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Growth and Soil Nutrient Responses to Stocking Rate and Nitrogen Source for Mid-Rotation Loblolly Pine in West-Central Arkansas

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Abstract: Fertilization is needed to replace nutrients removed from pine straw plantations, but tree response to fertilization could be influenced by stocking rate. Our objective was to determine effects of three N fertilizer sources on loblolly pine (*Pinus taeda* L.) growth and pine straw yield as a function of stocking rate (trees ha^{-1}, TPH) at about mid-rotation (12-14 years post-planting). Commercial mineral fertilizer (CF), poultry litter (PL, 5.4 Mg ha^{-1}), and pelletized poultry litter (PPL, 4.6 Mg ha^{-1}) were applied once in April 2006 at 0 (control) and 200 kg ha^{-1} of N at plantation stocking rates of 2300, 1200, and 970 TPH near Booneville, AR. Basal area (range 32.6 to 42.8 m^2 ha^{-1}) was very high and did not respond to fertilization, and pine straw yield also did not consistently increase with fertilization compared to the control. Concentrations of pine straw N and foliar N increased with fertilization, especially with CF compared to litter. Topsoil NO_3^--N and NH_4^+-N were greater for CF than PL and PPL 3 mo after fertilization, but responses $\geq$ 9 mo after application did not differ from the control. While the plantations were able to acquire N, overstocking seemed to constrain N utilization for increased BA or foliage production. Thinning should improve tree growth and pine straw yield responses to fertilizer applied at mid-rotation.

Keywords: Basal area, pine straw, *Pinus taeda* L., poultry litter, soil N.

INTRODUCTION

Demand for timber products in the US is projected to nearly double from 1994 to 2050, with the southeastern region expected to be the major source of expansion in softwood timber supply [1]. About 9 million ha in the southern US, much of it marginal crop and pastureland, could be converted to pine plantations to alleviate anticipated increases in prices of timber products [2]. Loblolly pine (*Pinus taeda* L.), one of the southern yellow pines, is the leading timber species in the US, predominating on 13.4 million ha and representing about 1.4 billion m^3 of southern pine growing stock [3]. The Ouachita region of Arkansas has 71 million m^3 of southern pine growing stock on 520 thousand ha [4]. Besides timber, this resource also offers tremendous untapped economic potential for pine straw production.

Pine straw is a renewable non-timber forest product widely used as a landscape mulch for highway, commercial, and residential applications [5]. Landowners with plantations of southern pines can realize a cash flow from selling pine straw early in the tree rotation, perhaps as early as 8 years after planting (depending on spacing), and this early return can be an important component to whole-farm economic viability [D.M. Burner *et al.*, 2009, unpublished data; 6-8]. Yield of loblolly pine straw in the southeast US commonly ranges from 4.2 to 7.7 Mg ha^{-1} [9, 10], valued at about \$250 ha^{-1} or \$62 million in 2006, a 161% increase from 2005 [11].

As for any conventional agricultural or silvicultural practice, fertilization of pine straw plantations is important either early in the rotation, and is generally considered a best management practice at about mid-rotation after the first thinning [10, 12]. Plantations also may be fertilized at least 3 to 4 years before thinning or harvesting for the residual tree stand to realize the most benefit to enhancing pine straw production and wood volume [10]. Southern pines usually respond to fertilization when foliar N and P concentrations are $\leq$ 12.0 and 1.2 g kg^{-1} [13], respectively. Poultry litter (PL) has been suggested for forest fertilization as an effective, environmentally sound, and less expensive N source than commercial fertilizer (CF) [14, 15]. While landowners have a choice of fertilizers, however, they may not be convinced of the inherent cost-benefit economics of fertilization *per se* [14].

When plantation-grown loblolly pine was measured 4 years after a single surface application of either 15.7 Mg ha^{-1} PL or CF (diammonium phosphate plus urea), stem diameter at 1.3-m above soil surface (dbh) tended ($P<0.10$) to be greater with PL than CF, but not stem volume ($P>0.23$) [16]. The single application was equivalent to 112 kg ha^{-1}of total N, comparable to that recommended for an emulated loblolly pine silvopasture [17].

Pine spacing and management often are objective-driven (including goals of tree farming activities) and site specific (varying with pine species, soil characteristics, harvest frequency, rotation length, and fertilization regime), but there has been little production [8] or pine straw research for Arkansas [18, 19]. The knowledge database needs to be expanded to enable growers to match plantation stocking rate

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and fertility management with specific growing conditions, goals, and budget.

Our objective was to determine effects of three N fertilizer sources on loblolly pine (*Pinus taeda* L.) growth and pine straw yield as a function of stocking rate (trees ha^{-1}, TPH) at about mid-rotation (12-14 years post-planting). We hypothesized that fertilization would significantly increase tree growth and pine straw yield compared to the control.

