Relationships between Leaflet Nitrogen: Potassium Ratio and Yield of Pecan

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ADDITIONAL INDEX WORDS. *Carya illinoensis*, fertilizer, leaf analysis, nutrient management, nutrient relationships

SUMMARY. This study examines the relationship between foliar nitrogen:potassium (N:K) ratio and in-shell yield of pecan [*Carya illinoensis* (Wangenh.) K.Koch]. Regression analysis of linear and curvilinear relationships between leaflet N:K ratio and in-shell yield identified associations relevant to orchard nutrition management. Analysis revealed that ON (heavy crop) year N:K ratio correlates with ON year yield ($r^2 = -0.69$), OFF (light crop) year yield ($r^2 = +0.34$), 2-year average yield ($r^2 = -0.52$), and difference between ON and OFF year yields ($r^2 = -0.69$) below the optimum yield level (less than 1800 kg·ha⁻¹) for southeastern U.S. pecan orchards. Pecan yield therefore appears to be associated with N:K ratio. This study suggests that a decline in pecan yield is associated with high N:K ratios in the ON year, thus meriting further investigation into the relationships of N and K to yield. It is suggested that pecan orchards be managed such that foliage contains a N concentration of 2.5% to 2.9% and a K concentration of 1.3% to 1.5% while maintaining the N:K ratio at $\approx 2:1$ for maximization of pecan yields in the southeastern United States over the long term.

Optimization of mineral nutrient element management is an important aspect of successful management of commercial pecan [*Carya illinoensis* (Wangenh.) K.Koch] orchards. Annual foliar analysis is an important practice facilitating this endeavor. The relationship between leaf mineral nutrient concentrations is well understood for the lower critical level regarding manifestation of visual symptoms pertaining to deficiency of essential mineral nutrients, although this relationship to yield is not clearcut (Pond et al., 2006). Two common fertilizer supplements to commercial orchards are nitrogen (N) and potassium (K). The lower and upper foliage sufficiency concentrations for these vary from 2.3% to 4.0% depending on the extension service recommendations among various U.S. states (Pond et al., 2006; Wells and Harrison, 2006). Additionally, there is evidence presented by Pond et al. (2006) that Georgia leaf nutrient concentrations for N and K may be too high for commercial nut-producing orchards.

The effect of N and K fertilization on pecan orchard yield varies with yield usually being more closely

linked to N than K. Most N studies report increased yields (Hunter and Hammar, 1947; Skinner, 1922; Smith et al., 1985; Sparks, 1968; Worley, 1974); however, excessive N reduces nut yield (Storey et al., 1986) and quality and is postulated to enhance alternate bearing (Sparks, 2003). Conversely, a documented effect of K fertilization on orchard yield is less dramatic, yet can in certain cases be substantial. For example, Sharpe et al. (1950) reported increased leaflet K with increasing rates of K; however, yield was unresponsive. One study indicated a positive correlation between leaf N and pecan yield when leaf N was between 1.94% and 2.27% N; however, leaf K was unrelated to yield (Hagler and Johnson, 1955). However, Smith et al. (1985) suggests an increase in nutmeat yield with increasing K rate. Nut yield increases resulting from K have been reported by Blackmon and Ruprecht (1934). Additionally, 'Desirable', and to a lesser degree, other cultivars, exhibit a foliar N scorch problem postulated to be a N-K imbalance (Sparks, 1977), but Worley (1990) concluded

that N:K ratio does not cause the N-scorch syndrome typically observed in 'Desirable' orchards.

A major challenge influencing nutritional research in pecan, as related to optimal yield, is the confounding effect of alternate, or irregular, bearing. Pecan trees and orchards typically alternate between years with a heavy nut crop load, the "on" year (ON), followed by a lighter load the following year, the "off" year (OFF). Within orchards, most trees are synchronized in either an ON or OFF mode for a given crop season. Such patterns introduce considerable variation in yield data as well as that of nutrient element concentrations in foliage; thus, data generated by nutritional studies are often inconclusive. By linking nutritional relationships to yield averaged over a 2-year, or multiple-year, average, the confounding effect of alternate bearing diminishes.

