demand and sorption capacity of the A horizon in the loblolly pine and bahiagrass silvopasture as indicated by increased in K concentrations in the E horizon after four annual applications.

			Date			
Nutrient	**Horizon**	**Treatment**	**1997**	**1998**	**2001**	**2002**
K	A	CONTROL	42.1 a	30.1 b	23.3 a	30.7 a
		IF	33.9 a	42.9 b	23.7 a	26.0 a
		PL5	33.2 a	44.3 b	31.4 a	30.1 a
		PL10	39.8 a	62.6 a	34.9 a	36.1 a
	E	CONTROL	22.8 a	22.2 a	21.3 c	34.1 b
		IF	22.7 a	27.2 a	28.8 bc	37.8 b
		PL5	21.7 a	34.2 a	39.7 ab	43.8 b
		PL10	30.8 a	36.8 a	51.5 a	60.0 a
Mg	A	CONTROL	30.5 b	33.8 b	107.7 bc	96.2 c
		IF	32.0 a	26.9 bc	103.7 c	89.3 c
		PL5	34.8 a	38.4 ab	113.5 ab	100.9 b
		PL10	35.2 a	44.4 a	120.6 a	114.8 a
	E	CONTROL	26.6 a	25.8 b	107.8 b	100.4 b
		IF	29.8 a	25.8 b	112.4 b	104.4 b
		PL5	34.8 a	28.2 ab	126.6 ab	114.3 ab
		PL10	57.6 a	34.9 a	145.1 a	137.6 a
Ca	A	CONTROL	184.6 a	194.6 a	134.4 c	70.2 c
		IF	177.2 a	157.2 a	89.6 c	20.8 c
		PL5	171.2 a	196.0 a	162.9 b	95.5 b
		PL10	186.0 a	226.0 a	229.9 a	174..3 a

Table 9. Effects of annually fertilizing a loblolly pine and bahiagrass silvopasture with poultry litter and inorganic fertilizer on soil K and Mg in the A and E soil horizons and on Ca in the A horizon. For each nutrient and horizon, means within a column followed by a different letter differ at $P < 0.05$. Adapted from Blazier et al. (2008a)

As with K, soil Mg concentrations were increased in the A and E horizons by repeated applications of litter in the SILVO study (Table 9; Blazier et al., 2008a). After two applications soil Mg in the A and E horizons was increased by the 10 Mg ha^{-1} rate relative to the CONTROL and IF treatments, and after four applications the 5 Mg ha^{-1} rate led to greater soil K concentrations in the A horizon than in the CONTROL and IF treatments. However, the 5 Mg ha^{-1} did not increase soil K concentrations in the E horizon and did not increase soil K concentrations to levels in the A horizon comparable to that of the 10 Mg ha^{-1} rate after the fourth applications. By the fourth application, soil Ca concentrations in the A horizon were also increased by the poultry litter treatments, with that of the PL10 treatment exceeding all other treatments and that of the PL5 treatment greater than the CONTROL and IF treatments.

7. Water nutrients

Poultry litter applications led to increases in NO_3-N in soil water in the AR-FORvsPAST study. Total N concentrations in soil water were greater for pastures than the loblolly pine plantation and greater for the PL9 treatment than the CONTROL treatment; differences in NO_3-N accounted for the majority of the total N differences between land use types and treatments. In both pasture and loblolly pine plantation, NO_3-N concentrations increased in response to poultry litter application (Figure 4). Soil water NO_3-N concentrations were

