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Effectiveness of Silviculture Best Management Practices for Forest Fertilization in Pine Straw Production to Protect Water Quality in Florida: Four Year Monitoring Results and Interpretation

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EXECUTIVE SUMMARY

A silvicultural fertilization BMP effectiveness monitoring project was conducted for four and a half years (October 2008 to March 2013), at two study locations having contrasting leaching potential, to observe the environmental fate of nitrogen and phosphorus applied at various amounts relative to BMP guidelines.

- Poor or negative pine stand responses were observed for DAP fertilization at both sites.
- Nitrate leaching through the soil profile was observed at both sites following each of two sequential annual fertilizations but was greater after the second fertilization.
- Peak NO_x-N concentrations at the deepest monitored depth (60-72") were observed at six months after the second application of the highest DAP rate (641 lb/acre) at Live Oak and at nine months at Blounstown. At these times, peak NO_x-N concentrations in the deepest monitored depth were 2.75 mg/kg at Live Oak and 1.29 mg/kg at Blountstown, significantly greater than the non-fertilized control. Concentrations remained elevated at that depth until one year after the second fertilization at Live Oak and two years after the second fertilization at Blountstown.
- Groundwater NH_4-N, TKN, and TP concentrations observed for wells monitoring the fertilized area did not increase when compared to pre-fertilization baseline levels or distant control wells through the 52-month monitoring period at either study site.
- At the sandy Live Oak site where depth to groundwater ranged from 32.9 to 42.4 ft, NO_x-N concentrations were below the PQL over the 52-month monitoring period, and averaged 0.19 mg/L, near the 0.148 mg/L MDL value.
- At the clayey Blountstown site where depth to groundwater was only 3.0 to 13.5 ft, NOx-N was elevated by fertilization, but concentrations were also related to well drawdown/recharge periods following fertilization. Peak treatment well NO_x-N concentrations were greater than the reference well concentrations by 1.2 mg/L following the first fertilization and by 1.4 mg/L at the time of the second fertilization. However, the maximum NO_x-N concentration during the 52-month monitoring period was 1.6 mg/L, not excessive in terms of water quality, and did not exceed state water quality standards. Treatment well NO_x-N concentrations gradually returned to baseline levels by approximately 43 months after the first fertilization.

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EXECUTIVE SUMMARY

A silvicultural fertilization Best Management Practices (BMPs) effectiveness monitoring project was conducted for approximately four and a half years (October 2008-March 2013), at two mid-rotation slash pine plantations on sites having contrasting leaching potential, to observe the environmental fate of nitrogen (N) and phosphorus (P) applied at various amounts relative to BMP guidelines. Two sequential annual diammonium phosphate (DAP; 18% N and 20% elemental-P) fertilizations in the spring of 2009 and 2010, providing 23/26, 69/78, or 115/130 pounds per acre N/P, were monitored in stands with and without pine straw raking and compared to non-fertilized controls. Two fertilizations using the highest DAP rate examined provided the near BMP maximum amount of N for a three-year period and also provided 300% of the three-year P maximum. Monitoring occurred for four years following the first fertilization and for three years after the second fertilization. Periodic monitoring included N and P concentrations in surficial groundwater, soil nutrient concentrations at various depths, foliar nutrient concentrations, amounts and nutrient concentrations of pine needle litter, and amounts and nutrient concentrations for harvested pine straw. Tree growth responses and disease incidence were also measured periodically. Soil physical properties were assessed at study initiation and two years after the first fertilization. Continuous rainfall and other weather parameters monitoring and soil moisture and temperature monitoring at various depths was done to support modeling of applied nutrient fate. Major findings to date include:

Well monitoring:

- Groundwater NH_4-N, total Kjeldahl nitrogen (TKN), and total phosphorus (TP) concentrations in monthly or quarterly samples taken from wells monitoring the fertilized area did not increase when compared to pre-fertilization baseline levels or distant control wells through the 52 month monitoring period at either study site. Measures of groundwater NH_4-N and TP did not exceed the Practical Quantification Limit (PQL), 0.5 mg/L and 0.01 mg/L, respectively. Groundwater TKN concentration averaged close to the Method Detection Limit (MDL) of 0.125 mg/L.
- Surficial groundwater NO_x-N concentrations were elevated by fertilization at the clayey Blountstown site where groundwater was close to the surface (3.0-13.5 ft), but not at the sandy Live Oak site where groundwater was deeper (32.9-42.4 ft). Changes in groundwater NO_x-N concentration at Blountstown were also related to changes in depth to groundwater, with increasing concentrations during drawdown periods following fertilization and decreasing concentrations during recharge periods (Figure 5).
- At the sandy Live Oak site, NO_x-N concentrations were below the PQL over the 52-month monitoring period, and averaged 0.19 mg/L, near the 0.148 mg/L MDL. There were no significant trends over sampling dates or between reference and treatment wells through the monitoring period.
- At the clayey Blountstown site, NOx-N was elevated by fertilization, but concentrations were also related to well drawdown/recharge periods following fertilization. During the year following the first fertilization, NOx-N concentrations in groundwater samples increased over time to a level 0.28 mg/L greater than the pre-fertilization baseline concentration, a value approximately twice the MDL. Peak treatment well NO_x-N concentrations were greater than the reference well concentrations by 1.2 mg/L following the first fertilization and by 1.4 mg/L at the time of the second fertilization. However, the higher values and peaks were ≤ 1.4 mg L^{-1} greater than background, not excessive in terms of water quality, and did not exceed state water quality standards. Treatment well NO_x-N concentrations gradually returned to baseline levels by approximately 43 months after the first fertilization.
- Significant regression models indicated that treatment well conductivity was increased relative to reference wells during both the first- and second-year post-fertilization drawdown periods at both

sites. Differences in conductivity between treatment and reference wells tended to return to baseline levels, or less, during winter recharge periods and beginning 10-11 months after the second-year fertilization.

Soil monitoring:

- DAP fertilization increased concentrations of soil NH_4-N, NO_x-N and TP, but not TKN.
- Concentrations of these nutrients generally increased with increasing DAP rate from 0 to 641 lb/acre, but the effect of the low (128 lb/acre) rate was usually not significant.
- After each sequential annual fertilization soil NH_4-N concentration increased rapidly and then gradually decreased due to nitrification, uptake by pine roots, and leaching, but also likely due to volatilization, which was not quantified.
- Maximum soil NH_4-N concentrations during the 52 month monitoring period (50.8 and 24.9 mg/kg at Blountstown and Live Oak, respectively) were observed at 0-6" depth one month after the second application of the highest tested DAP rate (641 lb/ac). Applied NH_4-N moved to the lowest monitored depth (60-72") at the sandy Live Oak site but remained within 0-12" at Blountstown where a somewhat poorly drained clayey soil with high cation exchange capacity occurred.
- Soil NO_x-N concentration increased as nitrification of the ammonium fertilizer occurred. The second application of 641 lb/acre DAP resulted in maximum NO_x-N concentrations observed. Peak NO_x-N concentrations then occurred at the 0-6" depth at Blountstown (11.6 mg/kg) and at the 24-36" depth at Live Oak (4.6 mg/kg). Elevated NO_x-N levels, as compared to the non-fertilized control, persisted after the second fertilization for three years at Blountstown, but only for a year after the second fertilization at Live Oak.
- Nitrate leaching through the soil profile was observed at both sites following each of the two sequential annual fertilizations but was greatest following the second fertilization.
- Peak NO_x-N concentrations at the deepest monitored depth (60-72") were observed at nine months after the second application of the highest DAP rate (641 lb/acre) at both sites, and concentrations were significantly greater than the non-fertilized control. At that time, peak NO_x-N concentrations in the deepest monitored depth were 2.75 mg/kg at Live Oak and 1.29 mg/kg at Blountstown. Concentrations remained elevated at that depth until one year after the second fertilization at Live Oak and two years after the second fertilization at Blountstown.
- TP concentration in the surface soil started to increase two months after the first fertilization and remained two (Live Oak) to three (Blountstown) times greater than base line values three years after the second fertilization. These results suggest that additional long-term research is needed to understand the fate of applied P in forests. This has been identified as a gap in current knowledge, for poorly drained soils in particular.
- The maximum soil TP concentrations (265 and 354 mg/kg at Live Oak and Blountstown, respectively) were observed at 0-6" depth nine and six months, respectively, after the second application of 641 lb/acre DAP. No increase in TP concentration was detected below the 12" depth during four years following the first fertilization at either site.
- We have not observed a meaningful effect of annual pine straw removal on any soil nutrient concentration.
- These results indicate NO_x-N leaching in both a somewhat poorly drained, high ion exchange capacity soil (Blountstown), as well as in an excessively drained, low ion exchange capacity soil (Live Oak).
- The results also indicate that repeated annual fertilizations may have a cumulative effect and that additional studies are needed, as this has been identified as a gap in current knowledge (Binkley et al., 1999).

Tree and stand growth responses:

- Pine straw raking had no effect on slash pine stand growth parameters except for greater dominant and co-dominant pine height for non-raked treatments at the sandy Live Oak site.
- DAP fertilization resulted in poor or negative pine stand responses at both sites for most growth parameters measured. Fertilization increased four-year pine diameter growth at Blountstown and increased four-year dominant and co-dominant pine height growth at Live Oak, but other pine stand attributes either showed no response to fertilization or responded negatively to increasing fertilization rate. Fertilization caused significant pine mortality at both sites.

Pine foliar nutrient responses:

- The high DAP fertilization rate temporarily increased pine foliar TKN concentration and decreased foliar TP concentration compared to the non-fertilized control. The effect on other nutrients is difficult to generalize, except that decreased concentrations sometimes occurred, possibly as a result of accelerated foliage growth and carbohydrate dilution. Pine straw removal had a minimal effect on foliar nutrient concentrations, except for the observed decrease in potassium concentration at the Blountstown site after the third and fourth annual raking.

Pine needle litter nutrient responses:

- During the four-year monitoring period at both study sites, pine needle litter TKN and (on most dates) K concentrations were greater following DAP application at 384 or 641 lb/acre as compared to 128 lb/acre or 0 lb/acre. No effect on TP was observed and Ca concentration was only affected by 641 lb/acre at Live Oak.
- Two annual applications of 128 lb/acre DAP did not increase pine needle litter concentration of any nutrient as compared to the non-fertilized control.

Pine straw yield and nutrient removal responses:

- At the Blountstown site, both pine straw dry weight and number of bales per hectare were greater for 384 or 641 lb/acre DAP than for the low DAP rate and non-fertilized control, when averaged over the four harvests. At the sandy Live Oak site the medium and high DAP rate tended to have greater yield than the non-fertilized control for harvests two, three, and four years after the first fertilization, but means were not significantly different.
- The effect of fertilization on nutrient concentrations in annually raked pine straw was less pronounced than in quarterly collected pine needle litter. TKN concentration was significantly greater for 641 lb/acre DAP than for the other treatments at Blountstown. A similar trend was observed at Live Oak but means were not significantly different.
- Treatment differences in pine straw yield and nutrient concentrations resulted in greater removal of TKN, TP, potassium (K), and calcium (Ca) from plots fertilized with 384 or 641 lb/acre DAP as compared to 128 lb/acre DAP or non-fertilized plots at Blountstown. A similar trend was observed at Live Oak (except for Ca), although differences were not significant.

Surface soil properties*:*

- At both study sites soil bulk density increased slightly in the 0-6” and 6-12” depths from 2009 to 2011 but was not related to fertilization or raking treatments (thought to be due to traffic on the site).

- This study showed no important effects of either fertilization or pine straw removal on soil organic matter content in in the 0-6” and 6-12” depths.

1 INTRODUCTION

1.1 BACKGROUND INFORMATION

1.1.1 A Statement of the Problem

While fertilization in conventional silvicultural practice may be declining somewhat (Albaugh et. al 2007), due to increasing fertilizer costs and reduced timber values, pine straw production is an expanding industry in north and central Florida, with estimated revenues in excess of $79 M in 2005 for Florida alone (Hodges et. al 2005). Because of high annual revenue prospective and the potential to double pine straw yields with fertilization in some conditions (Morris et. al 1992), growers may be applying fertilizers at luxury consumption rates, necessitating new research and science-based educational programs to safeguard surface and groundwater quality. A paucity of research is available regarding nutrient budgets and pine straw yield responses for this practice in the Coastal Plain of the southeastern US, particularly for the excessively drained sandy soils of the Florida Sand Ridge, where most pine straw production occurs in this state. Florida's largely unconfined aquifer and clear water springs are threatened by nitrogen (N) and phosphorus (P) pollution from mineral and organic fertilizer sources. Improved understanding of the fate of applied N and P and economic timber and pine straw response to fertilization will support better recommendations regarding efficient fertilization regimes for this practice, which will ultimately help to protect water quality in Florida and the region.

1.1.2 Previous Work and Information Gaps

Forest Fertilization

Fertilizers, in particular N plus P, are commonly applied in southern pine stands in the Coastal Plain of the southeastern United States at establishment or periodically during the rotation to increase financial returns by enhancing growth rates and shortening the time to harvest (Jokela et. al 1991, Jokela and Stearns-Smith 1993, Fox et al. 2007a). As a body of research beginning in the 1960's identified diagnostic tools to predict responses to fertilization with N, P, or both (Wells et. al 1973, Comerford and Fisher 1984), the practice of forest fertilization became more common (Albaugh et al. 2007, Fox et. al 2007b). During the 1970's and 1980's field trials demonstrated that N and P are the most limiting nutrients to pine growth and that a large and consistent growth response to forest fertilization with the combination of N (150-200 lb/acre) and P (25-50 lb/acre) occurred on the majority of soil types (Fisher and Garbett 1980, Comerford et. al 1983, Gent et. al 1986, Allen 1987, Jokela and Stearns-Smith 1983, Hynynen et. al 1998). The number of acres of mid-rotation pine plantations in the southeastern US receiving N+P fertilization increased from 15,000 acres annually in 1988 to between 1.2 and 1.4 million acres per year in 2000 (Fox et al. 2007a).

Fertilization for Pine Straw Production

Pine straw producers in North Florida typically use repeated applications of mineral fertilizers, with diammonium phosphate (DAP), ammonium nitrate, and urea being most common (Minogue et. al 2007). Nutrient use efficiencies for fertilization of southern pines are estimated at about 50% (Fox et al 2007a). Nitrogen and phosphorus removals from pine straw raking are largely a function of the harvestable area, site productivity, and stand conditions. Studies in the Georgia Piedmont showed removals for a single raking varied widely, ranging between 5-60 lb N and 0.5-5 lb P per acre (Morris et. al 1992). Morris et al. (1992) provide specific fertilization recommendations for Piedmont old field or cutover sites, different stand ages, raking frequencies, and various site types, but they do not recommend fertilization for sandhill sites characterized by soils with surface horizons greater than 40 inches deep, without fine textured subsoils. Such soils, which are common in the North and Central Florida, have high nutrient leaching potential (high infiltration rate and low ion exchange capacity), thus groundwater pollution is a concern. Specific BMP guidelines for sandy Coastal Plain soils are needed.

Concerns with Pine Straw Removal

Pine straw serves many important purposes in the tree stand and there are concerns that its removal can have detrimental effects on tree growth and stand health. Mineralization of pine straw is part of natural nutrient cycling in pine stands (Switzer and Nelson 1972, Gholz et. al 1985, Jorgensen and Wells 1986). Nutrients can be replaced by fertilization, but pine straw also has an important effect on soil moisture, improving water infiltration and reducing evaporative water loss in much the same way as it does when used in ornamental applications as mulch (Duryea 2003, Pote et al. 2004). Decomposing pine needles add to soil organic matter, thus improving nutrient availability and soil water holding capacity. Removing pine straw can increase tree water stress on dry sites (McLeod et. al 1979, Ginter et. al 1979) and can also increase soil bulk density (Haywood et. al 1998). In the Florida Sand Ridge region there are large areas of deep sandy, excessively drained soils with little soil profile development (CRIFF group G), where silvicultural practices should strive to maintain soil organic matter, thus providing better soil moisture availability and tree nutrition (Jokela and Long, 2000). Pine litter also protects the soil from erosion (Pote et al. 2004) and insulates against rapid temperature changes. Because of these important benefits of pine litter in the forest, it is recommended that pine straw should not be removed more than five times during the stand's life (Duryea, 2003).

Impacts of Forest Fertilization on Water Quality

Many published reviews have examined the impacts of forest fertilization on water quality (Tamm et al. 1974, Fredriksen et al. 1975, Norris et al. 1991, Bisson et al. 1992, Binkley and Brown 1993, Shephard et al. 1994, Binkley et al. 1999, Anderson 2002, Fulton and West 2002, Aust and Blinn 2004, Michael 2004, Grace, 2005). All of these reviews have reached a similar conclusion that standard forest fertilization practices, usually occurring one to three times in a 30 to 50-year rotation, are not detrimental to surface water quality. However, many pine straw producers are fertilizing annually without adequate guidance regarding appropriate fertilizer rates or precision in application. In their recent review, Binkley et al. (1999) **emphasized the need for further studies examining effects of repeated fertilizer applications** in larger scale studies, like the ones we are conducting. Most studies have focused on only two forms of N, nitrate-nitrite (NO_3^- - NO_2^-) and ammonium (NH_4^+). Very little is known about other forms on N, such as dissolved organic N, which is the predominant form of nitrogen in streams in conifer forests of the Southeast. In addition to inorganic N, our study assessed Total Kjeldahl Nitrogen (TKN) to quantify nitrogen in organic complexes.

Because soils in Florida have low P-fixing capacity, the fate of applied phosphorus is of special concern. Only one study in the US (Harris et al. 1980) has reported the effects of phosphorus fertilization on soil solution chemistry in forests. **This significant gap in the literature was addressed in this study**. Also, the effect of phosphorus fertilization is often delayed. Riekerk (1989) reported the maximum concentration of P was observed in streams in a significantly wet year four years after fertilization, suggesting that short-term studies may not be sufficient to determine runoff and leaching losses. Our studies have monitored P leaching for four years following two sequential annual fertilizations through quantification of total soil and groundwater phosphorus. In addition, our Ph.D. candidate, Daniela Chevasco, is developing her dissertation regarding the effect of DAP fertilization and pine straw removal on phosphorus pools in soil, tree foliage, and litter on these study sites.

Pines grown on sandy, excessively drained sites of the Florida Sand Ridge do not respond well to fertilization (Fisher and Garbett 1980) and nutrient leaching to groundwater, which can be as little as 10 m from the surface, is a real concern (German 1997). On an excessively drained, deep sandy site in the Florida Sand Ridge nitrate-nitrite movement to four-foot depth was observed using lysimeters only 12 weeks following spring DAP forest fertilization (Minogue et al. 2007, Minogue et al. 2011). Our study has contributed to the understanding of nutrient dynamics and leaching potential in mid-rotation slash pine stands growing at sites representing the extremes in leaching potential in North Florida.

1.1.3 Florida Silvicultural Fertilization BMPs

Current silvicultural fertilization BMPs include several specific criteria and recommend "developing a nutrient management plan based on soil, water, plant and organic material sample analysis based on desired timber yields to supply nutrient inputs efficiently; so that the benefit of fertilization is captured by target vegetation and the adverse effects to water resources are minimized" (Anonymous 2008). The BMP Manual also makes reference to the University of Florida Extension Circular 1230 (Jokela and Long 2012) that describes methodologies for accomplishing these recommendations. In addition, the Manual provides fertilizer application limits not to be exceeded – these are listed below:

Forestry fertilization BMPs for elemental N:
- No more than 1000 lbs/acre over any 20-year period.
- No more than 250 lbs/acre for any 3-year period
- No more than 80 lbs/acre during the first 2-years of newly established plantations

Forestry fertilization BMPs for elemental P:
- No more than 250 lbs/acre over any 20-year period
- No more than 80 lbs/acre for any 3-year period

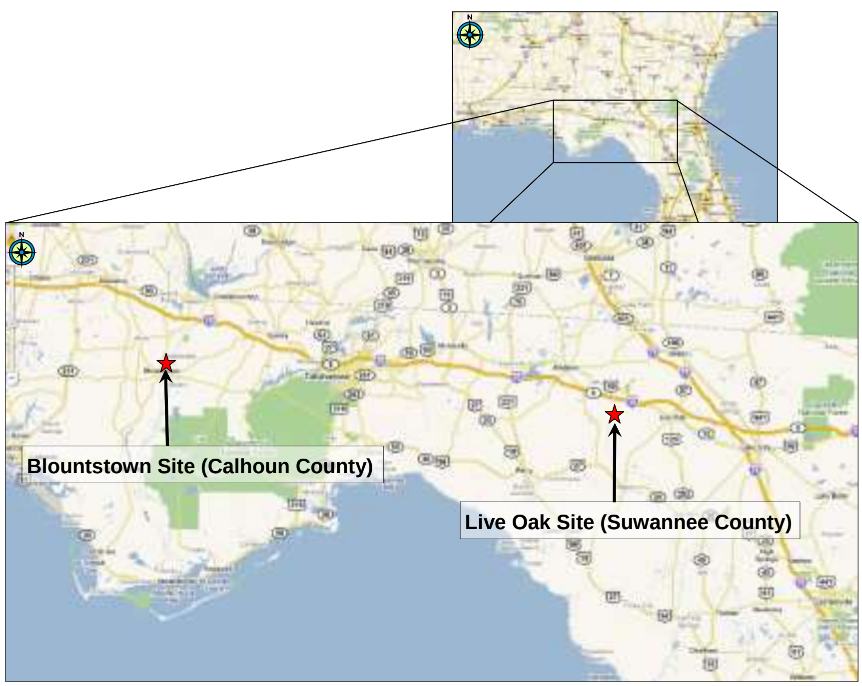

Figure 1. Study site locations in Blountstown and Live Oak, Florida

1.1.4 General Project Description

Under Florida DEP 319 funding initiated in 2008 (G0247) and with continuation of funding in 2011 (G0332), a large-scale demonstration and monitoring study was established in mid-rotation slash pine (*Pinus elliottii* L.) plantations in North Florida at two sites with soils having contrasting leaching potential to evaluate the effectiveness of current forest fertilization BMPs in reducing nonpoint source pollution for fertilization in pine straw production. The effects of a wide range of DAP fertilization rates, with and without pine straw removal, were examined. Periodic monitoring included N and P concentrations in surficial groundwater, soil nutrient concentrations at various depths, foliar nutrient concentrations, amounts and nutrient concentrations of pine straw litter, and amounts and nutrient concentrations for harvested pine straw. Tree growth responses and disease incidence were also measured periodically. Soil physical and chemical properties were assessed initially and at study completion. Continuous monitoring of rainfall, crown through-flow of rainfall, wind speed, air psychometric parameters, and soil moisture and temperature at various depths was conducted with elaborate data-recording instrumentation on site to allow interpretation of results and modeling of environmental fate of applied nutrients. These studies provide pertinent information regarding nutrient fate for fertilization in pine straw production, which is widely practiced by growers who are likely to over-fertilize because of the potential to double straw yields on some sites, and high potential revenues, which can exceed $300 per acre annually. Integrated project objectives include Extension educational programs for landowners and pine straw producers to safeguard water quality in Florida.

1.2 STUDY SITES AND CHARACTERISTICS

Two study sites within the region where fertilization for pine straw production is commonplace were selected for their similarity in stand characteristics and contrasting leaching potential (Table 1, Figure 1). The site in Suwannee County, FL, approximately 12.5 miles west of Live Oak, is characterized by excessively drained sandy soils and an unconfined aquifer. This study site represents a worst-case scenario with respect to leaching and groundwater contamination potential. In contrast, deep clay soils at the site in Calhoun County, FL, approximately 3 miles north of Blountstown, would be expected to have very limited leaching potential because of high soil ion sorption capacity.

Table 1. Geographic information for the two study sites

Study site	**Blountstown**	**Live Oak**
Geographic location	Calhoun County	Suwannee County
Latitude and Longitude	30.50000° N, 85.03333° W (30°30’ N, 85°02’ W)	30.300000° N, 83.20000° W (30°18’ N, 83°12’ W)
Impacted watershed name	Apalachicola Watershed	Lower Suwannee Watershed
HUC	031300110403	031102051012
Land owner	Burch Family Farms	Neal Land and Timber

1.3 POLLUTION REDUCTION STRATEGY

Landowners and pine straw producers who lease and manage pine stands for straw production may apply fertilizers at luxury consumption rates to enhance straw yield. This practice is of greatest concern in the Florida Sand Ridge Region where most pine straw production in Florida occurs. The deep sandy soils of the region are a recharge area of the Floridan aquifer (a major source of drinking water in Florida) and are susceptible to nutrient leaching. Although current Florida Silvicultural BMPs provide specific guidelines for amounts and frequency of N and P fertilization, they are intended for traditional forestry applications, not for the emerging pine straw industry. Thus, the effectiveness of current silviculture BMPs for the new practice is not certain, nor are specific nutrient management guidelines available for pine straw production in the Coastal Plain region.

The Suwannee County study is located in the Lower Suwannee River Basin (WBID: 3422B), which is listed as a 303(d) designation, for which dissolved oxygen and nutrients are parameters of concern. This project monitored N and P concentrations of shallow groundwater at the study site through periodic assessments to evaluate the effectiveness of current fertilization BMPs in preventing groundwater contamination.

1.4 SUMMARY OF EDUCATIONAL COMPONENTS:

Pine straw production is a relatively new industry in the Southeast, having been introduced during the 1980's as an alternative source of income for forest landowners. With intensive management, potential revenues to growers can exceed $300 per acre per year, exceeding the value of timber revenues when discounted financial returns are compared. Pine straw producers recognize that pine straw yields can be increased significantly though fertilization. In some soils of the Piedmont, pine straw yields have been shown to double with annual fertilization and intensive management (Morris et al. 1992). However, pine stands do not respond well to fertilization in the excessively drained soils of the Florida Sand Ridge (Jokela and Long 2012), where forest fertilization may be a threat to groundwater quality (Minogue et al. 2011).

At the same time, pine straw harvesting may have serious adverse effects on soil productivity and stand health due to removal of nutrients and organic matter. Again, this is particularly true for the infertile Florida Sand Ridge region, which supports the largest pine straw business in the state and was thus given priority in educational outreach.

Forest landowners lack adequate silvicultural guidance regarding the appropriate pine species for various sites, optimum planting spacing, vegetation management, nutrient management, straw harvesting frequency, and the economic analyses of integrated pine straw and timber returns. At the onset of this work, few research or Extension publications addressed these questions, particularly for the Coastal Plain region. Therefore, science based educational materials were developed to guide improved forest management and the efficient use of fertilizer, with the ultimate objective to safeguard Florida’s water resources. Information outputs included scientific papers, Extension publications, forest management guidelines, workshops, and field tours so that pine straw growers, natural resource managers and other researchers would benefit from this work.

2 PROJECT GOALS, OBJECTIVES, AND ACTIVITIES

2.1 GOALS AND OBJECTIVES – FOR G0332 CONTINUED MONITORING

The scope of this research includes applied and basic questions regarding the fate of applied N and P following application of a wide range of diammonium phosphate (DAP) fertilization rates, with and without straw removal. Periodic assessments determined forest stand-level nutrient budgets, effects of straw removal and fertilization on nutrient cycling, tree growth response to treatments, straw harvest yields, and soil chemical and physical properties. The goal was to determine biological and economic thresholds for fertilization in pine straw production as well as to ensure soil resource sustainability and protection of water quality. Specific objectives included:

1. Determine the environmental fate of applied N and P for three years following the second annual fertilization at each of two sites having contrasting leaching and soil sorption potential. Thus, to

evaluate and assess the effectiveness of current forest fertilization BMPs to reduce nonpoint source pollution, as is consistent with EPA's "iterative process" for long-term BMP development.

2. Examine leaching potential, soil physical and chemical properties, and nutrient budgets for fertilization in raked and non-raked stands to refine silvicultural fertilization BMPs and provide new information regarding the efficient use of fertilizers in pine straw production for the Coastal Plain region.

3. Determine tree growth and pine straw yield responses following a wide range of N+P fertilization rates to determine cost-effective fertilization practices for sites representing extremes in potential for soil sorption and leaching of applied nutrients.

4. Develop models to explain nutrient leaching as a function of soil physical and chemical properties, soil and atmospheric hydrology, soil and atmospheric temperature, and forest stand level nutrient dynamics (nutrient cycling), through a balance-sheet approach in raked versus non-raked forest stands.

5. Provide pertinent information in support of training and Extension education programs for fertilization practices associated with pine straw production.

2.2 MILESTONES, PRODUCTS AND COMPLETION DATES - FOR G0332 CONTINUED MONITORING PERIOD

The project milestone table identifies the completion of specific monitoring tasks by quarter, achievement of project objectives, and deliverables produced (Table 2).

Table 2. Project milestones for the continued monitoring period (GO332, July 2011-October 2013)

No.	Task/Activity Description	Deliverables	Start	Complete
1	Monitoring of groundwater, pine litter nutrients, soil moisture and temperature, weather; project site maintenance; data analysis and reporting (first quarter)	Groundwater, pine litter nutrient, soil condition and weather data provided. Quarterly report for Task 1 completed on time March 13, 2012. Two publications and presentations at the Water Institute Symposium (see 2.4 below)	Nov. 14, 2011	Feb. 29, 2012
2	Monitoring of groundwater; pine litter, foliar, and straw bale nutrients; pine straw yields; tree growth; soil moisture and temperature; weather; project site maintenance; data analysis and reporting (second quarter)	Groundwater, pine litter, foliar and straw bale nutrient, straw yield, tree height and diameter, soil condition and weather data provided. Quarterly report Task 2 completed on time June 15, 2012	March 1, 2012	May 31, 2012
3	Monitoring of groundwater, pine litter nutrients, soil nutrients, soil moisture and temperature, weather; project site maintenance; data analysis and reporting (third quarter)	Groundwater, pine litter and soil nutrient, soil condition and weather data provided. Quarterly report Task 3 completed on time September 13, 2012.	June 1, 2012	Aug. 31, 2012
4	Monitoring of groundwater, pine litter nutrients, soil moisture and	Groundwater, pine litter nutrient, soil condition and weather data provided.	Sept. 1, 2012	Nov. 30, 2012

	temperature, weather; project site maintenance; data analysis and reporting (fourth quarter)	Quarterly report Task 4 completed on time December 7, 2012.		
5	Monitoring of groundwater for NH_4-N, NO_x-N, TKN, and TP concentrations will be completed in February 2103 in the fertilized area and distant reference wells. Monitoring of the fate of applied fertilizer nutrients will be done for dormant season pine foliage, pine litter traps quarterly, harvested pine straw annually, and soil at various depths in Feb. 2013, all to be completed on or before February 2013. Automated weather monitoring of precipitation, wind speed, air temperature, relative humidity and PAR, as well as soil temperature at various depths, will be done through February 2013 to support nutrient fate modeling efforts.	Groundwater, pine litter, foliar and straw bale nutrient, straw yield, tree height and diameter, soil condition and weather data provided. Quarterly progress reports for Task 5 were completed on time March 4, 2013 and May 31, 2013. Final Report review draft completed August 31, 2013. Final Report with DEP and Florida Forest Service Co-PI comments due September 30, 2013. Other scientific publications in preparation based on these four-year findings (see Section 1.4, Summary of Educational Components).	Dec. 1, 2012	Nov. 13 2013

2.3 EVALUATION OF GOAL ACHIEVEMENT AND RELATIONSHIP TO THE STATE NPS MANAGEMENT PLAN

Objective 1: Determine the environmental fate of applied N and P for three years following the second annual fertilization at each of two sites having contrasting leaching and soil sorption potential. Evaluate and assess the effectiveness of current forest fertilization BMPs to reduce nonpoint source pollution, as is consistent with EPA's "iterative process" for long-term BMP development.

Achievement: Two large scale (12 acre) replicated research studies were established at sites with contrasting leaching potential to observe the environmental fate of N and P applied at various amounts relative to BMP guidelines. Two sequential annual diammonium phosphate (DAP) fertilizations, providing 22/24, 67/72, or 112/120 lb/acre N/P, were monitored in stands with and without pine straw raking and compared to unfertilized controls over a four year period (see 5.1.2 Treatments and Statistical Design). The environmental fate of applied N and P was determined by monitoring results for groundwater NH_4-N, NO_x-N, TKN, and TP concentrations (5.4.1), soil matrix concentrations of these same nutrients (5.4.2), and concentrations of TKN and TP in dormant season pine foliage (5.6.2), periodic litter trap samples (5.6.3), and in harvested pine straw (5.6.4). The implications of these results for refinement of silvicultural BMPs are presented in Section 4.

Objective 2: Examine leaching potential, soil physical and chemical properties, and nutrient budgets for fertilization in raked and non-raked stands to refine silvicultural fertilization BMPs and provide new information regarding the efficient use of fertilizers in pine straw production for the Coastal Plain region.

Achievement: Two sequential annual fertilizations using our study's highest DAP rate tested the near BMP maximum N allowed within a three-year period and also provided 300% of the three year P maximum limit. Monitoring occurred for four years following the first fertilization and for three years after the second fertilization. Periodic monitoring determined N and P concentrations in surficial groundwater, soil nutrient concentrations at various depths, foliar nutrient concentrations, amounts and nutrient concentrations of pine straw litter, and amounts and nutrient concentrations for harvested pine straw. Soil physical and chemical properties were determined initially and at study completion (5.5.1). Continuous rainfall and other weather monitoring and soil moisture and temperature monitoring at various depths was done to support modeling of applied nutrient fate.

Objective 3: Determine tree growth and pine straw yield responses following a wide range of N+P fertilization rates to determine cost-effective fertilization practices for sites representing extremes in potential for soil sorption and leaching of applied nutrients.

Achievement: To determine tree growth responses to fertilization and raking treatments, tree height, diameter at breast height, and disease incidence were determined prior to treatment and annually during the dormant season for four years (see Section 5.6.1). To determine pine straw yield responses to fertilization and the effect of pine straw raking on pines, pine litter was collected quarterly, pine straw was raked annually in the winter, and pine foliage from the first flush of the current year's growth was collected annually for nutrient analyses during each dormant season. Quarterly pine litter and annual straw dry weight yields were quantified (5.6.3 and 5.6.4). A summary of results is presented in Section 5.3.3, Tree Growth and Straw Yield Summary. Technical publications produced regarding fertilization in pine straw production and Extension education activities are listed in Section 2.4 below.

Objective 4: Develop models to explain nutrient leaching as a function of soil physical and chemical properties, soil and atmospheric hydrology, soil and atmospheric temperature, and forest stand level nutrient dynamics (nutrient cycling), through a balance-sheet approach in raked versus non-raked forest stands.

Achievement: This study determined the fate of applied nutrients using a balance sheet approach. Periodic soil nutrient assessments were done at various depths in the soil profile to quantify nutrient leaching, and periodic monitoring of surficial groundwater wells measured changes in NH_4-N, NO_x-N, TKN, and TP concentrations. Soil and atmospheric environmental parameters were monitored continuously to support system models describing nutrient polls and leaching. The breadth of parameters evaluated is facilitating several system model development efforts with various collaborators. The first of these to be published (Gonzalez-Benecke et al. 2012) used these data to verify a model that estimates yearly needle fall as a function of site quality and leaf area index. This work supported modeling of economic returns and carbon and nitrogen removals for pine straw raking in thinned or non-thinned stands (Susaeta et al., 2012). Now that four-year nutrient budgets have been determined, we are working with Professor Wendell Cropper, University of Florida, in systems modeling of nutrient pools and the environmental fate of applied N and P.

Objective 5: Provide pertinent information in support of training and Extension education programs for fertilization practices associated with pine straw production.

Achievement: Numerous publications, reports, extension materials, workshops, field tours, and presentations were developed, published, and distributed (see 2.4 Information and Education Outputs).

2.4 INFORMATION AND EDUCATION OUTPUTS

Pine Straw Producers Working Group: Partially funded by the 319 grant, a Pine Straw Producers Working Group was formed as a part of our IFAS Extension program, which currently reaches 121 pine straw growers in Florida, Georgia and Alabama with a periodic e-newsletter presenting science-based cultural recommendations.

Workshops: We conducted 14 workshops regarding forest fertilization in pine straw production with 699 growers attending. (see measured behavior modification, section 3.0 below)

Journal Publications, University Research Reports, Dissertations:

Chevasco, Els Daniela. (In preparation, May 2014 expected) Pine straw harvesting and fertilization effects on soil and plant phosphorus pools, bioavailability and potential losses in slash pine (*Pinus elliotii* Engelm.) plantations. Ph.D. Dissertation. University of Florida, Gainesville, FL.

Gonzalez-Benecke, C.A., Jokela, E.J., Martin, T.A. (In Press). Modeling the effects of stand development, site quality, and silviculture on leaf area index, litterfall, and forest floor accumulations in loblolly and slash pine plantations. Forest Science.

Susaeta, A.T., C.A. Gonzalez-Benecke, D.R. Carter, E.J. Jokela, T.A. Martin. 2012. Economic sustainability of pinestraw raking in slash pine stands in the southeastern United States. Ecological Economics 80:89-100.

Minogue, P.J., D.K. Lauer, M. Miwa, and A. Osiecka. 2012. Preliminary results: Effectiveness of silviculture best management practices for forest fertilization in pine straw production to protect water quality in Florida - Analyses of monitoring well nutrient concentrations to three years after fertilization. Institute of Food and Agricultural Sciences, North Florida Research and Education Center, Quincy, FL, Research Report 2012-02. 15 p.

Minogue, P.J., M. Miwa, A. Osiecka, J. Vowell, and R. Lima. 2012. Effectiveness of silvicultural BMPs in pine straw production to protect groundwater - third year results. Third University of Florida Water Institute Symposium. February 15-16, 2012. Gainesville, FL. http://waterinstitute.ufl.edu/symposium2012/abstract_detail.asp?AssignmentID=308

Minogue, P.J., M. Miwa, D.K. Lauer, and A. Osiecka. 2011. Preliminary results: Effectiveness of silviculture best management practices for forest fertilization in pine straw production to protect water quality in Florida. Institute of Food and Agricultural Sciences, North Florida Research and Education Center, Quincy, FL, Research Report 2011-02. 76 p.

Osiecka, A., P.J. Minogue, and J.T. Wright. 2010. Effect of pine straw removal on pine straw yield and quality, wood volume, and nutrient budgets in fertilized loblolly pine (*Pinus taeda*), slash pine (*Pinus elliottii*) and longleaf pine (*Pinus palustris*) plantations in the Florida Sand Ridge Region. Institute of Food and Agricultural Sciences, North Florida Research and Education Center, Quincy, FL, Research Report 2010-02. 19 pp.

IFAS Electronic Data Information Source (EDIS) Peer Reviewed Publications:

Minogue, P., D. Chevasco, F. Escobedo, and K. Bohn. 2010. Control y Biología del Helecho Trepador Japonés (*Lygodium japonicum*). University of Florida Cooperative Extension Service Circular FOR 282. 7 p. http://edis.ifas.ufl.edu/fr334

Minogue, P., S. Jones, K. Bohn, R. Williams. 2009. Biology and control of Japanese climbing fern (*Lygodium japonicum*). University of Florida Cooperative Extension Service Circular FOR 218/FR280. 7 p. http://edis.ifas.ufl.edu/fr280

Minogue, P., H. Ober, and S. Rosenthal. 2007. Overview of pine straw production in north Florida: Potential revenues, fertilization practices, and vegetation management recommendations. University of Florida Cooperative Extension Service Circular FOR125/FR180. 6 p. http://edis.ifas.ufl.edu/fr180

University of Florida Forest Vegetation Management Website – Creative Works
http://nfrec.ifas.ufl.edu/Forest_Vegetation_Management/

Extension Program Presentations – Creative Works

Financial returns for integrated pine straw and timber production (30 min.)
Overview of pine straw production in north Florida (30 min.)
Alternative forest crops: pine straw, energy crops, and ecosystem service (60 min.)
Alternative forest products (45 min.)
Pine straw production in North Florida (45 min.)
Alternative forest products: existing and evolving (30 min.)
Alternative forest crops, pine straw, energy crops, and carbon credits (50 min.)

University of Florida Web-based Extension Newsletters:

Minogue, P.J. 2010. Control understory vegetation to enhance pine straw yield. University of Florida, Institute for Food and Agricultural Sciences. Northwest Florida District Extension Newsletter, September 20, 2010. Vol. 12(9).

Miwa, M. and P.J. Minogue. 2010. What do we need to know for better forestry BMPs. University of Florida. North Florida Research and Education Center Newsletter. May 17, 2010. Vol.12(5).

Miwa, M. and P.J. Minogue. 2009. Fertilization for pine straw production, put back what you take, but don't over-fertilize. University of Florida. North Florida Research and Education Center Newsletter. July 20, 2009. Vol.11(7).

Minogue, P.J. 2009. Use of fertilizers to enhance pine straw production in the Florida Panhandle. Panhandle Agriculture. University of Florida, IFAS Extension. Vol. 1(3):5-6. May-June 2009.

Minogue, P.J. 2009. Does fertilization for pine straw pay on deep sandy soils? University of Florida. North Florida Research and Education Center Newsletter. April 2009. http://nfrec.ifas.ufl.edu/files/pdf/newsletters/2009/Newsletter_04_20_09.pdf

Minogue, P.J. 2009. Use of fertilizer to enhance pine straw production. University of Florida, Institute for Food and Agricultural Sciences. Northwest Florida District Extension Newsletter, April 14, 2008. Vol.10(4).

Minogue, P.J. 2009. Use of fertilizers to enhance pine straw production in the Florida Panhandle. Panhandle Agriculture. University of Florida, IFAS Extension. Vol. 1(3). Pp 5-6.

Annual Reports:

- First year study results were presented to FDEP on May 14, 2010.
- Second year study results were presented to FDEP on May 10, 2011.
- Study update presented to Florida Silviculture BMP Technical Advisory Committee on May 27, 2009.
- Study update presented to Florida Silviculture BMP Technical Advisory Committee on May 12, 2011.

Presentations at National, Regional and State Meetings:

Osiecka, Anna. 2013. Pine Straw Program. Alternative Income From Your Forest Expo. January 16, 2013. Bear Creek Educational Forest, Gadsden County, FL.

Minogue, P.J., M. Miwa (presenter), A. Osiecka, J. Vowell, R. Lima. 2012. Effectiveness of silvicultural BMPs in pine straw production to protect groundwater – third year results. Third University of Florida Water Institute Symposium. February 15-16, 2012. Gainesville, FL.

Chevasco, E.D. and P.J. Minogue. 2012. Can fertilization in pine straw production threaten water quality? (poster). Third University of Florida Water Institute Symposium. February 15-16, 2012. Gainesville, FL.

Chevasco, E.D. and P.J. Minogue. 2011. North Florida pine straw industry: distribution, raked species and fertilization practices (poster). Managing Public Lands and Waters - Doing More with Less.

School of Forest Resources and Conservation and the Society of American Foresters 42nd Annual Symposium. November 8-9, 2011. Gainesville, FL.

Minogue, P.J. 2011. BMP effectiveness monitoring for forest fertilization - groundwater. Florida BMP Technical Advisory Committee Meeting. May 12, 2011. Tallahassee, FL. (Invited)

Minogue, P.J. 2010. Alternative forest crops for today and tomorrow: pine straw, energy wood, ecosystem services. University of Florida, Forest Stewardship Workshop. November 16, 2010. Mayo, FL. (Invited)

Minogue, P.J. 2010. Economics of pine straw production. University of Florida, Pine Straw Production Workshop and In-Service Training (State-wide webinar). October 22, 2010. Live Oak, FL.

Minogue, P.J. 2010. Overview of pine straw production in North Florida. University of Florida, Pine Straw Production Workshop and In-Service Training. (State-wide webinar) October 22, 2010. Live Oak, FL.

Minogue, P.J. 2010. Alternative forest crops: pine straw, energy crops, and ecosystem services". University of Florida, Forest Stewardship Workshop: Diversify Income from Your Land. May 4, 2010. DeFuniak Springs, FL. (Invited)

Minogue, P.J. and M. Miwa. 2010. Effectiveness of silviculture BMPs for forest fertilization in pine straw production to protect water quality in Florida. State of Florida Dept. Agriculture and Consumer Services, Annual Forestry BMP Review (field tour). January 20, 2010. Blountstown, FL. (Invited)

Minogue, P.J. 2009. Effectiveness of Florida's silvicultural fertilization BMP's to protect water quality. Southern Group of State Foresters, Water Resources Committee Meeting. October 27-29, 2009. Suwannee County, FL (Invited)

Miwa, M. and P.J. Minogue. 2009. Effects of silvicultural practices on the nation's waters: How can we improve the effectiveness of BMPs? Society of American Foresters National Meeting. Sept. 30-Oct. 3, 2009. Orlando, FL.

Minogue, P.J. 2009. Alternative forest products. University of Florida, NFREC Fall Field Day. September 19, 2009. Quincy, FL.

Minogue, P.J. 2009. Pine straw production in north Florida. Florida Division of Forestry and University of Florida, Alternative Forest Products Workshop. June 26, 2009. Madison, FL.

Minogue, P.J. and M. Miwa. 2009. Research progress report on effectiveness of Florida's silvicultural fertilization BMP's to protect water quality. Florida Forestry BMP Technical Advisory Committee. Florida Department of Agriculture and Consumer Services, Division of Forestry. May 27, 2009. Tallahassee, FL. (Invited)

Minogue, P.J. 2009. Alternative forest crops, pine straw, energy crops, and carbon credits. University of Florida, Forest Stewardship Workshop: Manage for Multiple Objectives – Techniques and Demonstrations. Suwannee Valley REC. March 3, 2009. Live Oak, FL.

Field Tours:

- Hosted the South-wide Forest Disease Workshop February 9, 2011and presented an overview regarding pine straw removal and effects on forest health.
- Hosted the Florida BAP Advisory Committee meeting on January 20, 2010 and presented the first-year preliminary results to the group.
- Hosted the Southern Group of State Foresters annual meeting on October 28, 2008 and presented first-year preliminary results to the group.

3 LONG TERM RESULTS IN TERMS OF BEHAVIOR MODIFICATION, STREAM/LAKE QUALITY, GROUND WATER, AND/OR WATERSHED PROTECTION CHANGES

We conducted 14 IFAS Extension workshops regarding forest fertilization in pine straw production with 699 growers attending. Post workshop surveys (8) indicated 100% of respondents (54% of attendees responded) learned something new and 51% changed fertilization practices as the result of something they learned. The two most common changes were avoidance of fertilization for potentially non-responsive pine stands and the use of the appropriate rates of nitrogen and phosphorus fertilizers (following Long and Jokela, 2012). Of those surveyed, 56% said they learned something to either reduce their input costs or increase the profitability of their pine straw operation. The most common changes among respondents included: (1) not fertilizing pine stands with high pine stem density and closed canopies (because they are not responsive), and (2) not fertilizing sites with excessively drained soils and no clay micelles (because they are not responsive and leaching of applied N and P is a potential concern).

Pine Straw Production Needs Surveys

a. **County forester survey:** The response rate from the 39 county foresters surveyed was 77%, although several respondents indicated that pine straw was not being produced in their area, particularly south of Orlando. This survey provided an estimate of the geographic location and magnitude of pine straw production in Florida. As was expected, the Florida Sand Ridge supports the largest pine straw industry. This is likely due to the presence of many old-field pine plantations which are easily raked because of their clean understories. Although not expected, a second area of concentrated pine straw raking was identified in the Florida panhandle near Blountstown.

b. **Landowner survey:** The second survey response rate was 28%, representing 32,214 raked acres. Slash pine (*Pinus elliottii* L.) was the most important species for straw production, representing 89% of surveyed acres. Fifty percent of the surveyed producers had used fertilizers, and of these 94% fertilized pine stands on sandy soils. However, only 17% consulted an extension agent or consultant for fertilization recommendations. Moreover, soil testing was not done by 39% of producers that fertilized. Surveyed producers showed little knowledge about the type and amount of fertilizer that was applied. However, 69% of the surveyed producers were interested in learning about fertilization. Fertilizers were usually applied during the spring (53%) but there were also applications during the fall and winter, when nitrogen fertilizer use is less efficient. Information from this survey facilitated extension education efforts to promote sustainable pine straw production following BMPs to protect water quality.

4 BEST MANAGEMENT PRACTICES (BMPS) RECOMMENDATION

Current Practices

For established pine stands, fertilization with a combination of N and P is typically recommended on low fertility sites when pine basal area is less than 80 ft^2/acre. Diammonium phosphate (DAP), urea, superphosphates and ground rock phosphate are the most widely used fertilizers in Southeastern forestry and are commonly applied to provide 150-200 lb/acre elemental N and 25-50 lb/acre P_2O_5 (11-22 lb elemental P). Typical growth responses in Florida are 50 ft^3/acre/yr or more, and the response generally lasts for 6-8 years (Jokela and Long 2012). The cost of nitrogen fertilizers has increased dramatically in the past decade. At present, almost all N used to fertilize pine plantations in the Southern USA is applied in the form of urea. Urea is not only less expensive than DAP, but it is readily available, is highly soluble, and because of its high N concentration (46%N) it is easy to transport and apply in the forest. Fertilization with urea is recommended for January through May to avoid significant volatile losses of N.