MATERIALS AND METHODS

The experimental site was located near Booneville, AR at 150 m above sea level (35°N, 94°W). Soil was predominantly Leadvale silt loam (fine-silty, siliceous, semiactive, thermic Typic Fragiudult) on a 1 to 3% slope. Depth to friable shale is $\geq$ 1.2 m [20], but a restrictive fragipan occurs at 40 to 60 cm depth [17]. The site index for loblolly pine is about 20 m at 25 years [21].

In spring 1994, one-year-old loblolly pine seedlings selected for increased growth rate [22] were planted in east-west row orientation in one of three 0.4 ha spatial designs (plots): 1.2 (within row) x 2.4 m (between row), 2.4 x 2.4 m, and 3.6 x 2.4 m in a randomized complete block design with three replications. The 1.2 x 2.4, 2.4 x 2.4, and 3.6 x 2.4 m plots were a subset of those previously described [23], and had the equivalent of 2300, 1200, and 970 TPH, respectively, in April 2006. All plots had closed canopies when the study was initiated. The site was used as meadow for decades, and received no lime or fertilizer input for an undetermined number of years before tree planting or prior to imposing experimental treatments. Tree branches were pruned from soil surface to about 2 m stem height in winter 2004, and pruning debris removed from the site. Trees were not pruned during the remainder of the test.

Fertilization treatments consisting of control (no fertilization), untreated PL, pelletized poultry litter (PPL), and CF (NH_4NO_3,) were assigned at random to subplots (9.7 m wide [five tree rows] x 30 m long) in a randomized complete block design with three replications, and broadcast (surface) applied in early April 2006 prior to first thinning [10]. Treatments were designed to supply equivalent N loading rates of 200 kg ha^{-1} of elemental N for each fertilizer treatment. Litter rates were equivalent to 5.4 and 4.6 Mg ha^{-1} for PL and PPL, respectively. Triple super phosphate and KCl applied individually in CF supplied P (100 kg ha^{-1}) and K (150 kg ha^{-1}) at approximately the same rate as that applied in the PL and PPL fertilizers. Adjustments among the fertilizer sources for other macro- and micro-nutrients were not made.

The PPL was commercially available as Microstart60 (Perdue AgriRecycle, Seaford, DE), an organic, pasteurized, pelletized form of poultry litter (poultry species unknown) with a presumptive elemental N-P-K nutrient composition of 40, 20, and 30 g kg^{-1}, respectively) [24]. Untreated, dry PL [rice (*Oryza sativa* L.) hull bedding] was obtained from a commercial broiler (*Gallus gallus domesticus* L.) operation. The two litter fertilizers were analyzed for chemical and nutrient concentrations (dry basis) by the University of Arkansas diagnostic laboratory (Fayetteville, AR), which confirmed the presumptive elemental N-P-K concentrations of PPL, and that PL and PPL had similar chemical and nutrient composition (Table **1**).

A composite sample of first-flush foliage was collected from the upper one-third of five tree crowns $plot^{-1}$ in July 2005 (pre-test), oven dried at 60 °C, and analyzed for N by combustion (Vario Max CN, Elementar Americas, Inc., Mt. Laurel, NJ) to examine baseline concentration. While this preliminary sample was not dormant season foliage as recommended [25], mean N concentration was 12.4 g N kg^{-1} (range 10.6 to 15.0 g N kg^{-1}). Foliage was subsequently sampled in July 2006 and 2007, and January 2007 and 2008 [25, 26] and analyzed for N as described above.

One of the center three rows in each subplot was randomly selected, permanently marked, and co-dominant tree dbh was measured by diameter tape on 21 March 2006 (pre-test), 28 November 2006, and 31 March 2009. Basal area (BA) was calculated from mean dbh [27] for subplots and replications:

$$BA\ (m^2\ ha^{-1}) = TPH\ (\pi dbh^2/40{,}000) \qquad (1)$$

where dbh was measured outside bark, cm.

A permanent sub-subplot (5 m long x 2.4 m wide) was situated in an alley near the center of each subplot, and all accumulated pine straw and duff layer was removed in spring 2006 (pre-test). Yield of dry (60 °C) pine straw was measured annually in November 2006, October 2007, and November 2008 in a 1m^2 quadrat located at random within the permanent sub-subplot. A sample of pine straw was ground in a Wiley mill (Arthur Thomas Co., Philadelphia, PA) to pass a 1mm screen and stored at -20 °C prior to N analysis by combustion (Vario Macro CN, Elementar Americas, Inc., Mt. Laurel, NJ). Yield of pine straw was expressed as Mg dry mass ha^{-1} yr^{-1}. Following harvests, residual pine straw and duff layer was removed from the sub-subplot and discarded. The few weeds present within sub-subplots were controlled using spot applications of herbicides.