Although many studies examine the relationships between leaflet N and K on nut yield, the relationship between N:K ratio and pecan yield has received little attention. Blackmon (1938) postulated that application of N to trees marginal in leaf K would eventually exhibit a yield reduction. Worley (1974) examined the effect of leaf N and leaf K on pecan yield; however, relationships between the N:K ratio and yield were not examined. An understanding of this relationship could potentially lead to suggestions for improved orchard fertilizer management practices and contribute to efforts to tailor such practices to optimize yield, reduce fertilizer costs, and improve the environment. We report that pecan nut yield is linked to leaflet N:K ratio and provide guidelines relevant to commercial pecan husbandry in Georgia.

Materials and methods

The effect of N:K ratio on yield was investigated using a published data set for 'Stuart' trees growing in Georgia (Worley, 1974). Trees in this study were ≈ 40 years old 'Stuart' trees spaced 68 × 68 ft on a Tifton

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922

loamy sand soil near Tifton, GA. These yields and N and K levels were derived from a long-term N-P-K fertilizer study in which trees received different amounts of a 10N-4.4P-8.3K fertilizer. Treatments were 10N-4.4P-8.3K at 0 and 448 kg·ha⁻¹ biennially, and 0, 448, 896, and 1344 kg·ha⁻¹ annually, with fertilizer applied in nine replications to single-tree plots in a completely randomized design beginning in 1962. The perimeter of each single-tree plot was subsoiled to an 18-inch depth annually from 1962 to 1969 to restrict root system crossfeeding. In 1970 and 1971, plot perimeters were trenched to a depth of 48 inches. Fungicide and insecticide applications were applied based on University of Georgia Extension Service recommendations. Leaf samples, consisting of the middle leaflet pair of the middle leaf of exposed shoots, were collected in Sept. 1962 and 1963 and early August; thereafter, except for 1969 when August leaves were destroyed in a laboratory accident and mid-November leaves were used. Leaves were ashed in a muffle furnace from 1962 to 1967. The ash was then dissolved in 1.5 N nitric acid and diluted. Potassium levels were determined by atomic absorption spectrophotometry. Nitrogen was determined by a Kjeldahl method (Lepper, 1950). After 1967, leaves were analyzed by routine emission spectrographic and Kjeldahl procedures (Worley, 1974).

Both yield and leaf nutrient levels are taken as the annual mean of nine trees within each of the five treatments reported in Worley (1974). These foliar N and K data were used to calculate the relationship between nut yield and N:K ratio. Only data for 8 years, from 1964 to 1971, were examined because of a crop failure in 1962 and the 1963 yields were excluded because of severe overbearing as a consequence of the previous season crop failure.

N:K ratio and yield data were analyzed as ON and OFF crops, the difference between ON and OFF crops, as well as the average of 2 consecutive years. ON crops were considered to be the year with the highest average yield per tree within consecutive 2 years and OFF crops were considered the year with the lowest average yield per tree within consecutive 2 years. Values for the difference

between ON and OFF crop yields were estimated by subtracting the OFF crop yield from the ON crop yield for 2 consecutive years beginning with the 1964 data. Values for the 2-year yield average were estimated by taking the average yield of the ON and OFF crop for each data point during each 2-year period.

ON year N:K ratio was estimated using the N:K ratio based on the average leaf N and K level per tree during the ON crop year of each 2-year period. OFF year N:K ratio was estimated in a similar manner using the N:K ratio for the OFF crop year of the same 2-year periods. Differences in the N:K ratio for 2 consecutive years were estimated by taking the absolute value of the difference between N:K ratio in the ON crop year and the N:K ratio in the OFF crop year for 2 consecutive years beginning with the 1964 data. Two-year average N:K ratio values were estimated by taking the average N:K ratio of the ON and OFF crop for each data point during each 2-year period. Data were sorted by yield as follows: data were initially analyzed as a pooled data set across all yields. Yields were considered excessive if the average yield of the ON year of the 2 consecutive years exceeded 80 kg/tree (i.e., 1800 kg·ha⁻¹) at the given tree spacing. As a result, the data from 1970 to 1971 is excluded from the optimum yield data.

