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Pecan Response to Nitrogen Fertilizer Source

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Abstract. **A better understanding of the efficacy of various nitrogen (N) forms on pecan tree production would help growers make more sound decisions regarding the fertilization of their orchards. The following treatments were evaluated for their effect on pecan leaf tissue nutrient concentration, leaf chlorophyll index, trunk circumference growth, pecan yield, nut weight, percent kernel, pecan tree yield efficiency, and alternate bearing: 1) ammonium nitrate (AN; 34N–0P–0K) at 1.8 kg N per tree (AN1.8); 2) AN (34N–0P–0K) at 3.6 kg N per tree (AN3.6); 3) ammonium sulfate (AS) at 1.8 kg N per tree (AS1.8); 4) AS at 3.6 kg N per tree (AS3.6); 5) urea at 1.8 kg N per tree (U1.8); 6) urea at 3.6 kg per tree (U3.6); and 7) untreated control (C). Leaf elemental tissue analysis, pecan tree trunk growth, pecan yield, quality, and alternate bearing intensity (*I*) suggest that pecan trees are unaffected by differences in the fertilizer sources used in this study on the acidic soils of the Southeastern U.S. Coastal Plain. N rate also had little influence on measured variables. Based on these results and, perhaps more directly, upon agronomic N use efficiency (AE_N), it appears that pecans can be more efficiently fertilized at N rates of 108 kg N/ha compared with 215 kg N/ha under Southeastern U.S. Coastal Plain conditions regardless of N source.**

Nitrogen is the most commonly applied nutrient in orchard crops and there are multiple options with regard to the form of N applied (Weinbaum et al., 1992). The effect of N on pecan yield and nut growth has been studied since 1918 (Skinner, 1922). Numerous studies have assessed various rates (Hunter and Hammar, 1947; Skinner, 1922; Smith et al., 1985; Worley, 1974), application timings (Acuna-Maldonado et al., 2003; Smith, 1991; Smith et al., 1995, 2004), and areas of application within the orchard (Wells, 2013); however, little attention has been given to the suitability of various forms of N for pecan in Southeastern U.S. orchard systems characterized by acidic soils. Although N is a major component of pecan nutrient management, pecan tree response to N has been variable in multiple studies throughout the years (Hunter and Lewis, 1942; Smith et al., 1985; Storey et al., 1986; Worley, 1974, 1990).

Ammonium nitrate and urea are the most common forms of dry N fertilizer applied in southeastern U.S. pecan orchards. Ammonium nitrate is decreasing in popularity as a result of cost, and the risk potential for use in terroristic activities and storage-related problems.

Urea is the most widely used dry N fertilizer in the world. After application, urea is converted to ammonia (NH_3), which is then held in the soil or converted into nitrate (NO_3); however, NH_3 can be readily lost to volatilization under certain conditions (Havlin et al., 2005).

In the arid southwestern United States, AS is commonly used in pecan orchards as the N source where dry fertilizer is used. Pecan producers in the humid southeastern United States more commonly use the AN or urea forms of dry N fertilizer. The disparity between N source in the regions is likely the result of the hyperacidifying properties of AS. Because of the alkaline soils of the southwestern United States, the acidification resulting from the application of AS can be beneficial and is only rarely a cause of concern regarding the lowering of soil pH. However, in the acidic soils of the southeastern United States, further acidification can potentially lead to interference with plant uptake of macronutrients from the soil.

Kim et al. (2002) evaluated the effect of N form on growth, development, and nutrient uptake of hydroponically grown pecan seedlings; however, comparisons of N form on yield and growth parameters of mature pecan trees under orchard conditions is lacking.

N fertilization is a major component of pecan nutrient management and is a significant cost for producers (Weinbaum et al., 1992). A better understanding of the efficacy of various N forms on pecan tree production would help growers make more sound decisions regarding the fertilization of their orchards. The objective of this study was to investigate the effects of various dry N fertilizer sources at varying rates on pecan leaf tissue nutrient concentration, leaf chlorophyll index, trunk circumference growth, pecan yield, nut weight, percent kernel, pecan tree yield efficiency, and alternate bearing.