Table 1. Chemical and Nutrient Analysis of Poultry Litter (PL), Microstart60 Pelletized Poultry Litter (PPL), and Commercial Fertilizer (CF) Applied to Loblolly Pine Stands Near Booneville, AR

Fertilizer	pH[a]	EC[b]	N	P	K	Ca	C
		(μmhos cm^{-1})	---------- (g kg^{-1}) ----------				
PPL	7.1	11500	43.2	15.8	30.3	26.4	335.6
PL	7.5	10700	37.4	15.0	26.6	22.3	344.6
CF[c]	ND[d]	ND	340.0	200.7	498.1	ND	ND

[a] 1:2 litter:water, volume basis.
[b] Electrical conductivity.
[c] Based on labeled composition.
[d] Not determined.

Topsoil (0 to 10 cm depth), excluding surface duff layer, was sampled from each subplot in April 2006 (0 mo following fertilization), July 2006 (3 mo), January 2007 (9 mo), July 2007 (15 mo), and January 2008 (21 mo). Soil samples were air-dried, ground in a mortar to pass a 1.4 mm screen, and analyzed for N and C by combustion (Leco FP428, Leco Corp., St. Joseph, MI), and the ratio of C/N was calculated. Topsoil was analyzed for mineral N by extracting with 1.0 M KCl. Extracted NH_4-N was assayed by colorimetry and NO_3-N by Cd-reduction coupled colorimetry using procedures for an automated discrete analyzer (AQ2, SEAL Analytical US Inc., Mequon, WI). Topsoil was analyzed for pH (1:1, topsoil:water, w:v, 5 min mixing followed by 1 h equilibration), 1.0 M KCl extractable Al [28], and Mehlich III extractable P [29].

To characterize climatic conditions, air temperature and rainfall, measured 1.4 m above soil surface, were continuously recorded at 0.5 h intervals from 1 April 2006 through 31 January 2008 at an unshaded weather station located 1.3 km northwest of the pine plantation. Air temperature was measured with a Model 3667 external temperature probe (Spectrum Technologies, Inc, Plainfield, IL), and rainfall was measured with a Model 3525R tipping bucket rain gauge (Spectrum Technologies, Inc, Plainfield, IL). Data were averaged (air temperature) or summed (rainfall) across months. Long-term (1971 to 2000) mean monthly air temperature and rainfall were from an official weather station located 7.0 km east of the pine plantation [30].

Analysis of variance (ANOVA) used a mixed linear model, Proc Mixed [31]. Fixed effects were sampling date, stocking rate, fertilization treatment, and their interactions. Sampling date was month (0, 3, 9, 15, and 21 mo after fertilization) or year depending on variable. Data were analyzed by repeated measures [32] with a first-order autoregressive covariance structure using sampling date as the repeated effect. Replication and its interactions with fixed effects were random effects. The model used a restricted maximum likelihood estimation method with degrees of freedom calculated by the Satterthwaite approximation method. Means were considered different at $P<0.05$ using Tukey's honest significant difference (HSD) test. Trends and interactions were further examined using the Reg procedure [31].

RESULTS

Mean monthly air temperatures were usually greater than the long-term mean during the study interval, but followed the same general trend (Fig. **1**). The rainfall pattern during the study interval diverged substantially from the long-term mean, but mean rainfall for the interval (90.2 mm mo^{-1}) was similar to the long-term mean (102.1 mm mo^{-1}).

Tree Growth

Tree dbh was significantly affected by year, stocking rate, and the year x stocking rate interaction, but was not significantly affected by fertilizer treatment and its interactions ($P \geq 0.18$). The year x stocking rate interaction appeared to be caused by a different rate of change (slope) in dbh with month at the three stocking rates (Fig. **2**). Across years, tree dbh differed with stocking rate on the order 970 > 1200 > 2300 (21.2, 19.0, and 15.0 cm, respectively).

