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Long-term Response to Phosphorus Banding in Irrigated and Nonirrigated Pecan Production

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***Abstract*. An experiment was conducted to determine the effects of banded phosphorus (P) applications at differing rates in irrigated and nonirrigated pecan (*Carya illinoinensis*) plots on P movement within the soil, P uptake and movement within pecan trees, and the yield and quality of nuts. On 20 Mar. 2015, P applications of 0 kg·ha^{-1} (0×), 19.6 kg·ha^{-1} (1×), 39.2 kg·ha^{-1} (2×), and 78.5 kg·ha^{-1} (4×) were administered to bands of triple superphosphate to randomly selected trees in nonirrigated and irrigated plots of a 'Desirable' orchard bordered by 'Elliot' trees. When P was applied at the 2× and 4× rates, the total soil test P decreased linearly by 35% and 54%, respectively, in nonirrigated plots and by 41% and 59%, respectively, in irrigated plots over the course of the experiment. There was no change in soil test P over time at the 0× rate for either irrigation regimen; however, at the 1× rate, soil test P decreased 44% in the irrigated plot but did not change in the nonirrigated plot. The largest linear decrease of the soil test P from the start of the experiment to the end of the experiment occurred in the top 0 to 7.6 cm. In contrast, soil test P at a depth of 15.2 to 22.9 cm decreased linearly by 23% in the nonirrigated plot, but it did not decrease over time in the irrigated plot. Increasing the P application rate increased foliar P quadratically in the nonirrigated plot, but only the 4× application rate increased foliar P compared with the 0× control. In the irrigated plot, foliar P concentrations decreased linearly from 2015 to 2017, and foliar P concentrations were not influenced by the P application rate. No differences in pecan yield or quality were observed in either irrigated or nonirrigated plots. Overall, P banding may not be the most sustainable way to increase foliar concentrations of P quickly or to maintain concentrations of the nutrient in the long term.**

Approximately 3.1 million kg (6.8 million lb) of pecans were produced in Alabama in 2013 (Brown, 2013). The majority of production occurred in the southwest corner of the state in Mobile and Baldwin counties. Soils in those counties are mostly sandy loams and are typical of pecan orchards throughout the southeastern United States. Growers often experience difficulties maintaining recommended foliar phosphorus (P) levels in their orchard trees due to naturally low P in the soils and the nature of the movement and adsorption of P in those soils.

Recommendations for adequate foliar P concentrations in pecan vary; however, observations have shown that visual symptoms of P deficiency can be expected at foliar concentrations less than ≈0.11% (Alben, 1947; Sparks, 1978, 1986). The current standard recommendation for adequate foliar P is 0.14% (Smith, 2010; Smith et al., 2012). Pecan fertilizer recommendations are often based on a combination of the current year's soil test data and the previous year's foliar nutrient concentration data, with the latter considered more important. When correcting P deficiency, other essential plant nutrients must be considered because high concentrations of P can inhibit the uptake of nitrogen (N), iron (Fe), zinc (Zn), and copper (Cu) in pecan (Sparks, 1988; Wells, 2007).

In most soils, P is relatively immobile, and although it is often applied in combination with N and potassium (K), it is required in much lower quantities by plants. Therefore, a single broadcast application of 29.4 to 49 kg·ha^{-1} (26.2 to 43.7 lb/ac) P incorporated at planting can be adequate for several years during orchard establishment (Wells, 2007). The immobility of P in soils may result in the observed ineffectiveness of broadcast applications for correcting short-term deficiencies in established orchards (Alben and Hammar, 1964; Hunter and Hammar, 1947, 1952, 1957; Smith et al., 1960; Sparks, 1988; Worley, 1974). As a result, Sparks (1988) reported that 2.2 kg P per 6 m^2 per tree was required to significantly increase P concentrations in pecan leaves. Due to tree spacing, the rate reported by Sparks was not easily interpreted in the initial publication, and later interpretations ranged from 3670 kg·ha^{-1} (3274 lb/ac) (Smith and Cheary, 2013) to 14,985 kg·ha^{-1} (13,369 lb/ac) P per year (Worley, 2002). Broadcast applications at extremely high rates should be discouraged due to potential environmental contamination.

Previous research indicated that banded applications of P increase foliar P when applied annually at the rate of 127.3 kg·ha^{-1} (113.6 lb/ac) P (Smith and Cheary, 2013). Banded P applications increased leaf P concentrations, ameliorated foliar deficiency symptoms, and increased return bloom. However, Smith and Cheary (2013) also reported kernel darkening in response to repeated P banding. The reported kernel darkening is in contrast to the results of a previous study that reported that P application improved the color quality of pecans (Smith, 2010). Whether the reported kernel darkening was due to cultivar response, drought stress conditions, P banding, or some combination thereof is unknown (Smith and Cheary, 2013). The reported positive benefits of P banding have outweighed the negative for many growers in the southeast who have adopted it as a standard practice. Thus far, there have been no reports of observed kernel darkening due to P banding in Alabama.

The positive effects of irrigation on pecan are well-known and include precocity, increased nut size and yield, and improved nut quality (Alben, 1957; Brison, 1974; Daniell et al., 1979; Stein et al., 1989; Wells, 2015; Worley, 1982). The current recommended irrigation schedule for pecan in the southeast was established by Wells (2007) based on the data of Daniell (1985). Adequate soil moisture is important for pecans during the nut filling stage in August and September (Wells 2015). The adoption of irrigation practices among Alabama pecan growers has been slow, but some larger growers have started to invest in the required infrastructure.