Materials and Methods

Study site, experimental design, and soil sampling. Studies were conducted at the University of Georgia Ponder Research Farm located near Tifton, GA, at lat. 31°51′N and long. –83°64′W. Orchard soils were Tifton loamy sand (fine-loamy, siliceous, thermic Plinthic Paleudult). The study was conducted from 2015 to 2018 using ‘Desirable’ pecan trees with a 12.2- × 12.2-m spacing planted in 2008. All drip emitters were ported to the soil surface. The orchard was managed under commercial conditions according to University of Georgia Cooperative Extension recommendations (Wells, 2007). A 3.7-m-wide vegetation-free strip was maintained with the herbicide glyphosate along the tree row in all plots. Row middles consisted of bermudagrass (*Cynodon dactylon* L.) sod.

The following treatments were evaluated: 1) Ammonium nitrate (34N–0P–0K) at 1.8 kg N per tree (AN1.8); 2) ammonium nitrate (34N–0P–0K) at 3.6 kg N per tree (AN3.6); 3) ammonium sulfate at 1.8 kg N per tree (AS1.8); 4) ammonium sulfate at 3.6 kg N per tree (AS3.6); 5) urea at 1.8 kg N per tree (U1.8); 6) urea at 3.6 kg per tree (U3.6); and 7) untreated control (C). Nitrogen rates used in these treatments are equivalent to 108 kg N/ha and 215 kg N/ha. Treatments were arranged in a randomized complete block design using four blocks, with each treatment represented once per block. Single-tree plots were used with guard trees between treated trees. Individual trees received the same treatments from one year to the next throughout the course of the study.

Fertilizer N treatments were applied on 8 Apr. 2015, 5 Apr. 2016, 31 Mar. 2017, and 9 Apr. 2018. All fertilizer was applied as a broadcast application within the weed-free strip under the tree canopy of individual trees. Dolomitic lime was applied at 2240 $kg \cdot ha^{-1}$ in Feb. 2016 and 2018. Phosphorus (P) was applied at 44.8 $kg \cdot ha^{-1}$ in Mar. 2015 and 2017 to provide P. Potassium (K) was applied at 56 $kg \cdot ha^{-1}$ in Mar. 2015 and 2017.

Foliage was sampled in late July of each study year by collecting 30 leaflet pairs per tree. All leaflet samples were taken from the middle leaf of sun-exposed terminals. Leaflet samples were washed in a dilute phosphate-free detergent solution (0.1% detergent), followed by rinsing with deionized water. Leaves were then dried to a constant weight at 80°C and ground in a Wiley Mill (Wiley, Philadelphia, PA) to pass a 1-mm screen. Leaves for N analysis were ground with mortar and pestle. Samples were analyzed for N by combustion using a Leco FP528 protein/N determinator (Leco Corp., St. Joseph, MI). Trunk diameter was measured 30 cm above the soil surface in Mar. 2015 and again in Oct. 2018.

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Table 1. Pecan leaf nutrient concentration for ammonium nitrate at 1.8 kg N per tree (AN1.8), ammonium nitrate at 3.6 kg N per tree (AN3.6), ammonium sulfate at 1.8 kg N per tree (AS1.8), ammonium sulfate at 3.6 kg N per tree (AS3.6), urea at 1.8 kg N per tree (U1.8), urea at 3.6 kg N per tree (U3.6), and untreated controls.