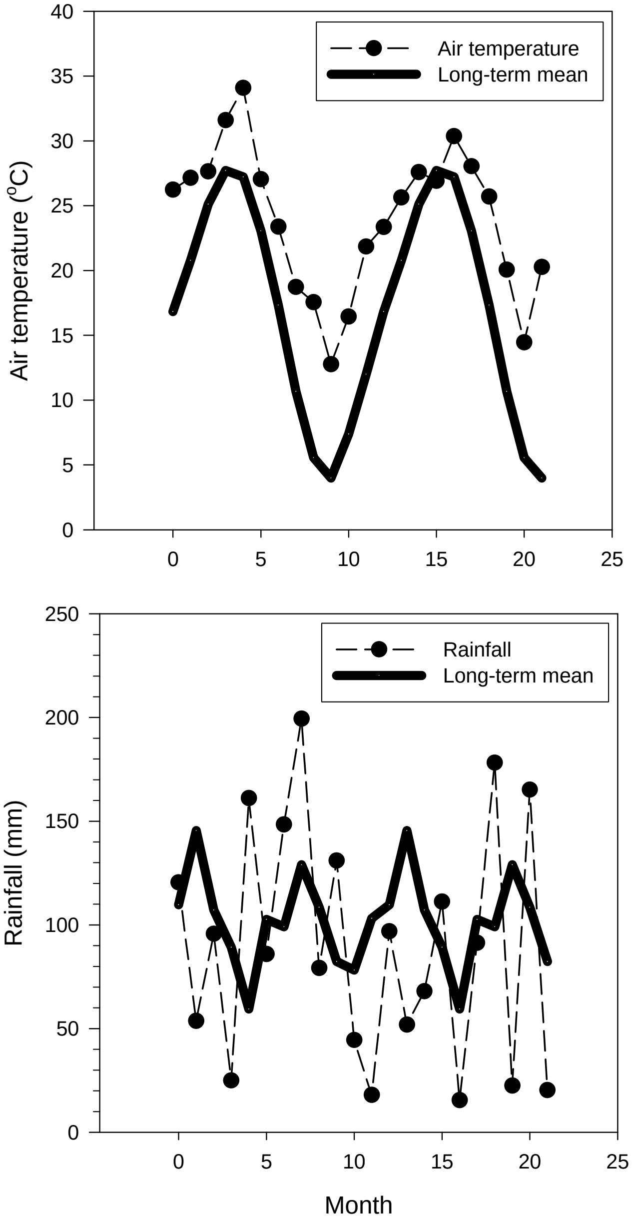

Fig. (1). Monthly climatic conditions near Booneville, AR from April 2006 (month 0) through January 2008 (month 21). Long-term mean air temperature and total rainfall were for the period 1971 to 2000 from a station located 7.0 km east of the experimental site [28].

Estimated BA was significantly ($P \leq 0.01$) affected by year, stocking rate, and stocking rate x fertilizer interaction, but not for the year x stocking rate interaction ($P=0.23$). The stocking rate x fertilizer interaction appeared to be caused by differing responses of BA to TPH (Fig. **3**); and only PL caused a significant BA response to TPH ($P=0.01$). For any given fertilizer, BA at the 2300 TPH stocking rate (range 39.7 to 42.8 m^2 ha^{-1}) usually exceeded that of the other stocking rates, range 32.6 to 35.5 m^2 ha^{-1}.

Foliar Responses

Pine straw yield was significantly affected by year, stocking rate, fertilizer, and the year x fertilizer interaction. Pine straw yield tended ($P \geq 0.04$) to decrease with time with or without fertilization (Fig. **4**), but regression responses

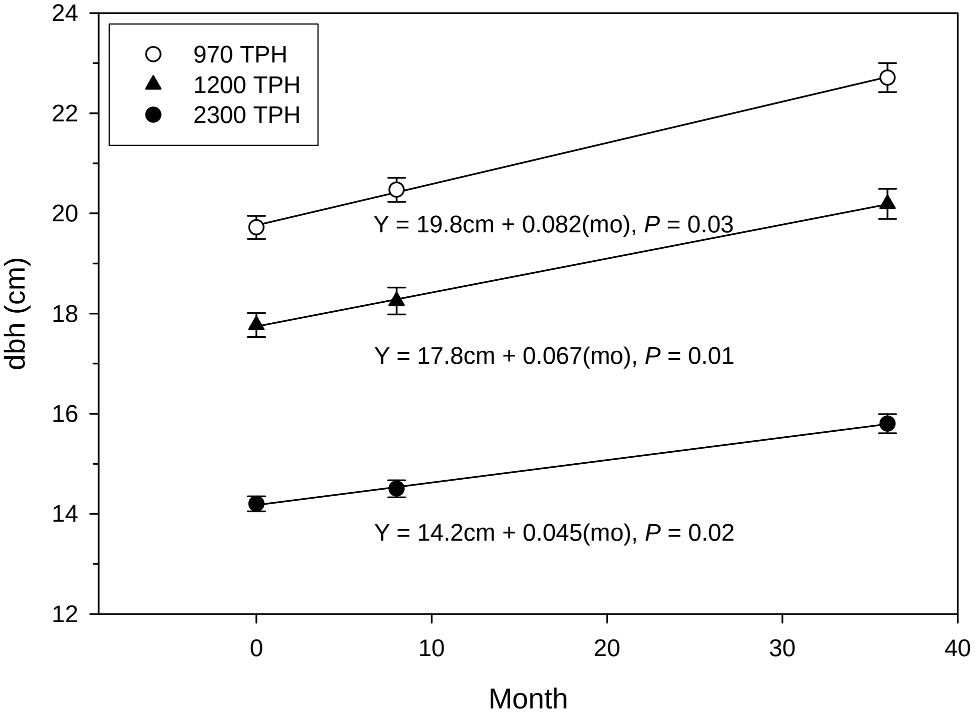

Fig. (2). Temporal change in dbh at three stocking rates (number trees ha^{-1}, TPH) for loblolly pine plantations near Booneville, AR.