Data were analyzed by stepwise linear regression using the forward elimination procedure. Curvilinear regression was also used to test for nonlinear relationships of the quadratic and cubic types. Dependent variables are the 2-year average pecan yield, the difference in yield between

ON and OFF years, ON year yield, and OFF year yield. Independent variables are the 2-year average N:K ratio, the difference between ON year N:K ratio and OFF year N:K ratio, ON year N:K ratio, and OFF year N:K ratio.

Where significant differences were observed with respect to N:K ratio and pecan yield, linear regression was performed to determine relationships between leaf N (percentage), leaf K (percentage), and pecan yield. Dependent variables included 2-year average pecan yield, difference in yield between ON and OFF years, ON year yield, and OFF year yield. Independent variables were the 2-year average leaf N, 2-year average leaf K, the difference between ON year leaf N and OFF year leaf N, the difference between ON year leaf K and OFF year leaf K, ON year leaf N, ON year leaf K, OFF year leaf N, and OFF year leaf K.

Results and discussion

Significant correlations between variables may be obtained by a direct effect of one variable on another or indirectly by the influence of a third factor; thus, correlation equates to circumstantial evidence. Therefore, interpretation of these data does not enable determination of cause and effect, but rather likely identifies potentially important relationships between foliage N:K ratio and in-shell pecan yield.

The data exhibited linear, but no curvilinear, relationships between N:K ratio and pecan yield. Although there was considerable variation below 2:5:1 on the N:K ratio scale, the difference in yield between ON and OFF years declined linearly ($y = 181.7 - 60.4x$) as the OFF year N:K increased (Fig. 1) from ≈ 2.2 to 2.8 for the data

Fig. 1. Relationship between OFF year leaf nitrogen:potassium (N:K) ratio and the difference in pecan yield (kg/tree) between ON and OFF year for all yield levels (1 kg = 2.2046 lb).

pooled without regard to yield. This relationship was weak yet significant (Table 1), suggesting some effect of high N, low K, or N:K on physiological processes regulating nut yield.

When data were pooled without regard to an optimum yield level, the difference in yield between ON and OFF years also exhibited weak but significant negative relationships with both OFF year leaf K and the difference in leaf N between ON and OFF years (Table 2).

There was considerable variation in the data; however, the difference in yield between ON and OFF years was reduced ($y = -143.7 - 174.8x$) as OFF year leaf K rose from 0.96% to 1.12% (Fig. 2A), suggesting that low K in the OFF year is weakly associated with a reduction in alternate bearing. It is possible that less leaf K is depleted with moderate ON year yields. As a result, subsequent OFF year K and OFF year yields are potentially increased, leading to reduced alternate bearing. This would likely influence the relationship between alternate bearing and OFF year N:K.

Similarly, the difference in yield declined ($y = 63.8 - 109x$) with a greater difference in leaf N between ON and OFF years (Fig. 2B), possibly providing further support that as ON year yields are reduced, there is a reduction in alternate bearing. This would potentially lead to less depletion of N in the ON year and higher yields in the subsequent OFF year. As a result, there could be more depletion of leaf N in the subsequent OFF year as well compared with typical OFF years.

These relationships indicate that alternate bearing is associated with both low K in the OFF year and fluctuations in leaf N between ON and OFF years, both of which likely influence the N:K ratio. Although the associations between these three independent variables and the difference in yield between ON and OFF years are significant, they are weak and are clouded by other potential factors influencing alternate bearing (i.e., soil moisture, environmental conditions, tree stress, disease, insect pressure, and so on), particularly at high and low yield extremes.

ON year yields ranged from 822 to 2333 kg·ha⁻¹ with an average of 1390 kg·ha⁻¹. The optimum yield data set ranged from 822 to 1755 kg·ha⁻¹ with an average of 1151 kg·ha⁻¹.

Table 1. Partial correlation coefficients and significance level for stepwise regression of in-shell nut yield (kg/tree)^z and foliar nitrogen:potassium (N:K) ratio of Stuart pecan.