		Leaf element concn										
Yr	Treatment	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	S (%)	B (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
2015												
	AN1.8	2.76 ab[z]	0.14 a	1.37 a	0.46 a	2.17 b	0.25 ab	58 a	57 a	589 a	61 a	11 a
	AN3.6	2.99 a	0.14 a	1.27 a	0.46 a	1.93 b	0.23 b	60 a	55 a	567 a	59 a	10 a
	AS1.8	2.72 b	0.14 a	1.36 a	0.46 a	2.14 b	0.25 ab	58 a	66 a	514 a	61 a	11 a
	AS3.6	3.01 a	0.12 a	1.19 b	0.45 a	1.87 b	0.24 ab	56 a	37 b	653 a	60 a	10 a
	U1.8	2.97 a	0.13 a	1.18 b	0.44 a	1.92 b	0.24 ab	59 a	50 ab	541 a	60 a	11 a
	U3.6	2.66 b	0.14 a	1.37 a	0.46 a	2.35 a	0.26 a	60 a	59 a	524 a	63 a	10 a
	Control	2.54 c	0.15 a	1.36 a	0.46 a	2.33 a	0.23 a	53 a	63 a	546 a	53 b	10 a
2016												
	AN1.8	2.76 a	0.13 a	1.16 a	0.47 a	2.28 a	0.22 a	57 a	67 a	936 a	57 a	9 a
	AN3.6	2.69 a	0.14 a	1.08 a	0.49 a	2.28 a	0.20 a	55 a	86 a	844 ab	58 a	8 a
	AS1.8	2.70 a	0.12 a	1.11 a	0.46 a	2.22 a	0.22 a	52 a	71 a	696 b	52 a	9 a
	AS3.6	2.78 a	0.12 a	1.04 a	0.49 a	2.39 a	0.22 a	57 a	73 a	937 a	54 a	8 a
	U1.8	2.69 a	0.13 a	1.15 a	0.48 a	2.22 a	0.20 a	58 a	64 a	740 b	53 a	8 a
	U3.6	2.66 a	0.13 a	1.11 a	0.47 a	2.41 a	0.22 a	58 a	76 a	899 a	56 a	8 a
	Control	2.31 b	0.14 a	1.10 a	0.48 a	2.38 a	0.21 a	48 b	85 a	565 c	58 a	9 a
2017												
	AN1.8	2.81 a	0.14 a	1.39 a	0.44 a	1.95 a	0.22 a	58 a	90 a	772 a	84 b	9 a
	AN3.6	2.82 a	0.14 a	1.25 a	0.40 a	2.07 a	0.22 a	56 a	95 a	983 a	59 b	9 a
	AS1.8	2.76 a	0.13 a	1.21 a	0.39 a	2.04 a	0.21 a	49 a	85 a	1,018 a	61 b	9 a
	AS3.6	2.89 a	0.12 a	1.22 a	0.41 a	1.89 a	0.23 a	55 a	94 a	1,074 a	104 a	9 a
	U1.8	2.80 a	0.14 a	1.28 a	0.41 a	2.08 a	0.23 a	55 a	89 a	733 a	86 b	9 a
	U3.6	2.79 a	0.14 a	1.44 a	0.44 a	2.09 a	0.24 a	60 a	93 a	903 a	67 b	10 a
	Control	2.63 a	0.14 a	1.36 a	0.41 a	2.06 a	0.22 a	65 a	114 a	798 a	86 b	9 a
2018												
	AN1.8	2.60 a	0.13 a	1.18 a	0.50 a	2.34 a	0.22 a	69 a	80 a	844 a	68 a	9 a
	AN3.6	2.58 a	0.14 a	1.20 a	0.40 a	2.10 a	0.23 a	58 a	104 a	972 a	63 a	10 a
	AS1.8	2.75 a	0.14 a	1.20 a	0.47 a	2.19 a	0.22 a	68 a	95 a	802 a	51 a	9 a
	AS3.6	2.71 a	0.13 a	1.18 a	0.37 a	2.07 a	0.23 a	62 a	93 a	1,286 a	56 a	10 a
	U1.8	2.55 ab	0.14 a	1.20 a	0.45 a	2.11 a	0.22 a	63 a	87 a	850 a	52 a	9 a
	U3.6	2.37 b	0.13 a	1.12 a	0.44 a	2.35 a	0.21 a	61 a	93 a	897 a	54 a	9 a
	Control	2.37 b	0.15 a	1.20 a	0.44 a	2.18 a	0.21 a	65 a	124 a	701 a	56 a	10 a

[z] Means followed by the same letter within each year are not different at $P < 0.05$ by Tukey's least significant difference test.

P = phosphorus; K = potassium; Mg = magnesium; Ca = calcium; S = sulfur; B = boron; Zn = zinc; Mn = manganese; Fe = iron; Cu = copper.

Table 2. Effect of nitrogen fertilizer source (NFS) and nitrogen fertilizer rate (NFR) on pecan leaf nitrogen concentration, 2015–18.

	Leaf nitrogen concn (%)[z]			
Treatment	2015	2016	2017	2018
NFS				
Ammonium nitrate	2.88 a[y]	2.72 a	2.81 a	2.59 a
Ammonium sulfate	2.86 a	2.74 a	2.83 a	2.73 a
Urea	2.82 a	2.67 a	2.79 a	2.46 b
NFR				
1.8 kg/tree	2.82 a	2.71 a	2.79 a	2.63 a
3.6 kg/tree	2.88 a	2.71 a	2.83 a	2.55 a
P value				
NFS	0.62	0.74	0.93	0.04
NFR	0.19	0.95	0.56	0.30
NFS × NFR	<0.001	0.70	0.67	0.68

[z] Recommended leaf sufficiency range for pecan in Georgia: N (%) = 2.5–3.0 (Wells, 2007).