This study evaluated the effectiveness of silvicultural BMPs for a wide range of rates of DAP, which has historically been one of the most widely used fertilizers in southern forestry, largely because it conveniently provides both N and P. It is often combined with urea to achieve the desired proportion of N plus P. A very common treatment is the application of 400 lb/acre urea plus 125 lb/acre DAP, which provides 208 lb/acre N and 62 lb/acre P_2O_5.

General Implications

As expected, the fate of applied nitrogen differed at the clayey, somewhat poorly drained Blountstown site versus the excessively drained, deep sandy Live Oak site, illustrating the need for site-specific recommendations. At present, Florida Silviculture BMPs (Anonymous, 2008) recognize this need in the "Fertilizer Application Limits" section. The current silvicultural fertilization BMPs recommend a "nutrient management plan based on soil, water, plant and organic matter sample analysis, along with expected or desired yields"; and to "see Florida Extension Service Circular 1230" (Using soils to guide fertilizer recommendations for southern pines, Jokela and Long, 2012).

Fertilization resulted in poor or negative slash pine stand responses at both sites. Except for increased four-year pine diameter growth at Blountstown and increased four-year dominant and co-dominant pine height growth at Live Oak, all pine stand attributes either showed no response to fertilization or responded negatively to increasing fertilization rate. Fertilization caused significant pine mortality at both sites. These results of induced pine mortality are consistent with other reports for N+P fertilization of non-thinned, mid-rotation pine plantations with stand basal area greater than 100 sq ft ac^{-1} (436 sq m ha^{-1}) (Ogden and Morris, 2004).

Our surveys indicated that about half of Florida pine straw growers are fertilizing to increase pine straw yield (Chevasco and Minogue, 2012), which can double with fertilization on some sites (Morris et al. 1992). Even though we observed a trend of increased yield with the medium (384 lb/acre) and high (641 lb/acre) DAP fertilization rates, the effect was significant only at Blountstown at three years after the first application and for the four-year average, when the high and medium DAP rates resulted in greater pine straw dry weight and bale count than the low rate or non-fertilized control. However, the increased yield at that site appears to be due in part to increased pine mortality and resultant needle cast observed with the medium and high rates. Mean pine straw dry weights and bale counts at Live Oak did not show significant differences between DAP fertilization treatments. However, at the sandy Live Oak site we observed a weak trend of increased pine straw yield with the medium and high fertilization rate.

Poor responses to fertilization are not unusual during mid-rotation when pine straw harvesting occurs. In a region-wide study of fertilization and vegetation control in mid-rotation slash and loblolly pines at 13 sites in the southeast, only 54% responded positively in volume growth (Albaugh et al., 2012). The current BMPs address this point "it should be understood that not all silvicultural strategies require or can benefit from forest fertilization".

Pine Straw Harvesting

Pine straw raking had no effect on pine stand growth parameters except for greater dominant and co-dominant pine height for non-raked treatments at the sandy Live Oak site. The effect of pine straw raking on foliar nutrients was only observed in 2011 and 2012 for K concentration at Blountstown, when mean foliar K concentration was greater for non-raked than for raked treatments. Annual pine straw removal had no meaningful effect on the concentration of any soil nutrient. Pine straw harvesting was not shown to have the potential to adversely affect water quality based on measures of soil nutrient leaching but may have adverse effects on soil productivity over extended periods.

Nitrogen Fertilization BMPs

Applied NH_4-N in the form of DAP moved to the lowest monitored depth (60-72") at the sandy Live Oak site but remained within 0-12" at Blountstown where a somewhat poorly drained clayey soil with high cation exchange capacity occurred.

Nitrate concentrations increased following fertilization as nitrification of the supplied ammoniacal nitrogen occurred. Nitrate leaching through the soil profile was observed at both sites following each of the two sequential annual fertilizations but was greatest following the second fertilization.

This study demonstrated the potential for rapid leaching in saturated soil conditions at the Blountstown site, where soil NO_x-N concentrations were greater than the non-fertilized control at two months after the first fertilization at all depths and for all DAP rates. However, mean NO_x-N concentrations below 12-inch depth during this initial flux were always less than half the PQL (2.5 mg/kg), and ranged from 1.06 to 0.16 mg/kg. During the year after the first fertilization at Blountstown, mean NOx-N concentrations below 12-inch depth exceeded the PQL value only once, and ranged from 0.04 to 2.99 mg/kg.

Following the second fertilization, nitrate leaching was clearly evident for the high (641 lb/acre) DAP rate to the deepest monitored depth at both sites. The medium rate (384 lb/acre) resulted in NO_x-N concentrations greater than the non-fertilized control to the 36-48" depth 12 months after fertilization (MAF) at Blountstown and to 60-72" depth 9 MAF at Live Oak. The low rate (128 lb/acre) resulted in NO_x-N concentrations greater than the non-fertilized control at 0-6" depth at 6 and 36 MAF at Blountstown but was never different from the control at any depth at Live Oak. These results demonstrate greater potential leaching for repeated sequential applications of rates within the 250 lb/acre N three-year BMP limit. In their review of water quality aspects, Binkley et al. (1999) emphasized the need for further studies examining effects of repeated fertilizer applications in larger scale studies. We had proposed additional sequential annual fertilizations on these sites under 319 FY 2011 funding, but this remains a need.

Peak NO_x-N concentrations at the deepest monitored depth (60-72") were observed at six to nine months after the second application of the high DAP rate (641 lb/acre), and concentrations were significantly greater than the non-fertilized control. During that period, peak NO_x-N concentrations in the deepest monitored depth were 2.75 mg/kg at Live Oak (LO) 6 MAF and 1.29 mg/kg at Blountstown (BT) 9 MAF. Concentrations remained significantly greater than the non-fertilized control (0.40 LO vs 0.07 BT) at that depth until one year after the second fertilization at Live Oak (1.04 mg/kg NO_x-N) and two years after the second fertilization at Blountstown (0.55 mg/kg NO_x-N). The greater sorption capacity and lesser hydraulic conductivity at Blountstown would explain the longer retention observed.

Surficial groundwater NO_x-N concentrations were elevated by fertilization at the clayey Blountstown site where groundwater was close to the surface (3.0-13.5 ft), but not at the sandy Live Oak site where groundwater was deeper (32.9-42.4 ft). However, during the 52-month monitoring period at Blountstown treatment well NO_x-N concentrations were never greater than the reference well concentrations by more than 1.4 mg/L. This is not excessive in terms of groundwater quality and does not exceed state water quality standards.

Phosphorus Fertilization BMPs

Because the DAP fertilizer rates applied were selected to provide various N amounts up to the near maximum BMP limit of 250 lb/acre N for a three year period, two applications of the high DAP rate provided 230 lb of N and 260 lb/acre elemental P, which exceeded the BMP limit of 80 lb/acre elemental P for a three year period by 180 lb, or 225%. Soil TP concentrations in the surface soil began to increase two months after the first fertilization and remained above baseline levels by two-fold at Live Oak and three fold at Blountstown at three years after the second fertilization. However, no increase in soil TP concentration, as compared to the non-fertilized control, was observed below 12-inch depth during four years following the first fertilization at either site. No increase in groundwater TP concentration occurred due to fertilization. Phosphorus is not a mobile nutrient, but P fertilization may increase soluble organic phosphorus (SOP), which is more prone to leach. Continued monitoring for several years would be needed to ascertain the fate of applied P in this study.

5 MONITORING RESULTS FOR DEMONSTRATION PROJECTS

5.1 MATERIALS AND METHODS

5.1.1 Study Site Characteristics

Two study sites with contrasting leaching and runoff potential were selected within the region where pine straw raking is common to evaluate the effectiveness of current forest fertilization BMPs in reducing nonpoint source pollution (Tables 1 and 3). The Suwannee County site is on an entisol with excessively drained deep sandy soils, characteristic of the Florida Sand Ridge and representing the worst-case scenario with respect to leaching potential and groundwater contamination (USDA NRCS, 2006). The Calhoun County site is on an ultisol having sandy loam surface soils (approximately 8-16 inches deep) and underlying clayey B horizon; thus, representing a site with high soil sorption and low leaching potential (USDA NRCS, 2004). The two study sites were established in slash pine (*P. elliottii*) stands age 17 to 19 years.

Table 3. Study site characteristics for Blountstown and Live Oak

Study site	**Blountstown (Calhoun County)**	**Live Oak (Suwannee County)**
Soil series	Dunbar fine sandy loam, and Kenansville loamy sand	Alpin fine sand
Soil taxonomic classification	Dunbar: fine, kaolinitic, thermic Aeric Paleaquults Kenansville: loamy, siliceous, subactive thermic Arenic Hapludults	thermic, coated Lamellic Quartzipsamments
Subsurface soil CEC	>45 meq/100g soil	<0.5 meq/100g soil
Soil depth class	Very deep	Very deep
Drainage class	Somewhat poorly drained	Excessively drained
Permeability class	Moderately slow	Moderately rapid
Slope	0-2%	0-5%
Geomorphic setting	Flats of inter-stream divide and low terrace adjacent to floodplain	Upland
Parent material	Fluvial or marine clayey deposits	Sandy marine deposits
CRIFF soil group	Groups A and B	Group G
Plantation species	*Pinus elliottii* Eng.	*Pinus elliottii* Eng.
Plantation establishment	1997	1995
Site index (25 years)	80 ft	68.5 ft

5.1.2 Treatments and Statistical Design

The effects of two sequential annual DAP fertilizations using a wide range of N and P in stands with and without annual pine straw removal was examined. Fertilization was conducted in February/March of 2009 and 2010. Diammonium phosphate, which is the most common fertilizer material in pine straw production, was applied at 0, 128, 384, and 641 pound per acre (lb/acre). The equivalent metric units for DAP fertilization rates are 0, 143, 430, and 718 kg/ha. The highest fertilizer rate was 90% of the maximum amount permitted under current three-year period BMP guidelines for N and 300% of the maximum for P (Table 4).

Table 4. Annual fertilization amounts

	------------------------- lb/acre -------------------------			
DAP	0	128	384	641
Elemental N	0	23	69	115
Elemental P	0	26	78	130

At each of the two study sites, twenty-four 1/2-acre plots were established to examine 8 different treatment combinations in a completely randomized design with 3 replications. The 4 x 2 factorial design included four levels of fertilization treatment (0, 128, 384, and 641-pound DAP per acre) and two levels of raking treatment (annual rake and non-rake). The factorial design facilitates statistical tests on the interaction of fertilization and pine straw removal.

Treatment plots were subdivided into equal small subplots (using tree rows to define the long dimension) and aliquot fertilizer parts were broadcast by hand in each subplot to obtain the desired uniform application rate. This provided the greatest attainable precision in application rate. Application rates of fertilizer and each N and P elements are shown in Table 4.

5.1.3 Sampling Methods

Prior to study installation, surface soil uniformity was examined by soil profile transects across each study site. Baseline information regarding groundwater nutrient concentrations, soil physical and chemical properties, foliar nutrient concentrations, pine straw yield (Blountstown site only), and initial pine size was collected prior to the first fertilization. The impact of fertilization and pine straw removal on soil chemical and physical properties, leaching potential, stand growth, nutrient concentrations of pine foliage and pine straw, as well as pine straw yield was examined relative to baseline data.

Soil nutrient, soil bulk density, pine foliage nutrient, and pine litter mass and nutrient samples, as well as all tree measurements, were collected from a 0.03-hectare (0.074 acre) measurement plot located in the center of each treatment plot. All groundwater, soil, and tissue samples were clearly labeled by plot location, date, and time (a unique acquisition number) for cross referencing when samples were submitted to the analytical laboratory. Analytical Research Laboratory (ARL) or Environmental Water Quality Laboratory (EWQL) code numbers for samples were also recorded by our laboratory for cross reference in the data base. All sampling followed the FDEP SOPs specified in Rule 62-160 FAC, found at http://www.dep.state.fl.us/labs.

Groundwater Sampling Methods

Potential nutrient movement into groundwater was assessed with measures of nitrate + nitrite nitrogen (NO_x-N), total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4-N), and total phosphorus (TP) concentrations, using wells in the midst of each study area and reference wells which were at least 1000 feet away from the fertilized area.

To assess groundwater quality change, one treatment well and one reference well was installed at the Blountstown site, and one treatment and two reference wells were installed at the Live Oak site. The well depths at Blountstown were: treatment 41.5 ft (12.6 m), reference 27.0 ft (8.2 m); at Live Oak: treatment 56.4 ft (17.2 m), reference 53.4 ft (16.2 m) and 55.2 ft (16.8 m), all sufficient to reach the shallowest surficial groundwater. A treatment well was installed in the midst of the treatment area, and reference wells were installed at least 1000 ft distant to the treatment plots to avoid fertilization treatment effects. Groundwater samples were collected monthly for the period starting three months before the first fertilization until one year after the second fertilization, and then quarterly for the next two years. Ten samples per sampling date ($5_{wells} + 4_{blanks} + 1_{random\ duplicate}$) were taken during the first 14 months, but the sampling scheme was changed to 14 samples per sampling date ($5_{wells} \times 2_{duplicates} + 4_{blanks}$) for the rest of the study period to minimize sampling error. The samples were analyzed at the UF/IFAS Environmental Water Quality Laboratory (EWQL) in Gainesville.

Number of groundwater samples analyzed:

$$(5_{wells} + 1_{dupricates} + 4_{blanks}) \text{ x } 14_{dates} + (5_{wells} \times 2_{dupricates} + 4_{blanks}) \text{ x } 21_{dates} = 434 \text{ samples}$$

Soil Nutrient, Organic Matter, and Root Mass Sampling Methods

The environmental fate of applied nutrients was examined with periodic soil nutrient analyses to a depth of six feet, which is generally the lower limit to nutrient uptake for mid-rotation southern pines.

At each sampling date, three sampling points (subsamples) were selected in each measurement plot between pine rows (in alleys). A bucket auger was used to collect loose soil samples from 7 depths in the upper soil profile, specifically 0-6, 6 -12, 12-24, 24-36, 36-48, 48-60, and 60-72 inches. The equivalent metric units for these depths are 0-15, 15-30, 30-61, 61-91, 91-122, 122-152, 152-183 centimeters. Samples were taken in December 2008 before the first fertilization (pre-treatment) to establish a baseline, then at two weeks (Live Oak only), one month, two months, three months, and subsequently every 3 months for a year following each of the two fertilization events. During the next three years (2011-2013), soil samples were collected annually at the beginning of each growing season. After samples were air-dried, all roots were carefully collected and dried at 60°C for at least 48 hr to measure root dry weight. After the roots were collected, soil samples were ground (Blountstown only), sieved through a 2-mm sieve, and an equal amount of soil from each subsample was mixed to create a composite soil sample to represent each depth at a plot. Composite soil samples (5484 samples) were analyzed for NO_x-N, NH_4-N, TKN, TP, K, Ca, Mg, and organic matter (OM) at Analytical Research Laboratory (ARL). Percent OM was only determined for the 0-6 and 6-12 inch depths (1584 samples).

Number of soil nutrient samples analyzed:

$$7_{depth\ composites} \text{ x } 24_{plots} \text{ x } 2_{sites} \text{ x } 15_{dates} = 5040 + 504 \text{ (Live Oak)} - 96 \text{ (Blountstown)} = 5448 \text{ samples}$$

Soil Bulk Density Sampling Methods (ρb)

Undisturbed core samples were taken two times (prior to initial fertilization and a year after the second fertilization) to determine fertilization and raking effects on surface soil bulk density. Two relatively undisturbed locations were selected near the center of each treatment plot between the pine rows (in alleys). Two core samples (subsamples) were taken from each 0-6" and 6 -12" depths.

Number of soil core samples analyzed for bulk density:

$$2_{depths} \text{ x } 2_{points} \text{ x } 24_{plots} \text{ x } 2_{sites} \text{ x } 2_{dates} = 384 \text{ samples}$$

Pine Tree Height and Diameter Measurements

Fifty slash pines in each measurement plot were identified by a metal tag with a unique number placed on the stem two inches below diameter at breast height (dbh, at 4.5 ft above ground) and measured for total live height and dbh (Avery and Burkhart, 2002). Measurements were made in the dormant season prior to the first fertilization (pre-treatment) and in the dormant seasons following next four growing seasons (2009-2012).

Number of pine tree measurements:

$$1200_{\text{trees}} \times 2_{\text{sites}} \times 5_{\text{years}} = 12{,}000 \text{ tree measurements}$$

Pine Needle Litter Sampling Methods

Litter traps were used to evaluate pine straw production and nutrient cycling changes due to fertilization and pine straw raking treatments. Three 0.5274-m^2 litter traps were placed in each measurement plot and sampled quarterly (end of March, June, September, and December) from the first quarter 2009 through fourth quarter 2012 to determine pine litter oven-dry weight. All material collected by traps other than pine needles was discarded. Subsamples from three traps in each measurement plot were combined to create a composite sample, which was oven-dried at 60°C for at least 48 hr and ground. Three aliquots of the ground composite sample were taken to assess extractable N, P, K, Ca, Mg, and Fe concentrations at ARL.

Number of pine needle litter samples:

$$3_{\text{composites}} \times 24_{\text{plots}} \times 2_{\text{sites}} \times 15_{\text{dates}} + 47_{\text{standards}} = 2207 \text{ samples}$$

Methods for Sampling Raked Pine Straw

Pine straw raking was conducted in the fourth quarter of 2008 (Blountstown only), and following the 2009, 2010, 2011, and 2012 growing seasons in raked treatment plots. Based on pile size, 2-6 pine straw bales were randomly selected from those bales made from a given pile and measured for bale size and field fresh weight. Before baling, pine straw sub-samples were collected from various parts of a loose pine straw pile to create one composite sample per pile. There were typically two to four piles in a given treatment plot. These samples were oven-dried at 60°C for at least 48 hr to determine moisture content, which was used to calculate dry bale weight. All dried samples from the same plot were ground and mixed to form a composite sample, and three aliquots of each composite sample were analyzed at ARL for extractable N, P, K, Ca, Mg, and Fe concentration. The total number of bales raked and removed from each plot was counted in order to estimate total fresh and dry weight of pine straw removed, and also to determine nutrient budgets.

Number of pine straw nutrient samples analyzed:

$$3_{\text{aliquots}} \times 12_{\text{plots}} \times 2_{\text{sites}} \times 4.5_{\text{dates}} + 16_{\text{standards}} = 340 \text{ samples}$$

Pine Foliar Nutrient Sampling Methods

Foliar nutrient concentrations in the first flush of the current year growth were assessed during the dormant season (January-February). Baseline samples were taken prior to first fertilization (pre-treatment) and subsequent sampling followed each of the four growing seasons 2009-2012. One composite sample of equal amounts of foliage from six dominant or co-dominant pines was taken within each measurement plot and analyzed at ARL for extractable N, P, K, Ca, Mg, and Fe concentration.

Number of pine foliar nutrient samples:

$$3_{\text{aliquots}} \times 24_{\text{plots}} \times 2_{\text{sites}} \times 5_{\text{dates}} + 13_{\text{standards}} = 733 \text{ samples}$$

We assessed pine nutrient use efficiency for fertilization in pine straw production by using a nutrient balance approach including periodic soil nutrient analyses from various depths through the soil profile, seasonal measures of foliar nutrient concentrations, and estimates of nutrient removal in pine straw. Measures of soil, groundwater, and tree nutrient concentrations and tree responses to fertilization support recommendations regarding efficient fertilization rates for N+P fertilization, which is most common.

5.2 QUALITY ASSURANCE REPORTING

The Quality Assurance Project Plan (QAPP) submitted in September 2008 (GO247) and in October 2011 (GO332) further detail the methods and quality assurance program used in this study. The University of Florida Environmental Water Quality Laboratory (EWQL) and the UF Analytical Research Laboratory (ARL) are responsible for all sample care and testing upon submission, in accordance with our Quality Assurance Project Plan.

5.2.1 Environmental Monitoring: Groundwater

The University of Florida EWQL laboratory is a National Environmental Laboratory Accreditation Program (NELAP) certified laboratory for solution analysis, and follows EPA methods (US EPA, 2011) for water analysis (Table 5).

Table 5. Summary of analytical methods used for water at the University of Florida EWQL Laboratory, showing the method detection limit (MDL) and the US EPA practical quantitation limit (PQL).

Nutrient analyte in solution	**EPA Method #** (certified)	**Digestion**	**Accuracy** (above PQL)	**MDL** (mg/L)	**PQL** (mg/L)
Nitrate + Nitrite Nitrogen	353.2	N/A	90-110%	0.148	0.5
Ammonium Nitrogen	350.1 (UF modified)	N/A	90-110%	0.0625	0.5
Total Kjeldahl Nitrogen	351.2	Kjeldahl	90-110%	0.125	0.5
Total Phosphorus	365.1	Ammonium persulfate	90-110%	0.0025	0.01

5.2.2 Engineering Modeling: Soil and Plant Tissues

The ARL laboratory follows NELAP recommendations for soil and tissue analyses but is not NELAP certified for these materials. For soil analyses, ARL follows SW846 according to Method of Soil Analysis in SSSA Book Series No. 5 (Sparks, 1996). For tissue analyses, ARL follows the CRC Reference Methods for Plant Analysis (Kalra, 1998). All soil and tissue analytes are tested in solution after extraction and digestion according to methods summarized in Tables 6 and 7.

Table 6. Summary of analytical methods used for soil at the University of Florida ARL Laboratory, showing the method detection limit (MDL) and the US EPA practical quantitation limit (PQL).

Nutrient analyte in soil	**EPA Method #**	**Extraction /digestion**	**Accuracy** (above PQL)	**MDL** (mg/kg DW)	**PQL** (mg/kg DW)
Nitrate + Nitrite Nitrogen	353.2	KCl	85-115%	0.74	2.5[1]
Ammonium Nitrogen	350.1 (UF modified)	KCl	85-115%	0.32	2.5[1]

Total Kjeldahl Nitrogen	351.2	Kjeldahl	85-115%	0.625	50[2]
Total Kjeldahl Phosphorus	365.1 (351.2 digestion)	Kjeldahl	85-115%	2.5	8[2]
K	200.7	Mehlich3	85-115%	12.5	50[3]
Ca	200.7	Mehlich3	85-115%	50	200[3]
Mg	200.7	Mehlich3	85-115%	20	100[3]

[1] Values reflect KCl extraction
[2] Values reflect Kjeldahl digestion
[3] Values reflect Mehlich 3 extraction

Table 7. Summary of analytical methods used for plant tissue at the University of Florida ARL Laboratory, showing the method detection limit (MDL) and the US EPA practical quantitation limit (PQL).

Nutrient analyte in tissue	**EPA Method #**	**Extraction/ digestion**	**Accuracy** (above PQL)	**MDL** (mg/kg DW)	**PQL** (mg/kg DW)
Total Kjeldahl Nitrogen	351.2	Kjeldahl	85-115%	250	1000
Total Phosphorus	200.7	HCl 6M	85-115%	125	500
K	200.7	HCl 6M	85-115%	125	500
Ca	200.7	HCl 6M	85-115%	500	2000
Mg	200.7	HCl 6M	85-115%	250	1000
Fe	200.7	HCl 6M	85-115%	50	200

5.3 STUDY SUMMARY

5.3.1 Water Quality

Groundwater Monitoring

This study monitored surficial groundwater NH_4-N, NO_x-N, TKN, and TP concentrations in a treatment well proximate to the fertilized area and in one (Blountstown) or two (Live Oak) distant reference wells over a 52 month study period, including 3 monthly samples taken as a baseline prior to the first fertilization (Section 5.4.1 Groundwater Nutrients). Measures of depth to groundwater identified periods of recharge/discharge that are important in the interpretation of sample concentrations. Groundwater was much closer to the surface at the Blountstown site (3.0-13.5 ft) than at Live Oak (32.9-42.4 ft).

Ammonium nitrogen in groundwater samples did not exceed the Practical Quantification Limit (PQL) at either site over the 52-month monitoring period. There were no significant trends in groundwater NH_4-N concentration over time or between treatment and reference wells noted at either site.

NOx-N was elevated by fertilization at Blountstown, but concentrations were also related to well drawdown/recharge periods following fertilization. During the year following the first fertilization, NOx-N concentrations in groundwater samples were variable, but the concentration in the treatment well increased over time to a level 0.28 mg/L greater than the pre-fertilization baseline concentration, a value approximately twice the ARL Method Detection Limit (MDL=0.148 mg/L). Relative to the reference well, which had decreasing NO_x-N concentrations through most of the first year, the treatment well NO_x-N concentration increased following the first fertilization to a peak 1.2 mg/L greater than the reference well. Concentrations in the treatment well returned to baseline values during the well recharge period prior to the second-year fertilization, but then increased to peak values 1.4 mg/L greater than the reference well on 3/2/2010, at the time of the second fertilizer application. NO_x-N concentrations remained elevated (1.3 to 1.4 mg/L) greater than the reference well until the second winter recharge period. Treatment well concentrations averaged about 1.0 mg/L through the second recharge period (0.7 mg/L above the reference well) followed by a gradual convergence to reference well concentrations over the remaining 28-month monitoring period. Treatment well NO_x-N concentrations returned to baseline levels by approximately 43 months after the first fertilization.

Nitrate-nitrite concentrations were below the PQL over the 52-month monitoring period at Live Oak, and averaged 0.19 mg/L, near the MDL value. There were no significant trends over sampling dates or between reference and treatment wells through the monitoring period.

Significant regression models indicated that treatment well conductivity was increased relative to reference wells during both the first- and second-year post-fertilization drawdown periods at both sites. Differences in conductivity between treatment and reference wells tended to return to baseline levels, or less, during winter recharge periods and beginning 10-11 months after the second-year fertilization. (Section 5.4.1 Groundwater Nutrients).

Soil Monitoring

This study also monitored the fate of applied nitrogen and phosphorus in the soil over a 52 month period at the two study locations with contrasting leaching and nutrient sorption capacity, including one sampling at study initiation to establish a baseline prior to the first fertilization. Periodic sampling at various depths to 72 inches examined NO_x-N, NH_4-N, TKN, TP, Ca, Mg, and Fe concentrations to determine the effects DAP fertilization and pine straw raking (Section 5.4.2 Soil Nutrients).

Annual pine straw removal had no meaningful effect on the concentration of any soil nutrient. Diammonium phosphate fertilization quickly increased soil NH_4-N concentration in the surface soil, which returned to the pre-fertilization level by six (Live Oak) or 12 months (Blountstown) following the first application, due in part to observed nitrification and leaching and to uptake by pine roots, but also likely due to volatilization, which was not quantified. Soil NH_4-N concentration increased with fertilization rate, but the magnitude was several times greater after the second than after the first fertilization. Maximum soil NH_4-N concentrations during the 52 month monitoring period (50.8 and 24.9 mg/kg at Blountstown and Live Oak, respectively) were observed at 0-6" depth one month after the second application of the highest tested DAP rate (641 lb/ac). Applied NH_4-N moved to the lowest monitored depth (60-72") at the sandy Live Oak site but remained within 0-12" at Blountstown where a somewhat poorly drained clayey soil with high cation sorption capacity occurred.

These results confirm those of many studies and demonstrate that DAP fertilization can rapidly increase ammonium nitrogen concentration in the surface soils of sites with clayey or sandy textures. The higher the fertilizer rate the greater the NH_4-N concentration increase and the longer the effect. The greatest effect generally lasted up to three months after fertilization and was most pronounced at 0-6" for up to 2 months following application of 641 lb/acre DAP, the highest rate tested. The NH_4-N concentration increase in subsurface soil observed soon after the first fertilization at Live Oak probably was a result of rapid NH_4-N ion leaching through the highly permeable sandy soil during spring rain events, before it could volatilize or be converted to NO_x-N.

Fertilization with DAP caused elevated soil NO_x-N levels as nitrification of the ammonium fertilizer occurred. Soil NO_x-N concentration generally increased with increasing DAP rate in a linear fashion (on a log scale), but the low 128 lb/acre rate was usually not different from the non-fertilized control.

Nitrate leaching through the soil profile was observed at both sites following each of the two sequential annual fertilizations but was greatest following the second fertilization. Measured NO_x-N concentrations decreased with soil depth. Peak NO_x-N concentrations at the deepest monitored depth (60-72") were observed at six months after the second application of the highest DAP rate (641 lb/acre) at both sites, and concentrations were significantly greater than the non-fertilized control. At that time, peak NO_x-N concentrations in the deepest monitored depth were 2.75 mg/kg at Live Oak and 1.29 mg/kg at Blountstown. Concentrations remained elevated at that depth until one year after the second fertilization at Live Oak and two years after the second fertilization at Blountstown.

Greater NO_x-N leaching was observed at Live Oak, as was expected for the sandy excessively drained soil with limited sorption potential. At both sites the second annual fertilization resulted in a quicker and greater NOx-N concentration increase than the first one, which demonstrates a cumulative effect of consecutive annual fertilizations. Elevated NOx-N concentrations were recorded for three years after the second fertilization at Blountstown, but only for one year at the Live Oak site. These results demonstrate NO_x-N leaching in both a poorly drained high ion exchange capacity soil (Blountstown) and an excessively drained low ion exchange capacity soil (Live Oak).

Soil TKN was not affected by fertilization treatments at the Blountstown site. At Live Oak a slight temporary increase in TKN concentration was observed after the second application, but the trend was not consistent across sampling dates. The inherent TKN concentration at Blountstown was generally greater than at Live Oak and is consistent with the greater soil organic matter content observed at Blountstown.

Fertilization with DAP increased TP concentration in the surface soil beginning two months after the first application. Soil TP concentration generally increased with increasing DAP rate in a linear fashion (on a log scale), but the response to the low 128 lb/acre rate was minor. The second fertilization had a cumulative effect, further increasing TP concentration.

The maximum TP concentrations (265 and 354 mg/kg at Live Oak and Blountstown, respectively) were observed at 0-6" depth nine and six months, respectively, after the second application of 641 lb/acre DAP. Three years following the second application, TP concentrations remained two to three times the pre-fertilization level, 237 mg/kg at Live Oak and 316 mg/kg at Blountstown. No increase in TP concentration was detected below the 12" depth during four years following the first fertilization at either site. However, because of the persistence of phosphorus in soil, there is still a possibility of a later movement to the deeper soil horizons or groundwater.

Overall, these results indicate a delayed but persistent and cumulative soil TP response to the two consecutive DAP fertilizations at both sites. Phosphorus accumulated mainly in the uppermost 0-6" of the soil, generally in amounts proportional to the fertilization rates. At both sites limited phosphorus movement to the 6-12" depth was observed, but not to the deeper soil. Annual raking did not affect soil TP concentration at either site. (Section 5.4.2 Soil Nutrients).

5.3.2 Surface Soil Properties

Bulk density (ρb) increased from 2009 to 2011at both sites and at both monitored depths (0-6" and 6-12"), but these changes were not related to raking or fertilization treatments. They might have been related to the monitoring activities, i.e., foot and field vehicle traffic, which occurred throughout the study sites. The bulk density increase at Blountstown was significantly higher at the 0-6" depth than at 6-12" depth, which seems reasonable since the soil closest to the surface should be most impacted by traffic.

In other studies, pine straw raking has been shown to have a significant effect on soil organic matter content, since removal of pine litter is known to increase temperature fluctuation, decrease rain infiltration, and remove pine needle litter from mineralization to soil organic matter and soil carbon aggregates. However, this study showed no fertilization or raking effects on soil organic matter content at 0-6" or 6-12" depths, where differences would be most likely to occur as a result of treatments. (Section 5.5 Surface Soil Property Results).

5.3.3 Tree Growth and Straw Yield

Pine Stand Responses

Pine straw raking had no effect on pine diameter at breast height (Dbh), total pines per hectare, pine basal area, or pine volume at either site. Raking had no significant effect on dominant and co-dominant tree height at Blountstown, but at the sandy Live Oak site dominant and co-dominant tree height was significantly greater for non-raked treatments.

Poor or negative pine stand responses were observed for DAP fertilization at both sites. At Blountstown the 384 and 641 lb DAP/acre fertilization rates had significantly greater four-year diameter growth (Dbh) than the non-fertilized control. Fertilization treatments did not differ in dominant and co-dominant four-year pine height growth. All other cumulative four-year pine stand responses to fertilization were negative, with the 384 and 641 lb DAP/acre rates resulting in significantly increased mortality, reduced stand basal area, and less volume growth than the low DAP rate or non-fertilized control.

At live Oak dominant and co-dominant four-year pine height growth was greater for the 641 lb/acre DAP rate than the 128 lb/acre rate or non-fertilized control. Fertilization treatments did not differ in four-year diameter growth (Dbh), basal area growth, or volume growth. The four-year change in trees per hectare showed greater mortality for the high DAP rate than the low rate or non-fertilized control. (Section 5.6.1 Pine Stand Responses).

Pine Foliar Nutrient Responses

Overall, these results indicate that the high and sometimes the medium DAP fertilization rates temporarily increased pine foliar TKN concentration and decreased foliar TP concentration, as compared to the non-fertilized treatment. In general, the temporal trend of foliar TKN concentration increase corresponded with TKN increases observed in the pine needle litter. The effect on other nutrients is difficult to generalize, except that decreased concentrations sometimes occurred, possibly as a result of accelerated foliage growth and carbohydrate dilution. Pine straw raking had a minimal effect on foliar nutrient concentrations, except for the observed decrease in potassium concentration with raking at the Blountstown site. (Section 5.6.2 Pine Foliar Nutrients).

Pine Needle Litter Nutrient Responses

Elevated concentrations of TKN, K, and Ca were observed in quarterly collected pine needle litter following applications of the medium or high DAP rates, as compared to the non-fertilized control. At both study sites, the high fertilization rate (641 lb/acre DAP) resulted in greater TKN concentration than the low rate (128 lb/acre) or non-fertilized control on most sampling dates during the four-year monitoring period. The TKN concentration following the medium DAP rate (384 lb/acre) was usually intermediate to the low and high rates. The strongest rate response was observed in 2012, two years after the second fertilization, when all collected needles had been affected by two annual fertilizations.

The fertilization effect on K concentration was also most consistent in 2012. At Blountstown, 384 and 641 lb/acre rates resulted in greater K concentrations than 128 lb/acre DAP or the non-fertilized control.

At the Live Oak site, litter K concentrations resulting from 384 lb/acre were intermediate to K concentrations obtained with the low and high DAP rates.

Ca concentration was only affected at Live Oak, where 641 lb/acre DAP resulted in greater Ca concentration than lower fertilization rates and the non-fertilized control, on most dates starting in 2010. Two annual applications of 128 lb/acre DAP were not effective in increasing the concentration of any pine needle litter nutrient as compared to the non-fertilized control. Pine needle nutrient concentrations of TKN, TP, and K were generally greater at Blountstown than at the sandy Live Oak site.

There were some observed effects of raking on concentrations of some nutrients in pine needle litter, but a consistent trend through sampling times was not clear, except for Mg concentration at Blountstown, where the concentration was greater for non-raked than for raked treatments for most of the last year of the study (Section 5.6.3 Pine Needle Nutrients).

Pine Straw Yield and Nutrient Removal Responses

At the Blountstown site, both pine straw dry weight and number of bales per hectare were greater for 384 or 641 lb/acre DAP than for the low DAP rate and non-fertilized control, when averaged over the four harvests. At the sandy Live Oak site, the medium and high DAP rate tended to have greater yield than the non-fertilized control for harvests two, three, and four years after the first fertilization, but means were not significantly different. At the Blountstown site the effect of fertilization on straw yield was strongest in 2011, two years following the second fertilization. That year, the number of bales and harvested pine straw dry weight were greater for 641 lb/acre DAP than for the non-fertilized control by 38% and 35%, respectively. At the Live Oak site, even though statistically not significant, these differences were 46% and 37%, respectively. At both sites smaller differences in number of bales and pine straw dry weight were observed between 384 lb/acre DAP and the non-fertilized control.

The TKN concentration in pine straw generally increased with increasing DAP rate from 128 to 641 lb/acre at both sites, but the effect was only significant at Blountstown in 2009 and 2010, when TKN concentration was significantly greater for 641 lb/acre than for the other treatments (except 384 lb/acre in 2010). In 2010 at the Live Oak site, the difference between pine straw TKN concentration for 641 lb/acre and the non-fertilized control was 22%, but means were not statistically different.

Treatment differences in pine straw yield and nutrient concentrations generally resulted in greater removals of TKN, TP, K, and Ca from plots fertilized with 384 or 641 lb/acre DAP than from 128 lb/acre plots or non-fertilized plots during four years following the first fertilization at Blountstown. When averaged across 2009-2012 harvest years, the amounts of TKN, TP, K, and Ca removed from the 641 lb/acre treatment were greater than removals from the non-fertilized control by 29%, 5%, 21%, and 11%, respectively. A similar trend was observed at Live Oak (except for Ca), even though the differences were not significant. Nonetheless, 30% more TKN and 27% more K was removed from the 641 lb/acre DAP treatment as compared to the non-fertilized control at Live Oak (Section 5.6.4 Pine Straw Yield and Nutrient Removal).

5.4 WATER QUALITY RESULTS

5.4.1 Groundwater Nutrients

Introduction

Periodic groundwater samples were drawn from a “treatment” well within the treatment area and from one or more distant reference wells (1000 ft minimum distance) at each site and were analyzed for NO_x-N,

NH_4-N, TKN, and TP concentrations. At the Live Oak site nutrient concentrations in both reference wells were similar. However, the results from the reference well that consistently measured more similar to the treatment well in depth to groundwater were used for statistical analyses. In addition, water table depth, pH, temperature, conductivity, dissolved oxygen (DO), and turbidity were recorded during each periodic sampling. Well water samples were drawn monthly beginning two months prior to the first fertilization and for two years following the first fertilization. The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425). Following March 2011, wells were sampled quarterly until the end of monitoring period in February 2013.

Objectives

There are two questions addressed in this analysis. First, were measured variables in treatment well samples higher or lower than levels of concern? Second, were treatment well changes related to fertilization or were they similar to those observed for the reference well?

Analytical Approach

Regression analysis was used to examine trends over time and models were fit to explain observed patterns. Dependent variables were of two types. The first was the measured attribute for the treatment well. The second dependent variable was the difference between wells calculated as the treatment minus reference well value. These models are explanatory in nature, not predictive. The methodology was to fit linear regressions with sampling day (day 1 = January 1, 2009) to determine the proportion of variation explained (R-square) and to determine if the estimated slope and intercept terms differed from zero. The interpretation of regressions require context. In some cases, regressions form a baseline to examine sampling dates that depart from the baseline. For some variables an extended regression model was fit to explain observed patterns of departure from this baseline and test if model components were significant. Alternatively, the average of all sampling dates is relevant if the slope of the regression does not differ from zero and there are no discernible patterns with sampling date.

Statistical Methods

Iteratively weighted least squares regression was used to account for the fact that water sample data often contain samples considered outliers, with the undesirable property that they inflate the estimate of variance and pull the regression line in their direction (Helsel and Hirsch 2002). Regressions were performed using the MM estimation method of the SAS ROBUSTREG procedure (SAS Institute, Inc. 2010) that was first introduced by Yohai (1987). The Tukey bisquare weight function with K_0=2.9366 was used for all regressions estimated with this procedure. One characteristic of iteratively weighted least squares is that it uses outlier points but limits their weight in the fitting process. Day and day squared were used as independent variables in many of the models with day 1 set as January 1, 2009. These variables were scaled as (day/1000) so that parameter estimates were on a convenient scale. Indicator variables were used to account for well drawdown periods.

Results

Depth to groundwater: Depth to groundwater varied in treatment wells over the study period with more fluctuation observed in the first two years, which is likely related to variation in amount and timing of precipitation. Soils and depth to groundwater were very different between the two sites and observed recharge/drawdown patterns (Figure 2) varied from year to year. The observed cycles in relation to fertilization timing are grouped in Table 8. Both sites experienced recharge during the first 1-2 months after the first fertilization, followed by a gradual drawdown observed until the end of 2009. Both sites

experienced water recharge during the 3-4 months preceding the second fertilization in 2010. Live Oak responses generally lagged those of Blountstown, with the post-2010 fertilization drawdown period lasting to December 2010 at Blountstown, but to February 2011 at Live Oak. The Blountstown regression (Table 9, eqn. 1) of depth differences had a significant negative slope due to convergence of about half a meter. This regression and observed departures (Figure 2) suggest that treatment and reference well depth converged during drawdown periods at this site with a relatively high-water table. The Live Oak regression (Table 9, eqn. 2) slope was not significant. Water depth differed between wells but changes in depths were consistent between the treatment and reference wells (Figure 2).
Conclusion: Measures of depth to groundwater identified periods of recharge/discharge that are important in the interpretation of sample concentrations. Groundwater was much closer to the surface at the Blountstown (3.0-13.5 ft) site than at Live Oak (32.9-42.4 ft).

Well water temperature: Well water temperature had a seasonal pattern (Figure 3) that is removed by fitting regressions to differences between treatment and reference wells. Neither Blountstown (Table 9, eq. 3) nor Live Oak (Table 9, eq. 4) regressions of temperature differences were significant with respect to slope or intercepts. Temperature differences were more variable at the Blountstown site as were differences in water depth.

Ammonium (NH4-N): Ammonium nitrogen samples at Blountstown were below the EPA practical quantification limit (PQL=0.5 mg/L) for all treatment and reference well samples. The regression of differences between treatment and reference well ammonium nitrogen regressed with sampling date (Table 10, eqn. 6) had a significant intercept of 0.013 mg/L indicating that the treatment well had a slightly higher initial concentration, but this magnitude is less than the MDL. The significant slope (p=0.001) was due to differences converging to zero over time (Figure 4). Regression slope and intercept did not significantly differ from zero (Table 10, eqn. 5). Treatment well samples averaged 0.09 mg/L over the four-year sampling period, and samples were below MDL (0.0625 mg/L) for 12 of the 34 sampling dates at Blountstown. At Live Oak, the intercept and slope of the difference regression regressed with sampling date were not significant (Table 10, eqn. 8) and ammonium nitrogen was below PQL for all samples (Figure 4). There were 19 of 32 treatment well samples above the MDL and the 9/3/2009 sample of 0.46 mg/L was the only one approaching PQL. Ammonium nitrogen averaged 0.08 mg/L over the multi-year monitoring period at Live Oak (Table 10, eqn. 7).
Conclusion: Ammonium nitrogen in groundwater samples did not exceed the PQL at either site over the 52-month monitoring period. There were no significant trends in groundwater NH_4-N concentration over time or between treatment and reference wells noted at either site.

Nitrate/Nitrite-N (NOx-N): At Blountstown, NOx-N concentrations for treatment well samples taken before fertilizer treatments were applied were elevated (1.1 to 1.2 mg/L), as compared to the reference well (0.4 to 0.5 mg/L) (Figure 5). Baseline reference well NOx-N concentrations were close to the aqueous sample PQL (0.5 mg/kg), and about three times the ARL MDL (0.148 mg/L). Reference well concentrations decreased and were close to the MDL by 7/1/2009 (four months after first fertilization) and remained low through 11/4/2010 (Figure 5). Reference well NO_x-N concentrations then increased to about 80% of PQL by the end of the four-year monitoring period but remained less than baseline concentrations. In contrast, treatment well NO_x-N concentrations increased from baseline concentrations to reach a peak concentration of 1.6 mg/L at 4/5/2010, approximately 1 month after the second fertilization. At that time, treatment well concentrations began to decrease over time to converge with reference well values close to the PQL at the end of the monitoring period in March 2013. These patterns where characterized by regressions for treatment well NO_x-N concentration (Table 10, eqn. 9) and differences in NO_x-N concentration between treatment and reference wells (Table 10, eqn. 10), with significant positive intercepts and negative slopes, that explained 25-27 percent of the variation. There were significant departures from regressions at Blountstown related to distinct periods that could be described with a regression model.

Blountstown models identified several processes affecting groundwater NOx-N concentration over time. Increases in treatment well NO_x-N concentrations observed during the first post-fertilization year occurred before winter recharge and a NO_x-N peak was observed at about the time of the second fertilization treatment (Figure 5). A reasonable model was developed that accounted for the decline/convergence of NO_x-N concentrations with a day squared term (day 1= January 1, 2009), a slope term for sampling day during the first post-fertilization period, and a separate intercept term to account for the second-year peak (Table 14, eqns. 37 and 38). Regressions were performed using NO_x-N concentration differences between wells (R^2=0.71) and for treatment NO_x-N concentrations (R^2=0.76) as dependent variables (Figure 5). Intercepts estimate that pre-fertilization treatment well NO_x-N concentrations of 1.1 mg/L were 0.7 mg/L above those of the reference well. Concentrations were variable during the post-fertilization period in the first year, but a significant slope for this period estimates an increase in NO_x-N concentration of 0.15 mg/L for treatment well samples and an increase of 0.28 mg/L relative to the reference well. Treatment NO_x-N concentrations dropped during the December-February 2009 recharge period to 1.0 mg/L and then increased about the time of second fertilization. Treatment well concentrations were elevated during the second post-fertilization drawdown period, with the peak concentration estimated by the parameter associated with the I_4 variable. Increases in NO_x-N concentrations in the second year were estimated at 0.54 mg/L for treatment samples, with an increase of 0.68 mg/L relative to the reference well. The highest NO_X-N concentration for treatment wells was 1.6 mg/L on 8/5/2010. Concentrations started to return to baseline values at the 1/6/2011 sampling date, with the treatment well elevated less than 0.6 mg/L above the reference well, with the exception of an outlier difference of 1.0 mg/L on 5/12/2011. Nitrate-nitrite concentrations in treatment and reference wells converged to concentrations below PQL at the end of the monitoring period in 2013.
Conclusion: NOx-N was elevated by fertilization at Blountstown, but concentrations were also related to well drawdown/recharge periods following fertilization. During the year following the first fertilization, NOx-N concentrations in groundwater samples were variable, but the concentration in the treatment well increased over time to a level 0.28 mg/L greater than the pre-fertilization baseline concentration, a value approximately twice the ARL Method Detection Limit (MDL=0.148 mg/L). Relative to the reference well, which had decreasing NO_x-N concentrations through most of the first year, the treatment well NO_x-N concentration increased following the first fertilization to a peak 1.2 mg/L greater than the reference well. Concentrations in the treatment well returned to baseline values during the well recharge period prior to the second-year fertilization, but then increased to peak values 1.4 mg/L greater than the reference well on 3/2/2010, at the time of the second fertilizer application. NO_x-N concentrations remained elevated (1.3 to 1.4 mg/L) greater than the reference well until the second winter recharge period. Treatment well concentrations averaged about 1.0 mg/L through the second recharge period (0.7 mg/L above the reference well) followed by a gradual convergence to reference well concentrations over the remaining 28-month monitoring period. Treatment well NO_x-N concentrations gradually returned to baseline levels by approximately 43 months after the first fertilization.

At Live Oak, NOx-N concentrations in treatment well samples were below the PQL throughout the monitoring period (Figure 5). A total of 7 of 32 samples were below the MDL. The slope of the regression for treatment well samples (Table 10, eqn 11) was not significant and concentrations averaged 0.19 mg/L, just above MDL, over the multi-year monitoring period. The significant regression for the difference between treatment and reference well NOx-N concentrations (Table 10, eqn. 12) indicated that reference well concentrations were initially 0.4 mg/L higher than treatment well concentrations and that this difference increased slightly over the monitoring period. The two outlier differences were caused by low readings on reference well samples and not by changes in treatment well concentrations, as shown by the treatment well concentration regression.
Conclusion: Nitrate-nitrite concentrations were below the PQL over the 52-month monitoring period at Live Oak, and averaged 0.19 mg/L, near the MDL value. There were no significant trends over sampling dates or between reference and treatment wells through the monitoring period.

Total Kjeldahl Nitrogen (TKN): Regressions indicated no significant trend in groundwater TKN concentration over the four-year monitoring period at either site (Figure 6). Slopes were not significantly different from zero (Table 11, eqns. 13-16) for treatment well concentrations or for differences between treatment and reference wells. Only 5 samples exceeded the PQL (0.5 mg/L), with the two highest values identified as outliers (0.74 and 0.66 mg/L on 5/6/2010 and 8/13/2013, respectively). At Blountstown, TKN averaged 0.15 mg/L (2 of 34 samples excluded as outliers above) which is close to the MDL (0.125 mg/L). The difference between treatment and reference well concentrations at Blountstown did not differ from zero, averaging 0.02 mg/L, with one excluded outlier from the reference well (1.24 mg/L on 7/1/2009). At Live Oak, the only samples that exceeded the PQL were the identified outliers of 0.72, 1.07, and 0.95 mg/L on 12/4/2009, 4/7/2010, and 9/3/2010, respectively. At this site groundwater TKN concentration averaged 0.13 mg/L (3 of 32 samples excluded as outliers above) which is essentially the MDL. These same samples were identified as outliers in the analysis of differences between treatment and reference well concentrations, along with two additional high reference well values, 1.03 and 11.13 mg/L observed on 4/6/2009 and 9/3/2009, respectively. Ignoring these outliers, the average of treatment and reference well differences, based on 27 of 32 sample dates, was 0.01 mg/L.
Conclusion: Groundwater TKN concentration averaged close to the MDL throughout the 52 month monitoring period at both sites with no consistent trends to increase or decrease. Treatment well samples exceeded the PQL approximately 15% and 10% of the time at Blountstown and Live Oak, respectively, but there was no discernible pattern with sampling date, and only 1 sample exceeded 1.0 mg/L.