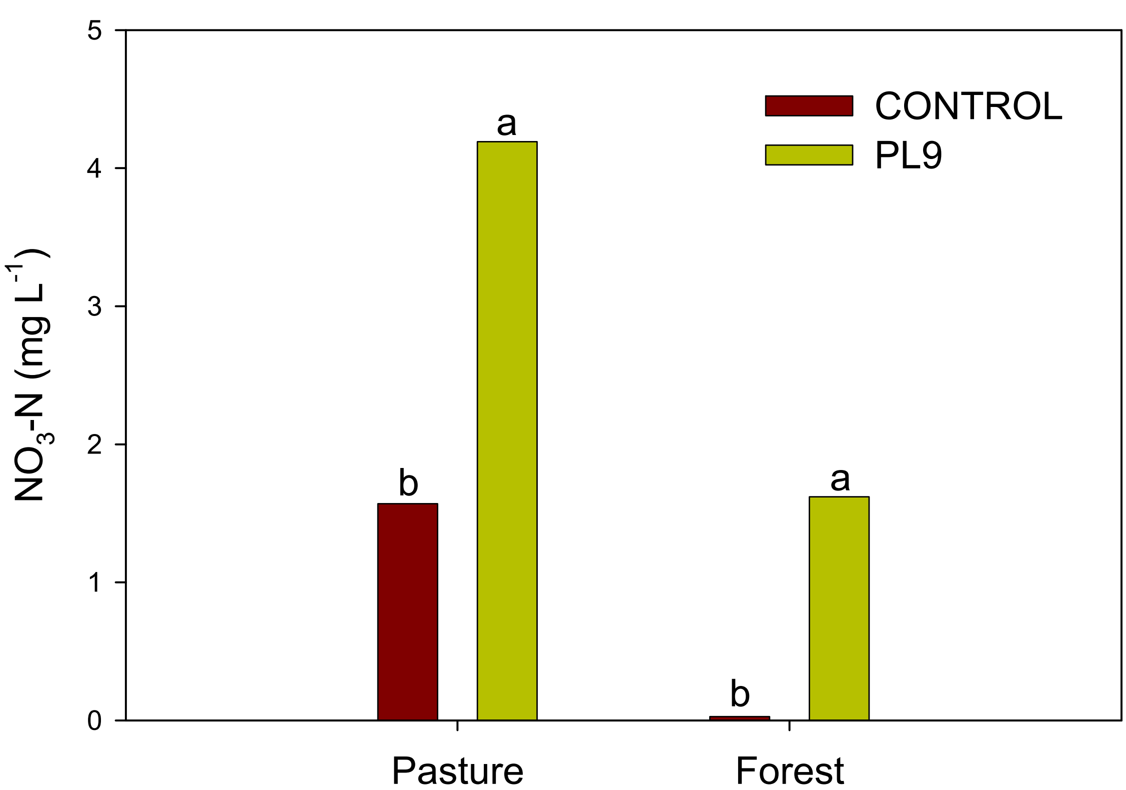

Fig. 4. Mean bi-weekly soil water (30 cm) NO_3-N concentrations in bermudagrass pasture and loblolly pine plantation treated with poultry litter. For each land use type, means headed by different letters differ at $P < 0.05$. Adapted from Liechty et al. (2009)

significantly positively correlated with potential nitrification rates. Although bi-weekly NO_3-N concentrations in soil water never exceeded the 10 mg L^{-1} drinking water standard of the U.S. Environmental Protection Agency in the loblolly pine plantation, this standard was exceeded in two or more sampling periods in pasture plots fertilized with poultry litter. Soil water N increased 51% more in pastures than in loblolly pine plantation, which suggests the potential for N pollution of water is greater for pastures fertilized with poultry litter than for loblolly pine plantations fertilized with poultry litter. However, because forest soils have an apparently greater propensity than pastures to retain proportionally greater NO_3-N in soil (described above), with long-term litter applications N losses in soil water from forests could be greater than in pastures (Liechty et al., 2009).

Repeated fertilization with poultry litter led to increases in total and dissolved P concentrations in runoff in pasture and loblolly pine plantation in the LA-FORvsPAST study. Total and dissolved P concentrations increased with increasing litter application rate in both land use types, although the P concentrations increased more markedly to 10 and 20 Mg ha^{-1} rates in pasture than in loblolly pine plantation. Total and dissolved P concentrations in runoff were positively correlated with Bray P concentrations in soil. These results indicate potential for losses of P in runoff in response to litter application in pasture and loblolly pine plantation, with modest evidence that P loss potential in loblolly pine plantation was lower. In the AR-FORvsPAST study, there were no significant differences in total P concentrations in soil water among treatments and land use types.

8. Conclusions

Poultry litter was a beneficial fertilizer for loblolly pine plantations and silvopastures in this series of studies. Unlike with inorganic fertilizer, soil pH did not decrease with poultry litter application, which sustained microbial biomass and activity at levels comparable to non-fertilized soil. Poultry litter application to soils that had annual pine straw harvesting maintained soil strength, organic matter, and soil moisture similar to those without straw harvesting, whereas applying inorganic fertilizer to soils with straw harvesting negatively impacted these soil attributes. Loblolly pine trees in plantations and silvopastures, as well as the grasses in silvopastures, responded to poultry litter fertilization with increased growth and nutrient concentrations. These increases in plant growth and nutrition provided some buffering against increasing soil nutrient concentrations when these plantations and silvopastures were annually fertilized with poultry litter. Nevertheless, poultry litter was more prone to lead to accumulation of NO_3-N and P in soil than inorganic fertilizer. Loblolly pine plantations were also more prone to increases in soil NO_3-N and P than pastures. Accumulations in soil NO_3-N and P were also associated with increased NO_3-N and P concentrations in soil water and runoff, respectively. As such, poultry litter fertilization of these loblolly pine plantations and silvopastures had the potential to contaminate soil water with N and P. Any poultry litter fertilization regimes for loblolly pine plantations and silvopastures must account for the greater tendencies of N and P accumulation in soil and water of these ecosytems; lower rates and/or frequencies than those used in these trials will likely be necessary for ecologically sustainable fertilization with poultry litter.

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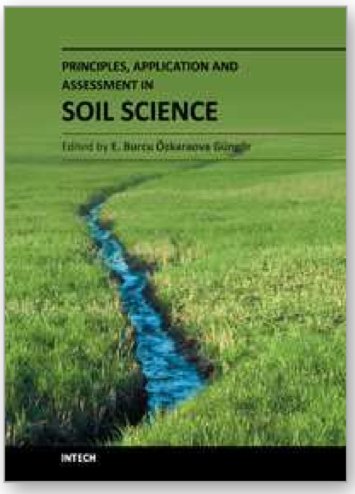

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Our dependence on soil, and our curiosity about it, is leading to the investigation of changes within soil processes. Furthermore, the diversity and dynamics of soil are enabling new discoveries and insights, which help us to understand the variations in soil processes. Consequently, this permits us to take the necessary measures for soil protection, thus promoting soil health. This book aims to provide an up-to-date account of the current state of knowledge in recent practices and assessments in soil science. Moreover, it presents a comprehensive evaluation of the effect of residue/waste application on soil properties and, further, on the mechanism of plant adaptation and plant growth. Interesting examples of simulation using various models dealing with carbon sequestration, ecosystem respiration, and soil landscape, etc. are demonstrated. The book also includes chapters on the analysis of areal data and geostatistics using different assessment methods. More recent developments in analytical techniques used to obtain answers to the various physical mechanisms, chemical, and biological processes in soil are also present.