[y] Means followed by the same letter within each year are not different at $P < 0.05$ by Tukey's least significant difference test.

Soil samples were taken at 15.2-cm depth from the vegetation-free strip adjacent to drip emitters in July 2018. Four soil cores per tree were combined for an individual sample per plot. Soil was dried and analyzed for pH. Soil pH was determined in a 0.01-M calcium chloride solution using a LabFit AS-3000 (LabFit, Perth, Australia) dual pH analyzer. Rainfall was recorded from a weather station at the study site.

At harvest, nuts were shaken from the trees onto a tarp under each tree, and all nuts were hand-harvested and weighed. Nuts were separated from leaves, shucks, and debris using a Savage (Madill, OK) pecan cleaner. A 50-nut sample was collected from each tree for analysis of individual nut weight and percent kernel. Nuts were shelled and percentage of edible kernel was calculated by dividing the kernel weight for the 50-nut sample by total nut weight.

Fluctuation in yield was expressed in terms of I, calculated as $I = 1/(n - 1) \times [|(Y_1 - Y_2)|/(Y_1 + Y_2) + |(Y_2 - Y_3)|/(Y_2 + Y_3) + \ldots |(Y_{n-1} - Y_n)|/(Y_n - 1 + Y_n)]$, where n is number of years and Y is tree yield for the corresponding year (Conner and Worley, 2000; Pearce and Dobersek-Urbanc, 1967). Agronomic N use efficiency (AE_N), defined as pecan yield per unit N applied, was determined by dividing yield (measured in kilograms per tree) by the total amount of fertilizer N applied (measured in kilograms per tree).

Statistical analyses of data were performed with SAS (SAS version 9.4; SAS Institute, Cary, NC). One-way analysis of variance (ANOVA) was used to compare treatment effects to that of the control. Two-way ANOVA was used to compare N fertilizer source and rate effects among treatments receiving N application. Means were separated using Tukey's least significant difference test ($P < 0.05$).

Results and Discussion

Pecan leaf tissue. All treatments increased ($P < 0.05$) leaf N concentration over that of the control in 2015 and 2016 (Table 1). Leaf N concentration of the control was below the recommended sufficiency range (2.5% to 3.0%) for pecans in Georgia (Wells, 2007) only during 2016 and 2018 (Table 1). Control treatments received minimal amounts of N when P was applied as diammonium phosphate in 2015 and 2017, which was enough to bring leaf N concentrations of control trees above the minimum sufficiency level. Kim et al. (2002) demonstrated that seedling pecan trees preferentially

Table 3. Effect of nitrogen fertilizer source (NFS) and nitrogen fertilizer rate (NFR) on soil pH (2018) and pecan leaf chlorophyll index, 2018.

Treatment	Soil pH	Pecan leaf chlorophyll index
NFS		
Ammonium nitrate	6.4 a^z	25.8 a
Ammonium sulfate	5.8 b	30.6 a
Urea	6.2 a	29.8 a
NFR		
1.8 kg/tree	6.3 a	28.7 a
3.6 kg/tree	5.9 a	28.8 a
P value		
NFS	0.05	0.28
NFR	0.14	0.37
NFS × NFR	0.84	0.76

^{z}Means followed by the same letter are not different at $P < 0.05$ by Tukey's least significant difference test.