			Leaf N:K (ratio)		
Yield		ON ^y yr	OFF ^y yr	2-yr avg	Difference
<i>All yields</i>					
ON year	r ²	NS	NS	NS	NS
	<i>P</i>				
OFF year	r ²	NS	NS	NS	NS
	<i>P</i>				
2-year avg	r ²	NS	NS	NS	NS
	<i>P</i>				
Difference between ON and OFF year	r ²	NS	−0.21	NS	NS
	<i>P</i>		0.04		
<i>Optimum yield level</i>					
ON year	r ²	−0.69	NS	NS	NS
	<i>P</i>	< 0.01			
OFF year	r ²	0.34	NS	NS	NS
	<i>P</i>	0.02			
2-year avg	r ²	−0.52	NS	−0.12	NS
	<i>P</i>	< 0.01		0.04	
Difference between ON and OFF year	r ²	−0.69	NS	NS	NS
	<i>P</i>	< 0.01			

^z1 kg = 2.2046 lb.

^yON = heavy crop; OFF = light crop.

^{ns}Nonsignificant at the 95% confidence level.

Table 2. Correlation coefficients and significance level for linear regression of in-shell nut yield (kg/tree)^z and leaf element concentrations of nitrogen (N) and potassium (K) of Stuart pecan.

		Leaf element concentrations							
		ON ^y yr N (%)	OFF ^y yr N (%)	2-yr avg N (%)	Diff. ^x N (%)	ON yr K (%)	OFF yr K (%)	2-yr avg K (%)	Diff. K (%)
Yield									
<i>All yields</i>									
Diff.	r ²	NS	NS	NS	-0.21	NS	-0.26	NS	NS
	P				0.04		0.02		
<i>Optimum yield level</i>									
ON year	r ²	NS	NS	NS	NS	NS	NS	NS	NS
	P								
OFF year	r ²	0.43	NS	NS	NS	NS	NS	NS	NS
	P	<0.01							
2-year avg	r ²	NS	NS	NS	NS	NS	NS	NS	NS
	P								
Diff.	r ²	NS	NS	NS	NS	NS	NS	NS	NS
	P								

^z1 kg = 2.2046 lb.

^yON = heavy crop; OFF = light crop.

^xDiff = difference between ON and OFF year.

^{ns}Nonsignificant at the 95% confidence level.

An evaluation of these data within the context of the putative optimum yield level appears appropriate, because several production problems occur when crop load is excessive. The putative optimum yield range is designated as such because the ON year's yield appears economically viable yet not excessive enough to prevent a reasonable return crop load. Excessive crops lead

to poor quality in the ON year and poor fruit set the next year (Reid et al., 1993; Smith et al., 1993; Smith and Gallott, 1990), yet it appears possible to have orchards with yield by individual trees being moderately high and consistent from year to year (Wood, 1991).

Optimum yield for individual trees or orchards may vary considerably from one year to the next; however,

Fig. 2. Relationships between leaf element concentrations (%) and the difference in pecan yield (kg/tree) between ON and OFF years for all yield levels (1 kg = 2.2046 lb).

for southeastern United States orchards, return fruit set is generally nil to poor when production is $\approx 2000 \text{ kg} \cdot \text{ha}^{-1}$ or greater, especially when soil moisture is inadequate (Sparks, 1994). This threshold is obviously affected by many factors such as cultivar, sunlight, soil moisture, and temperatures.

Excessive crop loads may be substantially influenced by factors (previous season crop load, environmental conditions, tree stress, disease, insect pressure, and so on) other than the N:K ratio, although this is difficult to determine from the current data given the limited number of observations at the excessive yield level. Because excessive crop loads occurred in the N:K ratio range of 2.19 to 3.08, it seems that other factors indeed may have a more significant influence on yield when crop load is excessive than does the N:K ratio. The leaf N:K ratio may be affected by a variety of factors, including foliar and soil-applied fertilizer, soil type, scion or rootstock genotype, competitive uptake by other nutrients, and assimilation based on tree demand as regulated by crop load (Sparks, 1985). For instance, elevation of leaf K concentration is

difficult in orchards on clayey soils, regardless of the K amount applied; as such, soils severely limit the availability of K for root uptake through adsorption of K^+ ions. Additionally, many orchards in Georgia have high soil calcium (Ca) and magnesium (Mg) levels as a result of annual applications of dolomitic lime (Wells, 2006). Both Ca^{++} and Mg^{++} compete with K^+ for uptake by the tree; thus, trees growing on soils high in one or both of these elements may have difficulty absorbing K^+ (Sparks, 1985).