Total Phosphorus (TP): Regressions of groundwater TP concentration over sampling date at Blountstown had significant intercepts and slopes (Table 11, eqns. 17 and 18). Treatment well TP concentrations prior to fertilization averaged 3.9 ug/L, which was just above the MDL of 2.5 ug/L. Treatment well TP concentrations decreased over the four-year monitoring period (Figure 7) with concentrations never exceeding the PQL of 10 ug/L. The significant regression for the difference in treatment and reference well concentrations was due to higher initial TP concentrations and increasing TP concentrations for the reference well over the sampling period. Slopes for regressions at the Live Oak site were not significant (Table 11, eqns. 19 and 20), but intercepts were significantly different from zero. This indicates that treatment well TP concentration and differences in TP concentrations between the treatment and reference wells were not related to sampling date. Treatment well samples averaged 35.4 ug/L (outlier of 21.4 ug/L on 10/30/2012 was excluded) over the monitoring period and averaged 30.1 ug/L (outlier of -3.2 on 2/2/2012 excluded) greater than the reference well.
Conclusion: Groundwater total phosphorus concentration at Blountstown was just above the MDL prior to fertilization and decreased over the four-year monitoring period, with no measurements exceeding the PQL. Treatment well TP concentration at Live Oak averaged 35.4 ug/L, which is above the 10 ug/L PQL, but there was no evidence of a significant change from pre-fertilization concentrations.

Dissolved Oxygen (DO): Slopes of regressions for treatment well percent dissolved oxygen and the difference in percent DO between reference and treatment wells were not significantly different from zero (Table 12, eqns. 21-24) at either site. At Blountstown, percent dissolved oxygen was elevated above the regressions during the second-year drawdown period (Figure 8). Treatment well or the difference between treatment and reference well DO regression models that included a slope term to account for this period explained 56 and 51 percent of the variation, respectively (Table 14 eqns. 39 and 40). These models indicate that DO at Blountstown was initially 24 percent for the treatment well compared to 14 percent for the reference well. This difference of 10 percent decreased over the monitoring period, except for an increase for treatment well samples during the second-year drawdown period, when DO ranged from 38 to 73 percent. At Live Oak there were significant differences between treatment and reference wells (mean difference significant, Table 12, eqn. 24) but no pattern was detected with sampling date. Percent dissolved oxygen for the treatment well averaged 8 percentage points lower than the reference well over the monitoring period.

Conclusion: The difference between treatment and reference well dissolved oxygen converged over the four-year monitoring period at Blountstown, with the exception of elevated DO for the treatment well drawdown period from March through December of 2010. At Live Oak, percent DO was lower for the treatment than reference well, but there was no significant relationship with sampling date.

Conductivity: At Blountstown, regressions of conductivity measures over time in treatment wells and for the difference in conductivity between treatment and reference wells were significant (Table 12, eqns. 25 and 26), with conductivity declining over the monitoring period and not exceeding 60 uS/cm on any sampling date (Figure 9). The increase in conductivity above the regression was modeled with quadratic day and slope terms (Table 14, eqns. 41 and 42), with models explaining 70 and 62 percent of the variation in treatment well conductivity and difference in conductivity, respectively. These models indicate that there was an increase in treatment well conductivity during the first- and second-year drawdown period followed by a convergence in treatment and reference well conductivity by the end of the monitoring period. The regression for conductivity at Blountstown estimates that the difference between treatment and reference well samples increased from about 5 to 12 uS/cm during the first year after fertilization, and then returned to 9 uS/cm during the recharge period. During the drawdown period that occurred at about the same time as the second fertilization, conductivity increased to about 14 uS/cm, and then dropped to 8 uS/cm during the recharge period at the end of the second year. At about 10 to 14 months after the second-year fertilization conductivity began to decrease gradually with sequential sampling dates. At Live Oak, conductivity averaged 508 uS/cm for treatment well samples over the four-year monitoring period. Regression slopes were not significant (Table 12, eqns. 27 and 28) but examination of differences (Figure 9) indicated that conductivity was elevated for treatment wells over some periods. The regression for treatment well conductivity (Table 14, eqn. 44) had a significant slope and intercept term for the second-year drawdown period but explained only 25 percent of the variation. The regression for the difference in conductivity between treatment and reference wells (Table 14, eqn. 44) had a significant slope term for the first year drawdown period, in addition to the second year drawdown terms, and explained 35 percent of the variation. The difference model indicates (Figure 9) that conductivity increased about 20 uS/cm over the first drawdown period following the first fertilization, and then returned to the baseline during the recharge period. Conductivity increased by about the same amount during the second-year drawdown period following the second fertilization, and then returned to baseline levels over the remaining monitoring period.
Conclusion: Significant regression models indicated that treatment well conductivity was increased relative to reference wells during both the first- and second-year post-fertilization drawdown periods at both sites. Differences in conductivity between treatment and reference wells tended to return to baseline levels, or less, during winter recharge periods and beginning 10-11 months after the second-year fertilization.

Turbidity: At Blountstown, turbidity was less than 1 NTU for treatment wells, except for samples from August through October 2010 and January through May of 2011, when the highest turbidity was about 5 NTU (Figure 10). The slope for the regression of treatment well turbidity over time (Table 13, eqn. 29) was not significant, and samples averaged 0.2 NTU over the four-year monitoring period. The regression for differences between the treatment and reference well (Table 13, eqn. 30) was significant, but appears to indicate only that reference well turbidity was initially 12 NTU higher than the treatment well, and that this difference increased to over 20 NTU by the end of the monitoring period. At Live Oak, treatment well turbidity was usually below 2 NTU except for samples after July of 2010, when values ranged from 6 to 29 NTU. The significant slope for the treatment well regression (Table 13, eqn. 31) is indicative of turbidity measures close to zero until August of 2010, after which a number of sampling dates have elevated turbidity. The regression of differences in turbidity between treated and reference wells (Table 13, eqn. 32) was not significant, which indicates little evidence of a relationship between turbidity and treatment.

Conclusion: Regressions of the difference in turbidity between treatment and reference wells over time indicate little evidence that turbidity was related to treatment. At Blountstown, turbidity was higher for the reference well and increased over the monitoring period. Treatment well turbidity was usually less than 1 NTU, except for a few sampling dates. At Live Oak, turbidity was less than 2 NTU for treatment well samples before August of 2010 and elevated turbidity observed for later sampling dates was similar to that observed for reference well samples.

pH: At Blountstown, significant regressions with positive slope (Table 13, eqns. 33 and 34) indicate that treatment well pH increased from 4.8 to 5.0 and that treatment and reference well pH were converging over the monitoring period. A regression model for the difference between treatment and reference well pH (Table 14, eqn. 45) describes the baseline convergence of pH over time (Figure 11), except for the second-year drawdown period, during which pH differences were significantly less. At Live Oak, regressions for treatment well pH and differences in pH between the treatment and monitoring wells (Table 13, eqns. 35 and 36) were not significant. Treatment well pH averaged 7.2 over the four-year monitoring period. A regression model of pH differences between wells (Table 14, eqn. 46) detected a significant divergence between treatment and reference well pH over the second year drawdown period, but the divergence of 0.15 over this period was small in magnitude and related to increases in reference well pH (Figure 11).

Conclusion: Treatment well pH increased from 4.8 to 5.0 at Blountstown and averaged 7.2 at Live Oak over the four-year monitoring period. There was significant convergence of treatment and reference well pH at Blountstown and minor divergence between treatment and reference well pH at Live Oak during the second drawdown period. The divergence at Live Oak was mostly related to changes in reference well pH.

Table 8. Well depth periods based on recharge/drawdown pattern, relative to fertilization timing.

Study Site	Period	Dates	Treatment well depth
Blountstown	1-Pre-fertilization 1	1/7/2009 to 3/3/2009	3.4 m
	2-April recharge/drawdown	4/3/2009 to 11/4/2009	1.6 m initial then 3.2 to 3.6 m
	3-Pre-fertilization 2 recharge	12/3/2009 to 2/2/2010	2.9 decrease to 2.4 m
	4-Fertilization 2 drawdown	3/2/2010 to 12/2/2010	range of 2.4-4.1 m
	5-Post-fertilization years	1/6/2011 to 2/5/2013	range of 3.8-4.5 m
Live Oak	1-Pre-fertilization 1	1/8/2009 to 3/4/2009	12.6 to 12.9 m
	2-May recharge/drawdown	4/6/2009 to 12/4/2009	12.9, 10.0, then 11.4 to 12.6 m
	3-Pre-fertilization 2 recharge	1/7/2010 to 3/3/2010	12.2 to 10.2 m
	4-Fertilization 2 drawdown	4/7/2010 to 2/4/2011	10.9 to 12.9 m
	5-Post-fertilization years	5/19/2011 to 2/6/2013	range of 11.5 to 13.3 m

Table 9. Analysis of differences (Diff) in water depth (m) and temperature (°C) between treatment and reference well samples using equation Y = intercept + slope (Day/1000) where Day = sampling day (January 1, 2009 = 1) and Y = depth or temperature differences (Diff = reference well subtracted from treatment well for each sampling date). Regressions were fit using iteratively weighted least squares to identify outliers and obtain robust estimates of variance. Estimates are considered significantly different from zero when Prob. < 0.050.

Site	Variable	Eqn.	R^2	Parameter	df	Estimate	Prob.	Std. error	95% CI	
BT	Depth Diff	1	0.245	intercept	1	1.138	**<0.001**	0.089	0.962	1.313
				slope	1	-0.378	**0.002**	0.124	-0.622	-0.135
				mean	34	0.941	**<0.001**	0.052		
LO	Depth Diff	2	0.017	intercept	1	0.081	**<0.001**	0.007	0.068	0.095
				slope	1	0.007	0.428	0.010	-0.011	0.026
				mean	33	0.085	**<0.001**	0.004		
BT	Temp Diff	3	0.005	intercept	1	-0.616	0.082	0.355	-1.312	0.079
				slope	1	-0.260	0.599	0.494	-1.228	0.709
				mean	33	-0.733	**0.003**	0.228		
LO	Temp Diff	4	0.002	intercept	1	-0.052	0.798	0.201	-0.446	0.343
				slope	1	-0.064	0.820	0.280	-0.612	0.485
				mean	31	-0.061	0.523	0.095		

Table 10. Analysis of ammonium (NH_4-N) and nitrite + nitrate nitrogen (NO_x-N) concentration (mg/L) regressions using equation Y = intercept + slope (Day/1000) where Day = sampling day (January 1, 2009 = 1) and Y = treatment well concentration (Treat) or Y = reference well concentration subtracted from treatment well concentration (Diff). Regressions were fit using iteratively weighted least squares to identify outliers and obtain robust estimates of variance. Estimates are considered significantly different from zero when Prob. < 0.050.

Site	Variable	Eqn.	R^2	Parameter	df	Estimate	Prob.	Std. error	95% CI	
BT	NH_4 Treat	5	0.023	intercept	1	0.104	**<0.001**	0.022	0.061	0.146
				slope	1	-0.026	0.3930	0.030	-0.085	0.033
				mean	33	0.089	**<0.001**	0.011		
BT	NH_4 Diff	6	0.131	intercept	1	0.013	**<0.001**	0.004	0.0057	0.020
				slope	1	-0.016	**0.001**	0.005	-0.026	-0.007
				mean	29	0.003	0.194	0.002		
LO	NH_4 Treat	7	0.008	intercept	1	0.065	**<0.001**	0.019	0.028	0.103
				slope	1	0.014	0.574	0.026	-0.036	0.064
				mean	30	0.076	**<0.001**	0.009		
LO	NH_4 Diff	8	0.015	intercept	1	-0.003	0.618	0.006	-0.014	0.009
				slope	1	0.006	0.419	0.008	-0.009	0.022
				mean	30	-0.001	0.851	0.003		
BT	NOx Treat	9	0.266	intercept	1	1.399	**<0.001**	0.112	1.180	1.619
				slope	1	-0.559	**<0.001**	0.158	-0.869	-0.249
				mean	33	1.096	**<0.001**	0.065		
BT	NOx Diff	10	0.255	intercept	1	1.165	**<0.001**	0.118	0.933	1.397
				slope	1	-0.564	**<0.001**	0.168	-0.894	-0.234
				mean	33	0.849	**<0.001**	0.073		
LO	NOx Treat	11	0.037	intercept	1	0.179	**<0.001**	0.017	0.145	0.212
				slope	1	0.027	0.264	0.024	-0.020	0.073
				mean	31	0.193	**<0.001**	0.008		
LO	NOx Diff	12	0.209	intercept	1	-0.373	**<0.001**	0.017	-0.406	-0.339
				slope	1	-0.087	**<0.001**	0.023	-0.132	-0.041
				mean	29	-0.419	**<0.001**	0.012		

Table 11. Analysis of total Kjeldahl nitrogen (TKN in mg/L) and total phosphorus (TP in ug/L) concentration regressions using equation Y = intercept + slope (Day/1000) where Day = sampling day (January 1, 2009 =1) and Y = treatment well concentration (Treat) or Y = reference well concentration subtracted from treatment well concentration (Diff). Regressions were fit using iteratively weighted least squares to identify outliers and obtain robust estimates of variance. Estimates are considered significantly different from zero when Prob. < 0.050.

Site	Variable	Eqn.	R^2	Parameter	df	Estimate	Prob.	Std. error	95% CI	
BT	TKN Treat	13	0.020	intercept	1	0.169	**0.002**	0.054	0.064	0.275
				slope	1	-0.079	0.309	0.077	-0.231	0.073
				mean	31	0.151	**<0.001**	0.031		
BT	TKN Diff	14	0.003	intercept	1	-0.002	0.971	0.054	-0.109	0.105
				slope	1	0.030	0.699	0.078	-0.122	0.182
				mean	32	0.018	0.601	0.034		
LO	TKN Treat	15	0.009	intercept	1	0.140	**<0.001**	0.041	0.060	0.221
				slope	1	-0.038	0.486	0.055	-0.146	0.069
				mean	28	0.125	**<0.001**	0.022		
LO	TKN Diff	16	0.003	intercept	1	0.029	0.439	0.037	-0.044	0.102
				slope	1	-0.026	0.589	0.049	-0.122	0.069
				mean	26	0.008	0.664	0.019		
BT	TP Treat	17	0.320	intercept	1	2.832	**<0.001**	0.284	2.276	3.389
				slope	1	-1.777	**<0.001**	0.408	-2.576	-0.978
				mean	33	1.927	**<0.001**	0.198		
BT	TP Diff	18	0.402	intercept	1	-2.074	**<0.001**	0.447	-2.951	-1.198
				slope	1	-3.623	**<0.001**	0.655	-4.907	-2.340
				mean	33	-4.194	**<0.001**	0.341		
LO	TP Treat	19	0.001	intercept	1	35.224	**<0.001**	1.466	32.351	38.098
				slope	1	0.261	0.903	2.129	-3.912	4.433
				mean	30	35.401	**<0.001**	0.730		
LO	TP Diff	20	0.009	intercept	1	21.109	**<0.001**	1.837	17.491	24.691
				slope	1	-1.593	0.550	2.664	-6.814	3.628
				mean	30	20.142	**<0.001**	0.886		

Table 12. Analysis of dissolved oxygen (DO in %) and conductivity (Cond in uS/cm) regressions using equation Y = intercept + slope (Day/1000) where Day = sampling day (January 1, 2009 =1) and Y = treatment well reading (Treat) or Y = reference well reading subtracted from treatment well reading (Diff). Regressions were fit using iteratively weighted least squares to identify outliers and obtain robust estimates of variance. Estimates are considered significantly different from zero when Prob. < 0.050.

Site	Variable	Eqn.	R^2	Parameter	df	Estimate	Prob.	Std. error	95% CI	
BT	DO Treat	21	0.087	intercept	1	29.575	**<0.001**	4.482	20.791	38.358
				slope	1	-11.439	0.069	6.292	-23.771	0.894
				mean	32	25.176	**<0.001**	2.610		
BT	DO Diff	22	0.041	intercept	1	16.354	**0.003**	5.474	5.625	27.083
				slope	1	-8.938	0.250	7.764	-24.154	6.279
				mean	33	13.062	**<0.001**	3.104		
LO	DO Treat	23	0.019	intercept	1	54.105	**<0.001**	4.340	45.598	62.612
				slope	1	-4.439	0.450	5.872	-15.948	7.069
				mean	30	50.071	**<0.001**	2.191		
LO	DO Diff	24	0.040	intercept	1	-3.324	0.551	5.575	-14.250	7.601
				slope	1	-8.229	0.282	7.650	-23.222	6.764
				mean	31	-8.339	**0.004**	2.647		
BT	Cond Treat	25	0.141	intercept	1	47.098	**<0.001**	1.621	43.922	50.274
				slope	1	-5.557	**0.017**	2.332	-10.127	-0.987
				mean	33	44.059	**<0.001**	0.913		
BT	Cond Diff	26	0.185	intercept	1	13.632	**<0.001**	1.602	10.493	16.772
				slope	1	-7.367	**0.001**	2.238	-11.752	-2.981
				mean	33	9.353	**<0.001**	0.972		
LO	Cond Treat	27	0.066	intercept	1	503.637	**<0.001**	3.842	496.107	511.167
				slope	1	7.448	0.160	5.302	-2.945	17.841
				mean	31	507.781	**<0.001**	1.830		
LO	Cond Diff	28	0.005	intercept	1	170.782	**<0.001**	5.347	160.302	181.261
				slope	1	-3.427	0.659	7.768	-18.652	11.799
				mean	31	168.031	**<0.001**	3.008		

Table 13. Analysis of turbidity (Turb in NTU) and pH regressions using equation Y = intercept + slope (Day/1000) where Day = sampling day (January 1, 2009 = 1) and Y = treatment well reading (treat) or Y = reference well reading subtracted from treatment well reading (Diff). Regressions were fit using iteratively weighted least squares to identify outliers and obtain robust estimates of variance. Estimates are considered significantly different from zero when Prob. < 0.050.

Site	Variable	Eqn.	R^2	Parameter	df	Estimate	Prob.	Std. error	95% CI	
BT	Turb Treat	29	0.002	intercept	1	0.220	**0.002**	0.070	0.083	0.357
				slope	1	-0.051	0.606	0.099	-0.246	0.144
				mean	26	0.197	**<0.001**	0.042		
BT	Turb Diff	30	0.358	intercept	1	-11.854	**<0.001**	0.991	-13.796	-9.912
				slope	1	-7.298	**<0.001**	1.415	-10.072	-4.524
				mean	31	-15.913	**<0.001**	0.732		
LO	Turb Treat	31	0.097	intercept	1	0.365	0.670	0.854	-1.309	2.038
				slope	1	2.850	**0.022**	1.248	0.403	5.296
				mean	29	2.182	**<0.001**	0.491		
LO	Turb Diff	32	0.013	intercept	1	-0.345	0.556	0.586	-1.493	0.803
				slope	1	0.913	0.277	0.840	-0.734	2.559
				mean	28	0.547	0.222	0.438		
BT	pH Treat	33	0.283	intercept	1	4.833	**<0.001**	0.028	4.779	4.886
				slope	1	0.137	**<0.001**	0.039	0.060	0.2140
				mean	33	4.909	**<0.001**	0.017		
BT	pH Diff	34	0.286	intercept	1	-0.570	**<0.001**	-0.030	-0.629	-0.510
				slope	1	0.171	**<0.001**	0.042	0.087	0.254
				mean	32	-0.469	**<0.001**	0.018		
LO	pH Treat	35	0.014	intercept	1	7.190	**<0.001**	0.020	7.151	7.230
				slope	1	0.025	0.393	0.029	-0.032	0.081
				mean	28	7.204	**<0.001**	0.014		
LO	pH Diff	36	0.010	intercept	1	-0.323	**<0.001**	0.021	-0.364	-0.283
				slope	1	0.017	0.576	0.030	-0.042	0.075
				mean	30	-0.316	**<0.001**	0.011		

Table 14. Parameter estimates for terms in regression models fit using iteratively weighted least squares to explain significant departures from regressions NOx-N concentration (mg/L), dissolved oxygen (DO in %), conductivity (Cond in uS/cm) and acidity (pH). Indicator variables I_2 and I_4 are zero except for site defined drawdown and recharge periods. At Blountstown, I_2=1 for months 4-11, 2009 and I_4=1 for months 3-12, 2010. At Live Oak, I_2=1 for months 4-12, 2009 and I_4=1 for months 4-12, 2010.

Site	Variable	Eqn.	R^2	Term	df	Estimate	Prob.	Std. error	95% CI	
BT	NOx-N Treat	37	0.758	intercept	1	1.078	<0.001	0.051	0.978	1.177
				I_2 (Day/1000)	1	0.715	0.027	0.322	0.083	1.347
				I_4	1	0.542	<0.001	0.060	0.423	0.660
				$(Day/1000)^2$	1	-0.350	<0.001	0.047	-0.441	-0.258
BT	NOx-N Diff	38	0.706	intercept	1	0.746	<0.001	0.053	0.642	0.851
				I_2 (Day/1000)	1	1.296	<0.001	0.325	0.658	1.934
				I_4	1	0.676	<0.001	0.062	0.554	0.798
				$(Day/1000)^2$	1	-0.336	<0.001	0.048	-0.430	-0.243
BT	DO Treat	39	0.560	intercept	1	24.162	<0.001	2.432	19.395	28.928
				Day/1000	1	-12.255	0.001	3.229	-18.584	-5.925
				I_4(Day/1000)	1	45.392	<0.001	5.550	34.513	56.270
BT	DO Diff	40	0.506	intercept	1	10.323	0.002	3.372	3.372	16.933
				Day/1000	1	-9.706	0.032	4.532	-18.589	-0.824
				I_4(Day/1000)	1	49.758	<0.001	7.144	35.756	63.760
BT	Cond Treat	41	0.699	intercept	1	41.704	<0.001	0.968	39.807	43.601
				(Day/1000)	1	11.539	0.005	4.086	3.532	19.547
				$(Day/1000)^2$	1	-12.431	<0.001	2.794	-17.907	-6.955
				I_4 (Day/1000)	1	10.306	<0.001	1.823	6.734	13.879
BT	Cond Diff	42	0.624	intercept	1	4.871	<0.001	1.093	2.729	7.013
				(Day/1000)	1	14.879	<0.001	3.931	7.174	22.583
				$(Day/1000)^2$	1	-13.574	<0.001	2.676	-18.819	-8.329
				I_2 $(Day/1000)^2$	1	52.244	0.001	15.941	21.001	83.488
				I_4	1	5.286	<0.001	0.968	3.389	7.182
LO	Cond Treat	43	0.254	intercept	1	506.238	<0.001	2.221	501.885	510.590
				I_4	1	-42.814	0.023	18.898	-79.853	-5.774
				I_4(Day/1000)	1	78.937	0.009	30.236	19.676	138.198
LO	Cond Diff	44	0.348	intercept	1	159.028	<0.001	3.142	152.869	165.187
				I_2(Day/1000)	1	60.526	0.001	18.964	23.356	97.695
				I_4	1	-54.698	0.006	19.712	-93.332	-16.064
				I_4(Day/1000)	1	111.179	<0.001	31.368	49.698	172.660
BT	pH Diff	45	0.370	intercept	1	-0.558	<0.001	0.024	-0.605	-0.511
				$(Day/1000)^2$	1	0.115	<0.001	0.026	0.064	0.166
				I_4	1	0.103	0.002	0.034	0.037	0.169
BT	pH Diff	46	0.268	intercept	1	-0.303	<0.001	0.012	-0.327	-0.280
				I_4 (Day/1000)	1	-0.500	0.002	0.159	-0.811	-0.189
				I_4	1	0.278	0.005	0.099	0.083	0.472

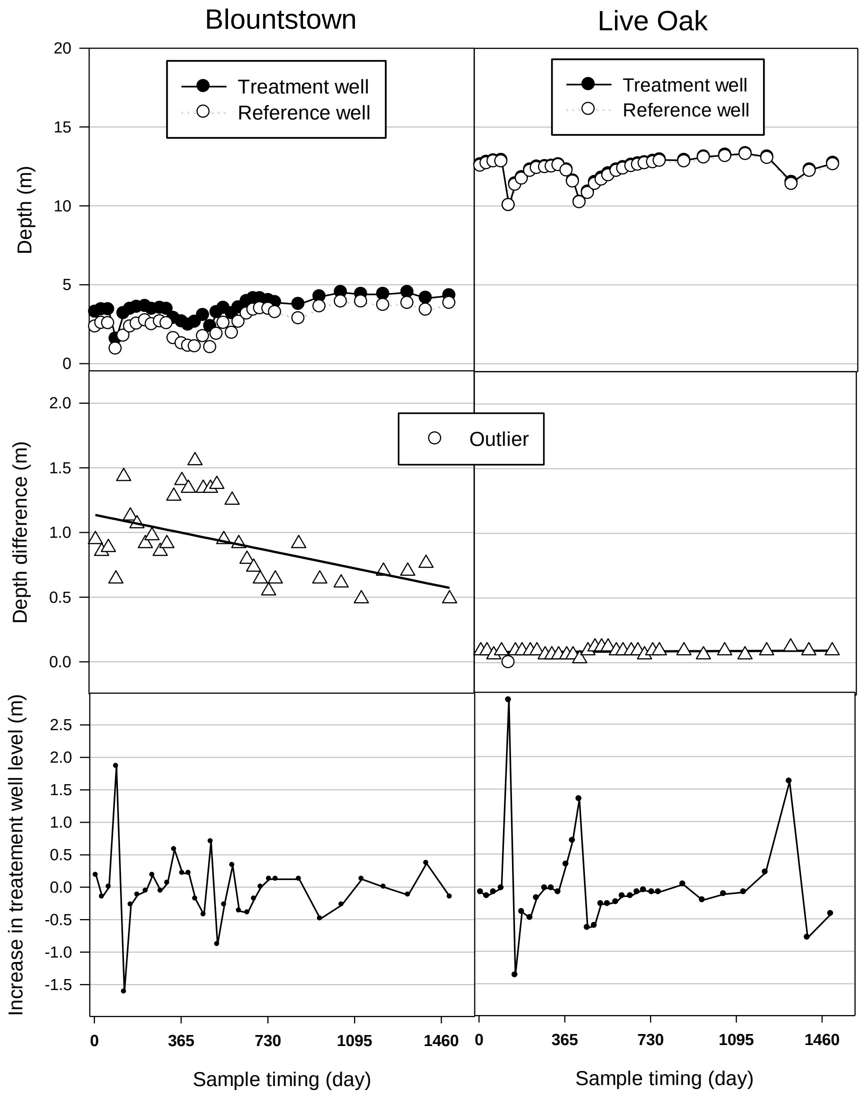

Figure 2. Comparison of treatment and reference well water depth at the Blountstown and Live Oak sites over the four-year monitoring period. Regressions for depth differences (treatment well minus reference well) regressed on sampling day (day 1 = January 1, 2009) were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

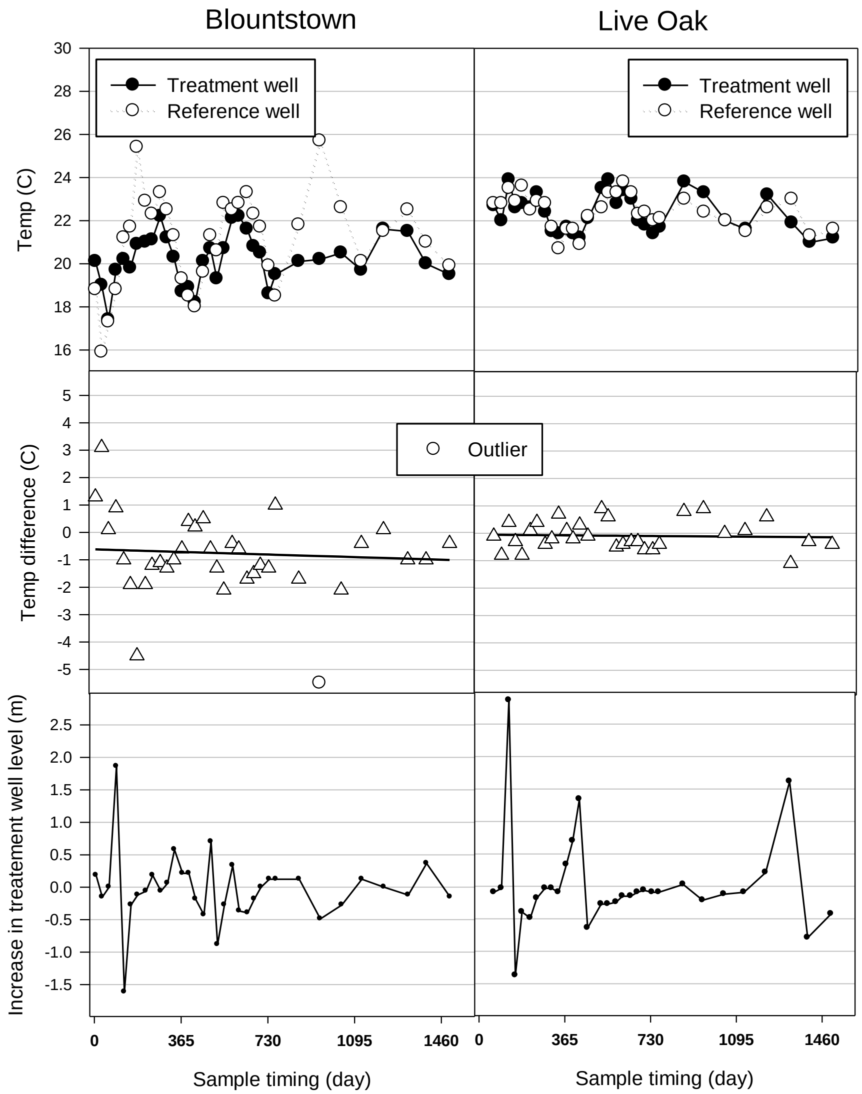

Figure 3. Comparison of treatment and reference well water temperature at Blountstown and Live Oak sites over the four-year monitoring period. Regressions for temperature differences (treatment well minus reference well) regressed on sampling day (day 1 = January 1, 2009) were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

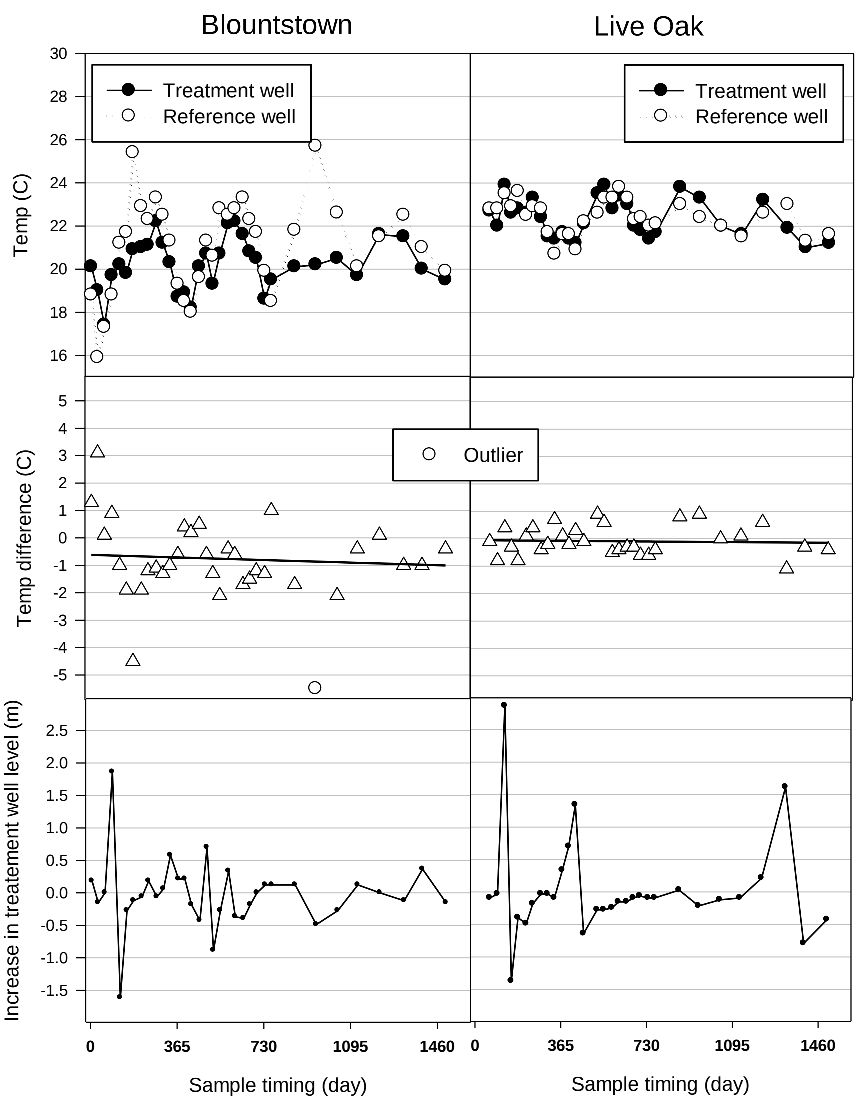

Figure 4. Comparison of treatment and reference well water ammonium nitrogen concentrations at Blountstown and Live Oak sites over the four-year monitoring period. Regressions for concentration differences (treatment well depth minus reference well depth) regressed on sampling day (day 1 = January 1, 2009) were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

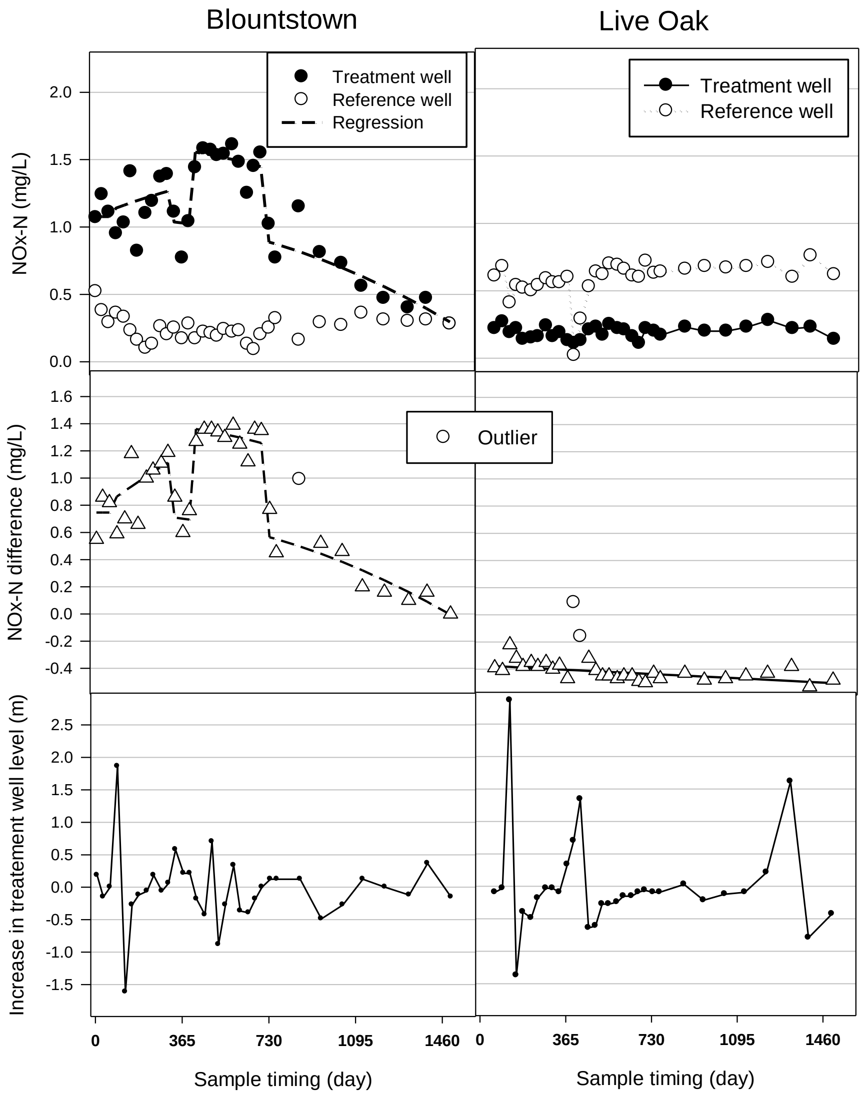

Figure 5. Comparison of treatment and reference well water NOx-N nitrogen concentrations at Blountstown and Live Oak sites over the four-year monitoring period. Blountstown regressions that relate treatment well concentrations and differences in concentrations to sampling date and drawdown period and the Live Oak regression for concentration differences (treatment well minus reference well) regressed on sampling day (day 1 = January 1, 2009) were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

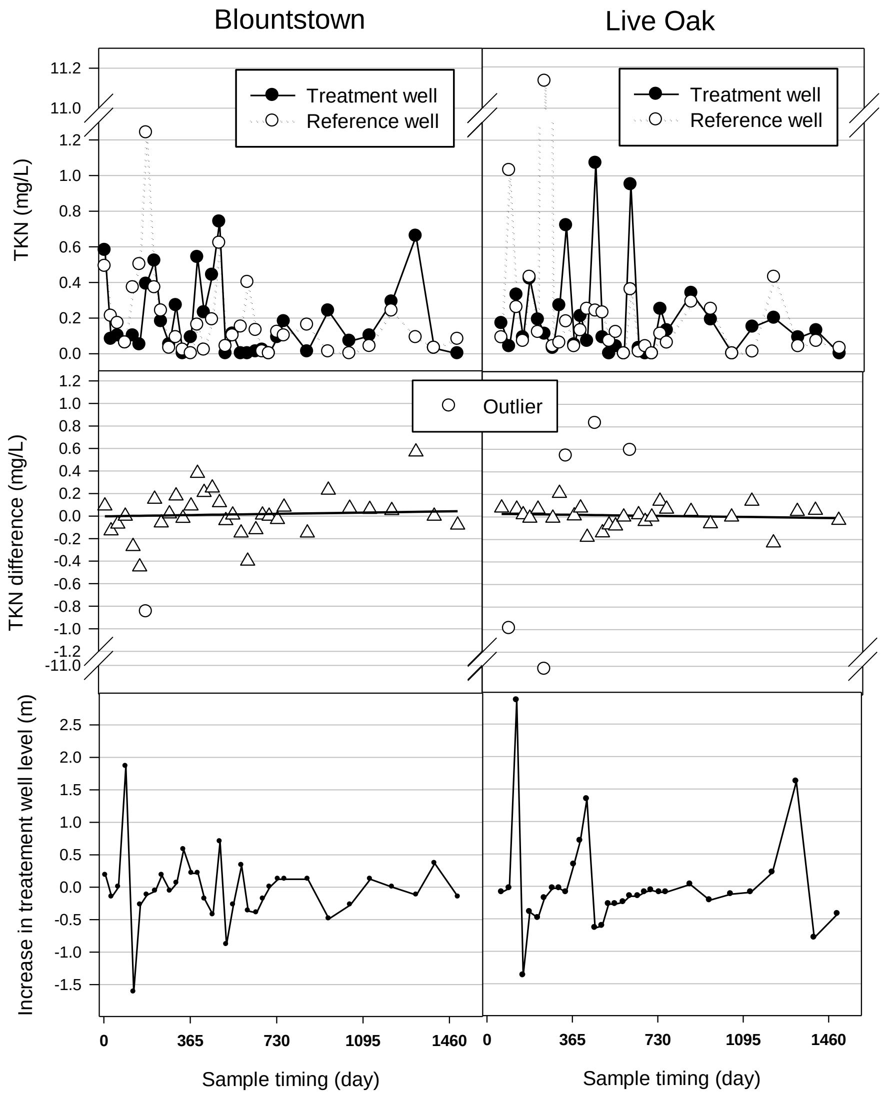

Figure 6. Comparison of treatment and reference well water total Kjeldahl nitrogen concentration at Blountstown and Live Oak sites over the four-year monitoring period. Regressions for concentration differences (treatment well minus reference well) regressed on sampling day (day 1 = January 1, 2009) were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

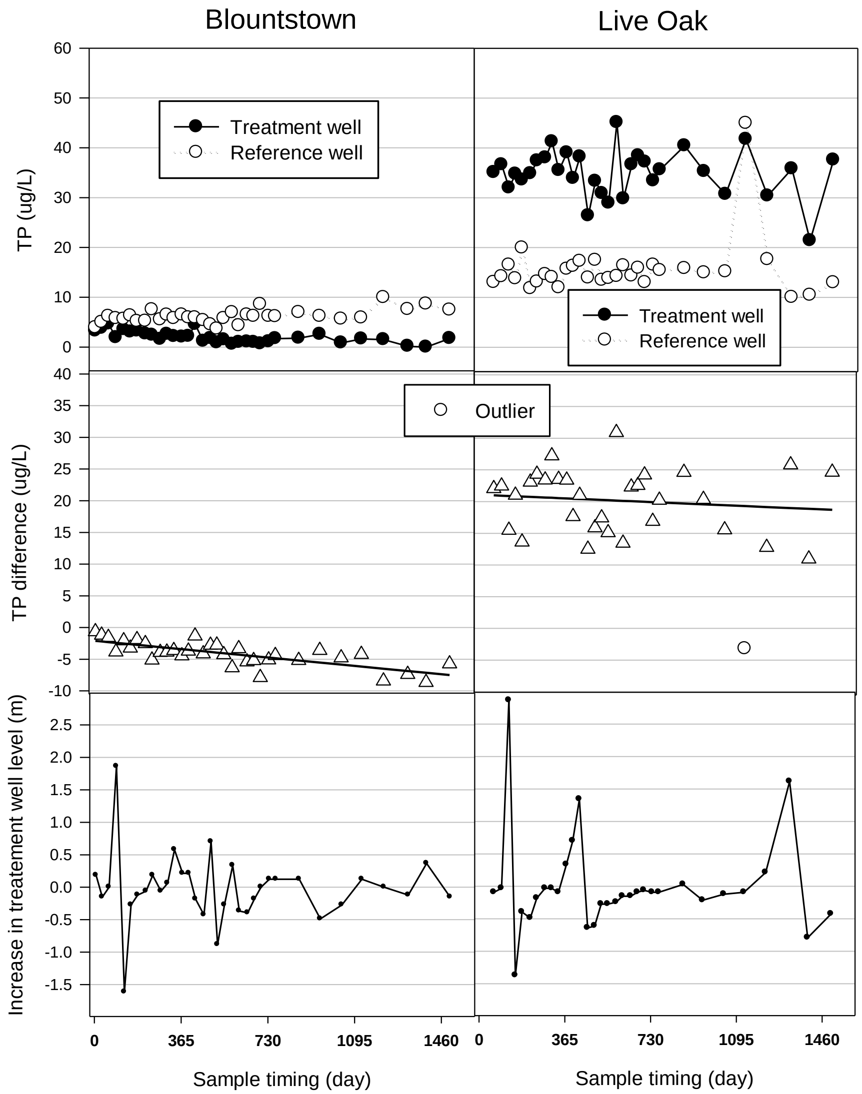

Figure 7. Comparison of treatment and reference well water total phosphorus concentrations at Blountstown and Live Oak sites over the four-year monitoring period. Regressions for concentration differences between wells (treatment well minus reference well) regressed on sampling day (day 1 = January 1, 2009) were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

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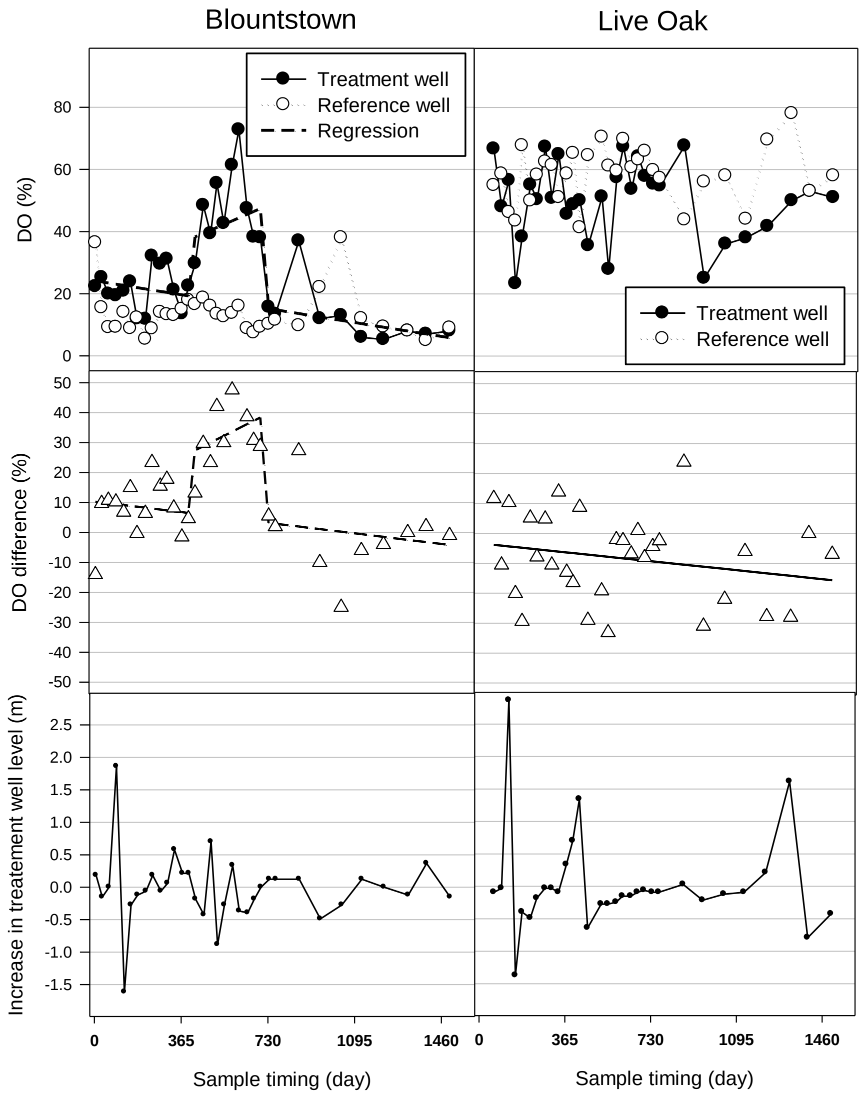

Figure 8. Comparison of treatment and reference well water dissolved oxygen (DO) at Blountstown and Live Oak sites over the four-year monitoring period. The Blountstown regression that relates DO difference to sampling date and the second year drawdown period and the Live Oak regression for differences (treatment well minus reference well) regressed on sampling day (day 1 = January 1, 2009) were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

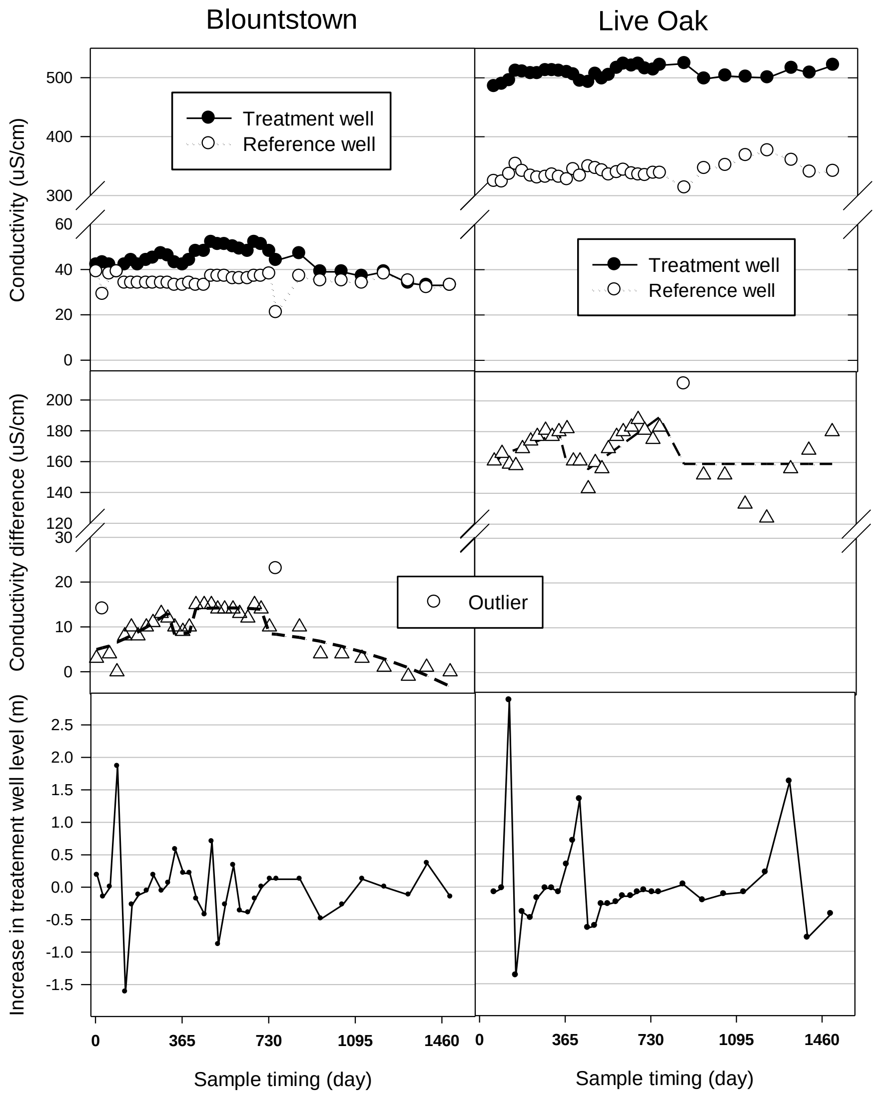

Figure 9. Comparison of treatment and reference well water conductivity at Blountstown and Live Oak sites over the four-year monitoring period. Regressions that relate conductivity differences (treatment well minus reference well) regressed on sampling day (day 1 = January 1, 2009), first year drawdown, and second year drawdown period variables were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