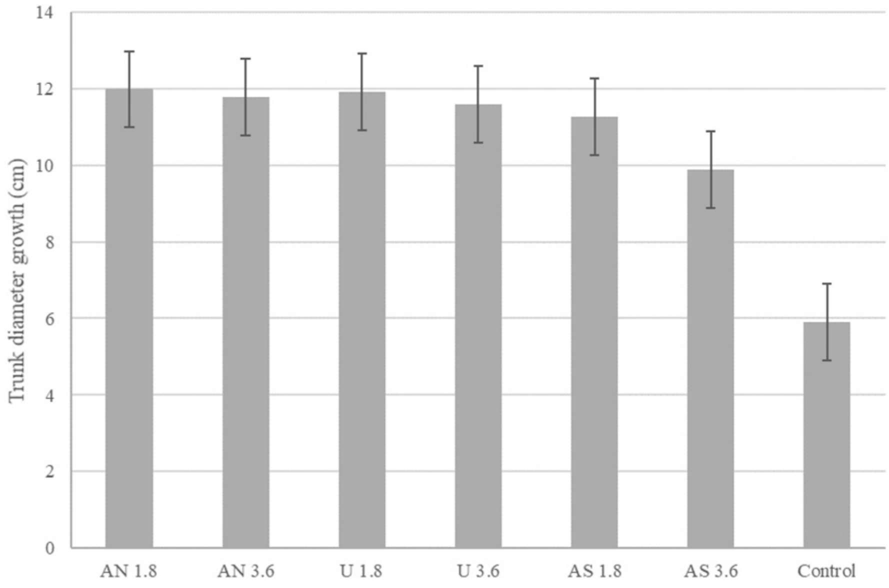

Fig. 1. Pecan tree trunk diameter growth from 2015 to 2018 for 'Desirable' pecan trees fertilized with ammonium nitrate at 1.8 kg N per tree (AN1.8), ammonium nitrate at 3.6 kg N per tree (AN3.6), ammonium sulfate at 1.8 kg N per tree (AS1.8), ammonium sulfate at 3.6 kg N per tree (AS3.6), urea at 1.8 kg N per tree (U1.8), urea at 3.6 kg N per tree (U3.6), and untreated controls.

take up ammonium (NH_4) over NO_3. Nitrate and ammonium are the major sources of N for plants. Nitrate is recognized as the main N source for plants under normal soil conditions.

During 2018, all treatments except urea at both rates significantly ($P < 0.05$) increased leaf N over that of the control (Table 1). Optimal conditions for performance of surface applications of urea exist when 0.25 cm or more of rainfall occur within the first 3 to 6 d after application, which minimizes NH_3 volatilization (Havlin et al., 2005). Rainfall at the study site during the month of Apr. 2018 only totaled 7.39 cm, compared with 17.55, 13.97, and 7.92 cm for 2015, 2016, and 2017, respectively. Average high air temperatures for the 7 d after N fertilizer application was 27.8, 23.3, 26.7, and 23.9 °C in 2015, 2016, 2017, and 2018, respectively. It is possible that urea was not as effective at increasing leaf N concentrations as AN and AS in 2018 due to NH_3 volatilization, resulting from the combination of cooler temperatures and lack of rainfall after surface application in Apr. 2018.

Among N fertilizer treatments, leaf N was affected by N fertilizer source in only one year out of four (Table 2). This occurred in 2018 when urea leaf N concentration was significantly ($P < 0.05$) less than that of AN and AS (Table 2). Nitrogen rate had no effect on leaf N concentration (Table 2). There was an N fertilizer source × rate interaction in 2015 (Table 2). For AS and AN, the greatest N rate had greater ($P < 0.05$) leaf N concentrations in 2015. Leaf N concentration for U1.8 was greater ($P < 0.05$) than that of U3.6 (Table 1). This may be a result of excessive losses of NH_3 with urea due to more volatilization at the greater N rate, as has been previously suggested (Havlin et al., 2005; Wood, 2001). In all other years there was no source × rate interaction (Table 2).

Leaf K was reduced in 2015 with the AS3.6 treatment and the U1.8 treatment when compared with all other treatments (Table 1). These two treatments, along with AN3.6, had the greatest leaf N concentrations during that year. Sparks (1989) previously suggested that excessive N application can limit uptake of K. Leaf calcium (Ca) concentration was greater with the U3.6 treatment and in the control compared with the remaining treatments in 2015, possibly as a result of localized soil acidification with the AN and AS treatments, which can limit Ca uptake (Table 1).

During 2016, all N treatments had greater leaf manganese (Mn) concentrations than that of the control (Table 1). Worley (1997) observed a reduction in pH and resulting loss of soil cations and increase in leaf Mn in the fertilized part of the pecan root zone. The low rate of AN and the high rates of AS and urea had greater leaf concentrations of Mn than the high rates of AS and urea in 2016 (Table 1). Kim et al. (2002) reported levels of Ca, magnesium (Mg), and Mn in leaves were greater with an NH_4:NO_3 ratio of 25:75 than 75:25. This suggests that greater rates of NH_4-based fertilizers can potentially contribute to reduced leaf concentrations of Ca, Mg, and Mn. Leaf iron (Fe) concentration was greater with all N treatments than in the control in 2015. Leaf Fe was enhanced with the AS3.6 treatment compared with all other treatments in 2017 (Table 1).