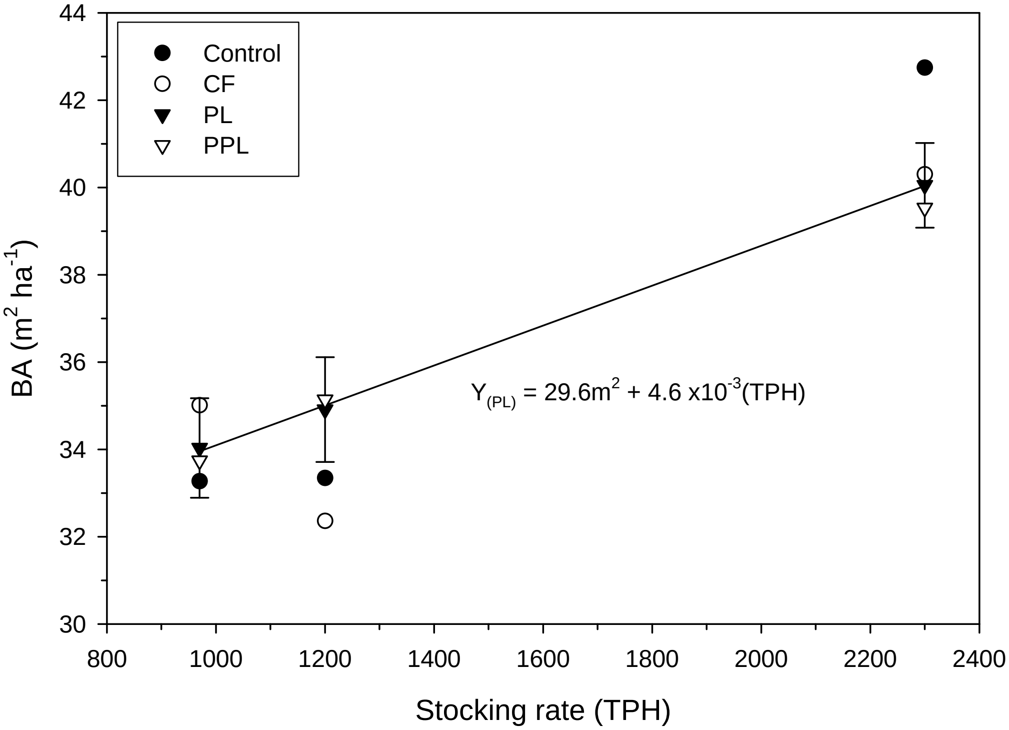

Fig. (3). Change in basal area (BA) with stocking rate (trees ha^{-1}, TPH) and fertilization (Control, CF = commercial fertilizer, PL = poultry litter, and PPL = pelletized poultry litter) for loblolly pine plantations near Booneville, AR. Only PL had a significant regression response (P=0.01). For clarity, SE bars are shown only for PL means.

were significant only for CF (P=0.04). Mean pine straw yield was greater for PL than PPL in 2006, PL yielded more (P=0.06) than the control in 2007, and treatments means did not differ in 2008. Across years, the control (4.6 Mg ha^{-1} yr^{-1}) yielded 9.4 and 12.4% less ($P\leq0.03$) pine straw than plots receiving CF (5.0 Mg ha^{-1} yr^{-1}) or PL (5.2 Mg ha^{-1} yr^{-1}), respectively, but yield did not differ for the control and PPL (4.9 Mg ha^{-1} yr^{-1}) (P=0.33). Yield of pine straw was greater at 1200 (5.2 Mg ha^{-1} yr^{-1}) than 970 TPH (4.7 Mg ha^{-1} yr^{-1}), while yield at 2300 TPH was intermediate (4.8 Mg ha^{-1} yr^{-1}).