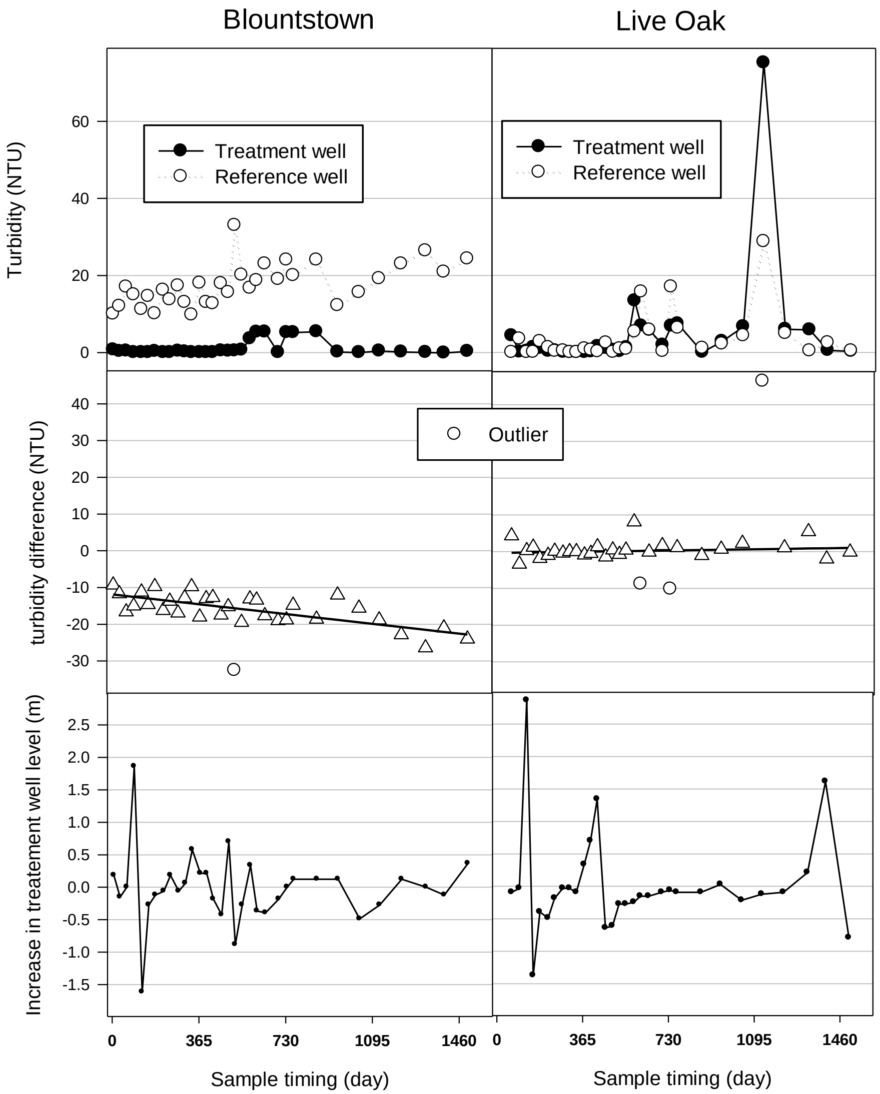

Figure 10. Comparison of treatment and reference well water turbidity at Blountstown and Live Oak sites over the four-year monitoring period. Regressions for turbidity differences (treatment well minus reference well) regressed on sampling day (day 1 = January 1, 2009) were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

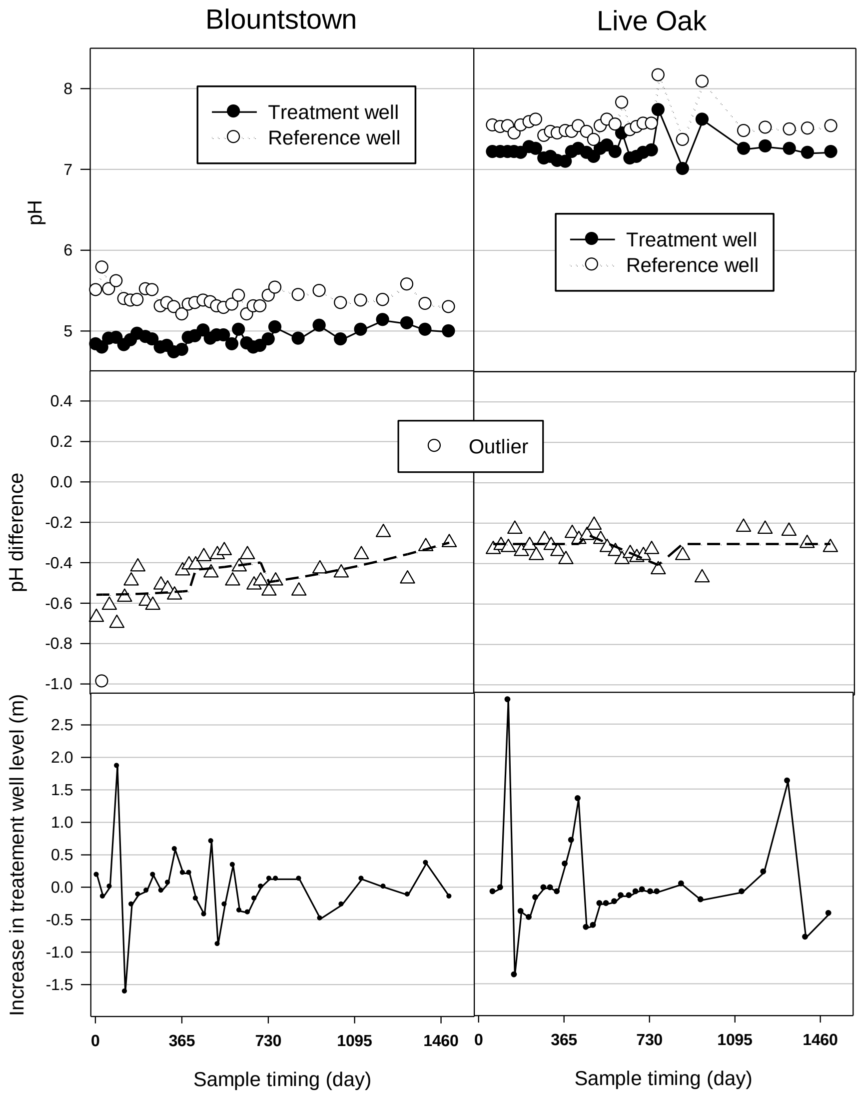

Figure 11. Comparison of treatment and reference well water pH at Blountstown and Live Oak sites over the four-year monitoring period. Regressions that relate pH differences (treatment well minus reference well) regressed on sampling day (day 1 = January 1, 2009) and second year drawdown period variables were estimated using iteratively weighted least squares to limit the influence of samples with large deviations (outliers). The first fertilization occurred within a few days of March 1, 2009 (day 60) and the second fertilization occurred within a few days of March 1, 2010 (day 425).

5.4.2 Soil Nutrients

Statistical Methods

The first soil nutrient samples were collected prior to the first fertilization treatment to establish baseline conditions. Subsequent soil nutrient samples were collected periodically throughout the monitoring period to evaluate soil nutrient changes due to the fertilizer application and pine straw raking. Samples were collected monthly for 3 months after each fertilization, then quarterly for the remainder of the year following fertilization, and annually for the rest of the monitoring period ending four years after the first fertilization. Additional sampling 2 weeks after each annual fertilization was conducted at the Live Oak site since the deep sandy soil at that site typically has a high leaching potential. Soil samples were taken at depths of 0-6", 6-12", 12-24", 24-36", 36-48", 48-60", and 60-72" (0-1.8 m). The exceptions to this were two sample dates when samples were not taken below 48" at Blountstown, due to a high-water table level. The percent organic matter was only determined to 12" depth. The objectives were to examine nutrient concentrations at different depths in the soil profile at periodic times following fertilization to determine if nutrients leached through the profile and to determine if distribution within the profile was fertilizer rate dependent and if it was affected by removing pine straw from the forest floor.

The statistical analysis was performed for each individual sampling date to compare nutrient concentrations at different depths in the soil profile following fertilization. Preliminary analysis using a fully specified model found that variation in residuals was related to the mean for all nutrients. Analysis was performed using the natural log of nutrient concentrations as the dependent variable to improve the homogeneity of variance and better condition the data with respect to having uniform variance with sample depth.

The analysis of variance was performed using Proc Mixed (SAS Institute) as a completely randomized design with sample depth nested within treatment plots. Treatment plots were considered subjects sampled at different depths. Sample depth is not a randomized sub-plot treatment as in a typical nested design and correlation among depths has a spatial adjacency component. Unspecified, banded unspecified, compound symmetry, heterogeneous compound symmetry, Huynh-Feldt, and spatial power structures were compared in terms of log-likelihood and patterns observed in covariance estimates. In this case, the spatial power structure was adopted based on both performance measures and theoretical considerations. Covariance was observed to be high for adjacent samples and then decrease rapidly as often noted by the good performance of the unspecified banded covariance matrix where non-adjacent sample covariance was assumed to be zero. The spatial power model uses the distance between samples, which is not constant in this experiment, as $\sigma^2\rho^{d_{ij}}$. There are only two parameters to estimate in this covariance model and d_{ij} is the distance between midpoints of sample depths i and j. The constant variance term with depth appeared to be reasonable after the log transformation of data.

The adoption of the spatial power structure to model the covariance structure is an improvement over the previous 2011 analysis that combined depths into groups to be able to approximate a spatial covariance structure. Probability tests such as F-tests and mean comparisons will differ from the earlier report because depths are no longer grouped prior to the analysis. This improves the estimate of the error structure and the resolution of the analysis. Main effect tests of depth and interactions of main effects with depth now use all depths as opposed to grouped depths. There are now 2 or 3 depths for each meaningful soil physical horizon. The 0-12" depths contain surface soil horizons (mainly A and E), 12-48" depths include the upper subsurface soil horizons (Bt at Blountstown and C1 at Live Oak), and 48-72" depths include the lower subsurface horizons (mainly the C horizon).

Nitrate/Nitrite Nitrogen (NO_x-N)

Although nitrogen was applied in the ammoniacal form, fertilization affected nitrate/nitrite nitrogen (NO_x-N) concentration in soil because one of the major metabolic pathways of applied ammonium (NH_4^+) is microbial nitrification. This biological process produces nitrate (NO_3^-), which is a relatively stable but mobile form of plant available nitrogen in soil. The nitrification process is mediated by a group of obligate autotrophic bacteria, such as *Nitrosomonas* and *Nitrobacter*, which require certain edaphic conditions to build their populations, i.e., favorable soil pH, moisture, temperature, and organic matter (carbon). Nitrification following DAP fertilization occurred more quickly at the Blountstown site than at Live Oak, which may be explained by observed differences in soil organic matter and moisture content, favoring microbial transformation at the Blountstown site. Although not measured, losses of ammonia gas would likely be greater for the porous, excessively drained Live Oak site.

At the Blountstown site, in spite of the statistical significance of depth before the first fertilization (Table 15), pre-fertilization NO_x-N differences among different depths were small and without any pattern or biological significance. Fertilizer rate had a significant effect on NO_x-N concentration on all dates between 2 and 9 months after the first application (2MAF and 9MAF). Following the second fertilization, the rate effect was significant 2MAF, and lasted for two years. The fertilization x depth interaction was significant on most dates starting two months after the first and one month after the second fertilization. Since the effects of raking and interactions involving raking were significant before the first raking was conducted and only on a few dates after raking, the raking effect does not appear important.

The highest rate (641 lb/acre DAP) resulted in a greater NO_x-N concentration than lower rates or non-fertilized control (Tables 17 & B) for all dates with a significant fertilization main effect at Blountstown. Except for a single date, one month after the first fertilization, the lowest rate (128 lb/acre DAP) did not result in an NO_x-N increase over the non-fertilized control. Nitrate/nitrite concentration following the medium fertilization rate (384 lb/acre DAP) was usually intermediate between low and high rates, but sometimes not different than the low rate.

Examining the NO_x-N concentration at different depths reveals how relatively quickly this mobile ion can leach through the soil profile, even at the Blountstown site where high clay content would limit nutrient ion mobility. Beginning two months after the first fertilization, we observed increasing NO_x-N concentration with increasing DAP rate at the three depth increments between 0 and 24", and an increase in NO_x-N concentration for fertilized over non-fertilized treatments at all depths to 72" (Table 17). The greatest NO_x-N concentration recorded following the first fertilization was 6.84 mg/kg at 0-6" depth two months after applying 641 lb/acre DAP. It gradually decreased with increasing sample depth from 0-6" to 36-48". Nitrate/nitrite concentration in the surface soil also decreased with time, as it moved down the soil profile or was utilized by plants and microorganisms. NO_x-N was either close to PQL levels or not different from the control at depths below 48". Elevated NO_x-N concentrations in the 36-48" depth of 1.00 and 2.02 mg/kg at 9 and12 months, respectively, were observed only for the high fertilization rate. At 12 months after the first fertilization, NO_x-N concentrations for the high fertilization rate were greater at the 24-48" depths than 0-24" depths.

Even though the trends for changing NO_x-N concentration at various depths through time were similar to the first fertilization at Blountstown, the observed responses to the second fertilization were quicker, more pronounced and longer lasting (Table 18). As soon as one month after the second fertilization we observed a linear increase in NO_x-N concentration with increasing fertilization rate from 0 to 641 lb/acre at 0-6" depth, and a significant concentration increase at 6-12" following 641 lb/acre, as compared to the lower rates or non-fertilized treatments. Demonstrating the quicker increase in NO_x-N concentration, at 1 MAF 8.06 mg/kg was observed, which is greater than the highest concentration observed following the first fertilization. At 2 MAF, a gradual concentration increase with increasing fertilization rate was observed at 0-6" and 6-12" depths, except for the large NO_x-N increase observed for the 641 lb/acre DAP rate, 11.61 and 8.59 mg/kg for the two depths, respectively. As was observed following the first fertilization, leaching of NO_x-N occurred over time. Following 631 lb/acre DAP, NO_x-N concentration first peaked at 0-6" depth 1 MAF to 3 MAF, later at 24-36" 6 MAF to 24 MAF, and then at 36-48" 36 MAF. Fertilization rate affected NO_x-N at all or most depths between 3 MAF and 24 MAF. Three years after the second fertilization, we still observed a linear increase in NO_x-N concentration with increasing fertilization rates at 24-60" depths.

The effects of raking on soil NO_x-N concentration at Blountstown were generally not significant and lacked any pattern of differences between raked and non-raked treatments over time. Initial pre-raking concentrations were significantly higher for designated rake plots (0.60 versus 0.39 mg/kg) except for the high fertilization rate, which explained the significant interaction with fertilization. This indicates that there were patterns of varying NO_x-N concentrations on the study site prior to application of treatments detectable when variation in concentrations was low. There were significant effects due to raking on only five other sampling dates. Concentrations were higher (1.14 vs. 0.49 mg/kg) after the first rake 9 MAF for the high fertilization rate without raking, explaining the significant rake x fert interaction. After the second raking and second fertilization, there were significant interactions with raking and depth at 2 and 3 MAF due mostly to differences at the 0-24" depths. NO_x-N concentrations were lower without raking (average of 1.6 versus 2.7 mg/kg) at all three sampled depths 2 MAF. At 3 MAF, NO_x-N concentrations were lower without raking only for the 12-24" depth (1.7 vs. 2.5 mg/kg). The significant 3-way interactions at the last two sampling dates (24 and 36 MAF) were indicative of treatment combinations with sporadic detects when levels were generally back at baseline.

Unlike the Blountstown site, the deep sandy soils at Live Oak have low inherent soil fertility, are low in soil organic matter, and have low nutrient holding capacity. At Live Oak there were no significant effects for fertilization, raking or any interaction of these factors on the pre-treatment soil NO_x-N concentration (Table 15), which indicated relatively uniform initial conditions for this variable. As at Blountstown, inherent pre-fertilization NO_x-N concentration differed among the soil depths. Even though not compared statistically between the separate studies, in general we observed lesser NO_x-N concentrations at Live Oak than at Blountstown (frequently below ARL MDL of 0.74 mg/kg), especially during the year following the first fertilization. This may be explained by the smaller soil organic nitrogen pool available for mineralization (lesser observed OM content and TKN concentration) to provide nitrogen, as well as the lesser exchange capacity and more active leaching of NO_3^- ions. Following the first fertilization, the effect of rate was only significant at 3 MAF. At that time, we observed a linear NO_x-N concentration increase with increasing fertilization rates at depths between 0 and 36". At 0-12" depths, NO_x-N concentration was greater for 641 lb/acre than 384 lb/acre, which was greater than for 128 or 0 lb/acre treatments. At 12-36" depths the two higher rates resulted in greater NO_x-N concentrations than for 128 or 0 lb/acre.

In contrast, soil NO_x-N concentration responses to the second fertilization at Live Oak were stronger and longer lasting than the first fertilization across all depths. The effect of fertilization was significant at four dates from 2 MAF to 9 MAF (Table 15). The fertilization x depth interaction was also significant on four dates from 3 MAF to 12 MAF, indicating different fertilization response at different depths, explained by NO_x-N downward movement in the soil profile. Application of 641 lb/acre resulted in greater NO_x-N concentration than the lower rates or no application 3 MAF at 0-36", 6 MAF and 9 MAF at 6-72", and 12 MAF at the 60-72" depth. Except for two cases, there were no significant differences among 384, 128 or 0 lb/acre treatments on any date at any depth, indicating low residual fertility effectiveness of DAP rates less than 641lb/acre. The greatest NO_x-N concentration (4.64 mg/kg) during the entire monitoring period at Live Oak, associated with highest fertilization rate, was observed 6 MAF at 24-46". By 9 MAF the peak NO_x-N concentation moved to the 60-72" depth where it remained till 12 MAF. Two years after the second fertilization there were no significant effects of fertilization on NO_x-N concentration at any depth, indicating that the applied N had either moved beyond the sampling zone or was utilized.

The effect of raking and the interaction between raking and depth were not significant for any sampling date at the Live Oak site (Table 15). The raking x fertilization interaction was significant on the last sampling date, three years after the second fertilization. This was primarily due to differences for the high fertilization rate where mean NO_x-N concentration across all depths was greater for non-raked plots fertilized with 641 lb/acre DAP (0.70 mg/kg) than for the raked plots receiving the same rate (0.46 mg/kg), results not shown.

Ammonium Nitrogen (NH_4-N)

Before the first fertilizer application at the Blountstown site, soil ammonium nitrogen (NH_4-N) concentration was greater in the surface 0-6" fraction than at lower depths. Although the effect of depth on NH_4-N was highly significant (Table 15), differences among the depths did not exceed 0.37 mg/kg, a value close to the ARL MDL of 0.32 mg/kg (results not shown).

Since N was supplied in the form of diammonium phosphate (DAP), fertilization quickly increased surface soil NH_4-N concentration, but the effect was short lived at the Blountstown site (Table 21). One and two months after the application, 384 lb/acre DAP resulted in a greater NH_4-N concentration at 0-6" than 128 or 0 lb/acre, but lesser than 641 lb/acre. Ammonium nitrogen concentration was greater following 641 lb/acre than for any other treatment 2MAF at 6-12" and 3MAF at 0-6" depth. The maximum NH_4-N concentration after the first fertilization at Blountstown (11.34 mg/kg) was recorded 2MAF at 0-6" depth as a result of the highest DAP rate. The significant fertilization rate main effect 9MAF was caused by the slightly greater NH_4-N concentration for 641 lb/acre than for the other treatments. Even though this effect was also significant 12MAF, the differences among the rates were small and without any pattern.

The response to the second fertilization at Blountstown showed a similar trend but was of a much greater magnitude than following the first fertilization (Table 22). At the 0-6" depth, as fertilization rate increased from 0 to 641 lb/acre the NH_4-N concentration increased in a gradient from 1.76 to 50.75 mg/kg 1MAF and from 0.77 to 16.24 mg/kg 2MAF. On those dates, 641 lb/acre DAP resulted in a greater NH_4-N concentration than the other fertilization treatments at 6-12", whereas at 3MAF both 641 lb/acre and 384 lb/acre treatments had greater NH4-N concentrations than 128 or 0 lb/acre DAP at 0-6".

According to ANOVA, the effect of raking and the raking x fertilization interaction were significant at the Blountstown site before the first raking (Table 15), which means inherent differences in NH_4-N occurred among treatment plots prior to initiation of treatments.

At the Live Oak site, the response to the first fertilization was evident at all depths within two weeks of the application (Table 23). At 0-6" depth, 128 lb/acre DAP resulted in the greatest and 0 lb/acre in the least NH_4-N concentration, while at 6-12" the concentrations for 128 and 384 lb/acre were greater than for 0 lb/acre but lesser than for 641 lb/acre. No differences among DAP rates were observed at the lower depths but DAP increased NH_4-N concentration over non-fertilized control at all depths. Two and three months after fertilization, at all depths NH_4-N concentration increased in proportion to increasing fertilization rates. Differences between rates were significant only at 0-12" depth at 1MAF and 2MAF, at 48-60" 1MAF and at 60-72" 2MAF. The highest peak, 18.84 mg/kg NH_4-N, was recorded 2MAF at 0-6" following 641 lb/acre DAP. The fertilization effect lasted till 3MAF when the two higher rates had higher NH4-N concentrations than the low rate and non-fertilized control.

An increase in NH_4-N concentration was also observed two weeks to 6 months after the second fertilization at Live Oak but was limited to 0-12" depths (Table 24). At 0-6", a pronounced gradient of increasing NH_4-N concentration corresponded with the increase of DAP rate on all sampling dates up to 3MAF. The biggest increase for fertilization relative to the non-fertilized control (from 0.85 mg/kg for 0 lb/acre DAP to 24.85 mg/kg for 641 lb/acre DAP) was recorded 1MAF. The modest NH_4-N concentration increase by the high DAP rate over the lower rates and non-fertilized control lasted for six months following fertilization.

The effect of raking on NH_4-N concentration was minimal at Live Oak. One and two years after the second fertilization NH_4-N concentration was greater for the non-raked than for the raked treatments, but the mean difference across all fertilization rates and depths was less than 0.1 mg/kg (results not shown).

Our results indicate that DAP fertilization can rapidly increase ammonium nitrogen concentration in the surface soils of different textures. The higher the fertilizer rate the greater the NH_4-N concentration increase and the longer the effect. The effect generally lasted up to three months after fertilization and was most pronounced at 0-6" for up to 2 months following application of 641 lb/acre DAP. The subsequent decrease in concentration may have occurred to some extent as pines utilized this preferred N source, but was probably more strongly influenced by volatilization and nitrification, which is consistent with the long lasting increase in soil nitrate/nitrite concentration observed. The NH_4-N concentration increase in subsurface soil observed soon after the first fertilization at Live Oak probably was a result of rapid NH_4-N ion leaching through the highly permeable soil during spring rain events, before it could volatilize or be converted to NO_x-N.

Total Kjeldahl Nitrogen (TKN)

Soil TKN concentration at the Blountstown site was not affected by fertilization or raking treatments but was depth dependent as evidenced by the highly significant main effect of depth throughout the study (Table 16). On the dates when the fertilization x depth interaction was significant, it was driven by differences among depths rather than fertilization rates (Tables 25 & 26). ANOVA showed a significant raking effect prior to the first raking (Table 16) which means that there were inherent differences in soil TKN among treatment plots prior to study initiation.

There was a consistent inherent TKN concentration gradient from the greatest at 0-6" (402 mg/kg overall mean for all fertilization rates and sampling dates) to the least at 60-72" (65 mg/kg, results not shown). This can be explained by the differences in organic matter content, since a large portion of TKN is organic nitrogen typically associated with the surface soil horizons. A change in TKN concentration from a mean of 402 mg/kg at 0-6" depth to 228 mg/kg at 6-12" corresponded with a similar change in OM content from 13.1 g/kg to 8.9 g/kg, respectively (results not shown).

At the Live Oak site, the effect of fertilization on soil TKN was minimal (Table 16). Two months after the first fertilization, TKN concentration was greater for non-fertilized plots than for any of the fertilized treatments (Table 27), but this may not be attributed to fertilization. Three months after the second fertilization (3MAF), TKN concentration was significantly greater for 641 lb/acre DAP than for 0 or 128 lb/acre, with intermediate values for 384lb/acre (Table 28). A similar trend was observed 1, 2, and 6 MAF, even though the differences were not significant.

As observed at Blountstown, raking had no consistent impact on soil TKN concentration at Live Oak. ANOVA indicated a significant raking effect on three isolated dates: on 5/25/09, before the first raking, on 5/10/2010, after the first raking, and on 2/21/11, after the second raking (Table 16). At each of these dates, soil TKN was generally less for raked treatments, but a consistent difference through time was not observed. Moreover, the differences between non-raked and raked treatments were similar before raking, after the 1st, and after the 2nd raking. When averaged across all fertilization rates and soil depths, TKN concentrations were 65, 75, and 60 mg/kg for non-raked treatments, and 59, 65, and 53 mg/kg for raked treatments on these dates, respectively (results not shown).

Similar to the Blountstown site, ANOVA showed soil TKN concentration to differ by depth at all sampling dates at Live Oak (Table 16). However, TKN concentration decreased with depth only to 48", from an overall mean of 260 mg/kg at 0-6" to 35 mg/kg at 36-48". Unlike Blountstown, TKN concentration did not generally decrease further with depth. The sandy excessively drained soils at the Live Oak site are conducive to rapid rates of organic matter oxidation. The difference in TKN concentration between 0-6" and 6-12" depths (overall means 260 and 150 mg/kg, respectively) correspond to differences in soil OM content (11.7 and 7.1 g/kg, respectively, results not shown).

Total Phosphorous (TP)

At the Blountstown site there was a consistent gradient of decreasing inherent soil TP concentration with increasing soil depth from 0-6" to 60-72", but the greatest change occurred from 0-6" to 12-24" (Tables 29 & 30, results for the depth main effect not shown). Fertilization magnified differences among depths, because it only affected TP concentration in the surface soil. This resulted in a significant fertilization x depth interaction rather than a significant fertilization main effect on most sampling dates throughout the study (Table 16). A significant effect of fertilization on surface soil TP concentration was first recorded two months after the first application (Table 29) and remained significant through the end of the monitoring period (four years after the first fertilization) except for 4/26/2010, when the same trend still persisted (Table 30). A significant linear fertilization rate response (on log sale) was also first observed 2MAF for the fertilization main effect and on most sampling dates after that for the 0-6" depth (Tables 29 & 30). In spite of this trend beginning 2MAF, only the high rate resulted in significantly elevated total phosphorus at 0-6" between three and nine months after the first fertilization (Table 29). At one year the medium rate also significantly increased TP concentration above the low rate and non-fertilized control, but to a lesser degree than the high rate. On the next sampling date, a month after the second fertilization, again only 641 lb/acre DAP resulted in greater TP concentration than the other treatments (Table 30). However, beginning 3MAF soil TP concentration at 0-6" resulting from the medium fertilization rate was on most sampling dates greater than the low rate or non-fertilized control and usually not significantly different from the high rate. The low fertilization rate did not significantly increase TP concentration over the non-fertilized control throughout the study except for 3/06/12, two years after the second fertilization.

The effect of fertilization on soil TP concentration at Blountstown was limited to the 0-6" depth for the first nine months, but a year after the first fertilization it extended to 6-12", where a linear fertilization rate response (on log sale) was observed and TP concentration was significantly greater for 641 lb/acre than to 0 or 128lb/acre DAP (Table 29). On most sampling dates during the three years following the second fertilization we recorded a similar trend of increasing TP concentration with increasing DAP rate, even though the differences were not statistically significant except for one date, two years after the second fertilization, when 641 lb/acre had greater TP concentration at 6-12" than the other treatments. These results suggest that some of the phosphorus applied with DAP at 641 lb/acre and, to lesser degree, 384 lb/acre moved down to the 6-12" depth with time. This may explain only moderately greater values for soil TP concentrations after the seconded fertilization as compared to the first one, even though a cumulative effect could be expected. The maximum TP concentration recorded at 0-6" was 314.0 mg/kg after the first and 353.6 mg/kg after the second application of 641 lb/acre DAP.

There was no raking effect on total phosphorus concentration in Blountstown (Table 16).

At the Live Oak site inherent soil TP concentration also decreased significantly with increasing soil depth, but mostly between 0-6" and 36-48", with little change below this depth and the biggest decrease from 0-6" to 12-24" (Tables 31 & 32, results for the depth main effect not shown). On most sampling dates total phosphorus concentration at 0-6" for the non-fertilized control was generally less at Live Oak than at Blountstown, which should be expected considering the lesser soil organic matter content and excessively drained deep sandy soil texture at the Live Oak site. The effect of the first fertilization on soil TP concentration at the Live Oak site was not clear and was significant only on two sampling dates (Table 16). In contrast, after the second DAP application the fertilization main effect or fertilization x depth interaction were significant on every sampling date. As early as two weeks after the second fertilization a significant linear trend of increasing TP concentration with increasing fertilization rate was observed at the 0-6" depth (Table 32). This trend persisted till the end of the monitoring period, three years after the second fertilization. The second DAP application of 641 lb/acre always resulted in TP concentrations greater than 0 lb/acre or 128lb/acre, while 384 lb/acre resulted in TP concentrations intermediate to the

128lb/acre and 641 lb/acre rates, though on certain dates not significantly different from one or the other. As in Blountstown, the low rate did not have significantly greater TP concentration at 0-6" as compared the non-fertilized control during the entire study.

There was limited phosphorus downward movement after the second application of the high DAP rate. On most dates TP concentrations at 6-12" resulting from this treatment were significantly greater than all or some of the other treatments (Table 32).

ANOVA indicated a significant raking effect on soil TP on most sampling dates at the Live Oak site (Table 16). On these dates mean TP concentrations across all fertilization rates were greater for non-raked than for raked treatments (results not shown). However, this difference was significant on six sampling dates before the first raking and not significant after the third and fourth raking. Therefore, we cannot conclude that raking affected soil TP concentration.

Overall, these results indicate a delayed but persistent and cumulative soil TP response to the two consecutive DAP fertilizations at both sites. Phosphorus accumulated mainly in the uppermost 0-6" of the soil, generally in amounts proportional to the fertilization rates. At both sites limited phosphorus movement to the 6-12" depth was observed, but not to the deeper soil. Annual raking did not affect soil TP concentration at either site.

Table 15. ANOVA for soil NO_x-N and NH_4-N concentrations by sampling date at two study sites

Factor	df[†]																	
		Raking / 1st Fertilization						Raking	2nd Fertilization						Raking	Raking	Raking	
NO_x-N Blountstown																		
		10/01/08		03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10		03/29/10	04/26/10	05/24/10	08/23/10	11/17/10	03/07/11	03/06/12	02/20/13
Fert	3	0.1940		0.2968	**<.0001**	**0.0194**	**<.0001**	**<.0001**	0.0654		0.1198	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.0832
Rake	1	**0.0036**		0.2180	0.2719	0.5195	0.8053	0.1542	0.8349		0.8786	**0.0038**	0.6686	0.2585	0.2201	0.6426	0.1130	0.8189
Fert*Rake	3	0.2143		0.2035	0.4108	0.9554	0.1100	**0.0018**	0.1837		0.1460	0.2928	0.8754	0.9128	0.4924	0.5207	**0.0016**	0.2448
Depth	6	**0.0011**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.1644	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	**0.0189**		0.3036	**<.0001**	**0.0003**	**<.0001**	0.0686	**0.0078**		**<.0001**	**<.0001**	**0.0097**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0009**
Rake*Depth	6	0.9879		0.3442	0.5465	0.5912	0.3188	0.8277	0.1286		0.4761	**0.0340**	**0.0302**	0.7617	0.6879	0.3838	0.1665	0.1091
Fert*Rake*Depth	18	**0.0101**		0.1991	0.8269	0.3333	0.7541	0.8119	0.0639		0.4853	0.7954	0.1198	0.6487	0.6598	0.7090	**0.0001**	**0.0020**
NO_x-N Live Oak																		
		11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
Fert	3	0.9910	0.0895	**<.0001**	0.1097	**0.0007**	0.2377	0.5142	0.0553	0.5046	0.3221	**0.0041**	**0.0002**	**<.0001**	**<.0001**	0.3365	0.6698	0.5228
Rake	1	0.2443	0.6660	0.3183	0.5064	0.8683	0.3719	0.7858	0.0569	0.3122	0.9885	0.5003	0.5821	0.9085	0.5168	0.3529	0.7181	0.3565
Fert*Rake	3	0.5584	0.3512	0.3230	0.1180	0.5094	0.1890	0.0855	0.8606	0.8734	0.4636	0.0929	0.6690	0.2519	0.9088	0.9505	0.2216	**0.0219**
Depth	6	**0.0144**	0.7039	0.0756	**0.0284**	**<.0001**	0.7542	**<.0001**	**0.0011**	0.1361	**0.0357**	**<.0001**	**0.0084**	**<.0001**	**0.0028**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.2454	0.4134	0.4433	0.9706	**0.0222**	0.5490	0.5446	0.4587	0.9463	0.4356	0.0653	**0.0396**	**<.0001**	**0.0152**	**0.0023**	0.9115	0.8845
Rake*Depth	6	0.5611	0.3378	0.6912	0.8458	0.3991	0.5946	0.4699	0.2061	0.5629	0.5565	0.2255	0.9000	0.2404	0.8016	0.8693	0.7885	0.6272
Fert*Rake*Depth	18	0.6796	0.7157	0.3244	0.3622	0.5583	0.9766	0.1233	0.4072	0.7041	0.7867	0.6172	0.0582	0.6335	0.3930	0.5034	0.2566	0.3727
NH_4-N Blountstown																		
		10/01/08		03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10		03/29/10	04/26/10	05/24/10	08/23/10	11/17/10	03/07/11	03/06/12	02/20/13
Fert	3	0.1279		**0.0109**	**<.0001**	0.4387	0.5934	**0.0047**	**<.0001**		**0.0005**	**<.0001**	0.1487	0.0908	**0.0395**	0.1065	**0.0300**	0.0944
Rake	1	**0.0046**		0.7329	0.2248	0.8481	0.8410	0.1356	0.6479		0.9767	0.1708	0.6621	**0.0467**	0.8327	0.6648	0.7890	0.8324
Fert*Rake	3	**0.0145**		0.4281	0.0725	0.6613	0.9167	0.0744	0.2497		0.2622	0.2074	0.7103	0.9531	0.8579	0.2808	0.4341	0.4283
Depth	6	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.3069		**0.0494**	**<.0001**	**<.0001**	0.2934	0.8977	**0.0064**		**<.0001**	**<.0001**	**0.0057**	**0.0017**	0.1789	0.6798	0.7922	0.8386
Rake*Depth	6	0.8723		0.5414	0.7626	0.9602	0.1574	0.9569	0.6939		0.7265	0.1018	**0.0385**	0.4928	0.5631	0.5589	0.3492	0.8345
Fert*Rake*Depth	18	0.4870		0.3506	0.9930	0.6769	0.2089	0.7083	0.1993		0.9790	0.9578	0.2136	0.7884	0.4575	0.5254	0.7582	0.6684
NH_4-N Live Oak																		
		11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
Fert	3	0.7766	**<.0001**	**0.0001**	**<.0001**	**0.0076**	0.5812	0.7639	**0.0492**	**<.0001**	**<.0001**	**<.0001**	**0.0021**	0.6111	0.7884	0.3997	0.3266	0.5181
Rake	1	0.7741	0.9969	0.6661	0.0573	0.9460	0.3476	0.9631	0.2453	0.6850	0.9590	0.4171	0.5063	0.2005	0.6677	**0.0042**	**0.0185**	0.7619
Fert*Rake	3	**0.0409**	0.1345	0.4597	0.4890	0.3453	**0.0451**	0.6150	0.6480	**0.0422**	0.3904	0.1336	0.8225	0.1219	0.0758	0.1098	**0.0223**	0.1113
Depth	6	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0016**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.6166	**0.0030**	**0.0117**	**<.0001**	**<.0001**	0.7527	0.5271	0.3180	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0074**	0.8814	0.9560	0.7616	0.8213
Rake*Depth	6	0.9324	0.3434	0.7444	0.7209	0.8628	0.8306	0.5727	0.1692	0.7983	0.2646	**0.0417**	0.7072	0.2832	0.8488	0.4380	0.4164	0.7921
Fert*Rake*Depth	18	0.9965	0.4070	0.9118	0.0652	0.8580	0.9406	0.6277	0.0696	0.1317	0.8705	0.9127	0.1934	0.2844	0.7514	0.1852	0.1188	0.1214

[†] df for Blountstown for 3/30/09 and 2/15/10: Depth=4, Fert*Depth=12, Rake*Depth=4, Fert*Rake*Depth=12 (due to less sampling depths because of high water table)

Table 16. ANOVA for soil TKN and TP concentrations by sampling date at two study sites

Raking — 1st Fertilization — Raking — 2nd Fertilization — Raking

Factor	df[†]																	
TKN Blountstown																		
		10/01/08		03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10		03/29/10	04/26/10	05/24/10	08/23/10	11/17/10	03/07/11	03/06/12	02/20/13
Fert	3	0.8604		0.3906	0.8569	0.1767	0.7293	0.1429	0.7776		0.1924	0.7364	0.9568	0.5188	0.9328	0.9202	0.8834	0.7148
Rake	1	**0.0049**		**0.0444**	0.3773	**0.0252**	0.1618	**0.0105**	0.9265		**0.0158**	0.6220	0.6163	0.6663	0.1087	0.4123	0.0565	0.6582
Fert*Rake	3	0.6766		0.2924	0.8275	0.2142	0.4954	0.5121	0.3092		**0.0217**	0.7759	0.4408	0.8749	0.5657	0.9443	**0.0184**	0.8823
Depth	6	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.9710		0.3077	0.1770	0.7087	**0.0234**	0.1075	0.9208		0.5093	**0.0157**	0.1462	0.3120	0.9497	0.5103	**0.0329**	0.9303
Rake*Depth	6	0.3559		0.3171	0.6592	0.6943	0.4424	0.3701	0.3999		**0.0124**	0.9831	0.5350	0.6968	0.9925	0.7333	0.9869	0.9464
Fert*Rake*Depth	18	0.9393		0.0807	0.7994	0.7278	0.0946	0.6741	0.3366		0.0648	0.9615	0.4835	0.2466	0.8929	0.6576	0.4079	0.8538
TKN Live Oak																		
		11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
Fert	3	0.7187	0.4454	0.2794	**0.0290**	0.1909	0.1241	0.3040	0.4511	0.8040	0.7712	0.6493	**0.0327**	0.3014	0.6263	0.0740	0.9263	**0.0261**
Rake	1	0.2288	0.8626	0.7974	0.4222	**0.0286**	0.1298	0.6313	0.4881	0.9629	0.7247	0.6939	**0.0192**	0.3962	0.9350	**0.0106**	0.8025	0.8757
Fert*Rake	3	0.9387	0.7284	0.2510	0.8913	0.1139	0.7904	0.1199	0.6633	0.1578	0.1154	0.5611	0.5082	0.9364	0.9939	0.1159	0.9171	0.9290
Depth	6	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.2351	0.1435	0.3379	0.4697	0.0583	0.6432	0.4776	0.3278	0.7876	0.3996	0.3064	0.5438	0.1837	0.6538	0.8524	0.4665	0.3453
Rake*Depth	6	0.2170	0.8543	0.0961	0.9801	0.0598	0.6460	0.5387	0.5195	0.8153	0.8415	0.2358	0.6295	0.7415	0.5518	0.9633	0.0833	0.5871
Fert*Rake*Depth	18	0.2868	0.3113	0.9042	0.5805	0.9706	0.5924	0.6475	0.3801	0.9792	0.3775	0.3882	0.9484	0.3780	0.3062	0.1524	0.5102	0.9829
TP Blountstown																		
		10/01/08		03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10		03/29/10	04/26/10	05/24/10	08/23/10	11/17/10	03/07/11	03/06/12	02/20/13
Fert	3	0.7274		0.6777	**0.0189**	0.1617	0.6524	0.6827	0.1005		**0.0020**	0.1817	0.3965	0.1474	0.6228	0.2859	0.5984	0.9764
Rake	1	0.6021		0.0887	0.0980	0.2757	0.1037	0.1268	0.6633		0.5033	0.4984	0.2953	0.2757	0.4793	0.2808	0.1303	0.5755
Fert*Rake	3	0.5275		0.4006	0.4749	0.1406	0.4558	0.3048	0.7467		**0.0276**	0.9729	0.5450	0.5213	0.9240	0.5020	**0.0008**	0.9897
Depth	6	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.7705		0.4722	0.2392	**0.0071**	**0.0006**	**0.0309**	**0.0079**		**0.0263**	0.2290	**0.0028**	**0.0155**	**<.0001**	**0.0023**	**0.0002**	**0.0005**
Rake*Depth	6	0.9986		0.7214	0.3435	0.7544	0.2193	0.2154	0.6355		**0.0314**	0.6601	0.9698	0.3001	0.6390	0.6327	0.1385	0.4855
Fert*Rake*Depth	18	0.8648		0.2205	0.1227	0.8410	0.7271	**0.0149**	0.7096		0.7949	0.9285	0.7687	0.5937	0.9535	0.5766	0.7330	0.2554
TP Live Oak																		
		11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
Fert	3	0.3429	0.2340	0.2659	0.1183	**0.0316**	0.0978	**0.0028**	0.2325	0.1338	0.0705	**0.0195**	**0.0075**	0.0656	**0.0028**	0.2967	0.4858	**0.0168**
Rake	1	**0.0215**	**0.0472**	0.1092	**0.0359**	**0.0004**	**0.0148**	**0.0292**	0.3377	**0.0015**	0.1442	**0.0218**	**0.0102**	**0.0158**	**0.0053**	**0.0108**	0.1038	0.1576
Fert*Rake	3	0.9742	0.8056	0.4774	0.5593	0.3157	0.5892	0.0914	0.4121	0.2088	0.5788	0.9739	0.7718	0.2555	0.8725	0.6323	0.3259	0.5874
Depth	6	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.6483	0.8112	0.9702	0.2988	0.1308	0.9153	0.1138	0.4393	**0.0178**	**0.0010**	0.0618	0.0665	**0.0451**	**0.0004**	**<.0001**	**0.0042**	0.1116
Rake*Depth	6	0.1093	0.5581	0.9575	0.5631	**0.0364**	0.6743	0.1824	0.1258	0.4985	0.0567	0.2571	0.7219	0.1289	0.6565	0.0668	**0.0490**	0.1007
Fert*Rake*Depth	18	0.2784	0.7167	0.1679	0.6104	0.7541	0.9595	0.5073	0.6198	0.8921	0.8902	0.9089	0.5349	0.9997	0.9185	0.2820	0.3171	0.8333

[†] df for Blountstown for 3/30/09 and 2/15/10: Depth=4, Fert*Depth=12, Rake*Depth=4, Fert*Rake*Depth=12 (due to less sampling depths because of high water table)

Table 17. Mean soil NO_x-N concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

1st Raking and 1st Fertilization: between 10/01/08 and 03/30/09. 2nd Raking: between 12/07/09 and 02/15/10.

Sample Depth	DAP lb/ac	Sampling Date: 10/01/08	03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10
		Months after last fertilization (MAF), approximate: Before	1	2	3	6	9	12
Avg. all depths§	0	0.43	0.55	0.27 d	0.37 L b	0.49 b	0.20 b	0.76
Avg. all depths	128	0.46	0.43	0.72 c	0.38 L b	0.40 b	0.16 b	1.17
Avg. all depths	384	0.44	0.58	0.97 b	0.55 L ab	0.51 b	0.31 b	0.84
Avg. all depths	641	0.62	0.59	1.40 a	0.93 L a	1.09 a	0.77 a	0.94
0-6"	0	0.54 b A	0.66	0.42 d	0.41 b	0.61	0.38	0.33 b B
0-6"	128	0.49 b	0.70	0.80 c	0.52 b	0.91 A	0.45	1.21 a
0-6"	384	0.39 b	1.20	1.72 b A	0.76 b	0.77	0.25	0.62 b B
0-6"	641	1.00 a A	1.05	6.84 a A	2.53 a A	0.87 B	1.03	0.43 b C
6-12"	0	0.29 B	0.65	0.40 c	0.36 L c	0.53	0.38	0.25 b B
6-12"	128	0.44	0.46	1.00 b	0.44 L bc	0.53 B	0.17	1.02 a
6-12"	384	0.47	0.64	1.29 b A	1.00 L b	0.57	0.28	0.35 b C
6-12"	641	0.53 B	0.63	2.55 a B	2.56 L a A	0.69 B	0.54	0.25 b C
12-24"	0	0.37 A	0.66	0.25 c	0.33 L bc	0.56 b	0.20	1.18 A
12-24"	128	0.33	0.32	0.70 b	0.27 L c	0.35 b B	0.11	1.33
12-24"	384	0.36	0.54	1.05 a B	0.79 L b	0.57 b	0.68	1.02 A
12-24"	641	0.50 B	0.51	1.06 a C	1.89 L a B	2.99 a A	0.61	1.10 B
24-36"	0	0.42 A	0.43	0.20 b	0.32	0.43 b	0.04	1.14 A
24-36"	128	0.45	0.38	0.63 a	0.36	0.26 b B	0.07	1.14
24-36"	384	0.51	0.35	0.84 a B	0.37	0.50 b	0.46	1.13 A
24-36"	641	0.50 B	0.35	0.74 a C	0.40 C	2.35 a A	1.60	1.46 A
36-48"	0	0.48 A	0.40	0.16 b	0.35	0.43	0.09	1.18 L b A
36-48"	128	0.47	0.34	0.63 a	0.37	0.28 B	0.09	1.15 L b
36-48"	384	0.42	0.33	0.66 a C	0.38	0.37	0.14	1.23 L b A
36-48"	641	0.56 B	0.50	0.67 a D	0.27 C	0.71 B	1.00	2.02 L a A
48-60"	0	0.42 A	n/a†	0.23 b	0.33	0.40	0.11	n/a
48-60"	128	0.54	n/a	0.64 a	0.37	0.28 B	0.09	n/a
48-60"	384	0.37	n/a	0.68 a C	0.38	0.44	0.23	n/a
48-60"	641	0.60 B	n/a	0.65 a D	0.23 C	0.54 B	0.53	n/a
60-72"	0	0.53 A	n/a	0.25 b	0.46	0.48	0.26	n/a
60-72"	128	0.51	n/a	0.68 a	0.35	0.29 B	0.17	n/a
60-72"	384	0.59	n/a	0.76 a B	0.33	0.37	0.19	n/a
60-72"	641	0.69 A	n/a	0.66 a D	0.27 C	0.57 B	0.34	n/a

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.

"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.

Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).

Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

§ Fertilization rate main effect.

†n/a=samples not collected due to the high groundwater table.