Nitrogen appears to affect the zinc (Zn) status of crops by both promoting plant growth and by changing the pH of the root environment (Storey, 2007). Leaf Zn concentration was reduced with the greatest rate of AS in 2015 in the current study (Table 1). Although AS did reduce soil pH (Table 3), it has been observed that applications of N in the absence of Zn can lead to Zn deficiency through a dilution effect brought about by an increase in growth resulting from the N application (Loneragan and Webb, 1993). Although acidifying N fertilizers such as AS can lead to an increase in the availability of Zn in soils of relatively high pH status, this was not observed in the naturally acidic soils of the current study. Sparks (1989) suggested that adequate Zn leaf concentrations can be maintained on acidic soils, even with liming, when Zn is also applied. Thus, it is more likely that Zn deficiencies may occur in pecans grown in acidic soils as a result of the dilution effect from overfertilizing with N, or potentially from interactions with other nutrients rather than from changes in soil pH.

Fertilizer N treatments did not affect soil pH compared with the control in the current study.

Table 4. Pecan yield, nut weight, and percent kernel for ammonium nitrate at 1.8 kg N per tree (AN1.8), ammonium nitrate at 3.6 kg N per tree (AN3.6), ammonium sulfate at 1.8 kg N per tree (AS1.8), ammonium sulfate at 3.6 kg N per tree (AS3.6), urea at 1.8 kg N per tree (U1.8), urea at 3.6 kg N per tree (U3.6), and untreated controls.

Yr	Treatment	Yield (kg per tree)	Nut wt (g)	Kernel (%)
2015				
	AN1.8	9 a^z	13.5 a	51.9 a
	AN3.6	7.5 a	13.3 a	51.5 a
	AS1.8	7.8 a	13.7 a	53.8 a
	AS3.6	10.5 a	13.3 a	47.8 a
	U1.8	8.7 a	13.4 a	50.2 a
	U3.6	7.0 a	12.6 a	49.3 a
	Control	3.7 a	12.9 a	47.0 a
2016				
	AN1.8	14.7 c	10.0 a	58.5 a
	AN3.6	19.1 b	10.6 a	58.1 a
	AS1.8	23.7 a	10.4 a	57.6 a
	AS3.6	24.1 a	9.4 a	56.7 a
	U1.8	22.2 ab	9.6 a	56.3 a
	U3.6	22.4 ab	10.3 a	57.5 a
	Control	16.3 c	9.8 a	60.2 a
2017				
	AN1.8	17.1 a	11.3 a	51.9 a
	AN3.6	23.6 a	10.9 a	51.1 a
	AS1.8	25.6 a	11.0 a	52.4 a
	AS3.6	13.3 a	11.6 a	50.6 a
	U1.8	7.7 a	11.7 a	49.8 a
	U3.6	17.8 a	11.0 a	55.4 a
	Control	12.4 a	10.6 a	52.5 a
2018				
	AN1.8	35.9 a	11.1 a	55.7 a
	AN3.6	25.5 a	10.7 a	55.6 a
	AS1.8	31.8 a	11.1 a	54.9 a
	AS3.6	29.3 a	10.7 a	54.5 a
	U1.8	28.6 a	11.2 a	54.0 a
	U3.6	30.1 a	11.2 a	54.8 a
	Control	16.5 b	11.3 a	56.3 a

^{z}Means followed by the same letter are not different at $P < 0.05$ by Tukey's least significant difference test.

Table 5. Effect of nitrogen fertilizer source (NFS) and nitrogen fertilizer rate (NFR) on pecan tree yield, 2015–18.

	Yield (kg per tree)			
Treatment	2015	2016	2017	2018
NFS				
Ammonium nitrate	3.8 a^z	16.9 b	20.4 a	30.7 a
Ammonium sulfate	4.1 a	23.9 a	19.5 a	30.5 a
Urea	3.6 a	22.3 a	12.7 a	24.2 a
NFR				
1.8 kg/tree	3.2 a	16.6 a	13.8 a	26.4 a
3.6 kg/tree	3.1 a	18.0 a	15.0 a	23.3 a
P value				
NFS	0.94	<0.001	0.30	0.95
NFR	0.95	0.12	0.75	0.31
NFS × NFR	0.80	0.19	0.10	0.42

^{z}Means followed by the same letter are not different at $P < 0.05$ by Tukey's least significant difference test.