The P banding study by Smith and Cheary (2013) was conducted in an irrigated orchard, but under drought conditions. Irrigation efficacy was compromised at the height of the drought because the irrigation source became unusable (M.W. Smith, personal communication). According to a separate and unrelated meta-analysis of the effects of drought stress on plant P concentrations, He and Dijkstra (2014) reported that drought stress may reduce P concentrations in plants by up to 9.18%. Despite the negative effects of drought stress, increased foliar P was observed with annual banded applications of 127.3 kg·ha^{-1} (113.6 lb/ac) P (Smith and Cheary, 2013).

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Phosphorus banding has yet to be replicated in an irrigated or nonirrigated environment like that present in the southern portion of Alabama. Additionally, the effects of a one-time band application have not been observed, nor have those of lesser, more sustainable application rates. An experiment was designed to determine the efficacy of a single P band at selected rates on soil test P and P uptake by plants over multiple years in a typical nonirrigated and irrigated Alabama pecan orchard.

Materials and Methods

The experiment was conducted at the Gulf Coast Research and Extension Center in Fairhope, AL. The soil type of the orchard was a mixture of a Greenville loam and an Orangeburg fine sandy loam. The mature orchard comprised 'Desirable' trees planted with 12 × 12-m (40 × 40-ft) spacing or ≈66 trees/ha (27 trees/ac). Six 49-m (160-ft) rows of 'Desirable' trees were bordered on all sides by a row of 'Elliot' trees. All trees in the orchard were originally grafted to open-pollinated 'Elliot' seedling rootstocks. The orchard had a recorded history of difficulty maintaining adequate foliar P concentrations that, along with the reduced alternate bearing of 'Desirable', made it ideal for the research conducted. The orchard was scouted frequently for pests and pathogens and treated as necessary. This was especially important because 'Desirable' is susceptible to pecan scab (*Fusicladium effusum*), which is endemic in the region.

For irrigation, the orchard was split into equal halves, with each half (plot) being treated as a separate experiment. A border row of 'Desirable' trees separated the plots to prevent water from the irrigated plot from crossing over into the nonirrigated plot. The existing sub-surface drip irrigation system in the orchard was turned off in the nonirrigated plot, so the trees only received natural rainfall (Table 1). Trees in the irrigated plot received supplemental irrigation to meet the requirements outlined by Wells (2007) (Table 1). The irrigation regimen was suspended for a 3-d period if rainfall of 2.54 cm (1 inch) or more occurred. The irrigation system was a sub-surface drip system with five emitters per tree, and each emitter delivered 3.8 $L\cdot h^{-1}$ when in use.

Table 1. Rainfall totals and supplemental irrigation in nonirrigated and irrigated 'Desirable' orchards from 2015 to 2017.[z]

	Yr and irrigation					
	2015		2016		2017	
Month	N	I	N	I	N	I
Apr.	26.6	26.6	17.1	17.1	8.5	8.5
May	6.7	6.7	7.5	7.5	27.5	27.5
June	12.8	15.3	11.2	13.8	31.5	32.5
July	17.1	19.0	13.0	15.0	19.8	21.8
Aug.	13.6	24.8	21.7	25.6	34.7	35.9
Sept.	9.1	23.4	16.1	25.2	2.2	20.5
Oct.	13.1	19.7	0.4	7.5	35.1	35.1
Nov.	16.7	16.7	1.6	3.6	0.4	4.2

[z]Rainfall totals are presented in centimeters.
I = irrigated; N = nonirrigated.

Phosphorus was applied in the form of triple superphosphate (0N–20.1P–0K). The rates applied were based on the standard broadcast recommendation [19.6 $kg\cdot ha^{-1}$ (17.5 lb/ac) of P] to correct P deficiency (Wells, 2007). Treatment levels were equivalent to 0 $kg\cdot ha^{-1}$ (0 lb/ac), 19.6 $kg\cdot ha^{-1}$ (17.5 lb/ac), 39.2 $kg\cdot ha^{-1}$ (35 lb/ac), and 78.5 $kg\cdot ha^{-1}$ (70 lb/ac) P, which are hereafter referred to as 0×, 1×, 2×, and 4×, respectively. Bands of triple superphosphate at each rate were applied on 20 Mar. 2015 under the south-side dripline of each tree located ≈3 m (10 ft) from the base of the trunk. Each band measured 6 m (20 ft) long and was ≈10 cm (4 inches) wide. No other sources of P were applied for the duration of the experiment, but broadcast applications of N and K were applied to maintain or achieve the recommended foliar concentrations (Smith et al., 2012).

Soil samples were collected within the application strip from three experimental unit trees at each treatment level starting 2 months after initiation on 20 May 2015, and continuing at 2-month intervals until 20 July 2017. Three 22.5-cm (9-inch) core samples were collected within each band (tree) and were pooled in three 7.5-cm (3-inch) increments, hereafter referred to as top, middle, or bottom. Soil samples were not collected on 20 Sept. 2016 for nonirrigated trees due to moderate drought conditions. Standard soil analysis was performed to determine pH (McLean, 1982), organic matter (Schulte and Hopkins, 1996), estimated nitrogen release (Schulte and Hopkins, 1996), Bray I P (Bray and Kurtz, 1945), exchange capacity (Gavlak et al., 2003), percent base saturation of cations (Gavlak et al., 2003), and Mehlich III extractable P, manganese (Mn), Zn, boron (B), Cu, Fe, aluminum (Al), sulfur (S), calcium (Ca), magnesium (Mg), K, and sodium (Na) (Mehlich, 1984) (Brookside Laboratories, New Bremen, OH).

Foliar samples were collected from all experimental trees once per year on 20 July 2015, 2016, and 2017, which falls within the standard recommended time for the collection of foliar samples (Smith et al., 2012; Wells, 2007). Samples were collected from both the south (treated) and north (untreated) sides of the canopy. Each sample contained 20 middle leaflet pairs of the current season's growth. After drying, 1 g was used for analysis. Samples were digested according to procedures for wet acid digestion using nitric and perchloric acids described by Mills and Jones (1996). Concentrated samples were diluted in 20 mL deionized water and analyzed for elemental concentrations using inductively coupled plasma optical emission spectroscopy (Brookside Laboratories, New Bremen, OH).