Table 18. Mean soil NO_x-N concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

2nd Fertilization (before 03/29/10); 3rd Raking (between 11/17/10 and 03/07/11); 4th Raking (between 03/07/11 and 03/06/12); 5th Raking (between 03/06/12 and 02/20/13)

Sample Depth	DAP lb/ac	03/29/10		04/26/10		05/24/10		08/23/10		11/17/10		03/07/11		03/06/12		02/20/13	
		Months after last fertilization (MAF), approximate															
		1		2		3		6		9		12		24		36	
Avg. all depths§	0	0.83		0.72 bc		1.01 bc		0.43 c		0.30 c		0.15 c		0.13 b		0.89	
Avg. all depths	128	1.13		0.88 bc		0.76 c		0.46 c		0.27 c		0.17 c		0.10 b		1.01	
Avg. all depths	384	0.97		1.22 b		1.39 b		0.82 b		0.80 b		0.47 b		0.14 b		1.09	
Avg. all depths	641	1.39		2.48 a		3.13 a		2.55 a		2.18 a		1.29 a		0.81 a		1.14	
0-6"	0	1.21 L c		0.88 c		1.02 c		0.63 b	B	0.16		0.38		0.13		0.73 b	BC
0-6"	128	2.26 L bc	A	1.56 bc		0.97 c		1.53 a	A	0.26		0.83	A	0.13		1.09 a	
0-6"	384	2.72 L b	A	2.67 b	A	2.10 b	A	1.00 ab	AB	0.48	C	0.50	B	0.06		0.80 ab	C
0-6"	641	8.06 L a	A	11.61 a	A	6.34 a	A	1.53 a	DE	0.58	C	0.47	D	0.14	E	0.62 b	D
6-12"	0	1.37 b		0.85 c		1.02 b		1.11 ab	A	0.15 L c		0.32		0.07		0.68	BC
6-12"	128	1.01 b	B	0.85 c		0.96 b		0.68 b	B	0.21 L c		0.37	B	0.09		0.87	
6-12"	384	1.11 b	B	2.30 b	A	1.59 b	BC	0.86 b	AB	0.76 L b	BC	0.31	B	0.02		0.85	C
6-12"	641	2.80 a	B	8.59 a	A	5.09 a	B	1.67 a	D	1.89 L a	B	0.30	D	0.18	E	0.59	D
12-24"	0	0.73 b		1.00		1.23 L c		0.33 c	B	0.28 L c		0.04 L b		0.16		0.63	C
12-24"	128	1.93 a	A	1.12		0.99 L c		0.34 c	BC	0.27 L c		0.06 L b	B	0.14		0.73	
12-24"	384	0.71 b	B	1.05	B	2.22 L b	A	1.29 b	A	1.94 L b	A	0.29 L b	B	0.17		0.89	C
12-24"	641	0.64 b	C	1.85	B	5.10 L a	AB	4.84 a	B	5.42 L a	A	1.14 L a	C	0.34	DE	0.73	D
24-36"	0	0.64		0.60		0.91 L b		0.31 c	B	0.36 c		0.07 c		0.26 b		0.90 L b	AB
24-36"	128	0.91	B	0.77		0.62 L b		0.25 c	BC	0.21 c		0.02 c	B	0.06 b		1.00 L ab	
24-36"	384	0.66	B	0.99	B	1.78 L a	AB	1.37 b	A	1.42 b	AB	1.24 b	A	0.25 b		1.37 L a	AB
24-36"	641	0.59	C	1.00	C	2.86 L a	C	8.88 a	A	6.00 a	A	5.66 a	A	3.29 a	A	1.34 L a	C
36-48"	0	0.71		0.63		0.92 b		0.28 b	B	0.41 L b		0.04 c		0.09 b		1.11 L b	A
36-48"	128	0.76	B	0.85		0.54 b		0.31 b	BC	0.27 L b		0.05 c	B	0.06 b		1.05 L b	
36-48"	384	0.70	B	0.81	B	0.92 b	CD	0.50 b	B	0.67 L b	C	0.55 b	B	0.20 b		1.45 L b	A
36-48"	641	0.67	C	1.19	BC	2.32 a	C	3.20 a	C	1.84 L a	B	2.62 a	B	1.95 a	B	2.34 L a	A
48-60"	0	0.66		0.55		0.94 ab		0.29 L b	B	0.38 b		0.19 b		0.13 b		1.09 L b	A
48-60"	128	0.76	B	0.61		0.57 b		0.21 L b	C	0.31 b		0.01 b	B	0.14 b		1.24 L b	
48-60"	384	0.72	B	0.74	B	0.76 b	D	0.50 L b	B	0.42 b	C	0.31 b	B	0.17 b		1.35 L ab	AB
48-60"	641	0.63	C	1.06	BC	1.60 a	D	1.32 L a	DE	1.46 a	B	1.08 a	C	0.81 a	C	1.78 L a	B
60-72"	0	0.66		0.61		1.05		0.21 L b	B	0.38 L b		0.04 L b		0.07 L b		1.20	A
60-72"	128	0.77	B	0.58		0.75		0.26 L b	BC	0.34 L b		0.02 L b	B	0.08 L b		1.15	
60-72"	384	0.73	B	0.73	B	0.83	D	0.44 L ab	B	0.41 L b	C	0.30 L ab	B	0.17 L b		1.02	BC
60-72"	641	0.81	C	0.99	BC	1.24	D	0.87 L a	E	1.29 L a	B	0.62 L a	CD	0.55 L a	CD	1.11	C

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table 19. Mean soil NO_x-N concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

1st Fertilization (between 11/01/08 and 03/09/09) — 1st Raking (between 11/30/09 and 02/08/10)

Sample Depth	DAP lb/ac	Sampling Date							
		11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10
		Months after last fertilization (MAF), approximate							
		Before	0.5	1	2	3	6	9	12
Avg. all depths§	0	0.72	0.49	0.50 a	0.74	0.24 L b	0.82	0.55	0.99
Avg. all depths	128	0.74	0.14	0.29 c	0.44	0.26 L b	0.56	0.53	1.32
Avg. all depths	384	0.73	0.32	0.32 bc	0.52	0.51 L a	0.76	0.47	0.83
Avg. all depths	641	0.72	0.55	0.35 b	0.62	0.65 L a	1.27	0.78	0.89
0-6"	0	0.94	0.49	0.49	0.94	0.22 L c	0.49	2.85	0.85
0-6"	128	0.70	0.11	0.33	0.77	0.27 L c	0.42	1.48	0.87
0-6"	384	0.78	1.79	0.34	0.67	0.60 L b B	0.50	2.02	0.90
0-6"	641	0.81	0.31	0.39	0.99	1.02 L a B	2.32	1.49	0.70
6-12"	0	0.82	0.47	0.52	0.65	0.24 L c	0.58	1.67	0.77
6-12"	128	0.79	0.14	0.30	0.54	0.30 L c	0.47	2.00	0.87
6-12"	384	0.77	0.22	0.32	0.70	0.81 L b A	0.49	1.67	0.87
6-12"	641	0.82	1.70	0.35	0.84	1.34 L a A	1.22	2.66	0.73
12-24"	0	0.73	0.59	0.50	0.80	0.26 L b	0.88	0.16	1.20
12-24"	128	0.73	0.27	0.27	0.34	0.30 L b	0.63	0.17	1.86
12-24"	384	0.77	0.22	0.36	0.47	0.82 L a A	1.29	0.19	1.05
12-24"	641	0.60	0.54	0.38	0.69	1.05 L a B	0.72	0.17	0.96
24-36"	0	0.87	0.49	0.52	0.60	0.32 L bc	0.91	0.22	1.00
24-36"	128	0.80	0.12	0.32	0.32	0.23 L c	0.57	0.18	1.77
24-36"	384	0.85	0.11	0.31	0.42	0.63 L ab A	0.92	0.16	0.82
24-36"	641	0.65	0.46	0.41	0.50	0.79 L a B	0.82	0.14	0.89
36-48"	0	0.62	0.47	0.48	0.96	0.22	1.10	0.13	1.13
36-48"	128	0.74	0.10	0.31	0.40	0.23	0.84	0.39	1.72
36-48"	384	0.69	0.12	0.30	0.60	0.39 C	0.66	0.11	0.72
36-48"	641	0.68	0.38	0.33	0.44	0.29 C	1.53	0.33	0.85
48-60"	0	0.52	0.48	0.49	0.68	0.20	0.89	0.13	1.12
48-60"	128	0.73	0.11	0.25	0.38	0.25	0.53	0.20	1.20
48-60"	384	0.63	0.12	0.30	0.39	0.24 D	0.88	0.10	0.74
48-60"	641	0.67	0.17	0.29	0.45	0.20 C	1.81	0.55	1.07
60-72"	0	0.61	0.48	0.50	0.57	0.23	0.96	0.16	0.92
60-72"	128	0.67	0.13	0.27	0.36	0.22	0.52	0.16	1.19
60-72"	384	0.65	0.22	0.32	0.40	0.24 D	0.73	0.10	0.76
60-72"	641	0.85	0.67	0.28	0.51	0.24 C	0.91	1.28	1.05

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.

"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.

Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).

Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

§ Fertilization rate main effect.

Table 20. Mean soil NO_x-N concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

2nd Fertilization ↓ (before 03/08/10); 2nd Raking ↓ (before 02/21/11); 3rd Raking ↓ (before 02/28/12); 4th Raking ↓ (before 02/27/13)

Sample Depth	DAP lb/ac	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
		Sampling Date								
		Months after last fertilization (MAF), approximate								
		0.5	1	2	3	6	9	12	24	36
Avg. all depths§	0	0.45	0.70	0.59 L b	0.80 L b	0.65 b	0.41 b	0.35	0.12	0.61
Avg. all depths	128	0.51	1.22	0.77 L b	0.85 L b	0.77 b	0.41 b	0.37	0.15	0.61
Avg. all depths	384	0.43	0.87	0.82 L b	1.10 L b	0.96 b	0.54 b	0.32	0.14	0.66
Avg. all depths	641	0.50	1.04	1.22 L a	1.95 L a	3.13 a	1.35 a	0.45	0.12	0.58
0-6"	0	0.39	0.62	0.79	0.54 L c	0.74	0.60 b	0.22 B	0.01	1.22
0-6"	128	0.49	0.67	0.92	0.55 L bc	0.77 B	0.54 b	0.27 BC	0.02	1.03
0-6"	384	0.37	0.64	1.49	1.22 L b	0.46 C	0.53 b	0.19 B	0.01	0.95
0-6"	641	0.49	1.09	2.55	2.95 L a A	1.31 E	1.34 a BC	0.21 D	0.00	1.04
6-12"	0	0.33	0.55	0.80	0.72 b	0.38 L b	0.60 L b	0.23 B	0.07	1.08
6-12"	128	0.41	0.63	0.79	0.57 b	0.54 L b B	0.48 L b	0.25 C	0.06	0.98
6-12"	384	0.37	0.69	1.17	0.90 b	0.80 L b C	0.75 L b	0.18 B	0.02	1.31
6-12"	641	0.44	0.97	2.95	2.71 a A	2.76 L a CD	1.20 L a BC	0.19 D	0.02	1.05
12-24"	0	0.81	0.84	0.64	1.07 b	0.77 L c	0.45 L b	0.52 A	0.23	0.49
12-24"	128	0.60	2.36	1.32	0.91 b	1.45 L bc A	0.43 L b	0.44 A	0.26	0.53
12-24"	384	0.53	0.87	0.72	1.15 b	1.72 L b A	0.43 L b	0.37 A	0.27	0.55
12-24"	641	0.58	0.94	1.33	3.04 a A	3.20 L a BCD	0.96 L a BC	0.38 C	0.16	0.40
24-36"	0	0.44	0.80	0.52	0.89 L b	0.57 c	0.35 L b	0.37 C	0.13	0.44
24-36"	128	0.48	1.64	0.77	1.05 L b	0.66 c B	0.35 L b	0.42 AB	0.17	0.45
24-36"	384	0.39	0.77	0.62	1.51 L b	1.44 b AB	0.43 L b	0.37 A	0.25	0.43
24-36"	641	0.73	0.93	0.82	2.84 L a A	4.64 a A	0.90 L a C	0.42 C	0.16	0.40
36-48"	0	0.47	0.74	0.45	0.80	0.71 b	0.32 L b	0.38 ABC	0.15	0.40
36-48"	128	0.47	1.43	0.72	1.12	0.73 b B	0.36 L b	0.44 AB	0.15	0.44
36-48"	384	0.45	1.16	0.70	1.36	0.93 b BC	0.48 L b	0.36 A	0.16	0.49
36-48"	641	0.40	1.00	0.70	1.48 B	4.31 a AB	1.19 L a BC	0.46 C	0.14	0.40
48-60"	0	0.32	0.68	0.49	0.93	0.62 b	0.29 b	0.38 ABC	0.14	0.39
48-60"	128	0.50	0.87	0.45	0.91	0.61 b B	0.31 b	0.41 ABC	0.21	0.46
48-60"	384	0.45	0.93	0.54	0.87	0.81 b B	0.52 b	0.38 A	0.14	0.50
48-60"	641	0.38	1.06	0.58	0.98 BC	4.02 a ABC	1.58 a B	0.60 B	0.17	0.36
60-72"	0	0.42	0.71	0.49	0.73	0.76 b	0.31 c	0.40 b ABC	0.14	0.46
60-72"	128	0.65	1.45	0.53	0.89	0.73 b AB	0.38 bc	0.39 b ABC	0.18	0.47
60-72"	384	0.45	1.10	0.70	0.81	0.81 b B	0.68 b	0.42 b A	0.18	0.53
60-72"	641	0.51	1.32	0.67	0.73 C	2.75 a D	2.69 a A	1.04 a A	0.17	0.53

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.

"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.

Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).

Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

§ Fertilization rate main effect.

Table 21. Mean soil NH_4-N concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

1st Raking — 1st Fertilization (between 10/01/08 and 03/30/09); 2nd Raking (between 12/07/09 and 02/15/10)

Sample Depth	DAP lb/ac	10/01/08 Before	03/30/09 1		04/27/09 2		06/01/09 3		08/31/09 6	12/07/09 9	02/15/10 12	
			Sampling Date — Months after last fertilization (MAF), approximate									
Avg. all depths§	0	1.52	1.58 L b		1.39 L b		1.33		1.41	1.36 b	0.98 b	
Avg. all depths	128	1.59	1.69 L b		1.65 L b		1.37		1.39	1.28 b	1.42 a	
Avg. all depths	384	1.52	2.53 L a		2.02 L a		1.35		1.28	1.34 b	1.06 b	
Avg. all depths	641	1.39	2.42 L a		2.23 L a		1.46		1.38	1.62 a	0.94 b	
0-6"	0	1.54	2.10 L c		2.22 c	A	1.96 b	A	1.99	1.78	0.90 c	A
0-6"	128	1.92	2.48 L c		2.02 c		2.37 b	A	2.31	1.92	1.95 a	A
0-6"	384	1.96	6.18 L b	A	4.54 b	A	2.22 b	A	1.86	1.65	1.28 b	A
0-6"	641	1.61	7.63 L a	A	11.34 a	A	4.56 a	A	2.23	2.81	0.86 c	B
6-12"	0	1.34	1.47		1.50 L b	B	1.55	B	1.42	1.75	0.59 b	B
6-12"	128	1.52	1.67		1.88 L b		1.61	B	1.38	1.49	1.37 a	B
6-12"	384	1.59	2.48	B	1.81 L b	B	1.63	B	1.43	1.67	0.79 b	C
6-12"	641	1.30	1.89	B	2.85 L a	B	1.82	B	1.37	1.99	0.64 b	C
12-24"	0	1.65	1.36		1.38	B	1.24	B	1.35	1.42	1.19	A
12-24"	128	1.61	1.46		1.73		1.26	C	1.43	1.34	1.53	A
12-24"	384	1.48	2.32	B	1.66	B	1.33	B	1.23	1.62	1.08	B
12-24"	641	1.42	1.35	B	1.32	C	1.24	C	1.44	1.58	1.22	A
24-36"	0	1.48	1.56		1.35	B	1.10	C	1.39	1.04	1.19	A
24-36"	128	1.63	1.43		1.59		1.38	B	1.19	1.14	1.24	B
24-36"	384	1.51	1.56	B	2.05	B	1.28	B	1.16	1.21	1.05	B
24-36"	641	1.47	1.31	B	1.62	C	1.24	C	1.21	1.37	1.05	A
36-48"	0	1.54	1.46		1.16	B	1.14	C	1.48	1.29	1.11	A
36-48"	128	1.60	1.53		1.48		1.14	C	1.20	1.14	1.09	C
36-48"	384	1.47	1.59	B	1.84	B	1.08	C	1.21	1.10	1.15	B
36-48"	641	1.43	2.47	B	1.44	C	0.92	D	1.07	1.33	0.98	A
48-60"	0	1.57	n/a†		1.13	B	1.23	C	1.26	1.24	n/a	
48-60"	128	1.44	n/a		1.51		1.04	C	1.15	1.05	n/a	
48-60"	384	1.42	n/a		1.60	B	1.10	C	1.12	1.13	n/a	
48-60"	641	1.29	n/a		1.32	C	0.89	D	1.30	1.30	n/a	
60-72"	0	1.56	n/a		1.13	B	1.18	C	1.07	1.12	n/a	
60-72"	128	1.42	n/a		1.38		1.04	C	1.21	1.02	n/a	
60-72"	384	1.29	n/a		1.49	B	1.03	C	1.05	1.12	n/a	
60-72"	641	1.26	n/a		1.27	C	0.92	C	1.20	1.27	n/a	

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.

"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.

Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).

Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

§ Fertilization rate main effect.

† n/a=samples not collected due to the high groundwater table.

Table 22. Mean soil NH_4-N concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

2nd Fertilization (before 03/29/10); 3rd Raking (between 11/17/10 and 03/07/11); 4th Raking (between 03/07/11 and 03/06/12); 5th Raking (between 03/06/12 and 02/20/13)

Sample Depth	DAP lb/ac	03/29/10		04/26/10		05/24/10		08/23/10		11/17/10	03/07/11	03/06/12	02/20/13
		Months after last fertilization (MAF), approximate											
		1		2		3		6		9	12	24	36
Avg. all depths§	0	0.74 c		0.77 L c		1.73		1.49		1.20 ab	0.95	0.79 b	1.82
Avg. all depths	128	1.01 bc		0.85 L c		1.55		1.54		1.09 b	0.96	0.79 b	1.95
Avg. all depths	384	1.25 b		1.19 L b		1.79		1.37		1.10 b	1.00	0.77 b	2.00
Avg. all depths	641	2.07 a		1.74 L a		1.86		1.50		1.23 a	1.08	0.90 a	1.72
0-6"	0	1.76 d		0.77 L d		3.04 b	A	1.95 b	A	1.53	1.26	1.03	2.00
0-6"	128	5.32 c	A	1.71 L c	A	3.07 b	A	3.14 a	A	1.70	1.43	1.10	2.28
0-6"	384	17.21 b	A	5.45 L b	A	5.00 a	A	2.12 b	A	1.63	1.43	1.08	2.33
0-6"	641	50.75 a	A	16.24 L a	A	4.50 a	A	2.35 b	A	1.81	1.55	1.32	1.89
6-12"	0	1.23 b		0.58 L b		2.58	A	1.99	A	1.30	1.15	0.75	1.52
6-12"	128	0.92 b	BC	0.51 L b	BC	2.58	B	1.69	B	1.25	1.11	0.85	1.68
6-12"	384	1.31 b	B	0.91 L b	B	2.73	B	1.49	B	1.34	1.21	0.79	1.73
6-12"	641	3.81 a	B	1.67 L a	B	2.63	B	1.63	B	1.40	1.23	1.04	1.52
12-24"	0	0.73		1.24		1.73	B	1.47	B	1.15	0.96	0.84	2.03
12-24"	128	1.48	B	1.33	AB	1.58	C	1.44	BC	1.07	0.95	0.79	1.91
12-24"	384	0.58	BC	0.98	B	1.57	C	1.32	BC	1.04	0.96	0.72	1.99
12-24"	641	0.75	C	1.04	BC	1.52	C	1.37	BC	1.22	1.03	0.76	1.54
24-36"	0	0.46		0.79		1.23	C	1.44	B	1.31	0.93	0.74	1.96
24-36"	128	0.67	BC	0.75	BC	1.12	D	1.29	C	0.93	0.81	0.74	2.11
24-36"	384	0.55	BC	0.87	B	1.15	D	1.15	C	1.00	0.89	0.73	2.08
24-36"	641	0.61	C	1.01	BC	1.41	C	1.52	BC	1.12	0.97	0.85	1.71
36-48"	0	0.55		0.76		1.32	BC	1.30	B	1.09	0.78	0.76	1.83
36-48"	128	0.43	C	0.73	BC	0.98	D	1.16	C	0.92	0.79	0.64	1.90
36-48"	384	0.43	BC	0.74	B	1.21	CD	1.19	BC	1.00	0.89	0.76	1.81
36-48"	641	0.63	C	0.96	BC	1.35	C	1.40	BC	1.06	1.06	0.80	1.90
48-60"	0	0.50		0.69		1.28	BC	1.21	B	1.02	0.81	0.77	1.78
48-60"	128	0.35	C	0.58	C	1.03	D	1.24	C	0.94	0.88	0.77	1.90
48-60"	384	0.34	C	0.77	B	1.23	CD	1.23	BC	0.90	0.89	0.71	2.27
48-60"	641	0.38	C	0.77	C	1.38	C	1.21	CD	1.09	0.91	0.77	1.78
60-72"	0	0.36		0.66		1.45	BC	1.19	B	1.02	0.79	0.68	1.68
60-72"	128	0.37	C	0.64	C	1.21	CD	1.23	C	0.91	0.83	0.64	1.91
60-72"	384	0.49	BC	0.71	B	1.16	CD	1.21	BC	0.91	0.83	0.62	1.84
60-72"	641	0.64	C	0.79	C	1.30	C	1.20	D	1.02	0.87	0.82	1.75

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.

"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.

Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).

Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

§ Fertilization rate main effect.

Table 23. Mean soil NH_4-N concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

1st Fertilization (after 11/01/08) — 1st Raking (after 11/30/09)

Sample Depth	DAP lb/ac	11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10
		Months after last fertilization (MAF), approximate							
		Before	0.5	1	2	3	6	9	12
Avg. all depths§	0	1.49	0.63 c	0.65 L b	0.98 c	1.32 L bc	1.61	1.55	1.39 b
Avg. all depths	128	1.41	2.43 b	0.99 L b	1.56 b	1.20 L c	1.21	1.62	1.68 a
Avg. all depths	384	1.41	3.03 ab	1.51 L a	1.73 b	1.63 L ab	1.65	1.52	1.31 b
Avg. all depths	641	1.40	3.48 a	1.81 L a	2.82 a	1.70 L a	1.56	1.83	1.40 b
0-6"	0	1.98	1.02 c	1.09 L b	1.61 d	2.04 c	2.04	5.13	1.77
0-6"	128	1.60	3.75 b	1.75 L b	2.95 c A	2.32 c A	1.83	3.48	1.63
0-6"	384	1.78	13.30 a A	4.65 L a A	4.99 b A	10.02 a A	2.25	4.55	1.65
0-6"	641	1.65	5.97 b A	5.98 L a A	18.84 a A	9.21 b A	3.83	3.90	1.62
6-12"	0	1.78	0.92 c	0.78 L c	1.05 c	1.59	1.50	3.66	1.30
6-12"	128	1.50	2.70 b	1.32 L bc	2.01 b B	1.43 B	1.25	3.99	1.42
6-12"	384	1.61	2.79 b B	1.88 L ab B	2.19 b B	1.81 B	1.53	3.90	1.41
6-12"	641	1.50	6.33 a A	2.57 L a B	6.76 a B	2.32 B	2.11	5.16	1.29
12-24"	0	1.51	0.60 b	0.63	1.01	1.27	1.54	0.97	1.55
12-24"	128	1.40	2.34 a	0.93	1.34 C	1.06 B	1.23	1.10	2.04
12-24"	384	1.34	2.37 a B	1.20 B	1.27 C	1.05 C	2.13	0.94	1.42
12-24"	641	1.25	2.70 a B	1.10 C	1.52 C	1.12 C	1.16	0.91	1.45
24-36"	0	1.33	0.50 b	0.59	0.89	1.18	1.52	0.94	1.28
24-36"	128	1.38	2.14 a	0.73	1.41 B	1.00 B	1.12	0.94	1.90
24-36"	384	1.29	2.15 a B	1.02 C	1.25 C	0.89 C	1.58	0.91	1.26
24-36"	641	1.34	2.88 a B	1.12 C	1.27 C	1.00 C	1.07	0.84	1.36
36-48"	0	1.20	0.48 b	0.66	1.02	1.15	1.68	0.84	1.35
36-48"	128	1.36	2.12 a	0.74	1.29 B	0.86 C	1.24	1.22	1.82
36-48"	384	1.35	2.14 a B	0.93 C	1.28 C	0.96 C	1.36	0.98	1.15
36-48"	641	1.48	3.01 a B	1.15 C	1.19 C	0.87 C	1.24	0.89	1.26
48-60"	0	1.30	0.49 b	0.42 L c	0.80	1.06	1.37	0.90	1.32
48-60"	128	1.36	2.21 a	0.85 L bc	1.19 C	1.16 B	0.92	1.02	1.49
48-60"	384	1.31	2.02 a B	1.10 L ab B	1.23 C	1.02 C	1.46	0.75	1.16
48-60"	641	1.32	2.27 a B	1.87 L a B	1.47 C	1.08 C	1.34	1.08	1.41
60-72"	0	1.38	0.52 L b	0.47	0.62 L b	1.10	1.69	0.82	1.20
60-72"	128	1.26	2.03 L a	0.79	1.11 L ab C	0.89 B	0.99	1.09	1.54
60-72"	384	1.25	2.15 L a B	1.15 B	1.31 L a C	0.83 C	1.35	0.85	1.15
60-72"	641	1.26	2.75 L a B	1.02 C	1.49 L a C	0.89 C	1.07	2.55	1.41

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table 24. Mean soil NH_4-N concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

2nd Fertilization (before 03/08/10); 2nd Raking (before 02/21/11); 3rd Raking (before 02/28/12); 4th Raking (before 02/27/13)

Sample Depth	DAP lb/ac	Sampling Date 03/08/10		03/22/10		04/19/10		05/10/10		08/16/10		11/22/10	02/21/11	02/28/12	02/27/13
		Months after last fertilization (MAF), approximate													
		0.5		1		2		3		6		9	12	24	36
Avg. all depths§	0	0.77 d		1.09 L c		0.63 L c		1.53 L b		1.29		1.34	0.87	0.76	0.99
Avg. all depths	128	1.24 c		1.81 L b		0.95 L bc		1.61 L b		1.44		1.43	0.86	0.78	0.98
Avg. all depths	384	1.61 b		1.98 L b		1.02 L b		1.75 L b		1.34		1.44	0.81	0.74	1.00
Avg. all depths	641	2.03 a		2.96 L a		1.70 L a		2.37 L a		1.45		1.46	0.85	0.70	1.06
0-6"	0	1.01 d		0.85 L d	B	0.63 L d		1.77 L c		2.12	A	1.72	1.09	0.94	1.60
0-6"	128	4.38 c	A	2.82 L c	A	1.57 L c	AB	2.23 L c		2.16	A	1.69	1.09	0.81	1.52
0-6"	384	14.90 b	A	9.25 L b	A	4.02 L b	A	4.55 L b	A	1.83	A	1.62	1.06	0.81	1.48
0-6"	641	22.74 a	A	24.85 L a	A	6.80 L a	A	11.32 L a	A	2.11	A	1.68	1.05	0.70	1.57
6-12"	0	0.58 c		0.18 L c	C	0.51 b		1.41 b		1.32 L b	B	1.36	0.96	0.67	1.31
6-12"	128	1.69 b	B	0.56 L c	C	0.71 b	C	1.34 b		1.43 L b	B	1.41	0.96	0.59	1.22
6-12"	384	1.80 b	B	1.46 L b	B	0.92 b	B	1.40 b	B	1.32 L b	B	1.43	0.96	0.61	1.34
6-12"	641	3.24 a	B	3.52 L a	B	3.33 a	B	3.24 a	B	2.16 L a	A	1.41	0.97	0.63	1.31
12-24"	0	1.30		1.38	AB	0.85		1.60		1.16 b	B	1.39	0.92	0.96	0.91
12-24"	128	0.98	C	3.06	A	1.71	A	1.35		1.92 a	A	1.69	0.88	0.96	1.00
12-24"	384	0.82	C	1.65	B	0.76	B	1.44	B	1.54 ab	AB	1.54	0.84	0.97	0.93
12-24"	641	0.96	C	1.59	C	1.37	C	1.88	C	1.24 b	B	1.50	0.85	0.75	0.93
24-36"	0	0.66		1.93	A	0.62		1.55		1.06	B	1.34	0.80	0.73	0.79
24-36"	128	0.78	C	2.15	AB	0.98	ABC	1.60		1.24	B	1.37	0.81	0.83	0.83
24-36"	384	0.81	C	1.56	B	0.61	B	1.37	B	1.20	B	1.35	0.72	0.74	0.81
24-36"	641	1.04	C	1.82	C	1.19	C	1.51	C	1.18	B	1.54	0.81	0.69	1.08
36-48"	0	0.68		1.28	AB	0.59		1.55		1.14	B	1.23	0.84	0.66	0.79
36-48"	128	0.73	C	1.71	AB	0.79	BC	1.68		1.20	B	1.31	0.79	0.76	0.82
36-48"	384	0.74	C	1.29	B	0.81	B	1.64	B	1.11	B	1.46	0.72	0.71	0.84
36-48"	641	0.84	C	1.63	C	0.91	C	1.38	C	1.16	B	1.32	0.75	0.73	0.87
48-60"	0	0.61		1.14	AB	0.65		1.56		1.06	B	1.22	0.76	0.73	0.85
48-60"	128	0.80	C	1.27	BC	0.48	C	1.67		1.08	B	1.23	0.82	0.76	0.74
48-60"	384	0.81	C	1.31	B	0.61	B	1.31	B	1.17	B	1.38	0.69	0.67	0.81
48-60"	641	0.76	C	1.66	C	0.70	C	1.38	C	1.18	B	1.39	0.79	0.70	0.80
60-72"	0	0.67		1.36	AB	0.59		1.32		1.29	B	1.19	0.75	0.64	0.79
60-72"	128	0.80	C	1.92	AB	0.72	C	1.47		1.25	B	1.37	0.70	0.76	0.87
60-72"	384	0.78	C	1.30	B	0.72	B	1.51	B	1.26	B	1.35	0.75	0.70	0.91
60-72"	641	0.78	C	1.57	C	0.86	C	1.31	C	1.33	B	1.41	0.78	0.71	0.94

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table 25. Mean soil TKN concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

1st Raking (before 03/30/09) | 1st Fertilization (before 03/30/09) | 2nd Raking (before 02/15/10)

Sample Depth	DAP lb/ac	10/01/08	03/30/09	04/27/09	06/01/09	08/31/09		12/07/09	02/15/10
		Months after last fertilization (MAF), approximate							
		Before	1	2	3	6		9	12
Avg. all depths§	0	109.0	142.7	137.9	141.8	138.3		137.7	186.8
Avg. all depths	128	110.7	144.0	136.4	129.4	133.6		146.0	184.0
Avg. all depths	384	114.9	193.5	144.4	142.6	140.9		143.7	182.0
Avg. all depths	641	106.1	131.5	130.2	120.2	130.1		126.8	175.0
0-6"	0	345.6	344.7	442.2	434.7	438.4	A	400.8	439.4
0-6"	128	345.2	431.0	447.1	395.6	434.0	A	431.3	430.3
0-6"	384	350.1	409.7	435.0	351.1	391.3	A	312.4	428.1
0-6"	641	310.3	304.6	457.5	429.3	419.4	A	384.7	422.6
6-12"	0	166.7	161.0	252.7	252.9	263.0	B	230.0	242.1
6-12"	128	219.0	242.0	246.8	223.0	187.4	B	223.2	249.0
6-12"	384	198.1	223.5	249.5	258.7	225.6	B	251.7	249.6
6-12"	641	191.3	144.5	256.4	255.1	209.9	B	210.5	250.3
12-24"	0	119.3	132.6	147.0	153.9	132.9	C	147.2	146.2
12-24"	128	112.8	142.7	160.8	143.3	165.8	B	175.1	145.9
12-24"	384	112.6	174.8	139.3	148.0	143.1	C	150.9	127.1
12-24"	641	116.3	97.5	120.2	118.0	122.0	C	135.7	134.0
24-36"	0	99.7	111.4	123.4	126.3	126.5	C	124.9	135.9
24-36"	128	98.7	77.3	117.0	108.5	111.9	C	141.9	133.0
24-36"	384	112.9	127.6	139.9	129.6	123.4	C	131.0	133.2
24-36"	641	99.4	81.9	116.2	101.8	123.1	C	107.2	122.1
36-48"	0	82.3	71.8	100.3	105.2	104.2	C	99.8	107.2
36-48"	128	71.3	53.2	91.1	90.9	92.8	C	102.1	101.0
36-48"	384	96.5	132.6	102.9	110.0	107.0	D	119.7	110.0
36-48"	641	80.9	111.5	94.3	79.9	98.5	D	92.4	94.5
48-60"	0	66.0	n/a†	91.7	75.5	74.5	D	84.2	n/a
48-60"	128	68.6	n/a	74.3	79.7	79.6	D	82.6	n/a
48-60"	384	64.5	n/a	83.5	92.4	90.7	E	93.8	n/a
48-60"	641	67.2	n/a	79.3	69.4	76.6	E	75.5	n/a
60-72"	0	48.4	n/a	50.2	67.2	63.5	D	65.4	n/a
60-72"	128	48.8	n/a	61.8	60.6	67.5	E	69.4	n/a
60-72"	384	47.5	n/a	71.3	67.3	72.3	F	72.0	n/a
60-72"	641	39.9	n/a	51.1	49.1	62.7	E	63.5	n/a

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect. †n/a=samples not collected due to the high groundwater table.

Table 26. Mean soil TKN concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

2nd Fertilization (before 03/29/10); 3rd Raking (before 03/07/11); 4th Raking (before 03/06/12); 5th Raking (before 02/20/13)

Sample Depth	DAP lb/ac	03/29/10		04/26/10		05/24/10	08/23/10	11/17/10	03/07/11	03/06/12		02/20/13
		Months after last fertilization (MAF), approximate										
		1		2		3	6	9	12	24		36
Avg. all depths§	0	103.0		149.3		141.4	130.8	147.7	146.1	143.7		150.0
Avg. all depths	128	78.8		139.7		141.2	137.3	143.1	142.7	137.7		139.2
Avg. all depths	384	109.8		146.5		147.5	145.4	147.2	152.0	137.3		148.0
Avg. all depths	641	105.0		139.5		142.6	142.0	150.2	145.6	144.6		132.6
0-6"	0	439.6		395.7	A	397.8	417.0	416.9	421.1	266.2	A	358.9
0-6"	128	444.3		420.1	A	426.8	465.4	453.8	419.2	336.4	A	401.0
0-6"	384	468.3		409.3	A	402.6	422.3	435.8	382.0	326.8	A	393.0
0-6"	641	489.3		416.1	A	394.4	394.7	432.0	419.5	376.0	A	362.0
6-12"	0	238.4		229.9	B	230.1	243.8	253.1	268.0	220.7 a	A	202.2
6-12"	128	234.3		225.6	B	245.4	250.4	252.4	239.9	176.6 ab	B	228.9
6-12"	384	236.5		223.9	B	225.0	234.4	248.6	272.4	131.2 b	BC	212.8
6-12"	641	244.1		227.7	B	241.3	254.9	254.2	251.5	214.7 a	B	191.0
12-24"	0	116.0		180.5	C	166.3	131.2	164.1	154.9	153.2	C	146.3
12-24"	128	84.2		163.4	C	177.6	152.6	148.4	164.1	167.3	B	129.7
12-24"	384	104.8		145.2	C	165.5	136.7	149.9	135.3	162.5	B	147.3
12-24"	641	112.7		132.6	C	136.5	138.7	140.8	134.9	140.2	C	123.4
24-36"	0	74.8		141.3	D	127.6	122.0	133.0	131.5	134.2	CD	153.2
24-36"	128	54.2		124.4	D	112.4	110.5	118.6	126.6	135.7	BC	126.9
24-36"	384	78.2		139.3	C	128.2	123.6	127.9	152.8	132.3	BC	156.3
24-36"	641	84.2		127.9	C	130.5	125.8	137.0	136.8	140.8	C	118.2
36-48"	0	57.6		117.9	E	112.7	89.6	104.5	103.9	120.4	CD	110.0
36-48"	128	39.0		105.1	E	94.1	93.9	101.4	106.4	113.9	C	104.3
36-48"	384	65.4		108.3	D	116.1	108.7	115.7	118.8	122.6	BC	119.9
36-48"	641	60.1		95.3	D	106.6	111.0	108.3	116.2	115.0	CD	107.1
48-60"	0	47.6	a	93.7	F	83.7	69.7	86.0	93.9	107.0	D	112.1
48-60"	128	28.3	b	89.6	E	83.3	79.6	87.0	83.6	91.9	C	83.3
48-60"	384	56.2	a	87.1	E	93.5	91.3	86.0	100.2	96.9	CD	92.6
48-60"	641	47.7	a	89.9	D	90.3	86.5	95.4	87.1	88.3	DE	93.6
60-72"	0	48.3		64.0	G	61.1	63.9	73.7	62.8	81.1	E	84.7
60-72"	128	34.6		56.6	F	67.7	62.1	68.4	64.2	66.1	D	76.6
60-72"	384	56.7		82.4	E	72.4	82.5	71.8	72.6	83.7	D	72.2
60-72"	641	42.6		74.3	E	72.8	68.7	78.2	70.0	81.4	E	70.8

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.

"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.

Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).

Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

§ Fertilization rate main effect.

Table 27. Mean soil TKN concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

1st Fertilization (between 11/01/08 and 03/09/09); 1st Raking (between 11/30/09 and 02/08/10)

Sample Depth	DAP lb/ac	11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10
		Months after last fertilization (MAF), approximate							
		Before	0.5	1	2	3	6	9	12
Avg. all depths§	0	72.0	68.7	69.2	75.3 a	56.8	57.9	64.4	62.0
Avg. all depths	128	74.9	75.6	56.8	54.7 b	64.9	57.8	63.1	65.4
Avg. all depths	384	74.8	68.0	56.2	55.5 b	63.7	79.0	57.7	74.0
Avg. all depths	641	71.7	74.8	57.7	59.6 b	62.4	69.4	67.9	72.7
0-6"	0	285.7	274.4	267.5	249.7	290.3	324.7	303.4	317.6
0-6"	128	264.1	280.5	220.6	230.1	281.8	290.5	269.4	254.0
0-6"	384	224.3	200.6	217.6	218.4	288.9	292.4	224.7	266.0
0-6"	641	264.9	166.2	176.0	244.4	277.5	289.0	308.6	297.6
6-12"	0	148.1	173.0	165.3	137.9	167.8	182.4	190.2	216.4
6-12"	128	149.2	183.1	125.8	144.7	144.2	156.2	187.5	147.4
6-12"	384	151.7	131.1	117.2	125.0	153.1	161.2	150.0	168.4
6-12"	641	135.6	180.9	88.2	126.2	144.7	144.8	157.1	173.4
12-24"	0	81.4	98.7	85.9	82.2	73.5	69.6	76.6	35.9
12-24"	128	79.6	108.9	67.5	73.0	75.5	79.0	70.8	73.0
12-24"	384	79.1	74.2	40.5	72.2	78.9	90.1	70.8	88.8
12-24"	641	74.6	89.7	65.6	65.8	82.6	90.7	94.1	86.2
24-36"	0	53.0	49.6	62.9	53.5	52.5	46.0	50.6	42.2
24-36"	128	58.0	60.6	43.8	54.5	45.5	46.7	47.8	48.1
24-36"	384	58.9	59.6	44.2	46.2	46.2	56.4	44.8	57.5
24-36"	641	55.2	54.8	49.0	55.3	46.2	57.4	50.0	53.8
36-48"	0	39.6	38.9	30.4	42.7	25.5	27.6	31.9	35.5
36-48"	128	45.3	35.1	33.2	30.5	40.7	29.1	32.2	36.0
36-48"	384	45.9	43.5	33.5	32.8	34.0	41.5	31.6	45.6
36-48"	641	43.1	59.0	33.3	32.8	33.8	40.6	36.3	37.8
48-60"	0	36.9	25.2	31.8	38.1	18.0	17.6	23.9	29.7
48-60"	128	38.7	33.8	23.7	17.6	33.2	20.4	27.3	30.0
48-60"	384	40.7	31.1	31.1	22.7	27.1	35.3	22.9	30.2
48-60"	641	37.8	37.3	40.5	26.7	25.7	28.2	29.4	35.9
60-72"	0	36.6	30.5	31.8	55.0	20.9	22.4	25.9	31.0
60-72"	128	40.7	34.0	28.5	19.4	24.8	20.5	25.4	35.2
60-72"	384	43.4	41.8	36.3	23.1	27.7	53.7	26.4	37.7
60-72"	641	39.8	39.6	31.0	26.3	26.7	30.2	26.3	32.3

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table 28. Mean soil TKN concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

Sample Depth	DAP lb/ac	03/08/10 (2nd Fertilization)	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11 (2nd Raking)	02/28/12 (3rd Raking)	02/27/13 (4th Raking)
		Months after last fertilization (MAF), approximate								
		0.5	1	2	3	6	9	12	24	36
Avg. all depths§	0	56.3	98.6	60.1	64.7 L b	59.0	57.2	58.7	66.4	35.8 L ab
Avg. all depths	128	55.0	95.2	66.1	63.3 L b	52.3	54.7	51.1	61.5	21.1 L b
Avg. all depths	384	58.3	110.9	68.7	70.6 L ab	58.5	53.4	58.8	64.5	48.1 L a
Avg. all depths	641	59.1	108.3	70.3	80.7 L a	68.3	60.1	56.7	60.8	64.1 L a
0-6"	0	262.7	281.5	255.4	284.6	282.0	289.1	298.1	256.3	221.0
0-6"	128	216.1	233.7	242.7	276.6	261.7	263.0	233.1	217.2	247.5
0-6"	384	261.1	269.7	242.1	243.3	263.9	251.7	250.7	213.2	208.4
0-6"	641	260.3	297.4	274.8	351.0	245.1	275.7	284.9	221.3	249.3
6-12"	0	147.7	141.0	162.0	147.3	159.2	167.4	161.8	133.9	122.5
6-12"	128	145.8	146.0	159.0	137.2	140.3	145.9	150.3	136.4	114.2
6-12"	384	127.4	168.7	154.5	144.9	151.9	140.6	147.3	120.9	114.9
6-12"	641	142.3	163.2	183.0	202.4	148.1	162.4	147.8	117.5	134.3
12-24"	0	76.8	117.5	74.8	73.6	70.9	73.8	75.0	72.3	46.6
12-24"	128	65.1	113.5	80.3	70.5	43.5	72.1	65.3	81.9	48.7
12-24"	384	71.7	107.1	78.3	83.0	63.7	66.6	74.0	72.4	55.9
12-24"	641	77.9	123.5	82.5	109.0	82.8	79.9	74.7	123.8	81.7
24-36"	0	41.8	89.6	51.4	49.1	54.8	53.4	47.1	51.0	35.0
24-36"	128	39.3	86.5	49.2	46.0	36.4	42.9	38.4	48.8	16.4
24-36"	384	45.7	105.9	50.4	53.5	39.6	38.8	46.2	59.2	35.8
24-36"	641	39.9	91.3	62.3	64.2	53.3	50.8	45.2	46.6	45.8
36-48"	0	31.0	71.9	17.9	33.2	17.5	28.3	26.8	32.1	14.2
36-48"	128	29.2	68.5	36.2	34.7	30.0	23.9	26.6	33.8	9.5
36-48"	384	30.9	92.4	36.1	45.3	31.7	29.0	30.4	43.6	18.9
36-48"	641	28.4	75.2	45.6	43.3	38.7	31.1	26.7	29.2	31.9
48-60"	0	19.2	57.3	27.8	28.4	26.2	18.1	21.6	33.2	10.3
48-60"	128	23.0	59.8	31.8	29.0	29.0	25.1	19.4	25.6	2.3
48-60"	384	24.4	70.4	36.6	31.5	26.6	21.7	25.0	31.1	26.0
48-60"	641	26.8	67.9	36.0	32.6	33.9	19.9	21.0	23.1	33.2
60-72"	0	23.2	51.9	34.3	32.3	29.5	19.4	23.2	41.3	10.3
60-72"	128	27.2	51.2	30.5	32.0	20.2	19.5	19.0	31.6	2.0
60-72"	384	26.7	61.0	36.0	38.1	26.6	20.6	24.5	30.5	24.3
60-72"	641	27.8	62.0	19.3	30.8	32.3	24.1	22.6	29.2	32.6

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table 29. Mean soil TP concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

1st Raking (before 03/30/09) | 1st Fertilization (before 03/30/09) | 2nd Raking (before 02/15/10)

Sample Depth	DAP lb/ac	10/01/08	03/30/09	04/27/09	06/01/09		08/31/09		12/07/09		02/15/10	
			Months after last fertilization (MAF), approximate									
		Before	1	2	3		6		9		12	
Avg. all depths§	0	46.4	67.3	86.8 L b	91.2		92.1		88.1		107.6	
Avg. all depths	128	45.3	82.1	98.8 L a	83.7		90.7		85.8		109.4	
Avg. all depths	384	44.5	64.1	101.5 L a	91.6		96.4		88.8		109.3	
Avg. all depths	641	48.9	58.6	102.4 L a	88.4		93.6		85.5		116.8	
0-6"	0	99.5	105.4	207.6	202.1 L b	A	194.2 L b	A	208.8 L b	A	204.2 L c	A
0-6"	128	98.0	173.1	239.7	200.0 L b	A	200.5 L b	A	205.0 L b	A	208.3 L c	A
0-6"	384	99.1	119.8	260.5	214.5 L b	A	212.4 L ab	A	211.9 L b	A	234.5 L b	A
0-6"	641	107.8	109.6	314.0	299.3 L a	A	251.9 L a	A	261.8 L a	A	274.7 L a	A
6-12"	0	61.6	61.4	125.6	126.5	B	131.6 a	B	131.1	B	126.6 L b	B
6-12"	128	68.6	118.5	140.2	118.9	B	101.8 b	B	126.9	B	129.5 L b	B
6-12"	384	66.0	67.7	153.1	141.8	B	135.2 a	B	151.0	B	133.6 L ab	B
6-12"	641	67.4	65.7	162.0	159.8	B	133.8 a	B	136.7	B	149.4 L a	B
12-24"	0	41.5	63.3	81.2	84.1	C	82.3	C	79.1	C	86.6	C
12-24"	128	44.6	70.1	93.3	80.1	C	97.5	B	81.8	C	91.1	C
12-24"	384	39.6	55.2	96.9	84.1	C	89.4	C	82.1	C	83.7	C
12-24"	641	47.4	45.1	91.5	74.7	C	80.5	C	79.1	C	87.9	C
24-36"	0	39.9	58.9	79.1	78.9	C	79.5	C	77.9	C	83.1	C
24-36"	128	40.3	64.4	88.8	74.2	C	84.6	C	82.8	C	83.3	C
24-36"	384	40.5	50.1	88.6	76.0	C	83.9	C	74.3	C	78.6	C
24-36"	641	44.6	42.4	82.3	70.7	C	83.3	C	69.6	C	79.8	C
36-48"	0	37.8	57.3	70.8	71.5	C	79.8	C	67.7	C	77.3	C
36-48"	128	36.1	40.0	82.4	72.6	C	75.8	D	69.8	D	76.4	D
36-48"	384	37.6	48.0	78.4	70.7	C	75.9	C	70.4	C	75.5	C
36-48"	641	40.7	49.9	77.6	64.3	C	73.5	C	62.4	D	75.0	D
48-60"	0	35.1	n/a†	61.5	66.5	C	66.4	D	62.6	D	n/a	
48-60"	128	32.8	n/a	63.5	62.2	D	68.6	E	61.0	EF	n/a	
48-60"	384	34.6	n/a	67.7	69.0	C	72.7	D	62.7	D	n/a	
48-60"	641	36.2	n/a	72.3	54.6	D	63.9	D	56.1	EF	n/a	
60-72"	0	34.2	n/a	50.5	64.5 a	D	63.2	D	57.1 a	D	n/a	
60-72"	128	27.2	n/a	62.5	44.6 b	E	57.5	F	45.3 b	F	n/a	
60-72"	384	25.2	n/a	60.7	56.7 ab	D	64.8	E	50.0 ab	E	n/a	
60-72"	641	29.0	n/a	54.2	46.9 b	E	58.7	E	47.7 b	F	n/a	

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.

"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.

Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).

Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

§ Fertilization rate main effect.

†n/a=samples not collected due to the high groundwater table.