Among N treatments, AS reduced ($P < 0.05$) soil pH compared with the other N fertilizer treatments during the last year of the study (Table 3). After their transformation to NO_3-N, AN, AS, and urea fertilizers can have an acidifying effect on the soil to which they are applied (Havlin et al., 2005; Haynes, 1990; Singh, et al., 1984). Fertilizer rate had no effect on soil pH in the current study (Table 3). The limited effect of N fertilizer treatments on soil pH found here are likely the result of lime application in 2016 and 2018. Sparks (1989) stated that N fertilizer in which all or part of the N is in the NH_4 form will reduce orchard soil pH, whereas N applied in the NO_3 form does not reduce, and may slightly increase, soil pH in southeastern pecan orchards. Furthermore, Sparks (1989) stated that lime counteracts the effects of N fertilization on the acidic soils found in southeastern U.S. pecan orchards.

Pecan leaf chlorophyll index was unaffected by fertilizer source or rate (Table 3). Pecan trunk diameter growth was greater with all N fertilizer treatments than in the control (Fig. 1). These results support that of previous studies that have demonstrated a similar pecan growth response to N (Blackmon and Ruprecht, 1934; Hunter and Lewis, 1942; Wells, 2015). Among N fertilizer treatments, pecan trunk diameter growth was not influenced by N fertilizer source or by N fertilizer rate. Smith et al. (2004) also demonstrated N rate did not affect trunk growth of fertilized pecan trees.

Yield was affected by N fertilizer treatment in 2016 and 2018 (Table 4). All N treatments except AN1.8 increased pecan yield over that of the control in 2016. Pecan yields for all N treatments were higher than that of the control in 2018 (Table 4). N fertilizer source only affected pecan yield in 2016, when yield was reduced ($P < 0.05$) for AN compared with AS and urea (Table 5). Among N treatments, N rate had no effect on pecan yield and there were no interactions between N fertilizer source and rate for pecan yield (Table 5). Neither pecan nut weight nor percent kernel was affected by N treatments (Table 4). These results suggest that among the N fertilizer sources used in the current study, differences in the form of N fertilizer rarely influence pecan yield under southeastern U.S. orchard conditions.

Agronomic N use efficiency was greater ($P < 0.05$) for AS and urea than for AN in 2016 (Table 6). Agronomic N use efficiency was greater ($P \geq 0.05$) at the low rate of N fertilizer among all N treatments in 2016, 2017, and 2018 (Table 6). There was an N fertilizer source × rate interaction ($P < 0.05$) in 2016 (Table 6). For AN, AS, and urea, AE_N was greatest ($P \leq 0.05$) at the lowest N rate (Table 6). These results suggest that N fertilizer rate has a greater effect on AE_N than the N fertilizer source, which supports the results of Smith et al. (2004).

Alternate bearing intensity was greater in the control and with the U1.8 treatment between the 2016 and 2017 growing seasons (Table 7). Throughout the course of the 4-year study, I was greater ($P < 0.05$) in the

Table 6. Effect of nitrogen fertilizer source (NFS) and nitrogen fertilizer rate (NFR) on agronomic N use efficiency (AE_N), 2015–18.

	AE_N ($kg\cdot kg^{-1}$)			
Treatment	2015	2016	2017	2018
NFS				
Ammonium nitrate	3.2 a^z	13.4 b	15.9 a	26.8 a
Ammonium sulfate	3.3 a	19.7 a	17.8 a	25.6 a
Urea	3.1 a	18.4 a	9.2 a	24.1 a
NFR				
1.8 kg/tree	4.3 a	22.3 a	18.5 a	35.3 a
3.6 kg/tree	2.1 a	12.1 b	10.1 b	15.6 b
P value				
NFS	0.99	<0.001	0.20	0.82
NFR	0.09	<0.001	0.04	<0.001
NFS × NFR	0.87	0.007	0.08	0.49

^{z}Means followed by the same letter are not different at $P < 0.05$ by Tukey's least significant difference test. Agronomic N use efficiency (AE_N) = Pecan yield ($kg\cdot ha^{-1}$)/Total amount of fertilizer N applied ($kg\cdot ha^{-1}$) per field hectare.