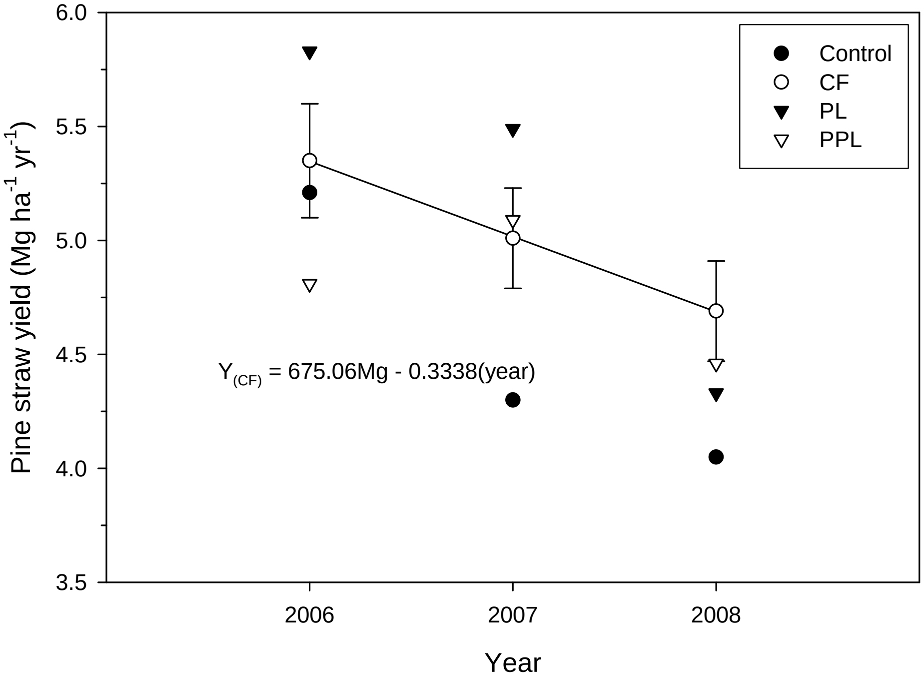

Fig. (4). Change in loblolly pine straw yield with stocking rate (number trees ha^{-1}, TPH) and fertilization (Control, CF = commercial fertilizer, PL = poultry litter, and PPL = pelletized poultry litter) for plantations near Booneville, AR. Only the regression response for CF was significant (P=0.04). For clarity, SE bars are shown only for CF means. Fertilizer means within a year followed by a common letter do not differ (P>0.05).

Pine straw N concentration was significantly affected by year, stocking rate, and fertilization. Pine straw N concentration increased across years in the order 2006 (6.4 g kg^{-1}) < 2007 (6.9 g kg^{-1}) < 2008 (10.0 g kg^{-1}), an indirect indication of fertilization response. The 2300 and 1200 TPH stocking rates (both 7.9 g N kg^{-1}) had greater pine straw N than the 970 TPH stocking rate (7.5 g kg^{-1}). Fertilization increased pine straw N concentration (7.8 to 8.1 g kg^{-1}) compared to the control (7.1 g N kg^{-1}). Averaged across fertilizer treatments, N removals in harvested pine straw were greater at 1200 TPH (41 kg ha^{-1} yr^{-1} of N) than (970 TPH (34 kg ha^{-1} yr^{-1} of N), with 2300 TPH being intermediate (38 kg ha^{-1} yr^{-1} of N). Ignoring potential losses through leaching, runoff, and denitrification, additions from mineralization, and utilization for tree growth, this would be equivalent to about 5 years production from a single application of 200 kg ha^{-1} of N fertilizer.

Foliar N was significantly affected by sampling date and fertilizer. There was a progressive increase (P=0.01) in foliar N from July 2005 (12.3 g kg^{-1}) to July 2007 (18.1 g kg^{-1}), followed by a decrease to 15.8 g kg^{-1} in January 2008. This suggested that a foliar response to fertilization diminished within 2 years after application. Across sampling dates, fertilization increased (P=0.01) foliar N (range 15.5 to 15.8 g kg^{-1}) compared to the control (14.3 g kg^{-1}).

Topsoil Nutrients

There was a significant sampling date x fertilizer interaction for topsoil NO_3^--N and NH_4^+-N, caused by spikes in these N fractions 3 mo after fertilizer application. At 3 mo, topsoil NO_3^--N was greater for CF than PL and PPL, and the litter amendments had more NO_3^--N than the control (Fig. **5**). Topsoil concentrations of NO_3^--N at 9 and 15 mo were slightly elevated compared to that at 0 mo, but the differences were not significant ($P \geq 0.15$). Similar results were found for topsoil NH_4^+-N.

Effects of sampling date and stocking rate on topsoil C and C/N were significant ($P \leq 0.05$). Topsoil C varied (P=0.02) with stocking rate in the order 2300 TPH (1.57 g kg^{-1}) > 1200 TPH (1.47 g kg^{-1}), while 970 TPH was intermediate (1.54 g kg^{-1}). The C/N ratio decreased (P<0.01) between 0 mo (11.6) and 21 mo (10.9), while other dates were intermediate. The 1200 TPH stocking rate (11.1) had lower C/N (P=0.02) than the 970 or 2300 TPH stocking rates (both 11.4).

Only the main effect of fertilizer was significant for topsoil pH (P=0.01). Means differed in the order PL (pH 5.0) > CF (pH 4.8), with PPL intermediate at pH 4.9 (data not shown). The PL and PPL have some liming capacity due to their Ca content (Table **1**).

There were significant stocking rate x fertilizer interactions for extractable topsoil Al and available topsoil P, which appeared to be caused by differences in soil nutrient trends and magnitudes with stocking rate (data not shown). Regression responses of the stocking rate x fertilizer interactions were non-significant ($P \geq 0.29$) for either Al or P. Extractable topsoil Al was greater ($P \leq 0.05$) for CF than PL at 2300 and 1200 TPH (61.6 µg g^{-1} and 23.5 µg g^{-1}, respectively), and intermediate for other fertilizer-stocking rate levels.