Table 30. Mean soil TP concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

2nd Fertilization ↓ (before 03/29/10); 3rd Raking ↓ (before 03/07/11); 4th Raking ↓ (before 03/06/12); 5th Raking ↓ (before 02/20/13)

Sample Depth	DAP lb/ac	03/29/10		04/26/10	05/24/10		08/23/10		11/17/10		03/07/11		03/06/12		02/20/13	
Months after last fertilization (MAF), approximate		1		2	3		6		9		12		24		36	
Avg. all depths§	0	88.3 ab		94.0	98.3		82.8		93.1		96.6		100.4		95.8	
Avg. all depths	128	80.9 b		93.1	97.1		90.1		94.9		95.7		102.2		98.6	
Avg. all depths	384	96.9 a		99.5	102.9		93.9		95.4		101.9		105.1		97.4	
Avg. all depths	641	95.6 a		100.8	103.7		98.2		98.7		99.2		104.8		96.9	
0-6"	0	208.5 L b	A	194.5	200.0 L b	A	199.0 L c	A	201.1 L c	A	200.6 L c	A	172.9 c	A	197.8 L c	A
0-6"	128	234.1 L b	A	207.3	215.0 L b	A	226.6 L bc	A	236.5 L c	A	224.6 L bc	A	222.2 b	A	221.9 L bc	A
0-6"	384	241.7 L b	A	254.6	268.8 L a	A	284.1 L ab	A	290.2 L b	A	257.8 L b	A	272.8 a	A	269.8 L ab	A
0-6"	641	299.3 L a	A	251.0	287.2 L a	A	353.6 L a	A	343.5 L a	A	319.3 L a	A	279.0 a	A	315.7 L a	A
6-12"	0	128.1	B	119.6	128.4	B	134.2	B	156.2	B	136.5	B	127.8 b	B	122.2	B
6-12"	128	124.1	B	126.2	141.2	B	132.4	B	138.1	B	130.4	B	121.1 b	B	122.3	B
6-12"	384	139.6	B	132.0	143.7	B	148.3	B	148.2	B	164.5	A	130.5 b	B	126.9	B
6-12"	641	153.5	B	134.7	160.6	B	161.1	B	159.7	B	151.1	B	174.3 a	B	141.9	B
12-24"	0	94.7	C	94.8	94.4	C	72.7	C	86.8	C	87.1	C	90.7	C	83.4	C
12-24"	128	76.6	C	88.5	95.4	C	82.8	C	86.2	C	91.6	C	94.0	CD	94.6	C
12-24"	384	91.7	C	89.1	93.0	C	81.7	C	84.1	C	81.3	C	97.2	C	92.5	C
12-24"	641	85.5	C	90.6	86.6	C	82.0	C	81.2	C	84.8	C	89.8	C	79.5	CD
24-36"	0	76.8	D	91.1	88.9	C	70.3	C	75.6	D	84.9	C	93.7	C	91.9	C
24-36"	128	67.6	C	85.5	85.0	CD	75.7	CD	78.0	CD	82.9	C	96.3	C	90.2	C
24-36"	384	79.9	CD	88.4	84.8	CD	73.0	CD	78.0	C	81.7	C	95.1	C	88.3	C
24-36"	641	80.8	C	89.7	88.0	C	69.4	D	78.0	C	81.6	C	87.7	C	81.6	C
36-48"	0	66.2	E	83.0	87.1	C	63.3	C	75.9	CD	80.1	C	89.2	C	80.0	C
36-48"	128	57.7	D	76.3	80.7	D	71.9	CD	73.1	DE	80.4	CD	86.9	CD	80.1	CD
36-48"	384	71.6	DE	80.3	85.7	C	71.5	CD	72.6	CD	77.6	CD	89.1	CD	82.2	C
36-48"	641	67.1	D	77.4	80.3	CD	69.6	CD	72.1	CD	75.3	CD	90.7	C	78.1	C
48-60"	0	58.2 a	EF	70.1	75.0	D	55.0	D	65.9	E	80.6 a	C	85.1	CD	79.8	C
48-60"	128	46.1 b	E	68.6	67.9	E	65.3	D	68.4	DE	67.5 ab	DE	77.1	DE	72.9	D
48-60"	384	67.7 a	DE	68.4	75.3	D	63.2	DE	66.4	D	78.7 a	CD	75.1	DE	63.2	D
48-60"	641	61.0 a	DE	76.8	72.8	D	66.1	CD	63.9	DE	64.2 b	DE	68.5	D	65.2	D
60-72"	0	55.7	F	55.1	62.8	E	55.9	D	58.4	E	59.9	D	72.0	D	62.3	D
60-72"	128	56.1	D	58.2	60.2	E	54.1	E	62.7	E	60.4	E	71.2	E	66.9	D
60-72"	384	66.6	E	65.9	61.6	E	56.4	E	52.4	E	65.8	D	64.0	E	57.1	D
60-72"	641	55.5	E	64.4	62.2	E	58.4	D	56.4	E	58.1	E	57.7	D	53.7	E

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.

"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.

Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).

Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

§ Fertilization rate main effect.

Table 31. Mean soil TP concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

Sample Depth	DAP lb/ac	11/01/08	03/09/09 (1st Fertilization)	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10 (1st Raking)
		Sampling Date							
		Months after last fertilization (MAF), approximate							
		Before	0.5	1	2	3	6	9	12
Avg. all depths§	0	85.7	79.5	81.4	83.0	76.6 L ab	77.1	80.4 a	78.6
Avg. all depths	128	76.1	72.1	74.9	73.1	70.8 L b	69.5	67.4 b	75.7
Avg. all depths	384	82.8	78.1	98.0	81.7	77.0 L ab	77.4	79.0 a	84.7
Avg. all depths	641	85.8	83.7	90.5	88.4	82.8 L a	82.3	82.0 a	88.2
0-6"	0	145.8	145.1	142.0	143.5	133.4	149.5	148.2	148.4
0-6"	128	123.2	121.1	130.6	125.9	129.6	133.4	122.3	137.3
0-6"	384	140.3	146.8	162.0	155.4	171.8	157.4	163.3	153.7
0-6"	641	145.8	141.3	147.9	200.5	170.9	173.7	184.7	195.9
6-12"	0	131.8	132.7	124.8	119.4	129.7	123.6	131.9	133.7
6-12"	128	116.9	117.2	116.8	110.2	104.4	110.1	97.8	103.9
6-12"	384	125.7	126.8	129.7	124.0	127.2	131.2	118.7	129.6
6-12"	641	134.2	144.5	129.2	146.8	137.9	146.2	136.2	153.8
12-24"	0	97.6	99.2	94.8	90.3	87.5	87.3	105.2	98.1
12-24"	128	81.2	81.8	82.7	82.5	78.4	81.6	72.5	85.5
12-24"	384	95.0	90.8	102.6	92.9	89.4	77.7	88.0	92.4
12-24"	641	95.7	99.9	90.8	97.4	90.9	89.3	94.9	97.4
24-36"	0	72.3	52.0	74.1	68.0	70.7	66.5	69.8	74.3
24-36"	128	70.4	67.3	64.1	68.0	63.6	62.7	60.9	67.7
24-36"	384	73.3	65.3	103.9	72.4	61.4	64.0	64.8	72.5
24-36"	641	82.3	67.4	82.3	70.8	73.4	72.4	71.0	74.1
36-48"	0	61.1	63.7	57.9	59.1	55.3	54.3	57.3	37.1
36-48"	128	60.7	52.7	54.2	53.9	53.0	48.0	51.7	57.7
36-48"	384	60.1	55.8	81.2	59.8	51.1	52.7	53.5	63.3
36-48"	641	66.1	65.5	71.3	66.7	62.0	55.9	57.2	63.4
48-60"	0	66.9	52.9	54.6	56.3	47.4	50.6	48.3	58.6
48-60"	128	57.8	50.3	51.1	49.5	49.9	43.1	46.1	51.7
48-60"	384	58.7	50.7	79.1	52.0	49.3	51.9	52.1	58.9
48-60"	641	58.5	52.8	69.3	54.8	53.3	51.5	49.9	54.5
60-72"	0	60.9	59.7	59.8	77.2	54.7	54.7	54.4	58.3
60-72"	128	51.0	48.6	58.7	53.7	49.8	50.0	49.9	57.4
60-72"	384	61.1	56.1	60.2	59.9	52.8	59.0	62.1	62.4
60-72"	641	57.2	60.3	70.5	56.5	51.2	53.6	50.9	55.0

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant)..
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table 32. Mean soil TP concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

	2nd Fertilization ↓						2nd Raking ↓	3rd Raking ↓	4th Raking ↓	
Sample Depth	**DAP** lb/ac	**Sampling Date** 03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
		Months after last fertilization (MAF), approximate 0.5	1	2	3	6	9	12	24	36
Avg. all depths§	0	84.7	84.9	82.4 L ab	82.0 L b	82.7	81.6 b	79.4	89.7	77.4 L b
Avg. all depths	128	79.9	85.2	76.7 L b	76.7 L b	75.2	73.0 b	75.1	81.7	75.8 L b
Avg. all depths	384	88.3	90.8	86.1 L a	84.8 L ab	78.1	81.7 b	79.9	89.8	87.2 L ab
Avg. all depths	641	88.8	97.7	92.1 L a	92.6 L a	89.0	95.8 a	87.1	93.4	94.3 L a
0-6"	0	160.7 L bc A	149.5 L b A	144.3	147.7	164.2 L b A	144.1 L c A	141.4 L c A	141.1 L c A	145.4
0-6"	128	147.1 L c A	146.2 L b A	140.0	152.6	160.6 L b A	155.8 L c A	143.1 L c A	143.4 L bc A	154.7
0-6"	384	185.3 L ab A	211.5 L a A	190.2	181.2	179.9 L b A	194.6 L b A	188.3 L b A	187.6 L ab A	210.2
0-6"	641	220.6 L a A	234.9 L a A	208.8	233.2	253.6 L a A	265.1 L a A	243.3 L a A	236.6 L a A	237.4
6-12"	0	128.5 B	129.3 L ab B	129.8	114.0	137.6 b B	132.1 b A	127.4 B	130.7 A	107.5
6-12"	128	117.2 B	108.6 L b B	108.1	93.4	113.8 b B	106.9 b B	111.6 B	115.0 B	106.8
6-12"	384	113.0 B	134.7 L a B	131.1	120.7	124.9 b B	124.8 b B	117.5 B	118.8 B	132.5
6-12"	641	134.6 B	146.9 L a B	159.8	153.0	186.0 a B	179.9 a B	142.4 B	136.1 B	156.2
12-24"	0	88.9 C	91.2 C	91.6	89.9	88.4 C	97.1 B	90.9 C	100.1 B	81.7
12-24"	128	86.4 C	90.8 C	85.2	85.5	71.4 C	83.3 C	83.1 C	102.0 B	89.4
12-24"	384	93.8 C	81.7 C	88.1	99.7	80.3 C	82.8 C	80.7 C	88.9 C	82.8
12-24"	641	87.4 C	90.7 C	89.1	99.5	88.9 C	95.5 C	86.4 C	100.9 C	98.8
24-36"	0	75.8 D	76.5 D	74.7	74.2	73.6 CD	74.4 ab C	71.5 D	82.0 C	67.8
24-36"	128	66.6 D	79.2 CD	69.2	71.1	64.2 CD	60.7 b D	69.1 D	80.5 C	61.9
24-36"	384	79.3 D	77.0 C	74.1	70.4	62.3 D	69.5 ab D	67.9 D	85.1 C	70.0
24-36"	641	75.0 D	82.4 CD	79.1	80.2	74.0 CD	82.1 a C	71.5 D	76.9 D	80.8
36-48"	0	64.6 E	68.7 DE	61.0	60.5	62.0 DE	59.4 D	58.2 E	64.9 D	57.1
36-48"	128	59.0 DE	68.6 DE	59.6	59.0	53.6 D	54.5 DE	54.5 E	59.6 D	57.2
36-48"	384	65.2 E	71.6 CD	59.7	59.0	53.7 DE	59.2 E	57.0 E	71.7 CD	57.8
36-48"	641	62.8 E	74.4 DE	62.2	63.1	62.1 D	66.5 D	59.0 E	64.9 DE	63.6
48-60"	0	57.5 E	58.6 F	55.9	57.5	53.4 E	53.0 D	51.1 F	65.9 CD	56.0
48-60"	128	52.7 E	66.1 E	54.4	55.1	52.7 D	49.8 E	53.0 E	59.7 D	52.2
48-60"	384	60.1 E	65.8 DE	56.0	55.8	49.1 E	52.1 E	53.7 E	63.8 D	55.7
48-60"	641	56.8 E	67.1 E	58.5	59.2	46.4 E	51.3 E	53.8 E	58.1 E	57.4
60-72"	0	60.0 E	58.3 EF	58.4	63.5	53.8 E	55.3 D	56.8 EF	71.7 CD	59.6
60-72"	128	67.3 D	63.0 E	53.5	55.3	57.5 D	47.9 E	50.7 E	50.0 D	52.1
60-72"	384	68.0 DE	59.9 E	64.2	62.2	59.3 DE	55.8 E	55.7 E	60.9 D	73.6
60-72"	641	62.5 DE	65.8 E	65.3	54.3	48.8 E	57.5 DE	55.4 E	65.6 D	60.7

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant)..
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

5.5 RESULTS FOR SURFACE SOIL PROPERTIES

Pine straw raking operations and fertilization may have a significant effect on surface soil edaphic conditions. Removal of pine litter decreases surface soil moisture content and increases temperature fluctuations, which may damage fine roots and weaken their nutrient and water absorbing functions. Fertilization often changes soil carbon to nitrogen ratio (C/N) and enhances soil microbial activities. Since soil microbial organisms use humus (fine organic matter) as an energy source, fertilization often decreases soil organic matter (OM) content. Decreases in fine root mass and OM content often cause soil bulk density (ρb) to increase, which results in slower tree growth. To assess these soil edaphic conditions, soil bulk density (ρb), OM, and root mass changes were monitored in the two uppermost depth fractions (0-6” and 6-12”).

5.5.1 Soil Bulk Density (ρb)

Two intact soil core samples were taken from 0-6 and 6-12” depths from each treatment plot during study initiation in February 2009 (pre-treatment) and in April 2011, two years after the first fertilization, to determine soil bulk density (ρb) change. The measured ρb for two samples within each treatment plot were averaged for each depth and the change in ρb was calculated by subtracting the 2009 plot average from the 2011 plot average for each of the 2 sample depths. The analysis of variance for the initial ρb and for the change in ρb over the 2-year period was performed using Proc Mixed with a compound symmetric error structure (SAS, 2010) to account for the covariance of sample depths within each plot (sample depths are nested within each treatment plot). The change from 2009 to 2011was also expressed as a percent increase to be more meaningful. This was done for each treatment plot by dividing the difference in ρb treatment means (2011-2009) by the 2009 treatment mean and multiplying by 100.

Analysis of the change in ρb helped to account for plot to plot soil variation at the time of study installation. This variation was evidenced by a significant pre-treatment (before treatment installation) effect of raking treatment at Blountstown and a significant three-way interaction at Live Oak, which are attributed to inherent site differences (Tables 33 and 34). The significant pre-treatment depth effect indicated that ρb initially differed among the depths, which was expected. Bulk density increased from 2009 to 2011at both sites and at both depths, but these changes were not related to raking or fertilization treatments. They might have been related to the monitoring activities, i.e., foot and field vehicle traffic, which occurred throughout the study sites. The bulk density increase at Blountstown was significantly higher at the 0-6” depth than at 6-12” depth, which seems reasonable since the soil closest to the surface should be most impacted by traffic.

Table 33. Analysis of variance for initial (pre-treatment) 2009 soil bulk density (ρb) and the change in bulk density from 2009 to 2011 for two study sites.

		Blountstown		Live Oak	
Source	df	Initial ρb (2009)	ρb Change (2011-2009)	Initial ρb (2009)	ρb Change (2011-2009)
		----- Probability of a greater F-Value -----			
Fertilization rate	3	0.3573	0.2620	0.1591	0.5940
Raking	1	**0.0376**	0.2387	0.8061	0.8093
Fert x Raking	3	0.1057	0.5674	0.2176	0.4674
Depth	1	**<0.0001**	**0.0140**	**<0.0001**	0.2058
Fert x Depth	3	0.7588	0.9772	0.2627	0.1270
Raking x Depth	1	0.5156	0.4198	0.2760	0.9175
Fert x Raking x Depth	3	0.4644	0.7708	**0.0115**	0.0975

Table 34. Mean comparisons for depth, raking, and fertilization rate treatment main effects for initial (pre-treatment) 2009 bulk density, and the change in bulk density from 2009 to 2011.

	Blountstown					Live Oak				
Effect	Initial (2009) (g/cm^3)		2011-2009 (g/cm^3)		2011-2009 (%)	Initial (2009)† (g/cm^3)		2011-2009 (g/cm^3)		2011-2008 (%)
Depth										
0-6”	1.45	b‡	0.33	a	22.5	1.46	b	0.24	a	16.5
6-12”	1.60	a	0.27	b	16.8	1.60	a	0.28	a	17.2
Raking										
No rake	1.55	a	0.31	a	19.9	1.53	a	0.25		16.6
Rake	1.50	b	0.29	a	19.2	1.52	a	0.26		17.1
Fertilization										
0	1.50	a	0.29	a	19.0	1.54	a	0.23		15.1
144	1.53	a	0.28	a	18.6	1.50	a	0.27		18.1
432	1.52	a	0.33	a	21.5	1.51	a	0.28		18.8
720	1.55	a	0.30	a	19.1	1.56	a	0.24		15.6

† Analysis of variance for initial 2009 bulk density at the Live Oak site indicated significant 3-way interaction.

‡ Means within a column for the same main effect (depth, raking, or fertilization rate) followed by the same letter are not significantly different (α=0.05). Percent change is not compared statistically but provided for information.

5.5.2 Soil Organic Matter (OM)

Soil organic matter content was determined in 0-6” and 6-12” soil depth fractions since soil OM is typically most abundant and important near the soil surface for the soil types occurring in these studies. Soil OM data were analyzed by the same methods as for soil nutrients, i.e., SAS Mixed procedure with a spatial power covariance structure (refer to section 5.4.2 Soil Nutrients).

Soil organic matter is very important because it buffers weather effects, enhances soil microorganism and invertebrate activities, sustains nutrient cycling, provides plant nutrient exchange sites and is generally held to be the most important measure of sustainability of forest and agricultural practices. Pine straw raking may decrease soil OM by removing pine straw as a source of organic matter. Fertilization may increase microbial activity. An increase in soil N increases demand for C, which accelerates humus breakdown.

No fertilization or raking effects on soil organic matter content has been observed at 0-6” or 6-12” depths at either site during four years following the first fertilization (Table 35). On a few isolated dates when ANOVA indicated significant effects, mean differences were trivial (in some cases 0.01%). As expected, OM differed significantly between the two depths at both sites even before any treatments were applied. At Blountstown, overall mean OM content across all fertilization rates and sampling dates was 1.31% (0.75-2.01% range) at 0-06” depth and 0.89% (0.51%-1.54% range) at 6-12” depth (results not shown). At the Live Oak site, overall mean OM contents for 0-6” and 6-12” depths were 1.17% and 0.71%, respectively, and the values ranged between 0.71-1.71% and 0.29-1.21%, respectively.

Table 35. ANOVA for soil organic matter content by sampling date at two study sites

Raking | 1st Fertilization | Raking | 2nd Fertilization | Raking

Blountstown

Factor	df*	10/01/08		03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10		03/29/10	04/26/10	05/24/10	08/23/10	11/17/10	03/07/11	03/06/12	02/20/13
Fert	3	0.0735		0.8882	0.1706	0.7010	0.4450	**<.0001**	0.8696		0.8806	0.3991	**<.0001**	0.2560	0.8127	0.8408	0.9704	0.8650
Rake	1	0.5728		0.4823	**0.0083**	0.1170	0.5284	**<.0001**	0.8987		0.4059	0.4048	**<.0001**	0.9316	0.0898	0.2252	0.7373	0.1587
Fert*Rake	3	0.1183		0.3230	0.2388	0.0842	0.1811	**<.0001**	0.5084		0.9225	0.6565	**<.0001**	0.1061	0.1839	0.4544	0.4484	0.5922
Depth	1	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.0565	**<.0001**		0.4094	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0004**	**<.0001**
Fert*Depth	3	0.7329		0.6293	0.1282	0.5358	0.2608	0.9905	0.5193		0.1754	0.3456	0.8474	0.3518	0.8616	0.3375	0.4109	0.1351
Rake*Depth	1	0.1097		0.7105	0.7085	0.9328	0.3787	0.5175	0.8453		0.2224	0.6501	0.2717	0.4576	0.7957	0.1988	0.5142	0.8669
Fert*Rake*Depth	3	0.4975		0.4689	0.1341	0.4685	0.7446	0.8893	0.0745		**0.0180**	0.5938	0.9666	0.1945	0.5468	0.4701	0.9119	0.8469

Live Oak

Factor	df*	11/1/08	3/9/09	3/23/09	4/20/09	5/25/09	8/24/09	11/30/09	2/8/10	3/8/10	3/22/10	4/19/10	5/10/10	8/16/10	11/22/10	2/21/11	2/28/12	2/27/13
Fert	3	0.9690	**<.0001**	0.3936	0.4164	0.9097	0.8592	0.9202	0.8463	0.4238	0.2304	0.1741	0.6656	0.9316	0.0863	0.9070	0.8126	0.8904
Rake	1	0.4467	**<.0001**	0.1462	0.4678	0.8197	0.5068	0.2149	0.8882	0.6312	0.6921	0.2474	0.5696	0.1391	0.9341	0.3223	0.9976	0.4078
Fert*Rake	3	0.1622	**<.0001**	**0.0257**	0.3985	0.1216	0.9963	0.3519	0.7950	0.0594	0.1229	**0.0072**	0.9642	0.5179	0.2613	0.2122	0.7922	0.7485
Depth	1	**<.0001**	**0.0114**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0001**	**<.0001**	**0.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	3	0.1509	0.5703	0.7363	0.5815	0.6548	0.8513	0.3557	0.8753	0.6009	0.1312	0.3744	0.8781	0.3045	0.8597	0.7479	**0.0130**	0.8589
Rake*Depth	1	0.7423	0.6547	0.1508	0.5298	**0.0453**	0.3530	0.6401	0.3557	0.4513	0.1833	0.5325	0.3413	0.3938	0.3203	0.8381	0.1221	0.0794
Fert*Rake*Depth	3	0.9450	0.8224	0.7771	0.5214	0.6687	0.8101	0.5030	0.4901	**0.0226**	0.1454	0.1752	0.2274	0.1400	**0.0479**	0.2920	0.1377	0.8664

5.5.3 Pine Root Mass

Statistical Methods

Root samples for dry weight determination were obtained from soil samples collected on multiple dates starting before the first fertilization in fall 2008 (Date 1 in Tables 36 & 37) and ending four years after the first fertilization in spring 2013 (Dates 15 and 18 in Tables 36 & 37, respectively). A composite sample for each of the seven soil depths (0-6", 6-12", 12-24", 24-36", 36-48", 48-60", 60-72") was taken from three cores per plot collected with a bucket auger. The determined root dry weights for the 0-6" and 6-12" depths were added and the root dry weight per soil volume was computed (mg/cm^3) for the combined 0-12" depth. The majority of roots were within 0-6" but the 0-12" depth was assessed because this is where most feeder roots are known to occur in these forest soils. There were too few roots below 12" for a meaningful analysis. The volume of the composite sample for each of the 0-6" and 6-12" depths was 1,800 cm^3.

Analysis of variance was performed on log transformed values to improve distributional properties and homogeneity of residuals. Preliminary analysis of covariance structure indicated that variance of transformed values was reasonably homogeneous across sampling dates and that correlations among sampling dates on plots were close to zero (if significant at all). This, in part, is reflective of how samples were a random selection for each plot on each sampling date. The analysis of variance was performed as a nested design with raking and fertilization treatments as main plots and sampling dates nested within randomly allocated measurement plots.

An ANOVA of all sample dates was performed but was also partitioned into meaningful tests of hypotheses based on the sampling date framework for each study site. The ANOVA was partitioned to examine: (1) seasonal effects during two years of fertilization, and (2) early growing season root dry weight through 2013. Seasonal samples were taken at multiple dates during each year of fertilization (2009-2010) to allow the comparison of sampling dates within each year, fertilization years, and interactions with fertilization and raking. Early growing season samples were taken in early spring through 2013 (four years after the first fertilization) to allow the comparison of root mass annually for the response to fertilization, raking, and interaction. Tables 36 and 37 identify sampling dates compared in these partitioned ANOVA's. The season analysis used samples in the shaded portion of the tables to test for differences in seasonal averages (averaged over 2009-10), differences in yearly averages of sampling dates that were represented in both years, and tests for interaction. The early growing season analysis compared annual samples across years (bold numbers) only for the early growing season samples.

Table 36. Root dry weight sampling order (1-15) at the Blountstown site listed by growth period (Season), sampling dates within year, and sampling year

Growth period (Season)	Sampling dates	Year					
		2008	2009	2010	2011	2012	2013
Early growing season	Feb. 15-Mar. 7			**7**[3]	**13**	**14**	**15**
March	Mar. 29-30[1]		2[2]	8			
April	Apr. 26-27		3	9			
May	May 24-Jun. 1		4	10			
August	Aug. 23-31		5	11			
October-November	Oct. 1-Dec. 7	1	6	12			

[1] Sampling dates 2 and 8 were March 29-30, 4 weeks after fertilization each year.
[2] Shaded sampling dates were used to test growth period differences (row averages), difference between fertilization years 2009 and 2010 (column averages), and interactions with fertilization and raking treatments.
[3] Sampling dates in bold were used to test early growing season difference among years 2010-2013 and interactions with fertilization and raking treatments.

Table 37. Root dry weight sampling order (1-18) at the Live Oak site listed by growth period (Season), sampling dates within year, and sampling year

Growth period (Season)	Sampling dates	Year					
		2008	2009	2010	2011	2012	2013
Pre-growing season	Feb. 08			9			
Early growing season	Feb.21-Mar.9[1]		**2**[2,3]	**10**	**16**	**17**	**18**
March	Mar. 22-23		3	11			
April	Apr. 19-20		4	12			
May	May 10-25		5	13			
June	Jun. 8		6				
August	Aug. 16-24		7	14			
October-November	Nov. 1-30	1	8	15			

[1]Sampling dates 2 and 10 were March 8-9, 2 weeks after fertilization each year.
[2] Shaded sampling dates were used to test growth period differences (row averages), difference between fertilization years 2009 and 2010 (column averages), and interactions with fertilization and raking treatments.
[3] Sampling dates in bold were used to test early growing season difference among years 2009-2013 and interactions with fertilization and raking treatment

Root Dry Weight Results

Sampling date had a significant effect on root dry weight at Blountstown, but not at the Live Oak site (Table 38). In particular, season affected root mass during fertilization years at Blountstown (P=0.0059), but differently in 2009 and 2010 (P=0.01790). Root dry weight was greatest in April in 2009, and in May in 2010. In both those years root dry weight was greater at these sampling dates than later during the year (Table 39). These results indicate greater root growth in the months preceding the April and May sampling, prior to the period of intense pine shoot growth during the spring flush.

There was no significant effect of raking or fertilization on root dry weight at either site shown by ANOVA. However, at Blountstown root mass decreased from 1.67 to 1.37 mg/cm^3 as fertilization rate increased from 0 to 641 lb/acre (Table 39). At Live Oak root mass was also least for the highest fertilization rate (Table 42). These results are similar to those of another study at these same sites, in which fertilization significantly reduced root volume in the uppermost 10 cm of soil (Chevasco, Ph.D. dissertation in preparation).

Table 38. ANOVA for root dry weight in the upper 0-12” of soil at two study sites

		Blountstown		Live Oak	
Date effects		df		df	
Sample Date (All Dates)		14	**0.0122**	17	0.5164
Season in years 2009-10 (Season)[1]		4	**0.0059**	5	0.8369
Year 2009 vs. 2010 (Year)[2]		1	0.8186	1	0.5857
Season x Year 2009-10		4	**0.0179**	5	0.2124
Early season annual samples through 2013 (Early)[3]		3	0.9248	4	0.7137
Fertilization effects					
Fert over All Dates		3	0.7416	3	0.4788
All Dates x Fert		42	0.4578	51	0.0787
Fert over 2009-10 Season/Years		3	0.3482	3	0.1546
Season x Fert		12	0.8888	15	0.4364
Year x Fert		3	0.3708	3	0.5716
Fert over Early		3	0.7926	3	0.4663
Early x Fert		9	0.8011	12	0.1748
Rake effects					
Rake over All Dates		1	0.7898	1	0.4907
All Dates x Rake		14	0.9556	17	0.6707
Rake over 2009-10 Season/Years		1	0.9888	1	0.3660
Season x Rake		4	0.3202	5	0.3804
Year x Rake		1	0.8587	1	0.4369
Rake over Early		1	0.5109	1	0.7137
Early x Rake		3	0.8713	4	0.8490
Fertilization x Rake interactions					
Fert x Rake over All Dates		3	0.9923	3	0.4440
All Dates x Fert x Rake		42	0.1612	51	0.5516
Fert x Rake over 2009 Season/Years		3	0.7204	3	0.7338
Season x Fert x Rake		12	0.3569	15	0.2112
Year x Fert x Rake		3	0.5618	3	0.7452
Fert x Rake over Early		3	0.9885	3	0.0856
Early x Fert x Rake		9	0.6266	12	0.6722

[1]Shaded sampling dates (row averages) in tables 36 and 37
[2]Shaded sampling dates (column averages) in tables 36 and 37
[3] Sampling dates in bold in tables 36 and 37

Table 39. Mean root dry weight (mg/cm^3) in the upper 0-12" of soil for the growth period ("Season") main effect in fertilization years 2009 and 2010 at the Blountstown site (averaged across all fertilization rates and raked and non-raked treatments)

Growth period	Year				2-year average	
	2009		**2010**			
March (2,8) [1]	1.37	b	1.79	ab	1.57	ab
April (3,9)	2.15	a	1.50	abc	1.81	a
May (4,10)	1.55	b	1.94	a	1.74	a
August (5,11)	1.49	b	1.26	c	1.37	b
October-November (6,12)	1.16	b	1.34	bc	1.25	b

Means within a column followed by different letters are significantly different at α=0.05 level.
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
[1] Sampling dates (refer to Table 36)

Table 40. Mean root dry weight (mg/cm^3) in the upper 0-12" of soil for fertilization and raking main effects at the Blountstown site

Main effect	Multiple seasons **Years 2009-10**[1]	**Early growing season** Years 2010-2013[2]
Fertilization DAP rate (lb/acre)		
0	1.67	1.39
128	1.63	1.33
384	1.49	1.54
641	1.37	1.43
Raking		
No Rake	1.54	1.49
Rake	1.54	1.37

[1] For fertilization rate main effect means averaged across raked and non-raked treatments and across all growth periods March-November in 2009 and 2010 (dates 2-6 and 8-12 in table 36)
For raking main effect means averaged across all fertilization treatments and across all growth periods March-November in 2009 and 2010 (dates 2-6 and 8-12 in table 36)
[2] For fertilization rate main effect means averaged across raked and non-raked treatments and across early growing season dates in 2010-2013 (7 and 13-15 in Table 36)
For raking main effect means averaged across all fertilization treatments and across early growing season dates in 2010-2013 (7 and 13-15 in Table 36)

Table 41. Mean root dry weight (mg/cm^3) in the upper 0-12" of soil for the growth period ("Season") main effect in fertilization years 2009 and 2010 at the Live Oak site (averaged across all fertilization rates and raked and non-raked treatments)

Growth period	Year		2-year average
	2009	**2010**	
February (2,10)[1]	1.30	1.35	1.33
March (3,11)	1.36	1.56	1.46
April (4,12)	1.55	1.38	1.46
May (5,13)	1.16	1.52	1.33
August (7,14)	1.50	1.26	1.37
October-November (8,15)	1.34	1.38	1.36

[1] Sampling dates (refer to Table 37)

Table 42. Mean root dry weight (mg/cm^3) in the upper 0-12" of soil for fertilization and raking main effects at the Live Oak site

Main effect	Multiple seasons **Years 2009-10**[1]	**Early growing season** Years 2009-2013[2]
Fertilization DAP rate (lb/acre)		
0	1.40	1.37
128	1.58	1.33
384	1.39	1.09
641	1.18	1.35
Raking		
No Rake	1.44	1.33
Rake	1.33	1.23

[1] For fertilization rate main effect means averaged across raked and non-raked treatments and across growth periods February-November in 2009 and 2010 (dates 2-5, 7-8, and 10-15 in table 37)
For raking main effect means averaged across all fertilization treatments and across growth periods March-November in 2009 and 2010 (dates 2-5, 7-8, and 10-15 in table 37)
[2] For fertilization rate main effect means averaged across raked and non-raked treatments and across early growing season dates in 2009-2013 (2, 10, and 16-18 in Table 37)
For raking main effect means averaged across all fertilization treatments and across early growing season dates in 2009-2013 (2, 10, and 16-18 in Table 37

5.6 TREE GROWTH AND PINE STRAW YIELD RESULTS

5.6.1 Pine Stand Responses to Fertilization and Pine Straw Raking

Statistical methods

Fertilization rate and raking treatments were applied in a completely randomized design at both study sites. Pine diameter at breast height (Dbh), total height, and condition code were measured at study installation in the 2008-2009 dormant season and in each subsequent dormant season for four years. This corresponded to four growing seasons following the first fertilization in March 2009. Total volume was computed using a volume equation (Brister et. al. 1980). Tree basal area and volumes were summed and expressed on a per hectare basis for each measurement plot. Average height of dominant and co-dominant trees was computed using trees that survived to 2012, using crown classes at the end of the 2012 growing season.

The analysis of annual measurements was performed using a repeated measures approach with measurement plots considered the subject on which measurements were repeated over time. There were two hypotheses of major importance. The first was that the pattern of response does not differ by treatment over the study period. This is negated if there is a significant interaction between a treatment effect and year. The second was that treatments do not differ in terms of cumulative response over the four-year study period. Cumulative response (including mortality for density or growth for diameter, height, basal area, and volume) may not differ even if the pattern of response differs (i.e., the pattern could differ even if average response does not). Likewise, it is possible to have no significant differences in the pattern of response but significant differences in cumulative response, due to the power of testing cumulative effects of small annual differences over the study period.

Preliminary analysis considered the covariance structure for annual measurements and the potential use of covariates to account for differences in initial conditions. Statistical tests (comparison of log likelihood, Akaike information criteria, and residual plots) and knowledge of stand development were used to determine the final approach. These mid-rotation stands were essentially fully stocked and variation in diameter, basal area, and volume would be expected to increase with size (year). Under these conditions, basal area (m^2 ha^{-1}) and total volume (m^3 ha^{-1}) required no covariates and a first-order heterogeneous autoregressive [ARH(1)] covariance structure was used. Quadratic mean Dbh could be related to differences in tree density and site quality at the plot level, and tests indicated that average height of dominant and co-dominant trees (dominant height) was a significant covariate at both locations, and that density should be added as a second covariate at Blountstown. A first-order autoregressive [AR(1)] and compound symmetry covariance structures were used for the analysis of density and dominant height, respectively.

Results

There were significant interactions between year and fertilization (fert) for stand density and stand basal area at Blountstown (Table 43). There were no significant interactions between year and pine straw raking effects (rake) for any variables. The significant 3-way interaction of fert, rake, and year for dominant height was the result of the non-fertilized raked treatment (F0R1) averaging 0.5 m less than the non-fertilized non-raked treatment (F0R0) in 2012. Heights for other rates of fertilization were 0.0 to 0.2 m greater with raking in 2012. At Blountstown the 384 and 641 lb DAP/acre fertilization rates had significantly greater four-year diameter growth (Dbh) than the non-fertilized control (Table 44). Fertilization treatments did not differ in dominant and co-dominant four-year pine height growth. All other cumulative four-year pine stand responses to fertilization were negative, with the 384 and 641 lb DAP/acre rates resulting in significantly increased mortality, reduced stand basal area, and less volume growth than the low DAP rate or non-fertilized control. Pine straw raking had no significant effect on any pine stand attribute at Blountstown.

There were no significant interactions between year and fertilization or year and raking effects at Live Oak for any variable (Table 45). At live Oak dominant and co-dominant four-year pine height growth was greater for the 641 lb/acre DAP rate than the 128 lb/acre rate or non-fertilized control (Table 46). Fertilization treatments did not differ in four-year diameter growth (Dbh), basal area growth, or volume growth. The four-year change in trees per hectare showed greater mortality for the high DAP rate than the low rate or non-fertilized control. There were no significant differences between rake treatments, except for significantly greater dominant and co-dominant tree height for non-raked treatments.

Table 43. Analysis of variance components showing the significance of DAP fertilization (Fert), pine straw raking (Rake) and measurement year for pine stand response variables including diameter at breast height (Dbh), dominant and co-dominant tree height (DTHT), total pines per hectare (TPH), stand basal area (BA), and total volume (Volume) for the Blountstown study site.

Effect	Partition	Dbh	DTHT	TPH	BA	Volume
		------------ Prob. > F-value ------------				
Fert Rate		0.2519	0.2507	0.2956	0.1889	0.1377
Rake		0.8985	0.9029	0.8279	0.7224	0.7411
Fert x Rake		0.6189	0.0628	0.4121	0.0664	**0.0374**
Year		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Year x Fert		0.0808	0.6802	**0.0271**	**0.0215**	0.0629
Year x Rake		0.5182	0.3448	0.7715	0.8591	0.8894
Year x Fert x Rake		0.2562	**0.0002**	0.9835	0.8189	0.4143
Cumulative growth						
Fert Rate		**0.0424**	0.4686	**0.0063**	**0.0048**	**0.0109**
	Fert vs. None[1]	**0.0197**	0.7600	**0.0157**	**0.0318**	**0.0156**
	Diff F1,F2, F3[2]	0.2297	0.2971	**0.0320**	**0.0109**	**0.0498**
Rake		0.4492	0.2075	0.8210	0.3575	0.3957
Covariates						
Initial dominant height		**<0.001**	-	-	-	-
Initial trees/hectare		**<0.001**	-	-	-	-

[1]Tests if the average of fertilization treatments F1,F2, F3 differ from no fertilization (F0).
[2]Overall test for differences among F1,F2, F3 fertilization treatments. F1, F2, and F3 correspond to 128, 384, and 641 lb diammonium phosphate (DAP) fertilizer per acre, respectively.

Table 44. Four year growth in quadratic mean diameter at breast height (Dbh), dominant and co-dominant tree height (DTHT), four year change in trees per hectare (ΔTPH), stand basal area (BA), and total stand stem volume (Volume) for DAP fertilization (F) and pine straw raking (R) main effects at Blountstown. For response variables showing significant main effects, means followed by the same letter are not significantly different using Tukey's test at P=0.05.

Main effect	Dbh		DTHT		ΔTPH		BA		Volume	
Fertilization[1]	(cm)		(m)		(trees ha^{-1})		(m^2 ha^{-1})		(m^3 ha^{-1})	
F0 growth	2.63	b	4.5		-221	a	5.7	a	101	a
F1 growth	2.80	ab	4.3		-250	a	5.7	a	95	a
F2 growth	2.98	a	4.5		-379	b	2.9	b	75	b
F3 growth	3.09	a	4.6		-401	b	2.1	b	73	b
Rake[2]										
R0 growth	2.92		4.4		-308		4.5		89	
R1 growth	2.83		4.5		-318		3.7		83	

[1] F0, F1, F2, and F3 correspond to 0, 128, 384, and 641 lb diammonium phosphate (DAP) fertilizer per acre, respectively.
[2]RO is non-raked, R1 is raked for pine straw.
[3]One hectare (ha) = 2.47 acres; One square meter per hectare = 0.2295 square feet per acre; One cubic meter per hectare = 14.291 cubic feet per acre

Table 45. Analysis of variance components showing the significance of DAP fertilization (Fert), pine straw raking (Rake) and measurement year for pine stand response variables including diameter at breast height (Dbh), dominant and co-dominant tree height (DTHT), total pines per hectare (TPH), stand basal area (BA), and total volume (Volume) for the Live Oak study site.

Effect	Partition	Dbh	DTHT	TPH	BA	Volume
		------------ Prob. > F-value ------------				
Fert Rate		0.2257	0.4099	0.6998	0.8028	0.6868
Rake		0.9549	0.3768	0.5021	0.3673	0.3476
Fert x Rake		0.7223	0.8575	0.7598	0.8208	0.8318
Year		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Year x Fert		0.2978	0.2843	0.0788	0.4963	0.8519
Year x Rake		0.9845	0.1371	0.7029	0.4723	0.4227
Year x Fert xRake		0.9654	0.4305	0.8354	0.6479	0.6010
Cumulative growth						
Fert Rate		0.1207	**0.0109**	**0.0186**	0.2704	0.9878
	Fert vs. None[1]	0.2152	**0.0109**	0.1200	0.6845	0.8132
	Diff F1,F2, F3[2]	0.1142	0.0817	**0.0208**	0.1556	0.9650
Rake		0.8943	**0.0180**	0.4123	0.7911	0.4795
Covariates						
Dominant height		**<.0001**	-	-	-	-
Trees/hectare		**-**	-	-	-	-

[1]Tests if the average of fertilization treatments F1, F2, F3 differ from no fertilization (F0).
[2]Overall test for differences among F1, F2, F3 fertilization treatments. F1, F2, and F3 correspond to 128, 384, and 641 lb diammonium phosphate (DAP) fertilizer per acre, respectively.

Table 46. Four year growth in quadratic mean diameter at breast height (Dbh), dominant and co-dominant tree height (DTHT), four year change in trees per hectare (ΔTPH), stand basal area (BA), and total stand stem volume (Volume) for DAP fertilization (F) and pine straw raking (R) main effects at Live Oak. For response variables showing significant main effects, means followed by the same letter are not significantly different using Tukey's test at P=0.05.

	Dbh		DTHT		ΔTPH		BA		Volume	
Fertilization	(cm)		(m)		(trees ha^{-1})		(m2 ha^{-1})		(m3 ha^{-1})	
F0 growth	2.16		3.6	c	-95	a	6.5		81	
F1 growth	2.13		3.7	bc	-86	a	6.9		82	
F2 growth	2.38		3.8	ab	-164	ab	6.4		84	
F3 growth	2.47		4.0	a	-235	b	5.5		81	
Rake										
R0 growth	2.29		3.9	a	-160		6.3		84	
R1 growth	2.28		3.7	b	-130		6.4		80	

[1] F0, F1, F2, and F3 correspond to 0, 128, 384, and 641 lb diammonium phosphate (DAP) fertilizer per acre, respectively.
[2]RO is non-raked, R1 is raked for pine straw.
[3]One hectare (ha) = 2.47 acres; One square meter per hectare = 0.2295 square feet per acre; One cubic meter per hectare = 14.291 cubic feet per acre

5.6.2 Pine Foliar Nutrients

Statistical Methods

Dormant season pine foliage samples were collected annually for five years (2008-1012) starting prior to the first fertilization. Preliminary analyses indicated that the variation of nutrient concentrations was homogeneous over the range of data for all nutrients. A common estimate of variance across years was adopted based on the observation that distributions of residuals were reasonably normal for all nutrients except for a small number of extreme values. This is consistent with the sampling methodology in which green needles were sampled using careful selection methods during the same dormant period each year. The repeated measures analysis of variance was performed by treating sample year as nested within plot (this assumes a compound symmetry covariance structure) for all nutrients.

Pine Foliar Nutrient Results

The effect of sampling year was significant for all nutrients at both study sites, while the interaction between sampling year and fertilization rate was significant for all nutrients except Mg at Blountstown (Table 47). This indicates a different effect of fertilization in different years. Iron is not discussed below because foliar concentrations were below the MDL for ARL laboratory.

At both sites, the effect of fertilization on foliar total Kjeldahl nitrogen concentration (TKN) was strongest in 2010, after the second fertilization (Table 48). That year at Blountstown 641 lb/acre DAP resulted in greater TKN concentration (1.23%) than the other treatments (1.04-1.1). During the next two years TKN concentration was also the greatest for 641 lb/acre. However, in 2011 the only treatment statistically different from 641 lb/acre was 128 lb/acre and in 2012 no differences were significant.

At the Live Oak site in 2010, foliar TKN concentration increased proportionally to the fertilization rate increase from 1.08% for 128 lb/acre to 1.31% for 641 lb/acre DAP (Table 48). TKN concentration for 128 lb/acre did not differ from the non-fertilized control. During the next two years TKN concentration was greater for the high fertilization rate than for any other treatment, but in 2012 these differences were not statistically significant.

These results suggest that some of the applied nitrogen, which included NO_x ions moving down the soil profile and ammoniacal forms remaining near the soil surface, was taken up by the pine roots and transported to the foliage. Since the samples consisted of the current year's foliage, the positive response to fertilization diminished as soil nitrogen declined in the surface horizons.

The effect of fertilization on foliar total phosphorus (TP) at both sites was significant only in 2011. That year at the Blountstown site, TP was significantly less for 641 lb/acre than for the other treatments, while at Live Oak both 641 lb/acre and 384 lb/acre resulted in less TP than 128 lb/acre or the non-fertilized control (Table 48). The decrease in foliar TP concentration observed for the high DAP rate may be attributed to accelerated foliage growth and "carbohydrate dilution", whereby the concentration of TP in foliage is diminished by the greater carbohydrate mass.

Foliar potassium (K) concentration was also significantly affected by fertilization only in 2011, but no clear rate trend emerged (Table 48). At Blountstown, K concentration was greater for 384 lb/acre DAP than for 641 lb/acre, but both treatments resulted in greater K concentrations than 0 or 128 lb/acre. At Live Oak in 2011, K concentration was greatest for 641 lb/acre (but not different from 0 lb/acre) and least for 384 lb/acre (but not different from 128 lb/acre).

The effect of fertilization on foliar calcium (Ca) concentration was observed at Blountstown in 2011 and 2012 and at Live Oak every year (Table 49). At Blountstown, application of high and medium DAP rates resulted in lesser Ca concentrations than the non-fertilized control in 2011 and 2012, suggesting that carbohydrate dilution as the result of fertilization had the effect of reducing Ca foliar concentration. Calcium concentration for the low rate was not significantly different from the non-fertilized control in 2011 and from any other treatment in 2012. At the Live Oak site, no clear rate response was evident. In 2009 and 2010 Ca concentration was greatest for the high fertilization rate, whereas in 2012 it was greatest for the non-fertilized control.

There was no effect of fertilization on foliar magnesium (Mg) concentration at Blountstown. At Live Oak the effect in 2010 was opposite to the effect in 2011 (Table 49). In 2010, Mg concentration for the high fertilization rate was greater than for the other treatments, while in 2011 the non-fertilized control resulted in a greater foliar Mg concentration than the other treatments.

The effect of pine straw raking on foliar nutrients was only observed in 2011 and 2012 for K concentration at Blountstown. Both years mean foliar K concentration was greater for non-raked than for raked treatments (Table 48). Since K is a mobile nutrient in pine forests, cycling readily from the crowns to the soil through needle cast and through-fall of rain, this is clear evidence of pine straw removal interrupting K cycling within the stand.

Overall, these results indicate that the high DAP fertilization rate temporarily increased pine foliar TKN concentration and decreased foliar TP concentration. The effect on other nutrients is difficult to generalize, except that decreased concentrations sometimes occurred, possibly as a result of carbohydrate dilution. Pine straw raking had a minimal effect on foliar nutrient concentrations, except for the observed decrease in potassium concentration with raking at the sandy Blountstown site.