Table 7. Alternate bearing intensity (I) of 'Desirable' pecan trees for ammonium nitrate at 1.8 kg nitrogen (N)/tree (AN1.8), ammonium nitrate at 3.6 kg N per tree (AN3.6), ammonium sulfate at 1.8 kg N per tree (AS1.8), ammonium sulfate at 3.6 kg N per tree (AS3.6), urea at 1.8 kg N per tree (U1.8), urea at 3.6 kg N per tree (U3.6), and untreated controls from 2015 to 2018.

Treatment	2015–16	2016–17	2017–18	2015–18
AN1.8	0.60 a^z	0.18 b	0.38 a	0.39 bc
AN3.6	0.71 a	0.11 b	0.09 a	0.30 c
AS1.8	0.77 a	0.19 b	0.25 a	0.40 bc
AS3.6	0.70 a	0.46 b	0.44 a	0.40 bc
U1.8	0.70 a	0.55 a	0.55 a	0.60 ab
U3.6	0.75 a	0.18 b	0.31 a	0.41 b
Control^y	0.84 a	0.69 a	0.59 a	0.71 a

^{z}Means followed by the same letter are not different at $P < 0.05$ by Tukey's least significant difference test.
$I = 1/(n-1) \times [|(Y_1 - Y_2)|/(Y_1 + Y_2) + |(Y_2 - Y_3)|/(Y_2 + Y_3) + \ldots |(Y_n - 1 - Y_n)|/(Y_n - 1 + Y_n)]$, where n is number of years and Y is tree yield for the corresponding year (Pearce and Dobersek-Urbanc, 1967).

Table 8. Effect of nitrogen fertilizer source (NFS) and nitrogen fertilizer rate (NFR) on alternate bearing intensity (I), 2015–18.

	I			
Treatment	2015–16	2016–17	2017–18	2015–18
NFS				
Ammonium nitrate	0.66 a^z	0.14 a	0.26 a	0.34 a
Ammonium sulfate	0.73 a	0.36 a	0.34 a	0.40 a
Urea	0.73 a	0.33 a	0.43 a	0.51 a
NFR				
1.8 kg/tree	0.69 a	0.31 a	0.39 a	0.46 a
3.6 kg/tree	0.72 a	0.25 a	0.29 a	0.37 a
P value				
NFS	0.83	0.13	0.48	0.13
NFR	0.79	0.53	0.39	0.18
NFS × NFR	0.79	0.03	0.21	0.47

^{z}Means followed by the same letter within each year are not different at $P < 0.05$ by Tukey's least significant difference test.

control than all other treatments except for the low rate of urea, suggesting that N fertilization usually minimized alternate bearing. From 2015 to 2018, the lowest I was observed in the AN3.6 treatment; however, this did not differ significantly from any other treatments except for both urea treatments and the control (Table 7). Among N fertilizer treatments, neither N fertilizer source nor N fertilizer rate affected I; however, there was an N fertilizer rate × source interaction between the 2016 and 2017 growing seasons, in which I was greater for U1.8 compared with U3.6 (Table 8). The negative effect of a greater I occasionally observed in urea treatments may have resulted from volatilization losses of NH_3 with urea treatments, which would have reduced available N for the trees.

Leaf elemental tissue analysis, pecan tree trunk growth, pecan yield, quality, and I suggest that pecan trees are unaffected by differences in the fertilizer sources used in the current study under most conditions for the acidic soils of the Southeastern U.S. Coastal Plain. This result suggests that pecan producers in this region should base their choice of fertilizer N source on the price difference between these sources from one year to the next, which can potentially enhance the profitability of pecan production. However, consideration must be given to the influence of environmental conditions (temperature and soil moisture) on the availability of N using various N sources.

Numerous studies have indicated that pecans respond to N only up to a certain point, at which excessive application rates lead to shoot growth suppression (Sparks and Baker, 1975), reduced percent kernel and oil content (Hunter, 1964), and reduced nut size (Storey et al., 1986). Based on these results, and perhaps more directly on AE_N, it appears that pecans can be more efficiently fertilized at N rates of 108 kg N/ha compared with 215 kg N/ha. This supports previous work (Wells, 2013; Worley, 1990) demonstrating that N rates should be between 112 and 140 $kg\cdot ha^{-1}$ for intensively managed commercial pecan orchards in the southeastern United States.

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