Fertilization caused a range of responses in available topsoil P that usually were poorly associated with stocking rate. At 2300 TPH, fertilizer treatments ranked ($P \leq 0.05$) on the order CF > PL > PPL = control in available topsoil P

(18.7, 12.4, 6.6, and 2.4 µg g^{-1}, respectively). At 1200 TPH, fertilizer treatments ranked ($P \leq 0.05$) on the order CF = PL > PPL > control in available topsoil P (17.5, 14.8, 9.2, and 2.3 µg g^{-1}, respectively). At 970 TPH, fertilizer treatments ranked ($P \leq 0.05$) on the order PL > CF = PPL = control in available topsoil P (13.5, 6.0, 5.3, and 1.8 µg g^{-1}, respectively). Across stocking rates, CF (14.1 µg g^{-1}) and PL (13.6 µg g^{-1}) did not differ significantly in available topsoil P and exceeded that of either PPL (7.0 µg g^{-1}) and the control (2.2 µg g^{-1}).

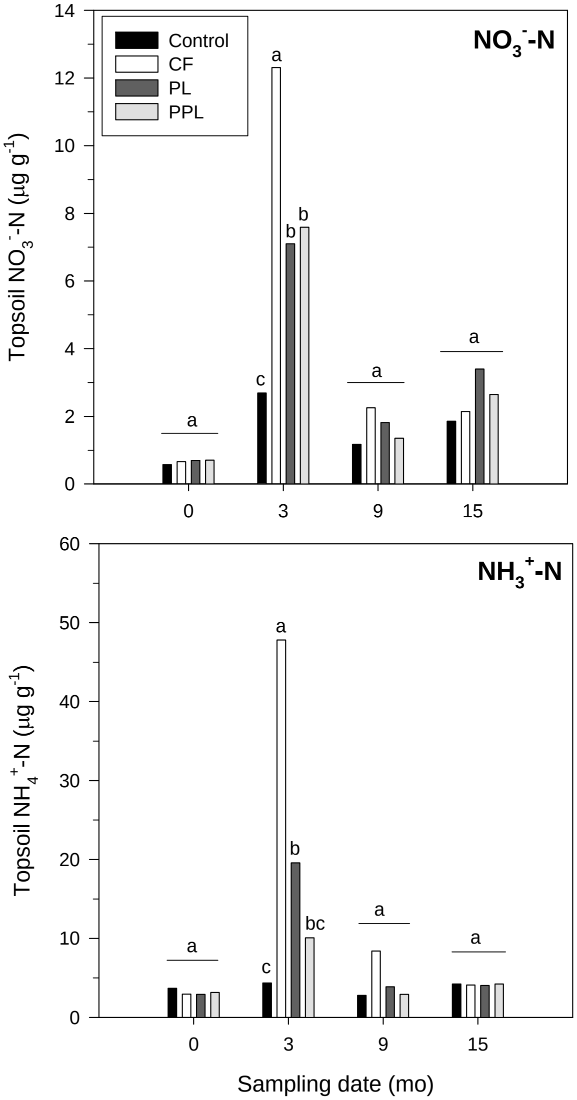

Fig. (5). Change in topsoil (0- to 10-cm depth) NO_3^--N and NH_4^+-N following fertilization (Control, CF = commercial fertilizer, PL = poultry litter, and PPL = pelletized poultry litter) for loblolly pine plantations near Booneville, AR. Fertilizer means within an evaluation date, or above a bar, followed by a common letter do not differ ($P > 0.05$).

DISCUSSION

Tree Growth

Pre-thinning fertilization of overstocked southern pines can cause a post-thinning yield response [10]. Further, fertilization with PL at 4.6 Mg ha^{-1} increased BA of an 8-year-old, lightly stocked (11 m^2 ha^{-1}) loblolly pine plantation in Mississippi [33]. We hypothesized that fertilization would also increase pre-thinning tree growth and pine straw yield. Basal area was high (32.6 to 42.8 m^2 ha^{-1}) and did not respond to fertilization (Fig. **3**).

Competition reduces growth of southern pines by affecting leaf area [34]. Competition-related mortality in intensively managed loblolly pine begins when BA reaches 30 to 35 m^2 ha^{-1} [35]. Similarly, annual stemwood biomass increment peaks as BA reaches 20 to 35 m^2 ha^{-1}, and the maximum BA attained at canopy closure is 45 to 48 m^2 ha^{-1} [35]. Thus, the lack of a BA response to fertilization was attributed to overstocking.

Foliar Responses

The limitation in stand growth as planting density increases appears related to a site's capacity to support leaf area [34]. Thus, N fertilization should foster increased N assimilation and conversion leading to increased leaf area, leaf mass, pine straw yield, and increased stem diameter growth. We observed a transient foliar response to fertilization that diminished within 2 years after application regardless of stocking rate. Foliar N of loblolly and slash (*P. elliottii* Engelm.) pines decreases with increasing stocking rate, because the N sink of densely-stocked stands exceeds the soil N supply source [36].