Although these and various other factors can make management of the N:K ratio difficult, production of individual trees can be managed for many commercial pecan cultivars through mechanical fruit thinning (Smith et al., 1993). Fruiting suppresses both the concentration and content of K in foliage; thus, ON trees exhibit lower N and K than does foliage of OFF trees (Sparks, 1985). The same relationship occurs in pistachio (*Pistachio vera* L.) (Rosecrance et al., 1998). It is possible that reducing fruit load by mechanical thinning may also affect nutrient levels within the tree, allowing for lower

N:K ratios resulting from reduced K depletion at the kernel filling stage.

As a result of the alternate or irregular bearing nature of pecan, 2-year average yield likely provides a more reliable estimate of an orchard or tree's productivity than a single year's yield. Regression analysis indicates that ON year N:K ratio made significant contributions to the regression equation estimating 2-year average pecan yield, accounting for 52% of the variation ($y = 28.8 - 10.4x$) in the 2-year average yield at the optimum yield level. Similarly, the ON year N:K ratio accounted for 69% of the variation in both the difference in yield between ON and OFF years ($y = 60.6 - 15.6x$) and ON year yield ($y = 62.2 - 0.87x$) at the optimum yield level. The ON year N:K ratio was inversely related to and moderately to strongly correlated with each of these three dependent variables (Figs. 3A–C). This indicates a probable current season effect of N, K, or N:K on either flowering or fruit set; however, neither leaf N nor leaf K was significantly correlated with 2-year average yield, difference in yield between ON and OFF years, or ON year yield at the optimum yield level (Table 2).

The strong negative correlation between the difference in nut yield between ON and OFF years and ON year N:K indicates less alternate bearing when ON year N:K ratio is near 3:1 and greater alternate bearing when ON year N:K ratio nears 2:1 (Fig. 3B). In other words, OFF year yields increased as the ON year N:K ratio increased. This further reduces the difference in ON and OFF year yields. As a result, a greater ratio between ON year N and K was associated with reduced alternate bearing at the optimum yield level. However, because the 2-year average yield and ON year yield decline as the N:K ratio increases from 1.8:1 to 3:1 (Figs. 3A and C), it would seem that an N:K ratio of 2:1 is more suitable for optimal pecan yields.

Moderate to heavy crop loads deplete pecan leaf K, and K within the tree is slowly replenished; thus, foliar K is less during ON years than in OFF years (Sparks, 1977, 1985). The same relationship also exists between ON and OFF shoots within the same tree (Sparks, 1977). The ON year

Fig. 3. Relationships between leaf nitrogen:potassium ratio (N:K) and pecan yield (kg/tree) at optimum yield level (80 kg/tree or less) (1 kg = 2.2046 lb).

leads to increased N assimilation relative to K, although foliar N and K can be increasingly depleted from foliage as kernel filling progresses (Sparks, 1985). Tree N reserves are often depleted early during canopy development, in May or June, and are replenished by N fertilization. After the N supply is replenished, N assimilation may be reduced during fruit enlargement and kernel filling in the OFF year as compared with the ON year, because there appears to be reduced demand with a lighter crop load (Wood, 2001). With relatively low demand for N and K during OFF years, OFF year yield is therefore not expected to be highly correlated with the OFF year N:K ratio. Conversely, during the ON year, linkage between the N:K ratio and 2-year average yield indicates a substantial current season effect of N:K on either flowering or fruit set (Fig. 2A). Neither leaf N nor

leaf K was significantly correlated with ON year yield (Table 2).

Two-year average N:K is inversely correlated ($y = 28.8 - 42x$) with 2-year average yield at the optimum yield level, although the relationship is weak (Table 1; Fig. 3D). Two-year average yields are greatest in trees possessing a mean foliar N:K ratio of $\approx 2.1:1$ (Fig. 2D). Again, neither leaf N nor leaf K was significantly related to 2-year average yield. This is further evidence that ‘Stuart’ orchards in Georgia soils and environment are likely to be most productive if managed to achieve an N:K ratio near 2:1.