Table 47. Repeated measures analyses for foliar nutrient concentrations sampled during dormant seasons following five consecutive growing seasons (Years): 2008-2012 at two study sites

				Blountstown		
Factor	**df**	**TKN**	**TP**	**K**	**Ca**	**Mg**
Fert	3	**0.0004**	**0.0113**	0.0694	0.2763	0.2097
Rake	1	0.2970	0.1084	0.0540	0.3848	0.2817
Fert*Rake	3	0.9865	0.3087	0.2529	**0.0372**	0.4791
Year	4	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Year*Fert	12	**0.0028**	**0.0003**	**0.0006**	**<.0001**	0.0814
Year*Rake	4	0.0927	0.1725	**<.0001**	0.3687	0.4433
Year*Fert*Rake	12	0.1176	0.4175	0.0840	0.1814	**0.0015**
				Live Oak		
Factor		**TKN**	**TP**	**K**	**Ca**	**Mg**
Fert	3	**<.0001**	0.1261	0.3385	**0.0193**	0.1482
Rake	1	0.2843	0.9435	0.4840	0.0877	0.1530
Fert*Rake	3	0.7374	0.6368	0.6687	0.7197	0.5371
Year	4	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Year*Fert	12	**<.0001**	**0.0002**	**0.0096**	**0.0003**	**0.0008**
Year*Rake	4	0.1283	0.9846	0.3158	0.2064	0.0543
Year*Fert*Rake	12	0.4362	**0.0484**	0.5175	0.0681	0.2561

† df for Blountstown TKN (results not available for 2009_Q1): Year_Q=13, Year_Q*Fert=39, Year_Q*Rake=13, Year_Q*Fert*Rake=39

Table 48. Mean foliar TKN, TP, and K concentrations (mg/kg) by sampling year for four DAP fertilization rates (averaged across non-raked and raked treatments) and for non-raked (NR) and raked (R) treatments (averaged across all fertilization treatments) at two study sites

			Raking; 1st Fertilization	Raking; 2nd Fertilization	Raking	Raking
DAP	Rake	Growing season following which foliar samples colected				
lb/ac		2008	2009	2010	2011	2012
TKN Blountstown						
0	.	9224	9829	10382 b	8902 a	9695
128	.	9054	10040	10321 b	7988 b	9507
384	.	8897	10442	10973 b	9294 a	9713
641	.	9012	10433	12347 a	9485 a	10392
.	NR	8953	10162	11111	9296	9828
.	R	9140	10209	10901	8539	9826
TKN Live Oak						
0	.	8429	10994	10727 c	8337 b	9073
128	.	7876	10936	10763 c	8017 b	8961
384	.	8306	11136	11897 b	8294 b	9158
641	.	8341	11298	13105 a	9094 a	9681
.	NR	8165	11046	11796	8467	9471
.	R	8311	11136	11451	8404	8965
TP Blountstown						
0	.	1362	1315	1037	1458 a	1195
128	.	1387	1256	1068	1437 a	1203
384	.	1331	1206	1106	1483 a	1153
641	.	1359	1204	1118	1232 b	1084
.	NR	1344	1272	1079	1432	1188
.	R	1375	1218	1085	1373	1130
TP Live Oak						
0	.	1264	1193	1045	1772 a	1117
128	.	1212	1204	1057	1742 a	1178
384	.	1253	1156	1050	1612 b	1147
641	.	1178	1121	1095	1563 b	1163
.	NR	1229	1175	1062	1669	1149
.	R	1224	1162	1061	1676	1154
K Blountstown						
0	.	5541	4297	4239	4165 c	4134
128	.	5729	4699	4130	4313 c	4452
384	.	5370	4604	4320	5227 a	4370
641	.	5525	4251	4430	4737 b	4255
.	NR	5299 b	4597	4249	4914 a	4527 a
.	R	5784 a	4329	4311	4308 b	4079 b
K Live Oak						
0	.	3895	3537	3227	4978 ab	3128
128	.	3657	3414	3462	4606 bc	3250
384	.	3543	3581	3354	4319 c	3190
641	.	3892	3453	3554	5059 a	3384
.	NR	3725	3524	3379	4840	3341
.	R	3769	3468	3420	4641	3135

Fertilization or raking treatments means within a column followed by different letters for each site and nutrient are significantly different at α=0.05 level.
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

Table 49. Mean foliar Ca and Mg concentrations (mg/kg) by sampling year for four DAP fertilization rates (averaged across non-raked and raked treatments) and for non-raked (NR) and raked (R) treatments (averaged across all fertilization treatments) at two study sites

			Raking / 1st Fertilization	Raking / 2nd Fertilization	Raking	Raking
DAP	**Rake**	**Growing season following which foliar samples colected**				
lb/ac		**2008**	**2009**	**2010**	**2011**	**2012**
				Ca Blountstown		
0	.	2916	2368	2341	2925 a	2277 a
128	.	2825	2073	2307	2863 a	1973 ab
384	.	3173	1980	2567	2403 b	1866 b
641	.	3104	2351	2483	2163 b	1773 b
.	NR	3045	2219	2481	2527	2076
.	R	2964	2167	2368	2651	1869
				Ca Live Oak		
0	.	3313	1851 b	1984 b	3405 ab	2096 a
128	.	3353	1830 b	1655 c	3155 b	1757 b
384	.	3049	1946 ab	2002 b	3690 a	1582 b
641	.	3315	2241 a	2357 a	3420 ab	1843 ab
.	NR	3327	1913	2093	3532	1864
.	R	3187	2021	1907	3303	1775
				Mg Blountstown		
0	.	947	798	1048	885	952
128	.	921	826	1095	991	1041
384	.	892	829	1203	960	916
641	.	910	807	1140	837	853
.	NR	912	837	1118	961	949
.	R	923	793	1126	875	931
				Mg Live Oak		
0	.	1061	1121	1167 b	1390 a	1286
128	.	1077	1091	1065 b	1238 b	1199
384	.	1042	1109	1189 b	1133 b	1107
641	.	976	1246	1340 a	1175 b	1221
.	NR	1102	1123	1190	1242	1265
.	R	976	1160	1191	1226	1142

Fertilization or raking treatments means within a column followed by different letters for each site and nutrient are significantly different at α=0.05 level.
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

5.6.3 Pine Needle Litter Nutrients

Statistical Methods

A repeated measures analysis was performed using SAS Mixed procedure (SAS, 2010) to account for measurements occurring on the same plot over time. Pine litter samples were collected quarterly (end of March, June, September, and December) in 2009 through 2012. Samples collected at the end of the first quarter of 2011 were not analyzed for nutrients because of interrupted funding between DEP grants. Preliminary analysis indicated that variance increased with concentration for tested nutrients and could vary by sample quarter. Analysis was performed using the natural log of nutrient concentrations for all nutrients to improve the homogeneity of variance. Analysis of the absolute value of residuals from the fit of the standard linear model indicated that variance could differ by sample date, but that there was no definitive pattern with quarter. Reasons for this are not clear, but variation might be expected to be higher post-fertilization before return to baseline levels, differ by quarter due to quantity and type of needles in the sample, and perhaps differ due to rainfall/leaching before collection, as well as other environmental factors that could differ by sample date. A heterogeneous compound symmetry covariance structure was adopted to allow for heterogeneous variance across sample dates and account for correlation among samples taken on the same plot over time. Based on information criteria, this structure ranked close to or better than other structures that allowed for heterogeneous variance for all nutrients and for both sites.

Pine Needle Litter Nutrient Results

Pine litter iron concentration was below ARL MDL at both study sites on all sampling dates. Therefore, Fe has been excluded from the discussion below.

Quarterly sampling date (Year_Q) and the interaction between sampling date and fertilization rate (Year_Q*Fert) were significant at both sites for all nutrients, while the sampling date x raking interaction (Year_Q*Rake) was significant for most nutrients (Table 50). This indicates a different effect of fertilization and raking treatments on different dates. However, no seasonal or annual pattern could be discerned. Therefore, the emphasis of our analysis is to compare treatments at each sampling date. The main effect of fertilization rate was significant for TKN and K concentrations at Blountstown and for TKN, K, Ca, and Mg concentrations at Live Oak; whereas the main effect of raking was not significant for any nutrient at either site (Table 50).

The fertilization rate effect on pine litter TKN concentration was similar at both sites (Table 51). The highest fertilization rate (641 lb/acre DAP) resulted in greater TKN concentration than the lowest rate (128 lb/acre) or the non-fertilized control on all dates at both sites, except for the 2009 1^{st} quarter (2009_Q1) sampling at both sites and the 2009_Q3 sampling at Blountstown. The lowest fertilization rate was not different from the non-fertilized control on any date at either site. This indicates that annual application of 128 lb/acre DAP is not effective in increasing nitrogen concentration in pine needles. Litter TKN concentration following the medium DAP rate (384 lb/acre) was usually intermediate between low and high rates and was significantly greater than the low rate or non-fertilized control on most dates, but lesser than 641 lb/acre on many dates. Starting in 2012, TKN concentration was consistently least for 0 and 128 lb/acre, greater for 384 lb/acre and greatest for 641 lb/acre DAP. Observing the strongest rate response at that time is understandable because two years after the second fertilization all collected needles had been affected by two annual fertilizations. Even though not compared statistically, we generally observed greater TKN concentration for all treatments at Blountstown compared to Live Oak.

A positive fertilization response in pine needle litter TP concentration was observed at both sites for the second quarterly sampling period following the first fertilization (Table 51). At that time, the high DAP rate resulted in greater TP concentration than the low rate or non-fertilized control at both sites. This same difference between the high DAP rate and the low rate and non-fertilized control was also observed seven quarterly sampling periods following the second fertilization at Blountstown, but a clear TP response to fertilization was not evident over time. Similarly, to TKN, litter TP concentration at Blountstown was generally greater than at Live Oak for all treatments on all dates.

We observed a significant fertilization effect on pine litter potassium (K) concentration on about half of all sampling dates at each site (Table 51). Starting in 2012, two years after the second fertilization, the rate effect was significant on all dates except 2012_Q4 at Live Oak. When the effect of fertilization was significant at Blountstown, 641 lb/acre and 384 lb/acre rates resulted in greater K concentration than 0 or 128 lb/acre DAP rates. When the effect of fertilization was significant at the Live Oak site, litter K concentrations for 384 lb/acre were intermediate between low and high DAP rates and on some dates did not differ from 128 lb/acre and on other dates did not differ from 641 lb/acre. As with TKN and TP, K concentration observed for 128 lb/acre DAP did not differ from the non-fertilized control on any date at either site. Potassium concentration in Blountstown was always much greater than in Live Oak, in some cases by 2.5-fold.

Fertilization had no effect on pine needle litter calcium (Ca) concentration at Blountstown, but at Live Oak 641 lb/acre DAP resulted in greater Ca concentration than lower fertilization rates and the non-fertilized control on most dates starting with 2010_Q4 (Table 52). This different response is interesting because the pine needle litter Ca concentration did not differ between the sites as much as the concentration of other nutrients and in some cases was even greater at Live Oak than Blountstown.

Pine litter magnesium (Mg) concentration was also similar at both sites (Table 52). It was not affected by fertilization at Blountstown on any sampling date, whereas at Live Oak Mg concentration was greater for 641 lb/acre DAP than lower rates and the non-fertilized control on 2011_Q2 and 2011_Q3 sampling dates.

The impact of raking on pine litter nutrient concentrations was minimal and was observed only at a few sampling dates for selected nutrients (Table 53). Compared to the non-raked plots, pine litter collected from raked plots was lower in following nutrients: TP at Blountstown on 2010_Q2, K at Live Oak on 2012_Q2 and 2012_Q4, and Ca at Blountstown on 2012_Q3. The most consistent trend was observed for Mg concentrations at Blountstown, where litter from raked plots had significantly lower Mg concentration than from non-raked plots during the last three quarters of 2012.

Table 50. Repeated measures analyses for pine needle litter nutrient concentrations sampled quarterly over multiple years (Year_Q) at two study sites

				Blountstown		
Factor	**df**[†]	**TKN**	**TP**	**K**	**Ca**	**Mg**
Fert	3	**<.0001**	0.1450	**0.0023**	0.8496	0.6400
Rake	1	0.2098	0.9912	0.1248	0.0641	**0.0152**
Fert*Rake	3	0.1967	0.3441	0.0673	0.2891	0.2188
Year_Q	14	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Year_Q*Fert	42	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0004**
Year_Q*Rake	14	**<.0001**	**<.0001**	**<.0001**	0.2112	**0.0451**
Year_Q*Fert*Rake	42	**0.0005**	0.1176	**0.0003**	**0.0045**	0.0896
				Live Oak		
Factor		**TKN**	**TP**	**K**	**Ca**	**Mg**
Fert	3	**<.0001**	0.5424	**0.0018**	**0.0392**	**0.0448**
Rake	1	0.8771	0.6032	0.1503	0.7731	0.2730
Fert*Rake	3	0.7511	**0.0424**	0.7733	0.7265	0.2492
Year_Q	14	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Year_Q*Fert	42	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Year_Q*Rake	14	0.2810	**0.0072**	**<.0001**	**0.0007**	0.5653
Year_Q*Fert*Rake	42	0.1257	**0.0073**	0.2846	0.3109	0.5269

[†] df for Blountstown TKN (results not available for 2009_Q1): Year_Q=13, Year_Q*Fert=39, Year_Q*Rake=13, Year_Q*Fert*Rake=39

Table 51. Mean pine needle litter TKN, TP, and K concentrations (mg/kg) by sampling year and quarter following four DAP fertilization rates at two study sites (averaged across raked and non-raked treatments)

Raking / 1st Fertilization (before 2009_Q1); Raking (before 2010_Q1); 2nd Fertilization (before 2010_Q2); Raking (before 2011_Q2); Raking (before 2012_Q1)

DAP	Pine litter collection period															
lb/ac	2009_Q1	2009_Q2	2009_Q3	2009_Q4	2010_Q1	2010_Q2	2010_Q3	2010_Q4	2011_Q2	2011_Q3	2011_Q4	2012_Q1	2012_Q2	2012_Q3	2012_Q4
TKN Blountstown																
0	n/a†	3938 b	4106	3967 b	5057 c	6020 b	3942 b	4451 b	3384 bc	3557 b	4275 b	5677 c	4634 c	3634 c	2999 c
128	n/a	3956 b	3913	4179 b	5143 c	5886 b	3968 b	4728 b	3121 c	3669 b	4491 b	5942 c	4509 c	3498 c	2844 c
384	n/a	4501 a	4227	4283 b	5903 b	6509 ab	4594 ab	5902 a	3930 ab	4352 a	4664 ab	7202 b	5652 b	4221 b	3548 b
641	n/a	4967 a	4647	5110 a	6654 a	6916 a	5327 a	6290 a	4248 a	4550 a	5053 a	7923 a	6499 a	4736 a	4135 a
TKN Live Oak																
0	4175	3035 b	3170 b	3213 c	4517 b	5304 b	3433 c	3914 c	3169 b	3182 b	3172 b	4269 c	3156 b	2392 c	2501 b
128	3946	3235 b	3191 b	3306 bc	4592 b	5200 b	3449 bc	3896 c	2952 b	3261 b	3168 b	4119 c	3275 b	2390 c	2412 b
384	4158	3784 a	3664 a	3580 ab	5134 ab	6464 a	3875 b	4385 b	3460 ab	3552 b	3533 b	4807 b	3566 b	2684 b	2590 b
641	4582	3749 a	3777 a	3891 a	5694 a	7084 a	4613 a	5261 a	3881 a	4341 a	4084 a	6186 a	4474 a	3087 a	3038 a
TP Blountstown																
0	575	539 b	549	543	553	734	663	507 b	571	561	459	681 b	629	527	590
128	546	539 b	491	554	594	710	679	559 ab	575	529	471	695 b	600	505	572
384	578	620 ab	584	602	638	737	678	600 a	588	536	497	743 ab	628	548	581
641	546	651 a	578	544	590	671	609	503 b	494	492	476	770 a	615	525	527
TP Live Oak																
0	540	405 c	429	405	483	560	466	469	504	339	371	513	397	406	522
128	537	428 bc	447	413	493	593	502	507	490	343	377	515	415	406	543
384	558	515 a	500	433	532	671	485	450	529	349	386	547	398	420	537
641	569	498 ab	483	419	553	639	415	401	451	332	353	593	394	385	454
K Blountstown																
0	1570	1244	1089	967 b	1192	1828	1495	1018 b	1983	1542	1021 b	1969 b	1383 b	997 c	812 b
128	1434	1259	929	921 b	1161	1699	1489	1105 b	1954	1450	1044 b	2149 ab	1413 b	1035 bc	817 b
384	1526	1365	1071	1107 a	1323	1729	1667	1394 a	2082	1575	1249 ab	2344 a	1741 a	1207 a	961 a
641	1369	1449	1048	980 ab	1297	1606	1690	1378 a	1890	1521	1383 a	2401 a	1822 a	1168 ab	1002 a
K Live Oak																
0	1010	458 c	502	369	741	867 c	486 b	486 b	968	408	349 b	990 b	337 b	319 b	369
128	920	519 bc	528	368	724	900 bc	503 b	523 b	943	405	350 b	960 b	379 b	321 b	367
384	960	644 ab	546	385	770	1086 ab	540 b	547 b	1105	431	363 b	1038 b	391 ab	351 ab	364
641	1008	692 a	633	470	979	1183 a	740 a	845 a	1194	582	545 a	1398 a	533 a	460 a	465

Means within a column followed by different letters for each site and nutrient are significantly different at α=0.05 level.
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
†n/a= Blountstown TKN results not available for 2009_Q1

Table 52. Mean pine needle litter Ca and Mg concentrations (mg/kg) by sampling year and quarter following four DAP fertilization rates at two study sites (averaged across raked and non-raked treatments)

Raking **1st Fertilization** **Raking** **2nd Fertilization** **Raking** **Raking**

DAP	Pine litter collection period														
lb/ac	2009_Q1	2009_Q2	2009_Q3	2009_Q4	2010_Q1	2010_Q2	2010_Q3	2010_Q4	2011_Q2	2011_Q3	2011_Q4	2012_Q1	2012_Q2	2012_Q3	2012_Q4
Ca Blountstown															
0	4127	3850	4473	3910	3815	4974	4463	4257	3914	3509	3075	3094	3852	3267	3403
128	4537	3829	4505	4052	4208	4863	4481	4591	3989	3437	3207	3230	3730	3403	3361
384	4367	3881	4705	4089	3991	4804	4724	4568	3795	3438	3205	3210	3588	3261	3188
641	4404	3872	4803	4014	3797	4986	5001	4568	3774	3838	3169	3154	3473	2925	3070
Ca Live Oak															
0	3471	4092	4414	3639 b	3741	4244	3878	3542 b	3732	2553 b	2897 b	3158	3414 b	3614 b	3239 ab
128	3494	4045	4457	3845 ab	3722	4161	3983	3557 b	3654	2643 b	2919 b	3269	3276 b	3530 b	3094 ab
384	3506	4096	4454	3699 b	3802	4276	3782	3852 b	3842	2588 b	3078 b	3254	3517 b	3615 b	2847 b
641	3583	3883	4638	4032 a	3985	4564	4297	4350 a	4422	3006 a	3536 a	3599	4000 a	4161 a	3386 a
Mg Blountstown															
0	1048	904	954	953	890	980	1140	937	833	905	777	994	815	757	773
128	1068	903	928	954	944	969	1103	966	876	885	815	1041	833	753	787
384	1034	873	942	950	940	886	1064	1019	888	878	818	1042	847	787	783
641	1006	850	950	910	859	882	1034	951	864	906	796	1049	839	770	746
Mg Live Oak															
0	1002	930	886	952	896	933	1000	971	824 b	767 b	883	1081	828	835	958
128	973	889	813	907	850	860	872	898	749 b	685 c	828	1025	788	785	927
384	981	969	823	851	869	882	903	917	817 b	754 bc	859	1058	788	804	861
641	1047	977	903	962	992	959	1061	1122	971 a	913 a	1012	1236	905	965	1009

Means within a column followed by different letters for each site and nutrient are significantly different at α=0.05 level.
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

Table 53. Mean pine needle litter nutrient concentrations (mg/kg) by sampling year and quarter for non-raked (NR) and raked (R) treatments at two study sites (averaged across all fertilization treatments)

Raking 1st Fertilization (before 2009_Q1); Raking (before 2010_Q1); 2nd Fertilization (before 2010_Q2); Raking (before 2011_Q2); Raking (before 2012_Q1)

Rake	2009_Q1	2009_Q2	2009_Q3	2009_Q4	2010_Q1	2010_Q2	2010_Q3	2010_Q4	2011_Q2	2011_Q3	2011_Q4	2012_Q1	2012_Q2	2012_Q3	2012_Q4
TKN Blountstown															
NR	n/a	4131 b	3978 b	4232	5416 b	6310	4293	5208	3833	4017	4606	6667	5400	3976	3301
R	n/a	4518 a	4466 a	4501	5902 a	6329	4557	5367	3464	4002	4618	6581	5131	4010	3388
TKN Live Oak															
NR	4147	3397	3449	3389	4911	6127	3780	4372	3281	3553	3463	4867	3612	2644	2635
R	4272	3474	3430	3589	5015	5801	3848	4289	3417	3560	3477	4698	3556	2603	2615
TP Blountstown															
NR	555	578	546	512 b	590	734 a	660	541	560	520	484	735	634	537	577
R	567	593	553	612 a	597	692 b	653	541	552	538	467	708	602	515	557
TP Live Oak															
NR	541	459	456	412	504	630	481	469	498	356	377	545	407	414	514
R	561	460	472	422	524	599	451	442	488	326	366	537	395	394	511
K Blountstown															
NR	1382 b	1288	977	798 b	1229	1731	1578	1191	1982	1497	1207	2282	1606	1103	895
R	1569 a	1367	1091	1232 a	1254	1696	1587	1234	1970	1546	1125	2138	1550	1094	892
K Live Oak															
NR	933	594	548	392	774	1104 a	583	604	1106	491	420	1156	435	393	424 a
R	1017	548	552	400	820	906 b	537	568	992	415	371	1016	375	328	358 b
Ca Blountstown															
NR	4471	3977 a	4684	4116	3988	4949	4738	4565	3946	3524	3201	3206	3764	3379 a	3335
R	4245	3742 b	4556	3918	3911	4864	4588	4424	3790	3579	3127	3137	3555	3047 b	3172
Ca Live Oak															
NR	3622	4050	4551	3823	3899	4336	3937	3863	3951	2664	3097	3231	3557	3665	3166
R	3408	4006	4429	3779	3725	4282	4025	3761	3852	2720	3098	3403	3527	3779	3104
Mg Blountstown															
NR	1051	899	944	958	933	948	1118	989	881	885	825	1059	862 a	803 a	808 a
R	1027	866	943	925	882	909	1052	947	849	902	778	1004	806 b	732 b	737 b
Mg Live Oak															
NR	1021	965	881	933	904	946	989	998	850	788	906	1118	851	866	952
R	981	917	831	901	897	871	924	949	823	762	880	1077	802	823	923

Pine litter collection period

Means within a column followed by different letters for each site and nutrient are significantly different at $\alpha=0.05$ level.
Means were not declared different using least significance difference unless the overall effects involved were significant at $\alpha=0.05$.

5.6.4 Pine Straw Yield and Nutrient Removal

Statistical Methods

Analysis of variance for bale count, dry weight, nutrient concentrations and amounts of nutrients removed by harvested pine straw was performed using the SAS MIXED procedure. Nutrient content was calculated for each plot as the product of that plot's sampled nutrient concentration and bale dry weight yield. Because of the differences in raking timing, the growing season preceding pine straw removal was always considered the harvest (sampling) year and was the repeated measures factor (year nested within plot). Correlation among harvest years was modeled using a compound symmetry covariance structure. Preliminary analysis indicated that variance increased with concentration and that a natural log transformation of nutrient concentration and content was required to improve the homogeneity of variance for all nutrients. Nutrient concentration analyses accounted for heterogeneity of variance with respect to both concentration and sample size. Observations were weighted by sample size to account for differences in variation due to within plot sample sizes of 9 in 2009 versus 3 in later years.

Pine Straw Yield Results

Estimates of pine straw dry weight (DW) and total bale counts per plot were used to estimate pine straw mass yield. Bale count can be affected by differences in bailer dimensions and in pine straw compaction between the raking crew members.

Harvested pine straw dry weight and bale count differed by year at both sites, while fertilization affected both of these parameters only at Blountstown. Since a variety of factors can influence year to year differences in pine straw yield, such as differences in growing season rainfall, raking timing, and differences in raking and baling technique and equipment, the focus has been on comparing fertilization rates within each year. At the Blountstown site there was a significant fertilization x year interaction for bale count, whereby fertilization had a significant positive effect on bale count in 2010 (P=0.0559) and 2011 (P=0.0001), but not in 2009 or 2012 (Table 54). A similar fertilization x year interaction was observed for pine straw dry weight at Blountstown, with a positive response to fertilization observed in 2010 (P=0.0571) and 2011 (P=0.0003), but not in 2009 or 2012. At the Live Oak site there was a significant bale count response to fertilization in 2011 (P=0.0128), despite the lack of significance for the overall response to fertilization at that site (P=0.0805). Pine straw yield following the 2011 growing season was a result of the cumulative effect of spring fertilizations in 2009 and 2010.

At the Blountstown site, when averaged across four years of raking, 641 and 384 lb/acre DAP resulted in greater pine straw DW and bale count than 128 or 0 lb/acre (Table 56). The differences were most pronounced for the 2011 growing season harvest, when pine straw yield, as measured by both of these parameters, was greatest for the high fertilization rate, intermediate (except DW) for medium and least for the low rate and non-fertilized control, which did not differ from each other. Even though the differences were not significant in 2010, a greater number of bales per ha were harvested from 641 or 384 lb/acre DAP treatments (more than 1500 bales) than from the other treatments, (less than1400), and a similar trend was shown for bale dry weight yields.

Mean pine straw dry weights and bale counts at Live Oak did not show significant differences between DAP fertilization treatments. However, we observed increased yield with the highest fertilization rate. When averaged across four harvest years, pine straw dry weight and bale count were greater for the high DAP rate than for the non-fertilized control by 11% and 20%, respectively (Table 56). Yield responses to fertilization were first observed in 2010 and continued through 2012. Yield responses were most pronounced in 2011 when the overall yield was lowest. That year the high DAP rate resulted in 37% increased dry weight and 46% increased bale count, compared to the non-fertilized control. At Live Oak pine straw yield was greater in 2009 than in any of the subsequent years because this was the first time straw was harvested and more than a year of needle accumulation was collected. At Blountstown the initial raking was conducted in 2008, prior to fertilization.

Pine Straw Nutrient Concentration Results

Repeated measures analyses revealed a significant effect of harvest year on the concentration of all nutrients in pine straw harvested from both sites and lack of significant fertilization effects, except for TKN concentration at Blountstown (Table 55). There were no significant fertilization x year interactions at either site, indicating a similar response to fertilization through the years in both studies. In addition to the effect of fertilization treatments, pine straw nutrient concentrations may also be affected by differences in the timing of pine straw raking, differences in growing season precipitation and rainfall prior to raking, and differences among laboratory runs (as observed by internal standards). Therefore, the focus has been to compare fertilization treatments within each year.

At the Blountstown site 641 lb/acre DAP resulted in greater pine straw TKN concentration than any other treatment when averaged across all years (Table 57). The same was true for the 2009 raking, following the first fertilization. At the 2010 harvest, pine straw TKN concentration for 641 lb/acre was greater than for 0 or 128 lb/acre, while the concentration for 384 lb/acre was intermediate and not significantly different from any treatment. A similar trend continued in 2011 and 2012, when the high DAP rate increased TKN concentration over non-fertilized control by 11 and 21%, respectively, but the differences were not statistically significant. At the Live Oak site, even though the effect of fertilization on pine straw TKN concentration was not significant, a similar trend was observed whereby the high DAP fertilization rate increased TKN concentration over the non-fertilized control in all years, with the greatest difference of 22% observed in 2010.

Pine Straw Nutrient Removal Results

The amount of nutrients removed from the site with harvested pine straw is a function of the harvested mass and nutrient concentration. Because harvested mass varied from year to year, annual nutrient removals also varied significantly (P=0.0001) for each nutrient (Table 54). At the Blountstown site the amount of all nutrients removed except magnesium was also affected by fertilization. The effect was greatest in 2011, after two consecutive fertilizations, when even Mg content was affected. At the Live Oak site the effect of fertilization was not significant for any of the nutrients removed, confirming the poor fertilization response observed on this sandy excessively drained site.

When averaged across four harvest years at Blountstown, the amount of TKN removed from plots fertilized with 641 or 384 lb/acre DAP (31.64 and 29.14 kg/ha, respectively) were greater than from non-fertilized plots (24.50 kg/ha) or those fertilized with 128 lb/acre DAP (23.69 kg/ha) (Table 58). The amounts of removed TP and K were greater for the high and medium fertilization rates than the low rate but did not differ significantly from the non-fertilized control. Similarly, the amount of calcium removed from 641 or 384 lb/acre treatments was greater than from 128 lb/acre, but the 128 or 384 lb/acre treatments did not differ significantly from 0 lb/acre. There were no significant differences for Mg, but a trend of increased removal with medium and high fertilization rates was also observed. The fertilization effect on all nutrient removals was most pronounced in 2011, two growing seasons after the second fertilization. For TKN and K the effect of fertilization was also significant in 2010, and the trend of increased removal following high and medium fertilization rates continued through 2012.

Although the effect of fertilization was not significant by ANOVA for any of the nutrients removed at Live Oak, we observed a trend of increased removal of some nutrients with medium and high DAP fertilization rates. On average, TKN removal from 641 lb/acre DAP fertilized plots was 30% greater than from the non-fertilized control, and in 2011 this difference was 50% (Table 58). That year, compared to the non-fertilized control, removals of all nutrients were greater from the 641 lb/acre and, to a lesser degree, from the 384 lb/acre treatment. A trend of greater removal with high fertilization rate was observed for three years 2010-2012 for TKN, K, Ca and Mg. Because of compositional variation in pine straw material, it appears that greater sampling intensity, a greater number of subsamples, would improve estimates nutrient removal.

Overall, nutrient removals following application of 128 lb/acre of DAP were not different from the non-fertilized control for any nutrient at either site. However, a trend was observed at both sites whereby nutrient removals were generally greater with increasing DAP rate.

Table 54. Repeated measures analyses for pine straw dry weight (Mg/ha), number of bales per hectare, and nutrient amounts (kg/ha) removed following 2009-2012 growing seasons for two study sites fertilized with four DAP rates

Factor	df	Pine straw	Bale	Nutrient removal amounts				
Year		DW	count	TKN	TP	K	Ca	Mg
					Blountstown			
Fert	3	**0.0037**	**0.0008**	**0.0098**	**0.0136**	**0.0101**	**0.0432**	0.0773
Year	3	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Year	9	0.1241	**0.0083**	0.5457	0.6295	0.5898	0.2696	0.1315
Fert at Year level								
2009	3	0.9677	0.9042	0.4177	0.8063	0.5926	0.9832	0.9429
2010	3	0.0571	0.0559	**0.0081**	0.3000	**0.0320**	0.0950	0.2109
2011	3	**0.0003**	**<.0001**	**0.0045**	**0.0150**	**0.0084**	**0.0083**	**0.0009**
2012	3	0.6797	0.7008	0.2328	0.6531	0.1776	0.7753	0.9200
					Live Oak			
Fert	3	0.2738	0.0805	0.0667	0.3079	0.1507	0.1671	0.0736
Year	3	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Year	9	0.4702	0.3798	0.7922	0.1696	0.8986	0.5581	0.3191
Fert at Year level								
2009	3	0.0669	0.2369	0.2934	0.1186	0.4805	0.1787	**0.0293**
2010	3	0.6462	0.2377	0.1019	0.8703	0.1982	0.5382	0.1659
2011	3	0.3402	**0.0128**	0.0898	**0.0268**	0.3758	0.0627	0.0706
2012	3	0.6329	0.2345	0.3362	0.8603	0.2590	0.8849	0.3882

Table 55. Repeated measures analyses for nutrient concentrations in pine straw raked and removed following 2009-2012 growing seasons from two study sites fertilized with four DAP rates

Factor	df	Nutrient				
Year		TKN	TP	K	Ca	Mg
				Blountstown		
Fert	3	**0.0147**	0.3799	0.0538	0.6770	0.7491
Year	3	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Year	9	0.5618	0.8638	0.6179	0.4111	0.2404
Fert at year level						
2009	3	**0.0031**	0.2703	0.1408	0.3344	0.5308
2010	3	**0.0390**	0.5107	0.1355	0.2074	0.3809
2011	3	0.6104	0.7358	0.6255	0.5989	0.1126
2012	3	0.0895	0.6815	0.2448	0.4547	0.9560
				Live Oak		
Fert	3	0.1066	0.1411	0.2935	0.6283	0.1036
Year	3	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Year	9	0.8759	0.3310	0.8912	0.9667	0.4640
Fert at year level						
2009	3	0.7033	0.7222	0.8268	0.5220	**0.0019**
2010	3	0.1373	0.0898	0.3169	0.7791	0.0769
2011	3	0.6013	0.4237	0.9811	0.7162	0.9968
2012	3	0.5666	0.2631	0.3630	0.7591	0.2640

Table 56. Mean pine straw dry weight (Mg/ha) and number of bales (#/ha) raked and removed from the site following 2009-2012 growing seasons for two study sites fertilized with four DAP rates

Fertilization: 1st and 2nd applications are marked by arrows (Blountstown: 1st before 2009, 2nd before 2010; Live Oak: 1st before 2009, 2nd before 2010).

DAP	Blountstown					Live Oak				
	Growing season preceding pine straw removal				Mean	Growing season preceding pine straw removal				Mean
lb/ac	**2009** 2nd raking	**2010** 3rd raking	**2011** 4th raking	**2012** 5th raking	**2009-2012**	**2009** 1st raking	**2010** 2nd raking	**2011** 3rd raking	**2012** 4th raking	**2009-2012**
	Pine straw dry weight (Mg/ha)									
0	5.78	7.16	6.96 bc	5.09	6.25 b	8.36	5.41	2.98	4.75	5.37
128	5.65	7.12	6.78 c	4.69	6.06 b	6.49	5.22	2.93	5.05	4.92
384	5.90	8.59	8.04 b	5.47	7.00 a	7.33	5.62	3.59	5.33	5.47
641	5.91	7.79	9.41 a	4.97	7.02 a	8.01	6.09	4.07	5.64	5.95
	Bale count per ha									
0	907	1360	1322 c	885	1118 b	1038	758	531	817	786
128	902	1370	1308 c	799	1095 b	980	758	495	862	773
384	912	1546	1551 b	910	1230 a	974	792	638	962	842
641	855	1534	1830 a	878	1274 a	1131	911	775	962	945

Means within a column followed by different letters for each variable are significantly different at α=0.05 level.
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

Table 57. Mean nutrient concentrations (mg/kg) in pine straw raked and removed from the site following 2009-2012 growing seasons for two study sites fertilized with four DAP rates

Fertilization: Blountstown 1st ↓ (2009), 2nd ↓ (2010); Live Oak 1st ↓ (2009), 2nd ↓ (2010)

DAP	Blountstown					Live Oak				
	Growing season preceding pine straw removal				Mean	Growing season preceding pine straw removal				Mean
lb/ac	2009 2nd raking	2010 3rd raking	2011 4th raking	2012 5th raking	2009-2012	2009 1st raking	2010 2nd raking	2011 3rd raking	2012 4th raking	2009-2012
TKN										
0	4507 b	5004 b	3272	3365	3970 b	4472	4620	3454	2712	3730
128	4508 b	4979 b	3293	3344	3965 b	4303	4396	3604	2582	3642
384	4352 b	5898 ab	3422	3575	4209 b	4465	5187	3291	2841	3836
641	5275 a	6080 a	3623	4076	4665 a	4660	5680	3836	3029	4188
TP										
0	488	609	365	519	487	350	462	446	452	425
128	459	568	343	530	467	355	472	470	459	436
384	484	584	359	507	476	367	472	479	436	436
641	480	562	357	496	467	361	400	429	401	397
K										
0	792	1185	304	684	665	338	498	929	321	473
128	678	1035	309	677	619	338	443	961	310	460
384	761	1216	339	766	700	343	483	953	309	470
641	738	1370	343	832	733	362	582	909	388	522
Ca										
0	4137	4985	3576	3819	4097	4477	4696	3908	3915	4235
128	4249	4454	3838	3722	4055	4256	4348	3724	3672	3988
384	3964	4836	3874	3472	4007	4241	4704	3569	3589	3998
641	4194	5126	3862	3517	4134	4164	4533	3872	3640	4039
Mg										
0	858	1040	725	721	827	824	954	825	885	870
128	811	895	759	747	801	697	810	816	824	785
384	802	963	863	713	831	743	895	825	812	817
641	811	988	865	730	843	799	967	829	922	877

Means within a column followed by different letters are significantly different at α=0.05 level.
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

Table 58. Mean nutrient amounts (kg/ha) removed with raked pine straw following 2009-2012 growing seasons for two study sites fertilized with four DAP rates

	Fertilization 1st ↓	Fertilization 2nd ↓				Fertilization 1st ↓	Fertilization 2nd ↓			
	Blountstown					**Live Oak**				
DAP	Growing season preceding pine straw removal				Mean	Growing season preceding pine straw removal				Mean
lb/ac	**2009**	**2010**	**2011**	**2012**	**2009-2012**	**2009**	**2010**	**2011**	**2012**	**2009-2012**
	2nd raking	3rd raking	4th raking	5th raking		1st raking	2nd raking	3rd raking	4th raking	
					TKN					
0	25.85	35.77	22.76	17.10	24.50 b	37.19	24.52	10.35	12.84	18.66
128	25.40	35.39	22.31	15.70	23.69 b	27.79	22.99	10.49	13.02	17.18
384	26.96	50.47	27.53	19.23	29.14 a	32.86	29.03	11.81	15.11	20.31
641	30.61	47.39	34.07	20.27	31.64 a	37.37	34.63	15.54	16.97	24.17
					TP					
0	2.81	4.36	2.54	2.63	3.01 ab	2.91	2.46	1.33	2.14	2.12
128	2.59	4.03	2.32	2.37	2.75 b	2.28	2.46	1.37	2.31	2.05
384	2.87	5.00	2.88	2.73	3.26 a	2.68	2.64	1.72	2.32	2.30
641	2.78	4.39	3.35	2.47	3.17 a	2.85	2.43	1.74	2.24	2.28
					K					
0	4.56	8.47	2.11	3.47	4.10 ab	2.80	2.66	2.77	1.52	2.37
128	3.83	7.35	2.09	3.07	3.67 b	2.17	2.31	2.80	1.56	2.16
384	4.47	10.40	2.73	4.12	4.78 a	2.51	2.70	3.42	1.64	2.48
641	4.30	10.69	3.23	4.14	4.98 a	2.87	3.55	3.68	2.17	3.00
					Ca					
0	23.73	35.66	24.86	19.39	25.27 bc	37.24	24.97	11.64	18.51	21.16
128	23.95	31.61	25.99	17.50	24.22 c	27.34	22.71	10.84	18.50	18.78
384	23.44	41.36	31.13	18.66	27.39 ab	30.96	26.32	12.80	19.07	21.12
641	24.49	40.03	36.27	17.48	28.08 a	32.91	27.59	15.68	20.37	23.20
					Mg					
0	4.93	7.44	5.04	3.66	5.10	6.84	5.08	2.46	4.18	4.35
128	4.57	6.35	5.14	3.48	4.77	4.47	4.23	2.38	4.15	3.70
384	4.70	8.23	6.94	3.83	5.66	5.43	5.00	2.96	4.31	4.32
641	4.73	7.71	8.13	3.63	5.73	6.33	5.89	3.36	5.16	5.04

Means within a column followed by different letters for each nutrient are significantly different at α=0.05 level.
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

6 PUBLIC INVOLVEMENT AND COORDINATION

6.1 STATE AGENCIES

University of Florida, Institute of Food and Agricultural Sciences, North Florida Research and Education Center (NFREC)

Financial support included salary and benefits for the principal investigator, an assisting senior biological scientist, graduate students, research technicians, non-reimbursed travel, office supplies and other miscellaneous expenses. The NFREC Forestry Program incurred all costs for continued monitoring between July 17 and November 13 during the interim between DEP GO247 and GO332 funding. Physical support included office, laboratory, and storage spaces; office, laboratory, and field equipment; non-reimbursed state vehicle use; and lodging in the NFREC dormitory for visiting scientists.

Florida Department of Agriculture and Consumer Services, Florida Forest Service (FFS)

The FFS provided salary match for Jeff Vowell, Bureau Chief/Forest Hydrologist (project advisor) and Roy Lima, BMP Program Manager, as they had significant involvement with study initiation and measurements throughout the course of the project. Cathy Hardin and Robin Holland also contributed strongly with sample collection and transport of samples to ARL and EWQL laboratories in Gainesville. Significant use of state vehicles and other travel costs incurred to travel to distant sites were used as a portion of the required match for this project.

Florida Department of Environmental Protection (FDEP), Site Investigation Section

Florida DEP Site Investigation Section personnel and drilling equipment, under the direction of William Martin, were responsible for the installation of a total of seven surficial groundwater sampling wells at the two sites.

6.2 FEDERAL AGENCIES

N/A

6.3 LOCAL GOVERNMENTS, INDUSTRY, ENVIRONMENTAL, AND OTHER GROUPS, PUBLIC AT LARGE

N/A

6.4 OTHER SOURCES OF FUNDS

Table 59. 6 University of Florida, Institute of Food and Agricultural Services, North Florida Research and Education Center (NFREC) matching contribution summary.

Project Funding Activity	Matching Contribution	Note
Salaries and Fringe Benefits	$14,083	UF Salary match, Dr. Osiecka 20%, Dr. Minogue 5%
Travel		
Equipment		
Supplies/Other Expenses		
Contractual Services		
Direct Costs		
Indirect	$29,759	UF Unrecovered indirect costs (36.4% of IDC, no equipment)

Total:	$43,842	
Total Project Cost:	$149,805	
Percentage Match:	29.3%	

Table 60. Florida Department of Agriculture and Consume Services, Division of Forestry (FDOF) matching contribution summary.

Project Funding Activity	Matching Contribution	Note
Salaries and Fringe Benefits	$11,028	FL Forest Serv. Salary match, J. Vowell and R. Lima
Travel	$5,006	FL Forest Serv. Vehicle travel match $0.445/mile
Equipment		
Supplies/Other Expenses		
Contractual Services		
Direct Costs		
Indirect		
Total:	$16,034	
Total Project Cost:	$149,805	
Percentage Match:	10.7%	

7 ASPECTS OF THE PROJECT THAT DID NOT WORK WELL

8 FUTURE ACTIVITY RECOMMENDATIONS

Planed Use of These Data

To date, we have summarized results for concentrations of NO_x-N, NH_4-N, TKN, and TP at various depths in the soil, but these concentration data do not address nutrient amounts. Estimates of the amounts of nitrogen leached can now be made using existing nutrient fate models or modified nutrient fate models as our research proceeds. To facilitate modeling efforts describing the fate of applied nitrogen, we will utilize the robust environmental data collected in these studies, including continuous measurements of temperature and moisture content at each of the depths where nitrogen concentrations where determined and continuous measurements of atmospheric temperature, relative humidity, rainfall, precipitation through-fall, photosynthetically active radiation (PAR), and wind speed within each of the stands. In addition, measures of TKN and TP concentrations in pine foliage, pine needle litter, and in removed pine straw will enable nutrient budgets and further describe the fate of applied nitrogen and phosphorus.

Future Silvicultural BMP Evaluation

The cost of nitrogen fertilizers has increased dramatically in the past decade. At present, almost all N used to fertilize pine plantations in the Southern USA is in the form of urea. Urea is not only less expensive than DAP, but it is readily available, is highly soluble, and because of its high N concentration (46%N) it is easy to transport and apply in the field. However, as urea dissolves and transforms to ammonium (NH_4^+) ions, it is subject to volatile losses of ammonia gas (NH_3), which have been observed to be between 3% and more than 50% during measurement periods that range from 14 to 60 days following silvicultural fertilization (Zerpa and Fox, 2011). This wide range in volatile losses is attributed to treatment types and the environmental conditions present in various studies. Volatile losses increase with temperature (Craig and Wollum, 1982) and differ with soil substrate type (Cabrera et al. 2005), initial soil moisture, and time of rainfall (Kissel et al. 2004). Our sandy Coastal Plain soils are of particular concern to volatile losses because they have low cation exchange capacity and low soil organic matter content, thus limiting NH_4^+ soil sorption, making more of the free ion available for transformation to the gaseous form.

Coated slow release fertilizers, including sulfur coated urea (SCU) and various polymer coated urea (PCU) fertilizers reduce volatile losses and also provide slow release of N, thus extending the period for plant uptake and reducing potential leaching losses as well. Polymer coated urea has been utilized in forest management, and its cost may be justified by high pine straw product values, which typically range between $100 and $200 per acre. Polymer coated urea is comprised of a soluble urea nitrogen source core, which is coated with one of several polymer materials including linseed oil, polyethylene, polypropylene, or various other organic polymers. Nitrogen is released through the polymer coating by diffusion, and the release rate increases strongly with increasing temperature. The rate of nitrogen release can be manipulated by coating thickness and composition. Polymer coated urea products are a newer technology than sulfur coated urea and generally are more expensive. However, they contain higher amounts of N (typically 44% vs. 34% N) and provide superior long-term fertilization, significantly reducing the amounts of N needed as compared to conventional mineral fertilizers.

We propose monitoring the environmental fate of applied nitrogen and phosphorus following two sequential annual applications of PCU controlled release fertilizer to provide 25, 50, and 125 lb N/acre, to be compared to a non-fertilized control and conventional fertilization treatment using a combination of DAP and urea to provide 50 lb of N per acre and 25 lb per acre P_2O_5. The conventional treatment provides a typical amount of P for forest fertilization and an N rate thought to be just above the threshold to obtain a pine growth response on this site. The 50 lb N rate of the conventional treatment compares to the middle PCU rate. Phosphorus will be added using triple superphosphate (TSP) to all the PCU treatments to provide the typical 25 lb/acre P_2O_5 rate, so N response comparisons may be made among the PCU treatments and conventional treatment with P held constant. We have located an ideal study site having excessively drained soil and high leaching potential in the Suwannee Valley, a region of special concern to groundwater pollution. The Suwannee Valley region supports the largest pine straw industry in Florida, and fertilization to enhance straw production is common, despite the potential to contaminate shallow groundwater.