Nut yield data were collected at the 50% shuck date, which for 'Desirable' occurred during the first week of Nov. 2015 and the first week of Nov. 2016. Yield data from 2017 were omitted due to a tropical weather system that caused the crop to fall early and mix on the orchard floor. The wedge method was used to determine total yield (Worley and Smith 1984). Quality data were collected from 40 nut samples taken in conjunction with those collected for yield in 2015 and 2016. Pecans were graded according to USDA guidelines (Goff et al., 1989; USDA, 1976).

An analysis of variance was performed for soil and foliar responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). Nonirrigated and irrigated data were analyzed as separate experiments. Soil data were analyzed as a split-split plot with the P rate in the main plot, sampling depth in the sub-plot, and sampling period in the sub-sub plot. Foliar data were analyzed as a split plot, with year in the main plot and application rate and side of application in the sub-plot. When residual plots and a significant covariance test indicated heterogeneous variance among treatments, a RANDOM statement with the GROUP option was used to correct heterogeneity. Least squares means are presented. Linear and quadratic trends regarding the P rate, sampling depth, and sampling period were tested using model regressions. All significance levels were set as $\alpha = 0.05$.

Results

The soil depth–P rate, P rate–sample date, and soil depth–sample date interactions were significant for soil test P in irrigated and nonirrigated plots. Over the course of the experiment, soil test P decreased linearly with increasing soil depth by 31% and 42% with the 1× and 2× application rates, respectively, and decreased quadratically by 40% with the 4× rate (Table 2). In contrast, there was no significant change in soil test P in the depth with the 0× application rate. Soil test P increased quadratically as the application rate increased at each soil depth. Similar trends were observed in the irrigated plot (Table 2).

Soil test P increased linearly or quadratically as the P application rate increased for all sampling periods (Table 3). During the first collection period (20 May 2015), soil test P increased linearly by 1624% from the 0× rate to the 4× rate. By the last collection period (20 July 2017), this trend had changed to a quadratic increase of 727% from the 0× rate to the 4× rate. Soil test P decreased linearly over time by 35% and 54% when P was applied at the 2× rate and 4× rate, respectively, but there was no change in the 0× rate or the 1× rate. Similar trends were observed in soil P according to the P application rate and sampling date of the irrigated plot, with two notable exceptions (Table 4). In the irrigated plot, soil test P increased quadratically with the increasing P rate, but the increase was lower (402%) compared with the increase in the nonirrigated plot (727%). Soil test P did not change over the course of the experiment at the 1× application rate in the nonirrigated plot, but it decreased quadratically by 44% in the irrigated plot.

Table 2. Soil phosphorus as affected by soil depth and application rate from 2015 to 2017 after a one-time application of triple superphosphate fertilizer for nonirrigated and irrigated 'Desirable' pecans.[z]

Nonirrigated	Depth[y]			
Rate[x]	0–7.5 cm	7.5–15.0 cm	15.0–22.5 cm	Sign.[w]
0×	67.5[v]	41.9	35.3	NS
1×	277.6	235.4	192.0	L**
2×	526.7	373.7	307.3	L***
4×	702.0	485.9	420.5	Q**
Sign.[w]	Q***	Q***	Q***	
Irrigated	**Depth**			
Rate	0–7.5 cm	7.5–15.0 cm	15.0–22.5 cm	Sign.
0×	63.2[v]	46.0	52.4	NS
1×	274.1	234.4	175.7	L***
2×	547.9	404.4	294.0	L***
4×	885.8	594.7	485.7	Q**
Sign.	Q***	Q***	Q***	

[z]The core depth–phosphorus rate interaction was significant at $P < 0.05$.
[y]Soil core samples measuring 22.5 cm (9 inches) in depth were collected within the application band and divided into 7.5-cm (3-inch) increments.
[x]Rates are the equivalent of 0 $kg \cdot ha^{-1}$ (0 lb/ac), 19.6 $kg \cdot ha^{-1}$ (17.5 lb/ac), 39.2 $kg \cdot ha^{-1}$ (35 lb/ac), and 78.5 $kg \cdot ha^{-1}$ (70 lb/ac) P and are referred to as 0×, 1×, 2×, and 4×, respectively.
[w]Significant (Sign.) linear (L) or quadratic (Q) trends using model regressions at $P < 0.01$ (**) or 0.001 (***). NS = not significant.
[v]Melich III extractable phosphorus values are reported in milligrams per kilogram.

Table 3. Soil phosphorus as affected by the application rate and collection period from 2015 to 2017 after a one-time application of triple superphosphate fertilizer for nonirrigated 'Desirable' pecans.[z]

	Rate[y]				
Date[x]	0×	1×	2×	4×	Sign.[w]
20 May 2015	47.1[v]	287.2	528.6	811.9	L***
20 July 2015	41.7	219.1	527.0	615.1	Q*
20 Sept. 2015	60.2	258.7	541.7	685.9	Q*
20 Nov. 2015	41.4	188.3	423.6	585.3	L***
20 Jan. 2016	49.7	260.4	484.7	577.7	Q*
20 Mar. 2016	47.2	272.2	403.1	655.6	L***
20 May 2016	51.2	293.7	433.7	596.4	L***
20 July 2016	42.9	256.1	378.7	602.4	L***
20 Sept. 2016	.	.	.	.	.
20 Nov. 2016	47.9	83.7	178.0	430.2	L***
20 Jan. 2017	82.2	206.4	318.1	338.0	L**
20 Mar. 2017	36.6	210.2	361.8	351.0	Q*
20 July 2017	33.7	219.2	309.2	346.2	Q*
20 July 2017	45.2	299.5	345.2	373.7	Q*
Sign.[w]	NS	NS	L***	L***	