The ON year N:K ratio correlates positively ($y = 0.26 + 17x$) with OFF year yield, accounting for 34% of the variation in OFF year pecan yield at optimum yield levels (Table 1; Fig. 3E). Heavy crop loads during the ON year suppress floral induction for the next year to a greater extent than do

smaller crop loads during the ON year (Wood et al., 2003). Therefore, the relationship between ON year N:K and OFF year yield would likely be indirectly influenced by a lighter crop load in the ON year with higher ON year N:K. As a result, the following OFF year yield is likely to increase compared with that of trees with heavier crop loads and smaller N:K values in the previous season.

OFF year yield was also positively correlated ($y = -6.05 + 10x$) with ON year leaf N at optimum yield levels (Fig. 4). This relationship accounted for 43% of the variation in OFF year yield (Table 2), suggesting that as ON year leaf N increases, there is likely greater carryover of N reserves in the tree for the subsequent OFF year leading to less chance for excess abortion of pistillate flowers and potentially higher yields in the OFF year. As a result, the positive correlation

Fig. 4. Relationships between ON year leaf nitrogen (N%) and OFF year pecan yield per tree (kg/tree) at optimum yield level (80 kg/tree or less) (1 kg = 2.2046 lb).

between OFF year yield and ON year N:K is likely influenced by the relationship between OFF year yield and ON year leaf N.

It appears that ON year yields are more highly associated with the N:K ratio than are OFF year yields at the optimum yield level. As a result, the N:K ratio needs to be closely managed for the ON year, because high levels of N are known to prevent uptake of K and both N and K requirements are normally greater with increased crop load.

Worley (1994) suggested that a leaf K threshold of 0.75% was adequate and practical for the low end of the sufficiency range for pecan. This recommendation was counter to the lower threshold of 1.25% leaf K previously recommended by Plank (1988). However, Worley (1994) did not discuss leaf N levels or the N:K ratio of trees used for the study, nor were the data separated into ON and OFF years or 2-year average yields. Thus, alternate bearing is not taken into consideration. Beverly and Worley (1992) attempted to establish diagnosis and recommendation integrated system norms for pecan using the same Worley (1974) data set used in our study. They suggest a ratio of 2.74:1 for 'Stuart' pecan in Georgia. However, again, the data were not separated into ON and OFF years nor were they analyzed based on 2-year average yields. As a result, alternate bearing is not taken into account.

When analyzed without regard to yield, there is a considerable amount of variation introduced into the data, as a result of alternate bearing, which may be influenced by a variety of factors aside from nutritional status.

This is particularly true at very high or low yield levels. Such variation makes it difficult to explain relationships between nutritional status and pecan yield. By examining the same relationships at more moderate or optimum yield levels, associations between pecan yield and various aspects of tree nutritional status can be observed with more clarity.

Although ON year N:K ratio was significantly correlated with pecan yield at optimum yield levels (Table 1; Fig. 3), OFF year N:K ratio had no significant linkage to pecan yield at optimum yield levels (Table 1). Therefore, these data indicate that there is a high level of association between N:K ratio and pecan yield in the ON year, at optimum yield levels, and that pecan orchard fertilizer management strategies with respect to N and K likely need to focus on ON year status.

Studies of greenhouse-grown pecan seedlings indicate that optimum growth occurs when foliar N is $\approx 2.6\%$ to 2.9% and K is $\approx 1\%$ (i.e., an N:K ratio of ≈ 2.6 to 2.9) (Sparks, 1968); however, the optimum N:K ratio for vegetative growth appears to be considerably higher than that of the approximate optimum of 2.1 for reproduction. Until further information becomes available regarding refinement of optimal N and K concentrations in foliage, it is therefore proposed that commercial pecan orchards in Georgia, and the southeastern United States, be managed such that foliage contain 2.5% to 2.9% N and 1.3% to 1.5% K while maintaining the N:K ratio at $\approx 2:1$ for maximization of pecan yield within the optimal yield range of $1800 \text{ kg}\cdot\text{ha}^{-1}$ or less.

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