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10 ATTACHMENTS

10.1 ADDITIONAL SOIL NUTRIENT TABLES

Table A 1. ANOVA for soil K and Ca concentrations by sampling date at two study sites

Raking **1st Fertilization** **Raking** **2nd Fertilization** **Raking**

K Blountstown

Factor	df†	10/01/08		03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10		03/29/10	04/26/10	05/24/10	08/23/10	11/17/10	03/07/11	03/06/12	02/20/13
Fert	3	**0.0234**		**0.0481**	0.9958	**0.0014**	0.2009	0.3012	**0.0237**		0.5828	0.9154	0.2033	0.2863	0.2246	0.6779	0.0772	0.5563
Rake	1	0.7415		0.2449	0.2426	0.8099	0.7337	0.3718	0.1809		**0.0002**	0.2351	0.3697	0.9564	0.9214	0.4708	0.2923	0.3983
Fert*Rake	3	0.6924		0.7606	0.4065	0.6629	0.3660	0.5753	**0.0478**		**0.0030**	0.3822	0.8710	0.6870	0.3679	0.4531	0.2511	0.2483
Depth	6	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.2105		0.4622	0.8332	0.5176	0.0811	0.4872	0.4634		0.8869	**0.0393**	0.2546	0.2258	0.3164	0.9702	0.0500	0.9994
Rake*Depth	6	0.4894		0.9080	0.7704	0.6761	**0.0106**	0.7796	0.4324		**<.0001**	0.6979	0.7941	0.2151	0.1223	0.0929	0.7552	0.0707
Fert*Rake*Dept	18	0.9758		0.6786	0.7456	0.6376	0.1769	0.3486	0.2488		**0.0036**	0.9273	0.8666	0.8319	0.2696	0.9109	0.2615	0.0684

K Live Oak

Factor	df†	11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
Fert	3	0.3761	**<.0001**	**0.0001**	**<.0001**	**0.0168**	0.5967	**0.0169**	0.6207	**0.0118**	0.9662	0.7547	0.5403	0.2453	0.6609	0.1692	0.8241	0.6759
Rake	1	0.9865	0.9747	0.1537	0.6792	**0.0277**	0.7971	0.1332	**0.0443**	0.7571	0.4167	0.9126	**0.0043**	**0.0252**	0.6866	0.5755	0.1807	0.6096
Fert*Rake	3	0.2014	0.5422	0.3805	0.0752	**0.0094**	0.4821	0.5837	0.0813	0.4715	**0.0256**	0.1579	0.9207	0.4975	0.4892	0.3320	0.1144	0.8943
Depth	6	**<.0001**	**<.0001**	**<.0001**	0.7181	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0031**
Fert*Depth	18	**0.0241**	0.9120	0.4399	0.3987	0.6304	0.1199	**0.0254**	0.1452	0.1832	0.3492	0.1765	0.2775	0.9290	0.4225	0.9153	0.8643	0.8123
Rake*Depth	6	0.8560	0.1298	0.6155	0.6863	0.1438	0.5752	0.5301	0.8756	0.3022	**0.0208**	0.4638	**0.0007**	0.8153	0.3413	0.8483	0.4306	0.9944
Fert*Rake*Dept	18	0.6000	0.5192	0.8170	0.6736	0.3314	0.3098	0.8893	0.8922	0.3895	0.0990	0.3082	0.1077	0.3534	0.5719	0.7105	0.9587	0.8810

Ca Blountstown

Factor	df†	10/01/08		03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10		03/29/10	04/26/10	05/24/10	08/23/10	11/17/10	03/07/11	03/06/12	02/20/13
Fert	3	0.8093		0.5212	0.9080	0.2864	0.7391	0.8735	0.1586		0.4203	0.9695	0.5448	0.8731	0.6600	0.9679	0.9745	0.3138
Rake	1	0.4062		0.1548	0.2832	0.4079	0.0745	0.8041	0.0789		**0.0006**	**0.0380**	0.5539	0.9185	0.0870	0.6665	0.8044	0.7820
Fert*Rake	3	0.3942		0.7646	0.6140	0.2268	0.4143	0.6944	0.1658		**0.0005**	0.3967	0.7553	0.9357	0.7046	0.9329	0.5734	0.4596
Depth	6	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**		**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.9708		0.8392	0.3245	0.5472	0.9455	0.5934	0.5452		0.2631	0.6744	**0.0127**	0.3185	0.5626	0.8553	0.9832	0.6410
Rake*Depth	6	0.9311		0.2371	0.1065	0.3074	0.1875	0.5734	**0.0080**		0.1839	0.2644	0.1070	0.2912	**0.0336**	0.1999	0.9063	**0.0226**
Fert*Rake*Dept	18	0.8691		0.5425	0.3181	0.7785	0.4290	0.7242	0.8402		**0.0006**	0.4892	0.2918	**0.0438**	0.1893	0.0920	0.6435	**0.0160**

Ca Live Oak

Factor	df†	11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
Fert	3	0.7640	0.0801	0.1050	**0.0451**	**0.0184**	0.3615	0.2453	0.6319	0.4006	0.7060	0.9675	0.1988	0.2095	0.2167	0.3520	0.3465	0.7225
Rake	1	0.2752	0.8380	0.8946	**0.0309**	0.3845	**0.0181**	**0.0361**	0.2256	0.2991	0.6689	0.2456	**0.0022**	0.0638	0.1142	0.1739	0.6725	0.0563
Fert*Rake	3	0.9851	0.3920	0.2227	0.6952	**0.0122**	0.3656	0.0784	0.2753	0.3154	**0.0398**	0.9844	0.7391	0.9764	0.7648	0.8779	0.6454	0.9133
Depth	6	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.1292	0.1313	0.9254	0.4175	0.1182	**0.0162**	0.6863	0.6439	0.8413	0.5402	0.5433	0.3056	0.7905	0.0720	0.9169	0.2403	0.7743
Rake*Depth	6	0.5197	0.2637	0.0867	**0.0247**	**0.0051**	0.8785	0.5958	0.5185	0.9328	0.9030	0.2808	0.1854	**0.0422**	0.1789	0.4436	0.5722	0.9544
Fert*Rake*Dept	18	0.5543	0.9663	0.5207	0.3783	0.2012	0.7395	0.8777	0.0667	0.5995	**0.0060**	0.4810	0.9939	0.8522	0.7123	0.3641	0.7897	0.9668

† df for Blountstown for 3/30/09 and 2/15/10: Depth=4, Fert*Depth=12, Rake*Depth=4, Fert*Rake*Depth=12 (due to less sampling depths because of high water table)

Table A 2. ANOVA for soil Mg concentrations by sampling date at two study sites

Raking | 1st Fertilization | Raking | 2nd Fertilization | Raking

Mg Blountstown

Factor	**df**[†]	10/01/08	03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10	03/29/10	04/26/10	05/24/10	08/23/10	11/17/10	03/07/11	03/06/12	02/20/13
Fert	3	0.7211	0.7843	0.5116	0.0688	0.2789	0.2085	**0.0219**	0.4641	0.6291	0.5329	0.2044	0.4983	0.5885	0.9531	0.1076
Rake	1	0.9959	0.9292	0.9546	0.5229	0.5833	0.9971	0.6433	**0.0017**	0.6414	0.4995	0.5146	0.9703	0.8033	0.8437	0.5182
Fert*Rake	3	0.3219	0.7494	0.2911	0.2475	0.3929	0.6462	**0.0224**	**0.0040**	0.2720	0.7534	0.1037	0.2534	0.5669	0.4547	0.3400
Depth	6	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0168**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.7702	0.3684	0.3883	0.4631	0.3284	0.8376	0.1726	0.1922	0.6235	0.2959	0.0910	0.3714	0.2471	0.8681	0.4055
Rake*Depth	6	0.4857	0.3818	0.9071	0.5870	0.5208	0.7941	0.7896	**<.0001**	0.6320	0.9347	0.7698	0.3801	0.3831	0.7499	0.8123
Fert*Rake*Depth	18	0.7166	0.5956	0.5501	0.9017	0.6341	0.5344	0.9762	**<.0001**	0.9964	0.8342	0.3726	0.5610	0.4579	0.7728	0.4109

Mg Live Oak

Factor	**df**[†]	11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
Fert	3	0.4460	**<.0001**	0.7455	**<.0001**	**0.0003**	0.4292	0.4267	0.8022	0.0886	0.9471	0.6369	**0.0125**	0.2450	0.5326	0.4492	**0.0034**	0.7659
Rake	1	0.6789	0.5653	0.7770	0.8348	0.0523	0.1008	0.2226	0.4802	0.2253	0.6210	0.4722	**0.0030**	0.1877	0.2765	0.3322	0.4560	0.1638
Fert*Rake	3	0.7063	0.3931	0.7901	0.0582	**0.0096**	0.5981	0.0918	0.3105	0.1479	0.0676	0.1899	0.4280	0.4004	0.9484	0.7075	0.8220	0.6917
Depth	6	**<.0001**	0.0626	**0.0107**	0.3833	**<.0001**	**<.0001**	**<.0001**	0.1018	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fert*Depth	18	0.7222	0.6760	0.4479	0.5584	0.2686	0.1861	0.7291	0.9274	0.9109	0.9151	0.4386	0.4071	0.9394	0.8988	0.3476	0.4587	0.8930
Rake*Depth	6	0.8412	0.1094	0.5072	0.5377	0.0515	0.3641	0.5235	0.9041	0.2584	0.6443	0.1841	0.6347	**0.0092**	0.4218	0.0684	0.3754	0.7846
Fert*Rake*Depth	18	0.3969	0.2671	0.5877	0.5991	0.5133	0.9026	0.7779	**0.0203**	0.8463	0.0524	0.7824	0.7006	0.9171	0.9051	0.7467	0.3122	0.9733

[†] df for Blountstown for 3/30/09 and 2/15/10: Depth=4, Fert*Depth=12, Rake*Depth=4, Fert*Rake*Depth=12 (due to less sampling depths because of high water table)

Table A 3. Mean soil K concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

		1st Raking	1st Fertilization					2nd Raking
Sample Depth	DAP lb/ac	10/01/08	Sampling Date 03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10
			Months after last fertilization (MAF), approximate					
		Before	1	2	3	6	9	12
Avg. all depths§	0	14.18 a	11.77 a	9.95	29.69 L a	16.55	31.21	17.54 ab
Avg. all depths	128	14.95 a	9.20 ab	9.64	21.59 L b	16.45	29.10	21.13 a
Avg. all depths	384	10.02 b	6.62 b	9.89	21.05 L b	13.70	26.49	18.75 ab
Avg. all depths	641	13.06 ab	9.24 ab	9.77	18.99 L b	15.03	25.76	15.56 b
0-6"	0	10.61	9.25	8.30	23.93	10.67	13.10	15.75
0-6"	128	17.09	4.66	7.93	16.64	10.18	12.89	16.79
0-6"	384	7.43	4.22	6.31	13.35	5.11	7.22	15.09
0-6"	641	8.94	5.68	8.69	15.12	5.21	9.57	12.81
6-12"	0	5.02	3.69	1.37	14.47	5.18	6.89	10.07
6-12"	128	6.85	1.05	1.13	10.63	5.06	7.43	9.37
6-12"	384	1.60	0.40	1.54	12.18	2.32	5.82	11.31
6-12"	641	4.73	0.88	1.51	9.04	4.80	6.93	7.20
12-24"	0	16.93	19.49	14.78	34.80	26.92	55.72	19.83
12-24"	128	15.80	19.68	14.45	24.79	18.87	49.35	27.30
12-24"	384	9.87	8.93	8.27	18.84	15.70	35.13	15.67
12-24"	641	17.52	16.83	7.17	18.80	22.53	37.89	17.10
24-36"	0	19.23	18.04	14.31	32.24	23.64	54.75	24.83
24-36"	128	18.74	22.70	16.26	27.84	22.19	49.17	32.76
24-36"	384	17.48	16.23	19.25	30.89	23.05	48.90	29.52
24-36"	641	19.92	20.72	19.99	28.67	28.79	43.67	26.21
36-48"	0	18.80	17.11	15.86	33.04	23.28	53.03	20.97
36-48"	128	18.57	18.47	16.11	33.98	24.46	44.38	29.12
36-48"	384	16.73	19.56	18.54	27.28	26.11	50.46	28.87
36-48"	641	20.61	22.07	18.14	26.93	23.41	40.05	21.34
48-60"	0	18.13	n/a†	14.89	40.97	24.42	49.37	n/a
48-60"	128	17.53	n/a	15.69	25.92	26.55	45.99	n/a
48-60"	384	15.91	n/a	16.60	27.31	24.11	53.51	n/a
48-60"	641	15.45	n/a	20.61	23.61	21.11	41.04	n/a
60-72"	0	18.31	n/a	12.28	38.13	15.75	36.56	n/a
60-72"	128	14.39	n/a	9.64	19.91	21.50	34.52	n/a
60-72"	384	13.89	n/a	14.14	25.46	25.71	40.81	n/a
60-72"	641	12.84	n/a	8.78	18.50	18.93	38.11	n/a

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.
†n/a=samples not collected due to the high groundwater table.

Table A 4. Mean soil K concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

	2nd Fertilization ↓							3rd Raking ↓	4th Raking ↓		5th Raking ↓
Sample Depth	**DAP** lb/ac	**Sampling Date** 03/29/10	04/26/10		05/24/10	08/23/10	11/17/10	03/07/11	03/06/12		02/20/13
		Months after last fertilization (MAF), approximate									
		1	**2**		**3**	**6**	**9**	**12**	**24**		**36**
Avg. all depths§	0	6.20	15.38		27.46	20.18	16.22	28.52	14.36		22.58
Avg. all depths	128	4.09	14.73		24.40	22.24	16.02	28.63	14.92		23.57
Avg. all depths	384	6.90	14.62		26.08	21.61	13.88	26.39	13.26		20.33
Avg. all depths	641	4.84	14.19		27.44	25.37	16.21	27.79	12.61		20.46
0-6"	0	10.36	3.87 bc	B	18.64	15.29	5.57	22.05	4.23	B	25.66
0-6"	128	18.67	7.64 a	B	19.60	17.95	4.88	20.25	4.96	B	31.12
0-6"	384	12.46	2.81 c	B	20.14	13.67	4.82	18.42	3.68	B	23.01
0-6"	641	11.85	6.62 ab	B	18.24	17.24	6.59	20.62	3.11	B	22.29
6-12"	0	7.03	2.59 a	B	14.43	9.11	3.66	17.26	1.98 L a	C	19.49
6-12"	128	7.81	1.42 ab	C	12.36	14.69	2.28	16.24	1.94 L a	C	20.92
6-12"	384	7.08	2.37 a	B	14.72	9.89	1.09	14.96	1.02 L b	C	16.14
6-12"	641	6.00	0.49 b	C	15.48	17.33	1.47	17.29	0.54 L b	C	16.63
12-24"	0	7.98	30.50	A	35.83	25.48	27.69	30.31	24.76	A	25.00
12-24"	128	3.42	24.34	A	29.88	27.50	26.49	42.91	25.58	A	25.55
12-24"	384	5.59	21.51	A	30.82	20.51	21.49	28.05	24.72	A	21.82
12-24"	641	5.20	19.79	A	25.70	18.37	21.45	34.94	24.72	A	19.04
24-36"	0	4.09	30.15	A	36.29	26.97	29.22	36.11	24.72	A	26.45
24-36"	128	2.35	26.77	A	30.43	29.20	30.52	33.90	27.52	A	26.31
24-36"	384	5.59	31.38	A	33.51	29.66	30.22	35.24	25.91	A	23.93
24-36"	641	3.66	31.89	A	40.69	28.99	33.76	36.47	25.60	A	23.80
36-48"	0	5.92	28.72	A	35.95	26.24	26.58	34.37	26.70	A	24.01
36-48"	128	2.07	28.28	A	29.51	26.55	29.75	33.04	25.75	A	22.42
36-48"	384	5.85	31.57	A	31.07	30.64	30.18	34.02	25.07	A	21.15
36-48"	641	3.48	30.49	A	37.39	39.13	31.09	35.45	26.56	A	20.89
48-60"	0	4.42	26.20	A	32.94	23.70	25.24	33.32	25.44	A	20.78
48-60"	128	2.03	26.32	A	29.17	23.82	29.34	31.88	25.55	A	20.92
48-60"	384	6.04	28.31	A	30.45	28.34	26.22	32.66	26.02	A	19.73
48-60"	641	3.19	28.11	A	33.87	34.87	31.41	29.49	26.09	A	22.72
60-72"	0	5.42	21.84	A	27.98	22.31	22.43	31.90	25.72	A	18.06
60-72"	128	2.74	19.21	A	26.71	19.94	25.46	30.95	26.46	A	19.63
60-72"	384	7.42	24.38	A	28.02	29.92	21.21	29.04	25.06	A	17.69
60-72"	641	3.76	25.11	A	30.84	30.70	28.36	26.70	25.77	A	18.78

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table A 5. Mean soil K concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

Sample Depth	DAP lb/ac	11/01/08		03/09/09 (1st Fertilization)	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09		02/08/10 (1st Raking)
		Months after last fertilization (MAF), approximate									
		Before		0.5	1	2	3	6	9		12
Avg. all depths§	0	2.57		8.96 a	4.00 a	6.62 a	0.07 L b	2.49	4.00 a		3.21
Avg. all depths	128	1.98		5.62 b	0.39 b	0.14 b	0.73 L ab	2.18	4.29 a		5.07
Avg. all depths	384	1.86		4.83 b	0.29 b	0.10 b	2.30 L a	1.62	2.27 b		3.73
Avg. all depths	641	2.50		5.33 b	0.87 b	0.18 b	3.05 L a	2.11	3.51 a		4.59
0-6"	0	4.99	A	13.91	15.72	10.61	0.34	9.30	4.22 a	A	7.15
0-6"	128	5.47	A	8.85	1.12	0.51	1.45	4.58	1.30 b	C	4.90
0-6"	384	5.29	A	7.26	0.45	0.00	2.00	5.41	0.15 c	B	3.64
0-6"	641	5.22		6.92	2.15	0.21	2.88	6.28	1.47 b	B	4.27
6-12"	0	1.55	D	10.03	3.12	7.73	0.00	2.66	0.05	B	0.82
6-12"	128	1.61	B	5.63	0.12	0.00	0.22	1.36	0.06	D	0.78
6-12"	384	2.14	B	4.68	0.00	0.00	0.49	2.13	0.00	B	0.57
6-12"	641	3.16		5.35	0.92	0.00	0.75	3.16	0.20	C	1.01
12-24"	0	3.02 a	A	7.40	1.96	6.62	0.00	1.95	6.48 b	A	4.64
12-24"	128	1.01 b	B	5.04	0.12	0.00	0.70	5.52	13.88 a	A	15.49
12-24"	384	0.90 b	C	3.90	0.00	0.00	1.04	1.18	4.56 b	A	7.18
12-24"	641	2.16 ab		4.75	0.99	0.70	3.57	1.63	6.91 b	A	5.80
24-36"	0	3.79	A	7.90	3.37	5.43	0.00	1.54	4.87	A	3.23
24-36"	128	1.28	B	4.94	0.23	0.00	0.64	1.12	7.25	B	5.81
24-36"	384	1.57	B	4.49	0.56	0.15	4.00	0.57	3.83	A	5.75
24-36"	641	1.90		5.30	0.35	0.00	3.78	0.79	4.96	A	6.12
36-48"	0	1.95	C	6.18	3.73	4.75	0.22	1.45	4.88	A	2.73
36-48"	128	1.27	B	5.27	0.87	0.71	0.97	1.26	6.55	B	5.41
36-48"	384	1.39	B	4.00	0.30	0.00	4.07	0.59	3.45	A	4.70
36-48"	641	1.76		4.93	0.50	0.00	3.70	0.88	4.25	A	7.23
48-60"	0	1.51	C	8.18	2.87	5.48	0.00	1.29	7.36	A	3.64
48-60"	128	3.90	A	5.51	0.18	0.00	0.68	1.31	6.21	B	5.54
48-60"	384	1.44	B	4.44	0.21	0.00	3.28	1.62	3.94	A	3.84
48-60"	641	2.00		4.79	0.55	0.59	3.98	1.08	4.66	A	5.07
60-72"	0	2.36	B	10.99	3.75	7.08	0.00	2.95	5.60	A	2.80
60-72"	128	1.40	B	4.84	0.41	0.00	0.64	2.42	6.13	B	5.16
60-72"	384	1.80	B	5.68	0.68	0.72	3.25	1.98	4.82	A	3.79
60-72"	641	2.30		5.49	1.12	0.00	4.14	4.01	8.21	A	5.69

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.

"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.

Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).

Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.

§ Fertilization rate main effect.

Table A 6. Mean soil K concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

2nd Fertilization (before 03/08/10); 2nd Raking (before 02/21/11); 3rd Raking (before 02/28/12); 4th Raking (before 02/27/13)

Sample Depth	DAP lb/ac	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
Months after last fertilization (MAF), approximate		0.5	1	2	3	6	9	12	24	36
Avg. all depths§	0	8.38 a	6.71	1.51	8.95	7.88	0.51	9.28	2.98	5.60
Avg. all depths	128	7.15 a	6.31	1.30	7.92	7.09	0.42	9.25	2.93	6.72
Avg. all depths	384	5.21 b	7.33	1.04	7.85	6.60	0.30	9.15	2.59	7.47
Avg. all depths	641	6.52 ab	7.04	1.22	8.10	6.39	0.32	10.74	3.04	5.00
0-6"	0	6.09	1.40	11.22	2.79	16.44	5.46	12.57	8.89	16.10
0-6"	128	3.22	0.61	7.32	1.52	12.80	2.21	10.47	9.09	13.73
0-6"	384	2.31	0.09	5.88	0.17	12.81	2.33	11.73	7.35	9.11
0-6"	641	2.67	0.00	8.06	1.11	13.50	3.16	13.65	8.47	10.81
6-12"	0	2.42	0.00	4.15	0.13	11.15	0.52	9.49	2.79	10.21
6-12"	128	1.09	0.00	1.99	0.46	8.60	0.23	8.17	3.40	8.93
6-12"	384	0.03	0.00	1.88	1.33	10.21	0.01	9.79	3.90	7.31
6-12"	641	0.54	0.00	5.84	0.18	9.54	0.51	10.84	3.19	7.28
12-24"	0	11.49	13.52	0.87	17.27	7.30	0.66	8.74	1.58	4.08
12-24"	128	14.56	12.72	3.28	16.90	8.80	1.69	9.05	2.25	10.99
12-24"	384	11.22	15.81	1.73	15.69	7.41	0.65	8.33	2.49	7.42
12-24"	641	9.09	13.28	0.30	16.59	5.84	0.00	9.77	1.52	3.95
24-36"	0	8.68	13.66	0.28	17.42	5.49	0.00	8.37	1.77	3.70
24-36"	128	10.40	14.47	0.35	15.23	6.70	0.09	8.90	1.85	5.60
24-36"	384	7.72	22.75	0.26	15.34	4.34	0.14	8.37	1.20	8.73
24-36"	641	15.36	18.01	0.23	17.69	4.87	0.00	9.87	1.70	3.64
36-48"	0	7.83	14.29	0.32	16.77	5.94	0.00	8.44	2.24	4.03
36-48"	128	9.33	14.09	0.08	14.71	5.39	0.00	9.00	2.51	4.39
36-48"	384	7.33	20.02	0.17	15.56	4.41	0.00	8.14	1.34	6.22
36-48"	641	10.37	18.99	0.27	17.22	3.97	0.00	9.65	2.16	3.89
48-60"	0	7.76	14.31	0.51	17.89	5.11	0.00	8.29	3.08	3.39
48-60"	128	11.28	13.66	0.24	15.38	4.96	0.00	9.14	2.38	3.68
48-60"	384	11.09	16.62	0.04	16.64	4.04	0.00	8.59	1.46	6.55
48-60"	641	9.54	21.38	0.16	16.78	5.10	0.10	9.71	3.01	3.67
60-72"	0	27.27	12.45	1.11	19.00	8.02	0.11	9.69	3.50	4.42
60-72"	128	11.04	13.84	0.79	15.42	4.96	0.00	10.21	1.98	4.62
60-72"	384	8.74	16.32	0.76	18.56	6.71	0.00	9.53	3.22	7.32
60-72"	641	11.12	16.89	0.84	18.47	5.48	0.00	12.26	4.14	4.45

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table A 7. Mean soil Ca concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

1st Raking | 1st Fertilization | 2nd Raking

Sample Depth	DAP lb/ac	10/01/08	03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10
		Before	1	2	3	6	9	12
Avg. all depths§	0	123.5	178.6	143.1	174.4	155.6	236.8	172.7
Avg. all depths	128	121.6	188.8	135.1	146.5	162.1	242.8	181.5
Avg. all depths	384	139.9	189.0	147.9	166.4	171.2	241.6	213.7
Avg. all depths	641	117.8	219.6	153.5	146.6	152.5	223.3	192.5
0-6"	0	212.9	199.3	221.3	248.4	219.1	218.4	198.5
0-6"	128	184.9	220.9	218.7	212.2	206.1	215.2	191.3
0-6"	384	182.9	208.0	218.0	241.8	206.6	170.1	209.2
0-6"	641	228.1	302.5	265.7	213.4	210.2	218.0	228.5
6-12"	0	123.6	134.0	128.6	161.3	142.6	153.8	132.7
6-12"	128	104.8	128.1	132.6	132.8	117.4	146.4	127.0
6-12"	384	107.9	112.9	130.5	187.6	131.1	140.2	164.1
6-12"	641	114.8	159.5	141.0	138.1	98.3	161.4	159.6
12-24"	0	171.2	207.5	217.5	239.4	208.4	448.2	189.9
12-24"	128	182.3	243.1	228.3	216.6	187.2	497.1	186.5
12-24"	384	164.1	194.1	196.3	196.4	170.3	372.5	190.7
12-24"	641	160.4	230.3	139.5	131.7	165.4	337.4	163.9
24-36"	0	229.3	225.1	267.3	264.6	284.8	471.2	227.5
24-36"	128	233.0	245.5	223.7	238.8	318.3	510.0	267.1
24-36"	384	249.8	255.7	279.4	302.3	289.1	563.2	308.5
24-36"	641	219.8	255.2	241.3	207.4	297.5	449.0	259.9
36-48"	0	112.5	145.5	178.1	188.9	168.5	304.8	134.9
36-48"	128	134.0	141.9	129.7	145.8	205.4	251.2	162.6
36-48"	384	188.5	206.9	173.6	157.7	227.9	335.9	220.4
36-48"	641	121.2	179.9	171.7	182.9	199.8	266.0	170.4
48-60"	0	73.8	n/a†	78.5	121.7	112.2	163.8	n/a
48-60"	128	75.4	n/a	84.2	103.4	114.7	226.8	n/a
48-60"	384	109.6	n/a	99.7	109.2	143.1	224.1	n/a
48-60"	641	63.3	n/a	150.0	126.9	116.8	170.1	n/a
60-72"	0	50.7	n/a	52.6	83.8	62.5	117.4	n/a
60-72"	128	46.9	n/a	50.3	65.7	86.3	109.0	n/a
60-72"	384	62.4	n/a	56.8	75.7	99.0	127.1	n/a
60-72"	641	44.0	n/a	61.4	77.5	80.3	114.3	n/a

Sampling Date; Months after last fertilization (MAF), approximate.

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.
†n/a=samples not collected due to the high groundwater table.

Table A 8. Mean soil Ca concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

Sample Depth	DAP lb/ac	03/29/10 (2nd Fertilization)	04/26/10	05/24/10		08/23/10	11/17/10	03/07/11 (3rd Raking)	03/06/12 (4th Raking)	02/20/13 (5th Raking)
		Sampling Date								
		Months after last fertilization (MAF), approximate								
		1	2	3		6	9	12	24	36
Avg. all depths§	0	101.6	146.0	149.6		171.8	151.9	154.7	108.3	154.6
Avg. all depths	128	75.1	147.6	148.0		184.0	138.3	154.0	103.7	172.5
Avg. all depths	384	98.5	155.7	166.0		188.7	157.9	162.5	111.1	173.1
Avg. all depths	641	93.3	152.6	166.3		172.8	155.0	153.1	109.6	140.3
0-6"	0	198.8	205.5	250.6	AB	240.1	235.6	204.5	64.9	180.1
0-6"	128	200.0	231.7	225.5	A	250.4	178.2	203.2	54.8	173.3
0-6"	384	211.8	236.3	280.3	A	236.9	225.1	213.7	51.2	182.7
0-6"	641	230.7	223.1	259.8	A	200.1	195.4	196.0	56.5	151.1
6-12"	0	139.4	134.8	168.8	C	165.8	149.6	161.2	46.5	138.0
6-12"	128	142.0	149.2	160.9	B	182.4	117.9	141.9	42.4	147.8
6-12"	384	140.2	160.1	164.0	D	186.8	154.6	157.6	39.1	151.4
6-12"	641	153.6	166.5	207.3	B	182.7	160.5	155.6	40.7	134.4
12-24"	0	148.6	212.5	195.2	BC	241.0	191.0	195.7	180.3	165.6
12-24"	128	65.1	210.2	226.5	A	306.0	196.0	211.3	216.3	247.3
12-24"	384	101.8	169.1	211.4	BC	227.0	202.9	174.1	203.8	227.7
12-24"	641	102.5	155.6	149.1	C	206.9	171.8	162.4	198.0	158.8
24-36"	0	112.4	244.4	255.2	A	320.6	263.2	229.3	249.6	219.5
24-36"	128	70.2	236.6	218.4	A	308.9	241.3	252.9	262.1	257.5
24-36"	384	101.1	223.0	254.7	AB	287.3	292.1	287.9	250.8	276.2
24-36"	641	100.5	238.3	228.7	AB	270.8	262.7	258.2	258.3	232.7
36-48"	0	92.8	173.0	148.7	C	187.3	152.6	175.3	183.6	192.7
36-48"	128	48.2	161.9	128.4	B	171.9	159.7	172.5	166.8	183.4
36-48"	384	73.1	167.2	169.8	CD	225.5	186.9	215.8	205.0	197.5
36-48"	641	70.1	147.4	192.6	ABC	215.6	164.9	200.5	177.1	164.6
48-60"	0	56.9	99.6	92.0	D	106.0	94.9	106.2	107.3	130.4
48-60"	128	41.2	97.3	91.0	C	118.5	95.0	102.9	89.7	138.6
48-60"	384	67.1	114.3	102.0	E	133.2	93.7	118.3	115.2	130.7
48-60"	641	52.1	122.2	121.8	C	125.8	111.4	106.7	114.0	104.9
60-72"	0	45.4	56.7	57.7	E	71.9	72.3	76.6	64.5	92.9
60-72"	128	51.9	56.0	73.8	C	80.8	63.9	74.8	64.4	109.2
60-72"	384	59.5	81.1	80.6	E	98.0	67.5	69.2	85.0	103.5
60-72"	641	45.9	77.5	81.3	D	82.6	82.6	71.7	78.8	82.2

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table A 9. Mean soil Ca concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

Sample Depth	DAP lb/ac	11/01/08	03/09/09 (1st Fertilization)	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10 (1st Raking)
			Months after last fertilization (MAF), approximate						
		Before	0.5	1	2	3	6	9	12
Avg. all depths§	0	32.1	38.2	37.2	32.1 a	27.1 c	47.6	43.1	60.1
Avg. all depths	128	22.8	20.3	17.4	12.6 b	30.3 bc	40.8	40.4	49.1
Avg. all depths	384	27.7	18.4	18.1	19.0 ab	59.6 ab	48.4	40.8	60.2
Avg. all depths	641	28.6	24.0	23.4	15.4 b	76.4 a	50.9	51.0	74.9
0-6"	0	98.8	107.9	102.8	83.0	84.0	124.5 a	98.2	113.3
0-6"	128	78.7	65.3	58.3	49.1	78.4	71.8 b	74.7	64.0
0-6"	384	59.8	57.9	45.0	48.1	92.2	68.2 b	58.6	77.7
0-6"	641	96.1	45.7	69.8	63.3	160.7	74.6 b	84.1	94.4
6-12"	0	45.7	58.4	64.7	59.0	42.0	55.2	52.8	72.6
6-12"	128	34.8	36.6	34.5	22.8	39.4	42.1	46.7	42.0
6-12"	384	55.2	29.6	38.0	34.6	67.6	58.1	41.6	64.4
6-12"	641	52.8	65.7	46.3	39.3	107.0	54.2	62.0	67.9
12-24"	0	42.2	41.5	39.8	33.7	26.6	50.6	42.6	65.3
12-24"	128	18.3	21.4	18.9	12.8	32.5	47.5	47.5	59.4
12-24"	384	29.1	12.6	23.4	20.3	52.6	49.8	53.5	71.3
12-24"	641	33.0	33.9	29.2	26.6	80.2	56.5	64.4	79.0
24-36"	0	31.8	31.2	28.5	23.5	24.4	38.6	37.6	51.6
24-36"	128	15.4	17.2	14.3	11.6	30.4	35.8	35.3	44.8
24-36"	384	20.3	9.9	15.5	14.6	79.5	48.7	35.9	57.7
24-36"	641	22.9	17.4	14.7	9.3	101.8	46.4	44.1	73.7
36-48"	0	16.4	20.6	22.7	19.6	12.6	33.4	29.6	45.1
36-48"	128	12.8	12.9	5.8	9.0	19.4	35.7	28.3	45.7
36-48"	384	16.7	13.0	9.6	13.5	57.2	36.1	33.6	51.7
36-48"	641	16.6	16.4	10.3	6.4	58.9	44.3	38.9	68.9
48-60"	0	16.5	23.6	21.6	19.1	16.7	31.0	28.0	43.7
48-60"	128	16.1	9.1	6.6	4.8	17.9	30.0	30.1	44.7
48-60"	384	16.3	13.6	7.1	7.9	42.6	41.5	31.5	51.5
48-60"	641	15.4	13.5	14.2	4.9	50.9	39.3	35.4	61.7
60-72"	0	20.7	29.5	25.9	23.7	21.5	39.3	39.9	51.5
60-72"	128	19.2	12.9	20.6	6.3	21.5	33.7	35.0	46.9
60-72"	384	23.1	18.1	13.9	16.0	41.9	43.0	37.5	52.2
60-72"	641	15.4	11.2	17.7	9.0	35.7	47.9	44.0	83.6

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table A 10. Mean soil Ca concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

2nd Fertilization (after DAP column); 2nd Raking (before 02/21/11); 3rd Raking (before 02/28/12); 4th Raking (before 02/27/13)

Sample Depth	DAP lb/ac	03/08/10		03/22/10		04/19/10	05/10/10	08/16/10		11/22/10		02/21/11		02/28/12		02/27/13
		Months after last fertilization (MAF), approximate														
		0.5		1		2	3	6		9		12		24		36
Avg. all depths§	0	67.6		77.0		52.9	56.4	59.6		47.5		46.0		55.0		64.6
Avg. all depths	128	58.2		60.6		50.3	45.6	44.0		38.7		37.5		43.4		58.3
Avg. all depths	384	59.0		72.0		51.7	42.0	43.2		36.1		37.7		41.5		56.3
Avg. all depths	641	66.3		81.7		55.4	50.1	55.2		39.4		44.1		44.2		59.8
0-6"	0	111.7	A	98.8	AB	123.3	108.9	118.9	A	104.8	A	83.8	A	195.2	A	94.7
0-6"	128	76.3	A	60.4	C	95.9	63.0	90.7	A	70.6	A	61.0	A	171.6	A	69.5
0-6"	384	79.7	A	55.9	D	85.0	49.2	64.8		45.7		53.6	A	162.6	A	60.1
0-6"	641	110.7	A	64.5		107.1	81.3	87.8	A	64.5	A	70.9	A	194.2	A	66.4
6-12"	0	75.2	B	57.4	C	94.0	74.1	95.3	B	80.3	B	62.7	B	130.3	B	69.7
6-12"	128	59.0	BC	38.9	D	68.5	38.8	57.2	B	47.7	B	44.1	B	124.1	B	47.3
6-12"	384	62.9	B	44.9	D	68.4	41.6	55.1		43.1		46.8	A	132.6	B	47.9
6-12"	641	78.3	B	56.6		66.8	56.3	68.2	B	50.2	B	53.7	B	136.7	B	49.1
12-24"	0	67.6	BCD	91.9	AB	60.8	62.9	71.6	C	55.0	C	47.6	C	44.8	C	73.2
12-24"	128	67.7	AB	91.1	AB	60.7	53.9	46.0	BC	39.4	C	37.0	C	37.2	C	78.1
12-24"	384	63.0	AB	85.4	BC	49.5	43.9	43.2		42.4		43.2	AB	30.6	C	70.2
12-24"	641	69.5	BC	92.2		55.9	56.6	64.3	B	44.2	BC	46.2	BC	29.2	C	73.0
24-36"	0	58.3	BCD	103.4	AB	39.4	48.2	51.0	D	38.7	D	39.1	CD	36.1	CD	61.4
24-36"	128	53.0	C	109.2	A	46.6	45.1	40.5	CD	34.2	CD	35.4	BC	27.5	D	60.6
24-36"	384	59.1	B	139.6	A	41.2	40.1	37.7		35.0		35.2	C	25.7	CD	61.9
24-36"	641	58.6	CD	114.6		51.3	50.7	54.6	BC	37.9	CD	41.4	CD	25.6	C	63.9
36-48"	0	59.4	BCD	77.5	AB	32.7	36.8	41.8	D	30.7	E	33.8	D	32.9	CD	57.5
36-48"	128	50.2	C	65.1	BC	35.1	41.9	30.0	E	29.9	D	30.3	C	20.6	E	51.6
36-48"	384	49.5	B	103.7	AB	38.0	35.9	33.2		29.4		30.3	C	21.7	CD	51.7
36-48"	641	53.1	CD	103.8		43.2	40.9	42.4	CD	31.1	DE	35.0	D	25.1	C	55.8
48-60"	0	50.9	D	64.6	AB	32.8	42.2	36.9	D	29.4	E	33.0	D	28.2	D	50.9
48-60"	128	50.9	BC	46.2	CD	32.7	39.5	30.3	DE	30.9	CD	30.4	C	25.6	CDE	52.0
48-60"	384	46.6	B	62.0	CD	41.3	38.7	34.9		27.3		29.3	C	20.0	D	51.5
48-60"	641	50.2	D	85.5		38.0	39.2	37.5	D	28.7	E	32.3	D	24.5	C	57.9
60-72"	0	64.3	BC	59.3	BC	38.5	47.6	41.7	D	33.4	DE	39.6	CD	38.9	C	53.7
60-72"	128	54.7	ABC	42.5	CD	37.7	41.9	36.2	CDE	31.0	CD	31.9	BC	24.2	DE	54.8
60-72"	384	57.7	AB	51.7	CD	52.7	46.0	41.5		34.1		31.7	BC	27.3	C	54.0
60-72"	641	59.9	BCD	71.0		47.5	37.3	46.5	B	30.5	DE	39.0	BC	25.8	C	55.8

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table A 11. Mean soil Mg concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

1st Raking | 1st Fertilization | 2nd Raking

Sample Depth	DAP lb/ac	10/01/08	03/30/09	04/27/09	06/01/09	08/31/09	12/07/09	02/15/10
		Months after last fertilization (MAF), approximate						
		Before	1	2	3	6	9	12
Avg. all depths§	0	52.1	49.5	47.4	57.9	51.2	87.7	50.1 a
Avg. all depths	128	47.0	51.0	48.6	51.4	58.7	95.5	52.5 a
Avg. all depths	384	48.1	43.7	51.3	62.1	58.4	94.6	54.8 a
Avg. all depths	641	41.6	49.0	39.6	39.2	46.3	69.3	40.5 b
0-6"	0	29.2	29.1	28.5	33.7	31.3	33.2	31.8
0-6"	128	25.2	27.4	27.9	30.1	26.8	29.7	29.9
0-6"	384	21.9	23.6	23.8	33.7	29.2	25.7	29.3
0-6"	641	22.2	33.0	22.5	23.4	19.2	21.1	21.1
6-12"	0	23.9	28.9	20.3	31.8	27.6	31.1	30.7
6-12"	128	17.6	27.7	27.6	26.3	31.2	32.7	29.4
6-12"	384	15.2	19.5	22.4	33.8	26.2	24.8	32.4
6-12"	641	18.4	26.8	18.2	25.5	14.9	21.5	20.8
12-24"	0	49.4	66.1	59.0	61.0	61.8	136.3	54.5
12-24"	128	57.3	74.7	61.2	61.1	58.3	152.4	68.9
12-24"	384	45.4	46.9	49.2	51.6	52.7	110.5	51.1
12-24"	641	45.3	60.4	36.9	37.7	50.9	99.4	48.4
24-36"	0	85.7	79.3	84.0	75.9	90.3	150.4	74.8
24-36"	128	74.9	77.9	77.0	74.2	89.5	182.9	84.7
24-36"	384	82.7	79.1	88.6	104.9	78.7	191.4	98.6
24-36"	641	69.9	74.7	66.8	55.5	92.8	142.7	79.8
36-48"	0	73.1	66.6	73.3	78.8	74.0	146.9	78.6
36-48"	128	72.5	76.9	65.8	78.9	80.1	154.3	76.9
36-48"	384	94.1	91.6	85.0	91.3	104.5	188.8	102.4
36-48"	641	72.2	70.3	61.1	57.2	82.5	117.1	63.2
48-60"	0	77.1	n/a†	51.2	77.4	68.4	136.9	n/a
48-60"	128	66.9	n/a	61.7	65.7	84.5	154.0	n/a
48-60"	384	80.9	n/a	76.2	87.2	102.1	188.7	n/a
48-60"	641	55.4	n/a	66.7	53.9	77.0	109.6	n/a
60-72"	0	61.4	n/a	49.4	71.2	37.3	91.8	n/a
60-72"	128	53.3	n/a	42.8	50.4	80.2	109.8	n/a
60-72"	384	60.8	n/a	60.8	71.9	67.0	136.3	n/a
60-72"	641	40.6	n/a	36.3	36.4	51.2	89.6	n/a

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.
†n/a=samples not collected due to the high groundwater table.

Table A 12. Mean soil Mg concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Blountstown (averaged across raked and non-raked treatments)

Sample Depth	DAP lb/ac (2nd Fertilization)	03/29/10	04/26/10	05/24/10	08/23/10	11/17/10	03/07/11 (3rd Raking)	03/06/12 (4th Raking)	02/20/13 (5th Raking)
		Months after last fertilization (MAF), approximate							
		1	2	3	6	9	12	24	36
Avg. all depths§	0	24.9	47.5	50.0	65.2	54.5	51.2	32.5	41.4
Avg. all depths	128	13.3	50.0	52.9	76.0	56.6	55.3	34.8	56.3
Avg. all depths	384	20.2	48.6	56.4	72.0	56.6	56.3	34.6	55.0
Avg. all depths	641	17.2	41.1	41.5	54.0	44.4	43.4	32.6	35.9
0-6"	0	26.9	24.7	35.7	36.1	33.4	30.1	6.0	25.1
0-6"	128	28.5	29.8	38.0	39.8	31.3	30.8	5.1	27.0
0-6"	384	22.7	22.9	34.9	30.8	28.2	26.4	5.2	23.6
0-6"	641	19.1	17.4	21.7	19.6	16.5	17.8	5.7	16.7
6-12"	0	25.0	27.5	37.7	37.5	38.2	32.5	4.6	28.9
6-12"	128	28.5	27.5	37.4	48.4	33.6	34.4	3.5	35.3
6-12"	384	23.9	21.6	33.5	38.9	31.4	27.4	2.9	27.3
6-12"	641	20.8	23.3	27.0	21.0	19.4	17.5	3.9	18.8
12-24"	0	26.4	59.0	56.5	71.2	58.2	50.9	54.3	38.4
12-24"	128	8.2	61.6	66.5	107.4	58.2	63.8	69.5	68.5
12-24"	384	16.7	49.2	61.4	72.6	58.0	48.1	59.9	58.5
12-24"	641	17.4	43.2	39.0	58.6	46.1	44.6	56.1	37.6
24-36"	0	25.6	79.7	77.4	106.1	79.1	78.0	77.2	54.2
24-36"	128	11.6	77.8	70.0	108.9	80.2	80.8	87.9	78.6
24-36"	384	17.7	78.6	85.1	107.4	96.3	86.7	89.7	85.9
24-36"	641	20.4	69.4	64.7	93.7	81.4	82.0	84.1	64.9
36-48"	0	27.6	73.6	65.7	95.3	73.2	74.2	77.6	60.7
36-48"	128	9.0	74.8	59.3	99.5	80.3	74.6	82.5	75.5
36-48"	384	15.9	80.4	81.7	118.2	92.1	98.0	90.4	88.1
36-48"	641	16.6	62.2	64.5	98.1	74.9	84.3	79.1	58.5
48-60"	0	22.4	58.2	56.0	77.7	63.6	65.7	68.2	53.5
48-60"	128	8.9	66.8	58.9	92.8	76.5	65.6	74.8	72.9
48-60"	384	21.5	71.3	67.6	100.9	75.1	87.0	82.3	79.5
48-60"	641	13.9	57.2	54.9	83.9	67.6	62.2	67.0	49.2
60-72"	0	21.1	39.5	36.0	65.9	52.0	48.3	50.5	41.7
60-72"	128	11.2	39.6	49.7	69.8	61.3	58.3	67.8	62.9
60-72"	384	24.7	57.4	53.6	88.6	53.9	68.2	71.1	65.9
60-72"	641	13.9	45.1	39.8	69.4	54.0	46.8	54.3	34.0

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table A 13. Mean soil Mg concentrations (mg/kg) by sampling date after the first application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

1st Fertilization (between 11/01/08 and 03/09/09); 1st Raking (between 11/30/09 and 02/08/10)

Sample Depth	DAP lb/ac	11/01/08	03/09/09	03/23/09	04/20/09	05/25/09	08/24/09	11/30/09	02/08/10
		Months after last fertilization (MAF), approximate							
		Before	0.5	1	2	3	6	9	12
Avg. all depths§	0	5.55	4.78 a	1.16	4.53 a	0.53 c	4.93	7.10	5.13
Avg. all depths	128	4.52	0.15 b	0.59	0.01 b	4.14 b	3.83	7.40	5.40
Avg. all depths	384	3.68	0.04 b	0.52	0.10 b	8.70 ab	4.70	6.04	7.16
Avg. all depths	641	5.47	0.34 b	1.44	0.14 b	14.86 a	5.40	8.52	9.34
0-6"	0	8.75	8.04	1.93	5.71	1.64	11.65	12.88	11.89
0-6"	128	8.26	0.46	0.62	0.07	5.33	4.52	8.74	8.53
0-6"	384	6.52	0.15	0.34	0.00	4.91	4.72	7.69	9.08
0-6"	641	10.16	0.52	1.76	0.26	11.01	5.99	9.71	11.41
6-12"	0	5.27	4.54	1.36	5.75	0.00	3.68	7.84	9.57
6-12"	128	5.34	0.27	0.47	0.00	2.55	1.98	7.24	5.96
6-12"	384	5.11	0.00	0.33	0.00	3.93	4.15	5.86	8.58
6-12"	641	6.88	0.28	1.74	0.00	10.57	3.56	6.88	8.71
12-24"	0	7.09	5.85	2.02	4.88	0.71	5.44	7.11	4.71
12-24"	128	4.31	0.18	0.53	0.00	4.02	5.74	9.44	6.03
12-24"	384	4.01	0.00	0.36	0.30	9.00	4.21	7.28	8.36
12-24"	641	6.34	0.23	1.90	0.25	12.15	5.50	9.84	8.52
24-36"	0	6.78	4.06	0.78	4.28	0.77	4.54	6.32	4.15
24-36"	128	4.35	0.20	0.54	0.00	5.18	4.15	7.73	4.26
24-36"	384	3.61	0.00	0.63	0.00	14.54	5.53	5.40	6.26
24-36"	641	4.88	0.48	1.47	0.00	18.38	4.68	7.92	9.16
36-48"	0	3.71	3.14	0.61	2.79	0.08	3.41	5.21	3.33
36-48"	128	3.26	0.00	0.85	0.03	3.13	3.60	5.67	4.42
36-48"	384	2.09	0.00	0.57	0.00	11.14	3.46	4.93	5.81
36-48"	641	3.56	0.42	1.08	0.00	13.56	5.26	8.23	8.53
48-60"	0	3.90	4.00	0.29	3.99	0.07	3.46	5.29	3.27
48-60"	128	4.02	0.00	0.49	0.00	3.77	3.60	6.48	4.35
48-60"	384	2.03	0.00	0.52	0.00	9.72	4.84	5.17	6.10
48-60"	641	3.69	0.51	0.87	0.54	19.41	5.97	7.75	7.97
60-72"	0	4.83	4.97	1.86	4.97	1.14	5.21	7.02	3.40
60-72"	128	3.37	0.00	0.62	0.00	5.96	4.11	7.07	5.17
60-72"	384	3.97	0.15	0.94	0.49	12.70	6.48	6.38	6.57
60-72"	641	4.83	0.00	1.48	0.00	23.03	7.58	9.75	11.66

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

Table A 14. Mean soil Mg concentrations (mg/kg) by sampling date after the second application of four DAP fertilization rates at Live Oak (averaged across raked and non-raked treatments)

2nd Fertilization (before 03/08/10); 2nd Raking (before 02/21/11); 3rd Raking (before 02/28/12); 4th Raking (before 02/27/13)

Sample Depth	DAP lb/ac	03/08/10	03/22/10	04/19/10	05/10/10	08/16/10	11/22/10	02/21/11	02/28/12	02/27/13
		Months after last fertilization (MAF), approximate								
		0.5	1	2	3	6	9	12	24	36
Avg. all depths§	0	11.84	13.85	9.64	10.99 a	11.48	5.09	3.95	11.67 L a	5.80
Avg. all depths	128	9.90	10.53	8.72	8.07 b	8.72	4.45	3.00	8.58 L b	5.84
Avg. all depths	384	9.06	12.78	8.18	7.34 b	9.09	3.60	2.20	7.99 L b	4.88
Avg. all depths	641	9.96	13.30	9.67	8.26 b	10.56	4.68	2.96	7.73 L b	6.07
0-6"	0	13.28	6.86	11.57	15.76	12.97	9.39	2.98	26.25	11.03
0-6"	128	8.84	2.80	8.71	10.73	10.52	6.85	2.11	19.66	9.10
0-6"	384	8.04	2.72	8.84	8.40	8.26	4.73	0.65	21.11	7.12
0-6"	641	10.35	2.70	11.69	13.15	10.46	6.91	1.58	19.98	9.45
6-12"	0	8.98	2.22	9.46	13.19	11.31	6.42	1.53	29.19	7.78
6-12"	128	6.75	0.74	7.27	8.72	7.91	4.74	0.77	24.42	6.06
6-12"	384	6.52	1.28	6.45	8.08	7.03	2.93	0.70	19.49	5.68
6-12"	641	7.69	1.16	6.51	10.82	7.86	4.55	1.17	20.29	6.53
12-24"	0	11.89	17.46	10.87	11.24	14.44	5.77	5.28	7.97	6.15
12-24"	128	12.38	18.20	11.42	8.23	10.15	4.03	3.45	6.29	7.34
12-24"	384	9.60	18.70	7.97	5.46	9.73	3.40	3.14	4.68	4.17
12-24"	641	10.59	18.87	8.47	6.52	11.14	3.80	2.63	4.34	5.70
24-36"	0	11.83	23.59	8.82	9.34	12.11	4.54	5.31	8.26	5.13
24-36"	128	10.35	25.97	9.59	7.60	9.51	3.32	4.35	5.73	5.80
24-36"	384	10.12	33.71	7.28	6.84	9.43	3.85	3.49	5.02	4.52
24-36"	641	10.42	27.29	10.46	8.02	11.10	4.37	3.46	4.51	5.56
36-48"	0	13.17	23.34	8.41	7.22	10.02	3.29	4.01	7.44	4.83
36-48"	128	9.72	19.91	8.05	6.85	7.31	3.60	3.45	5.03	4.24
36-48"	384	9.22	26.54	7.28	6.36	8.60	2.97	2.55	4.87	3.33
36-48"	641	10.36	30.76	9.74	7.51	10.44	4.34	3.49	5.09	5.33
48-60"	0	10.87	23.71	8.37	10.10	8.66	3.32	4.05	6.93	3.60
48-60"	128	10.19	17.62	7.38	6.96	7.13	4.39	3.54	6.05	4.53
48-60"	384	9.29	22.91	8.29	7.25	9.06	2.93	2.78	5.25	4.21
48-60"	641	9.18	29.49	10.19	6.67	10.32	4.24	4.05	5.44	4.77
60-72"	0	13.55	22.01	10.42	11.96	11.71	4.82	6.19	10.49	4.42
60-72"	128	12.19	19.27	9.25	7.96	9.09	4.91	5.20	5.77	4.95
60-72"	384	11.40	23.81	12.08	9.73	12.28	4.80	3.93	7.35	5.96
60-72"	641	11.62	27.07	11.69	6.87	13.26	5.00	6.47	6.51	5.99

Means for different fertilization rates within the same depth followed by different lower-case letters for each sampling date are significantly different at α=0.05 level.
"L" following means indicates a significant linear fertilization rate response (on a log scale) within the same depth for each sampling date.
Means for different depths within the same fertilization rate followed by different upper-case letters for each sampling date are significantly different at α=0.05 level (compared only if Fert*Depth significant).
Means were not declared different using least significance difference unless the overall effects involved were significant at α=0.05.
§ Fertilization rate main effect.

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