[z]The phosphorus rate–sample period interaction was significant at $P < 0.05$.
[y]Rates are the equivalent of 0 $kg \cdot ha^{-1}$ (0 lb/ac), 19.6 $kg \cdot ha^{-1}$ (17.5 lb/ac), 39.2 $kg \cdot ha^{-1}$ (35 lb/ac), and 78.5 $kg \cdot ha^{-1}$ (70 lb/ac) P and are referred to as 0×, 1×, 2×, and 4×, respectively.
[x]Soil samples were collected from three trees at each treatment level 2 mo. after initiation starting on 20 May 2015, and collection continued at 2-mo. intervals until 20 July 2017. The ninth collection period (20 Sept. 2016) was omitted because collection was prevented by drought conditions.
[w]Significant (Sign.) linear (L) or quadratic (Q) trends using model regressions at $P < 0.05$ (*), 0.01 (**), or 0.001 (***). NS = not significant.
[v]Melich III extractable phosphorus values are reported in milligrams per kilogram.

In the nonirrigated plot, soil test P decreased linearly by 54% from the top to the bottom depth during the first collection period, but it decreased quadratically at all other dates (Table 5). On the final collection date, the quadratic decrease was 25% from the top to the bottom depth. Over time, the top depth had the largest linear decrease in soil test P, with an overall reduction of 53%. The middle and bottom depths had lesser linear decreases over time of 17% and 23%, respectively. Similar trends were observed in soil test P according to the soil depth and sample date of the irrigated plot (Table 6), with the exceptions of a larger linear percentage decrease of soil test P at the middle depth (42% compared with 17%) and no decrease of soil test P observed at the bottom depth over time.

The P rate and year main effects were significant for foliar P in the nonirrigated plot, but not for the irrigated plot. Foliar P concentrations increased quadratically with the increasing P application rates in the nonirrigated plot (Table 7). Only the 4× application rate increased foliar P compared with the 0× control rate. Foliar P concentrations for the 1× and 2× rates were less than those observed at the 0× rate.

The year main effects were significant for foliar N, P, K, Mg, S, B, and Cu, but there were no differences in foliar Ca, Fe, and Mn in the nonirrigated plot. Foliar N and K concentrations increased linearly from 2015 to 2017 (Table 8). Foliar P concentrations followed a quadratic trend, decreasing from 2015 to 2016, and then increasing from 2016 to 2017. Foliar Mg and S had linear or quadratic trends over the years, but Mg concentrations were within the recommended range (Smith et al., 2012); therefore, they were not considered biologically significant. Zinc is the micronutrient of most concern in pecan production, but it did not change over the years. No differences in yield or quality were observed in the nonirrigated plot.

In the irrigated plot, the year main effects were significant for N, P, K, Mg, Ca, and S; the year and P rate main effects were significant for Fe and Cu; and the year, P rate, and application side main effects were significant for B. No differences were observed for Mn or Zn. Foliar N changed quadratically, decreasing from 2015 to 2016, and then increasing from 2016 to 2017 (Table 9). Foliar K increased while P decreased linearly from 2015 to 2017. Plant nutrients that also decreased linearly or quadratically over time were Mg, Ca, S, and B. Foliar Fe and Cu concentrations followed a quadratic trend over time similar to N, with higher observed concentrations in 2015 and 2017 than in 2016. Zinc was unaffected by the year. Of the elements that changed over time, only P, K, S, and Fe had levels lower than the ranges of sufficiency, and they were potentially biologically significant (Smith et al., 2012). Foliar concentrations of B increased linearly by 10%, whereas Cu decreased linearly by 13% with the increasing P rate (Table 10). Foliar Fe decreased quadratically by 9% from the 0× rate to the 4× rate. Foliar B concentrations were influenced by the application side of the P band in the irrigated plot, increasing on the proximal side and decreasing on the distal side compared with the application site. No differences in yield or quality were observed in the irrigated plot.

Discussion

The irrigated and nonirrigated plots had linear decreases in soil test P of the soil depth at rates of 1× and 2×, followed by a quadratic decrease at the 4× rate. This confirmed that the majority of P applied remained in the top depth but was moving steadily down to lower depths. As the P application rate increased, the soil test P increased at each depth.

In the nonirrigated plot, soil test P concentrations remained higher for the 2× and 4× rates at the end of the experimental period than for the 1× rate at the start of the experimental period. This was significant because there was no change in the concentration of soil test P present over time at the 1× rate in the nonirrigated plot. It is likely that because soil test P concentrations were nearly constant for the experimental period with the 1× application rate, the 1× rate introduced what is or is close to the P-holding capacity of the orchard soil, and the soil simply maintained P concentrations at or near the maximum equilibrium concentration. Changes in the concentrations of soil test P throughout the soil profile at higher application rates would further support this reasoning. However, data collected during this experiment

Table 4. Soil phosphorus as affected by application rate and collection period from 2015 to 2017 after a one-time application of triple superphosphate fertilizer for irrigated 'Desirable' pecans.[z]

	Rate[y]				
Date[x]	0×	1×	2×	4×	Sign.[w]
20 May 2015	64.1[v]	387.0	498.9	1114.9	L***
20 July 2015	50.3	217.2	413.4	674.0	L***
20 Sept. 2015	47.9	352.7	454.4	747.4	L***
20 Nov. 2015	44.4	177.0	395.4	667.7	L***
20 Jan. 2016	59.8	273.7	385.4	707.2	L***
20 Mar. 2016	53.2	264.0	509.6	862.2	L***
20 May 2016	62.4	177.4	514.0	702.6	L***
20 July 2016	50.3	191.3	427.8	616.6	L***
20 Sept. 2016	50.0	182.2	486.7	606.4	L***
20 Nov. 2016	54.3	128.9	244.7	572.1	L***
20 Jan. 2017	43.4	228.8	399.9	450.3	L***
20 Mar. 2017	37.3	130.8	364.2	466.6	L***
20 May 2017	44.4	266.8	427.3	525.7	L***
20 July 2017	92.0	215.2	294.3	461.8	L***
Sign.[w]	NS	Q*	L*	L***	