Compared to the control, fertilization with PL caused only a transient increase in pine straw yield during 2006 and 2007 (Fig. **4**). Pine straw yield at 2300 TPH was intermediate perhaps due to incipient competition-related mortality [D.M. Burner *et al.*, 2009, unpublished data]. Mineral fertilizer and municipal sludge increased yield of pine straw from longleaf pine (*P. palustris* Mill.) on a deep sand in South Carolina [9]. However, our findings generally support those of Haywood [37], who reported that fertilization of longleaf pine (*P. palustris* Mill.) in Louisiana over 15 years did not directly affect tree growth or pine straw yields at age 34 years, perhaps because of competition, repeated prescribed burning, and pine straw removal.

Topsoil Nutrients

Approximately two-thirds of total poultry litter N is in the organic fraction, and there is an initial rapid N release within 7 d of surface application, followed by a slower release during 90 d [38]. Two PL sources had 40 to 60% mineralization of initial organic-N within 120 d when incubated at 25 °C under high humidity [39]. High topsoil NO_3^--N and NH_4^+-N at 3 mo was consistent with relatively low rainfall between 0 and 3 mo, and perhaps rapid N mineralization from PL [37, 39] and topsoil NO_3^--N from CF [40]. The temporal dynamic of topsoil NO_3^--N was very similar to that of a PL-fertilized loblolly pine plantation on a Paleudult topsoil in Mississippi [33], but differed somewhat from [39] who reported substantial soil NO_3^--N ($\geq$125 mg kg^{-1}) 120 d after incorporation. Differences we detected among fertilizers in topsoil NO_3^--N and NH_4^+-N responses might have been caused by differences in organic and mineral N fractions, while transient changes in topsoil NO_3^--N and NH_4^+-N concentrations might have been caused by mineralization of the organic fraction (Fig. **5**). Persistence of relatively high topsoil NH_4^+-N concentration at 3 mo was unexpected, because there was little available soil NH_4^+-N 30 d after incorporating fresh PL in a controlled environment study [39].

Our results confirmed those for 4-year-old loblolly pine plantations [41] in which fertilization effected only a short-term (≤ 2 years) enhancement of soil available N. While we failed to detect an effect of stocking rate on foliar N, that of 4-year-old southern pines decreased from 12.2 to 10.1 g kg^{-1} of foliar N at 740 and 3,700 TPH, respectively [41]. Fertilization also had no effect on topsoil C concentrations or C/N ratios for a loblolly pine plantation in Florida [42].

We confirmed an acidifying effect of CF on topsoil pH [43] relative to the Ca-induced liming effect of PL and PPL (Table **1**). Increased pH resulting from application of PL and PPL fertilizers also could decrease exchangeable Al compared to CF and the unfertilized control [43], and some evidence of this response was observed for PL. Commercial fertilizer was expected to increase exchangeable Al because NH_4NO_3 decreases soil pH [43], but it was not clear why this response was confined to the 2300 TPH stocking rate.

Available topsoil P in the control, 1.8 to 2.4 μg g^{-1}, was below the reported critical range of 3 to 5 μg g^{-1} [44]. All fertilization treatments except PPL generally increased available topsoil P compared to the control, but fertilization generally failed to boost tree growth probably due to high stocking rate. Concentrations of topsoil P were similar to those of this study, and also differed little from the control, for a loblolly pine plantation fertilized with 4.6 Mg PL ha^{-1} in Mississippi [33]. The topsoil P concentration of a loblolly plantation in Florida also was not affected by fertilization, although fertilization increased P mineralization [42]. Since total litter P includes about 54% organic and 41% inorganic fractions [45], it seemed likely that P mineralization differed among fertilizers [38, 46]. Competition also might have altered the understory microenvironment, such as soil water potential [47], affecting P mineralization and P utilization.

A constraint to this study was that fertilizers were broadcast applied to a ground surface which was covered with pine straw, the usual method for fertilizing pine stands [9, 12, 33]. Since the fertilizer granules have poor soil contact there is risk of N loss through NH_4^+-N nitrification [48]. Further, above normal rainfall after 3 mo (Fig. **1**) might have caused the system to lose N through surface runoff. Thus, surface application might have reduced N available for tree use. While alley tillage is generally impractical and unadvised in pine stands [20], mechanized subsurface banding technology is being developed for perennial grasslands which reduces N and P loss in runoff [49]. Such technology might eventually be adapted to pine plantations.

Contrary to our hypothesis, the response to fertilization was mitigated by stocking rate. Stocking rate had a greater effect than fertilization on BA. While fertilization *per se* rarely increased pine straw yield compared to the control, it increased N concentration in pine straw and foliage suggesting that slow N release from litter might benefit tree growth and pine straw yield at lower stocking rate. While the plantations were able to acquire N, overstocking seemed to constrain N utilization for increased BA or foliage production. Future research should include an evaluation of post-thinning growth and yield responses as influenced by pre-thinning fertilization.

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ABBREVIATIONS

BA = Basal area
CF = Commercial fertilizer
PL = Poultry litter
PPL = Pelletized poultry litter
TPH = Trees ha^{-1}

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