[z]The phosphorus rate–sample period interaction was significant at $P < 0.05$.
[y]Rates are the equivalent of 0 kg·ha^{-1} (0 lb/ac), 19.6 kg·ha^{-1} (17.5 lb/ac), 39.2 kg·ha^{-1} (35 lb/ac), and 78.5 kg·ha^{-1} (70 lb/ac) P and are referred to as 0×, 1×, 2×, and 4×, respectively.
[x]Soil samples were collected from three trees at each treatment level 2 mo. after initiation starting on 20 May 2015, and collection continued at 2-mo. intervals until 20 Sept. 2017. The ninth collection period (20 Sept. 2016) was omitted because collection was prevented by drought conditions.
[w]Significant (Sign.) linear (L) or quadratic (Q) trends using model regressions at $P < 0.05$ (*) or 0.001 (***). NS = not significant.
[v]Melich III extractable phosphorus values are reported in milligrams per kilogram.

Table 5. Soil phosphorus as affected by soil depth and collection period from 2015 to 2017 after a one-time application of triple superphosphate fertilizer at various rates for nonirrigated 'Desirable' pecans.[z]

	Depth[y]			
Date[x]	0–7.5 cm	7.5–15.0 cm	15.0–22.5 cm	Sign.[w]
20 May 2015	627.4[v]	341.6	287.1	L***
20 July 2015	472.3	322.1	257.8	Q**
20 Sept. 2015	517.5	333.9	308.4	Q*
20 Nov. 2015	392.4	286.8	249.8	Q**
20 Jan. 2016	442.6	329.2	257.6	Q***
20 Mar. 2016	456.3	318.5	258.8	Q**
20 May 2016	423.7	331.9	275.7	Q***
20 July 2016	409.2	292.0	258.9	Q**
20 Sept. 2016	.	.	.	.
20 Nov. 2016	246.5	173.0	135.3	Q***
20 Jan. 2017	297.6	220.2	190.8	Q***
20 Mar. 2017	277.8	239.3	202.6	Q***
20 May 2017	259.3	221.5	200.5	Q***
20 July 2017	292.2	285.0	220.5	Q***
Sign.[w]	L***	L***	L***	

[z]The sample depth–sample period interaction was significant at $P < 0.05$.
[y]Soil core samples measuring 22.5 cm (9 inches) in depth were collected within the application band and were divided into 7.5-cm (3-inch) increments.
[x]Soil samples were collected from three trees at each treatment level 2 mo. after initiation starting on 20 May 2015, and collection continued at 2-mo. intervals until 20 July 2017. The ninth collection period (20 Sept. 2016) was omitted because collection was prevented by drought conditions.
[w]Significant (Sign.) linear (L) or quadratic (Q) trends using model regressions at $P < 0.05$ (*), 0.01 (**), or 0.001 (***). NS = not significant.
[v]Melich III extractable phosphorus values are reported in milligrams per kilogram.

were insufficient to confirm or deny this explanation. With further observations, soil test P concentrations would likely level-off over time for the 2× and 4× rates and approach those present at the 1× rate.

In the irrigated plot, soil test P was higher with the 4× rate at the end of the experimental period than it was with the 1× rate at the start of the experimental period. The same was not true for the 2× rate. A quadratic decrease of soil test P over time was observed at the 1× rate in the irrigated plot, which was different from what was observed for the nonirrigated plot. Diffusion is the primary way that P moves within the soil (Lewis and Quirk, 1967), but these data suggested that irrigation played a significant role in moving P within the soil profile. Previous research supports our observation that the residual effectiveness of superphosphate decreases as soil water content increases (Bolland and Baker, 1987). This residual effectiveness may be due to the reduced diffusion of P that occurs in dry soils, although it has been reported that reduced soil moisture does not reduce bioavailability of P (McBeath et al., 2012). Our data did not reveal the extent to which P movement occurred laterally over the course of the experiment or how potential lateral movement was influenced by irrigation. Previous research of the diffusion of P at rates of 10 and 20 kg·ha^{-1} showed that concentrations of P in bands decreased logarithmically from the band center and varied substantially along the direction of band application (Stecker et al., 2001).

During the irrigated and nonirrigated experiments, most foliar plant nutrients remained within the sufficiency ranges published for pecan (Smith et al., 2012), except for P, K, S, and Fe. Sulfur and Fe levels were just below the sufficiency range; therefore, application of the nutrients was not necessary. High concentrations of soil test P can reduce Fe uptake in pecan (Sparks, 1988). The small decrease in foliar Fe observed in the irrigated plot as the P application rate increased could have been caused by the high concentrations of soil test P in the banded area, but the expected increase in foliar P was not observed. Potassium concentrations were corrected by separate fertilization over the course of the study. The increase in foliar concentrations of N during the study was also attributed to fertilization.

Foliar P concentrations were quadratic over the years in the nonirrigated plot, with higher concentrations in 2015 and 2017 than in 2016. In contrast, foliar P concentrations decreased linearly in the irrigated plot from 2015 to 2017. Trends similar to those observed in the nonirrigated orchard were reported by other studies and have been attributed to the alternate bearing phenomenon observed for pecan (Krezdorn, 1955; Smith, 2009). In those studies, higher foliar P concentrations were observed during higher yielding years than during lower yielding years. The trend in the irrigated plot differed from what was reported in those studies.

The differing trends observed between the experiments are notable because 'Desirable' is known for reduced alternating bearing characteristics (Wells, 2007), and there was no difference in yield between 2015 and 2016 in either setting. 'Desirable' trees self-abort flowers each year, which reduces yield variance between years (Wells, 2007). Our data indicate that P partitioning within the plant still follows an alternate bearing pattern regardless of self-thinning in a nonirrigated orchard. Furthermore, irrigation might ameliorate the tendency of P in 'Desirable', but that comes with the tradeoff of steady use of the nutrient.

The 4× application rate was required in the nonirrigated orchard to increase foliar P concentrations to more than that of the 0× rate. Foliar P concentrations at the 4× rate would still be considered deficient for a high-input orchard (0.14%), but they would be considered sufficient for a low-input orchard (0.12%) (Smith et al., 2012). In contrast, none of the P rates increased foliar P concentrations to more than the 0× rate in the irrigated orchard, and all foliar P concentrations were less than those needed in a high-input orchard. This indicates either that a higher rate of application would be necessary to increase foliar concentrations to those recommended for a high-input commercial orchard in both

Table 6. Soil phosphorus as affected by soil depth and collection period from 2015 to 2017 after a one-time application of triple superphosphate fertilizer at various rates for irrigated 'Desirable' pecans.[z]

	Depth[y]			
Date[x]	0–7.5 cm	7.5–15.0 cm	15.0–22.5 cm	Sign.[w]
20 May 2015	801.8[v]	429.8	317.1	L***
20 July 2015	488.8	298.3	229.2	Q***
20 Sept. 2015	547.0	370.7	284.2	Q***
20 Nov. 2015	423.0	306.2	234.3	Q***
20 Jan. 2016	459.7	337.8	272.1	Q***
20 Mar. 2016	547.4	396.7	322.7	Q***
20 May 2016	491.6	336.0	264.8	Q***
20 July 2016	420.4	294.8	249.4	Q***
20 Sept. 2016	419.9	322.0	252.0	Q***
20 Nov. 2016	266.9	279.1	204.0	Q***
20 Jan. 2017	344.8	276.4	220.6	Q***
20 Mar. 2017	301.8	245.8	201.7	Q***
20 May 2017	373.8	335.0	239.4	Q***
20 July 2017	311.5	250.1	235.8	Q***
Sign.[w]	L***	L**	NS	

[z]The sample depth–sample period interaction was significant at $P < 0.05$.
[y]Soil core samples measuring 22.5 cm (9 inches) in depth were collected within the application band and were divided into 7.5-cm (3-inch) increments.
[x]Soil samples were collected from three trees at each treatment level 2 mo. after initiation starting on 20 May 2015, and collection continued at 2-mo. intervals until 20 July 2017. The ninth collection period (20 Sept. 2016) was omitted because collection was prevented by drought conditions.
[w]Significant (Sign.) linear (L) or quadratic (Q) trends using model regressions at $P < 0.01$ (**) or 0.001 (***). NS = not significant.
[v]Melich III extractable phosphorus values are reported in milligrams per kilogram.

Table 7. Foliar phosphorus concentrations from 2015 to 2017 as affected by application of a one-time band of triple superphosphate for nonirrigated 'Desirable' pecans.[z]

	Rate[y]				
Element[x]	0×	1×	2×	4×	Sign.[w]
Phosphorus[x]	0.125	0.122	0.124	0.129	Q*

[z]The phosphorus rate main effect was significant at $P < 0.05$.
[y]Rates are the equivalent of 0 kg·ha^{-1} (0 lb/ac), 19.6 kg·ha^{-1} (17.5 lb/ac), 39.2 kg·ha^{-1} (35 lb/ac), and 78.5 kg·ha^{-1} (70 lb/ac) P and are referred to as 0×, 1×, 2×, and 4×, respectively.
[x]Data are reported as the percent of foliar dry weight.
[w]Significant (Sign.) quadratic (Q) trend using model regressions at $P < 0.05$ (*).

Table 8. Foliar nutrient concentrations as affected by year after application of a one-time band of triple superphosphate or nonirrigated 'Desirable' pecans.[z]

	Yr			
Element	2015	2016	2017	Sign.[y]
Nitrogen	2.44[x]	2.47	2.63	L***
Phosphorus	0.128	0.120	0.127	Q***
Potassium	0.913	0.990	1.080	L***
Magnesium	0.445	0.462	0.378	Q***
Calcium	1.587	1.611	1.475	NS
Sulfur	0.187	0.189	0.181	L*
Boron	48.33[w]	41.84	40.50	Q*
Iron	47.19	48.05	49.50	NS
Manganese	624.58	628.21	542.22	NS
Copper	7.58	6.53	6.90	Q*
Zinc	96.30	84.20	85.20	NS

[z]The year main effect was significant at $P < 0.05$.
[y]Significant (Sign.) linear (L) or quadratic (Q) trends using model regressions at $P < 0.05$ (*) or 0.001 (***). NS = not significant.
[x]Data are reported as percent of the foliar dry weight.
[w]Data are reported as parts per million of the foliar dry weight.

irrigated and nonirrigated environments or that Desirable trees have a lower P requirement compared with other cultivars. Foliar sufficiency ranges are reported at the species level, not the cultivar level, and it is likely that cultivar differences exist. More importantly, the application of exceedingly high rates of P fertilizers to pecan orchards may not be an environmentally sustainable option due to the potential negative impacts of P on surface water quality and aquatic life. Agriculture was implicated in 38% of global anthropogenic P loads in freshwater from 2002 to 2010 (Mekonnen and Hoekstra, 2018).

Regardless of the application rate and potential cultivar differences, the difficulty increasing foliar P concentration is likely due to the lack of root hairs in pecan (Woodruff and Woodruff, 1934). In most plant species, uptake of P is greatly aided by root hairs. For example, spring barley plants, *Hordeum vulgare* L., with root hairs absorbed nearly two-times more P than mutants without root hairs (Gahoonia and Nielsen, 2001). The high P application rates that were needed to increase P uptake reported by Sparks (1988) and Smith and Cheary (2013) were likely necessary because P uptake in pecan is inherently inefficient due to the lack of root hairs. Although there is evidence that P banding can increase return bloom and ameliorate P deficiency (Smith and Cheary, 2013), the exceedingly high rates of P necessary due to the lack of root hairs in pecan should promote careful consideration regarding the sustainability of those large applications.

Although Fe, Cu, and B foliar concentrations were influenced by the P rate when combined with irrigation, the magnitude of these changes are not likely biologically significant. Boron foliar concentrations in the irrigated orchard were also affected by

Table 9. Foliar nutrient concentrations as affected by year after application of a one-time band of triple superphosphate for irrigated 'Desirable' pecans.[z]

	Yr			
Element	2015	2016	2017	Sign.[y]
Nitrogen	2.56[x]	2.45	2.67	Q**
Phosphorus	0.133	0.125	0.121	L***
Potassium	0.845	0.879	1.017	L**
Magnesium	0.435	0.426	0.374	L*
Calcium	1.64	1.55	1.36	L**
Sulfur	0.190	0.183	0.181	L*
Boron	49.74[w]	42.00	41.41	Q*
Iron	48.11	42.79	46.89	Q**
Manganese	811.25	744.92	711.71	NS
Copper	7.74	6.85	7.16	Q*
Zinc	89.70	95.66	102.23	NS

[z]The year main effect was significant at $P < 0.05$.
[y]Significant (Sign.) linear (L) or quadratic (Q) trends using model regressions at $P < 0.05$ (*), 0.01(**), or 0.001 (***). NS = not significant.
[x]Data are reported as percent of the foliar dry weight.
[w]Data are reported as parts per million of the foliar dry weight.

Table 10. Foliar iron, copper, and boron concentrations from 2015 to 2017 as affected by the application of a one-time band of triple superphosphate for irrigated 'Desirable' pecans.[z]

	Rate[y]				
Element[x]	0×	1×	2×	4×	Sign.[w]
Iron	49.07	43.22	46.81	44.63	Q*
Copper	7.43	7.74	7.34	6.49	L**
Boron	43.34	40.46	46.04	47.69	L**

[z]The application main effect was significant at $P < 0.05$.
[y]Rates are the equivalent of 0 kg·ha^{-1} (0 lb/ac), 19.6 kg·ha^{-1} (17.5 lb/ac), 39.2 kg·ha^{-1} (35 lb/ac), and 78.5 kg·ha^{-1} (70 lb/ac) P and referred to as 0×, 1×, 2×, and 4×, respectively.
[x]Data are reported as parts per million of the foliar dry weight.
[w]Significant (Sign.) linear (L) or quadratic (Q) trends using model regressions at $P < 0.05$ (*) or 0.01 (**).

the side where P was applied. The side where the P band was applied had higher B concentrations than the side without the P band. The practical applications of this phenomenon are unknown because B was available in sufficient amounts even without P application.

Overall, it appears that P banding may not be the most sustainable way to increase concentrations of P quickly or to maintain foliar concentrations of the nutrient in the long term. A very high application rate of 78.5 kg·ha^{-1} (70 lb/ac) P was necessary to increase the foliar concentration of the nutrient in a nonirrigated setting; however, it was still less than the recommended range. The practicality of P banding could be increased in the region if 19.6 kg·ha^{-1} (17.5 lb/ac) P was more effective because it remained stable within the soil profile in the nonirrigated orchard, and although it decreased quadratically over time in the irrigated orchard, the loss of P through the soil profile was the least. Banding may be a valuable tool if used in combination with foliar application of P. This approach is not unprecedented for pecan and has been used as a more long-term solution for correcting Zn deficiency. Foliar sprays of Zn are commonly used to correct short-term deficiency of the element, but band application of the nutrient has been shown to have long-term efficacy (Wood, 2007). The adoption of this two-pronged approach has been proven advantageous for pecan growers in areas where foliar applications of Zn paired with a banded application can eventually make future foliar applications unnecessary. Research should be performed to create a similar protocol involving P for pecan.

Literature Cited

Alben, A.O. 1947. Analysis of pecan leaves as an aid in fertility studies. Proc. Oklahoma Pecan Growers Assn. 25:24–27.

Alben, A.O. 1957. Results of an irrigated experiment on Stuart pecan trees in East Texas in 1956. Proc. Texas Pecan Growers Assn. 36:16–23.

Alben, A.O. and H.E. Hammar. 1964. Soil penetration and uptake of P and K in a 10 year NPK fertilizer experiment with 'Schley' pecan trees. Soil Sci. 97:179–182.

Bolland, M.D.A. and M.J. Baker. 1987. Increases in soil water content decrease the residual value of superphosphate. Austral. J. Expt. Agr. 27:571–578.

Bray, H.R. and L.T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59:39–45.

Brison, F.R. 1974. Pecan culture. Capital Printing, Austin, TX.

Brown, C. 2013. Encyclopedia of Alabama: Pecan industry in Alabama. 11 Oct. 2014. <http://www.encyclopediaofalabama.org/face/Article.jsp?id=h-1647>.

Daniell, J.W. 1985. The cumulative production through the 12th year (overgrown at that time) of pecan trees in a high density planting with and without irrigation. Proc. Georgia Pecan Growers Assn. 16:11–18.

Daniell, J.W., R.B. Moss, and B. Deal. 1979. The use of irrigation in pecan orchards. Pecan South 6:84–85.

Gahoonia, T.S. and N.E. Nielsen. 2001. Measuring and modelling phosphorus uptake by root hairs. In: W.J. Horst et al. (eds) Plant nutrition. Developments in plant and soil sciences, vol 92. Springer, Dordrecht.

Gavlak, R., D. Horneck, R. Miller, and J. Kotuby-Amarcher. 2003. Soil, plant, and water reference methods for the western region. Western Region Ext. Publ. WREP-125.

Goff, W.D., J.R. McVay, and W.S. Gazaway. 1989. Pecan production in the southeast. Alabama Coop. Ext. Publ. ANR–459.

He, M. and F.A. Dijkstra. 2014. Drought effect on plant nitrogen and phosphorus: A meta-analysis. New Phytol. 204:924–931.

Hunter, J.H. and H.E. Hammar. 1947. The results of applying different fertilizers to the Moore variety of pecan over a 10 year period. Proc. Southeast Pecan Growers Assn. 40:10–32.

Hunter, J.H. and H.E. Hammar. 1952. Influence of cultivation, mulching, and fertilizers on chemical composition of pecan leaves and their relation to yield and quality of nuts. Soil Sci. Proc. 16:346–349.

Hunter, J.H. and H.E. Hammar. 1957. Variation in composition of pecan leaves. Better Crops Plant Food 41(2):18–25.

Krezdorn, A.H. 1955. The nutrient status of pecan leaves in relation to alternate bearing. Proc. Texas Pecan Growers Assn. 34:43–53.

Lewis, D.G. and J.P. Quirk. 1967. Phosphate diffusion in soil and uptake by plants. Plant Soil 26:99–118.

McBeath, T.M., M.J. McLaughlin, J.K. Kirby, and R.D. Armstrong. 2012. Dry soil reduces fertilizer phosphorus and zinc diffusion but not bioavailability. Soil Sci. Soc. Amer. J. 76:1301–1310.

McLean, E.O. 1982. Soil pH and lime requirement, p. 199–223. In: A.L. Page et al. (ed.) Methods of soil analysis, part 2. Agron. Monograph 9, 2nd ed. ASA and SSSA, Madison, WI.

Mehlich, A. 1984. Mehlich-3 soil test extractant: A modification of Mehlich-2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

Mekonnen, M.M. and A.Y. Hoekstra. 2018. Global anthropogenic phosphorus loads to fresh water and associated grey water footprints and water pollution levels: A high-resolution global study. Water Resour. Res. 54:345–358.

Mills, H.A. and J.B. Jones, Jr. 1996. Plant analysis handbook II: A practical sampling, preparation, analysis, and interpretation guide. MicroMacro Publishing, Inc., Athens, GA.

Schulte, E.E. and B.G. Hopkins. 1996. Estimation of soil organic matter by weight loss on ignition, p. 21–32. In: Soil organic matter: Analysis and interpretation. F.R. Magdoff, M.A. Tabatabai, and E.A. Hanlon, Jr. (ed.) Special publication No. 46. Soil Sci. Soc. Amer. Madison, WI.

Smith, C.L., O.W. Harris, and H.E. Hammar. 1960. Comparative effects of clean cultivation and sod on tree growth, yield, nut quality, and leaf composition of pecan. Proc. Amer. Soc. Hort. Sci. 75:313–321.

Smith, M.W. 2009. Partitioning phosphorus and potassium in pecan trees during high- and low-crop seasons. J. Amer. Soc. Hort. Sci. 134:399–404.

Smith, M.W. 2010. Relationship of leaf necrosis and defoliation to phosphorus and potassium concentrations in selected tissue and to certain fruit quality parameters of pecan. Scientia Hort. 125:117–122.

Smith, M.W. and B.S. Cheary. 2013. Response of pecan to annual soil band applications of phosphorus and potassium. HortScience 48:1411–1415.

Smith, M.W., C.T. Rohla, and W.D. Goff. 2012. Pecan leaf elemental sufficiency ranges and fertilizer recommendations. HortTechnology 22:594–599.

Sparks, D. 1978. Nutrient concentrations of pecan leaves associated with deficiency symptoms and normal growth. HortScience 13:256–257.

Sparks, D. 1986. Growth and nutrition of pecan seedlings from potassium phosphate foliar sprays. HortScience 21:451–452.

Sparks, D. 1988. Growth and nutritional status of pecan in response to phosphorus. J. Amer. Soc. Hort. Sci. 113:850–859.

Stecker, J.A., J.R. Brown, and N.R. Kitchen. 2001. Residual phosphorus distribution and sorption in starter fertilizer bands applied in no-till culture. Soil Sci. Soc. Amer. J. 65:1173–1183.

Stein, L.A., G.R. McEachern, and J.B. Storey. 1989. Summer and fall moisture stress and irrigation scheduling influence pecan growth and production. HortScience 24:607–611.

USDA. 1976. United States standards for grades of pecans in the shell. 41 F. R. 39303.

Wells, M.L. (ed.) 2007. Southeastern pecan growers' handbook. Univ. Georgia Coop. Ext. Publ. 1327.

Wells, L. 2015. Irrigation water management for pecans in humid climates. HortScience 50:1070–1074.

Wood, B.W. 2007. Correction of zinc deficiency in pecan by soil banding. HortScience 42:1554–1558.

Woodruff, J.G. and N.C. Woodruff. 1934. Pecan root growth and development. J. Agr. Res. 49:511–531.

Worley, R.E. 2002. Compendium of pecan production and research. Edwards Brothers Inc. Ann Arbor, Mich.

Worley, R.E. 1974. Effect of N, P, K, and lime on yield, nut quality, tree growth, and leaf analysis of pecan (*Carya illinoensis* W.). J. Amer. Soc. Hort. Sci. 99:49–57.

Worley, R.E. 1982. Tree yield and nut characteristics of pecan with drip irrigation under humid conditions. J. Amer. Soc. Hort. Sci. 107:30–34.

Worley, R.E. and M. Smith. 1984. A method for estimating pecan yield. J. Amer. Soc. Hort. Sci. 19:644.