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Manure and Soil Zinc Application to 'Wichita' Pecan Trees Growing Under Alkaline Conditions

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Abstract**. The effect of cattle manure or combined manure and zinc (Zn) application on Zn uptake, mineral composition, and yield and nut quality in pecan trees [*****Carya illinoinensis***** (Wangenh.) C. Koch] was evaluated. In 2006, treatments evaluated were: manure (12 ton/ha; M), manure plus Zn (12 ton/ha plus 129 kg Zn/ha as $ZnSO_4$; MZ), and an untreated control. During 2007, two more treatments were added with doubled manure and Zn rates. New treatments were manure 2× (24 ton/ha; M2) and manure 2× plus Zn 2× (24 ton/ha plus 258 kg Zn as $ZnSO_4$; M2Z2). Manure was broadcast on the soil in a 2.5-m wide band 2 m from the trunk. Zinc sulfate was broadcast over the manure, and then manure and Zn were disked into the top 10 cm of soil. In 2008, in five of nine sampling dates, significant treatment effects were detected on leaf Zn concentrations. On all of the dates, M2Z2 had the highest foliar Zn levels. During the Summer 2008 (17 July) foliar Zn in M2Z2, treatment reached 66 $\mu g \cdot g^{-1}$; the control treatment level was 45 $\mu g \cdot g^{-1}$. Nut yields were higher in treatments receiving manure, with or without Zn in the first year, and highest in the untreated control the second year. No differences were observed in trunk growth, leaf area, leaf weight, or nut growth. Kernel percentages were over 61.4 in the 3 years of study in all treatments. Largest differences among treatments in nut size were found in 2007; nut weight in the control treatment was 7.5 g per nut and in M was 8.0 g per nut. Nut weight was smaller during 2008 when nut yield was high, and the untreated control nuts were smaller than those from treated trees. The manure and manure plus Zn treatments increased foliar Zn levels in pecan trees after 3 years of annual applications. In 2008, significant differences in leaflet Zn concentration among treatments were detected with M2Z2 having the highest concentrations.**

Pecan trees growing in alkaline and calcareous soils are prone to zinc (Zn) deficiency (Malstrom and Fenn, 1981; Smith et al., 1980). Soluble Zn compounds such as Zn sulfate applied to alkaline soil react with hydroxides and carbonates and are converted to compounds unavailable to plants (Essington, 2003; Lindsay, 1972; Sadiq, 1991; Udo et al., 1970). Acidification using large quantities of strong acids such as sulfuric acid can increase Zn uptake by pecan (Fenn et al., 1990). Acid-forming compounds such as sulfur (S) and organic matter can increase Zn availability (Essington, 2003). Humic acids can also complex metals, including Zn, increasing mobility and solubility in calcareous soil (Bunluesin et al., 2006; Chien et al., 2006; Ozkutlu et al., 2006). Addition of manure, S, and Zn can decrease rosette symptoms caused by Zn deficiency in pecans growing in heavy-textured alkaline soils (Alben and Hammer, 1944). Fertilization of alkaline soils with Zn, in combination with sulfuric acid, was evaluated by acidifying a shallow trench making up less than 1% of the effective root zone of a mature Texas pecan trees by applying a mixture of 9 kg $ZnSO_4$ and 113 L of 36 N H_2SO_4/tree. Leaf Zn did not change in the first 3 years, but 4 years after application, leaves of the treated trees contained 54 $\mu g \cdot g^{-1}$ Zn versus 39 $\mu g \cdot g^{-1}$ in the untreated control. After 9 years, leaf Zn levels were 58 and 45 $\mu g \cdot g^{-1}$ for treated and untreated trees, respectively, and 56 $\mu g \cdot g^{-1}$ in trees receiving $ZnSO_4$ alone. Soil pH was decreased to a depth of 60 cm; however, roots did not grow into the acidified soil, proliferating instead at the interface of the acidified and calcareous soil (Fenn et al., 1990).

Increased soil organic carbon increased levels of DTPA-extractable Zn in tropical desert soils in Nigeria; DTPA-extractable Zn rose 0.17 $mg \cdot kg^{-1}$ with each percent increase in soil organic matter (Agbenin, 2003). It is not surprising then that addition of organic matter to soil can increase Zn levels and plant growth in annual plants such as rice, sorghum, and soybean (Battacharyya. et al., 2006; Pinto et al., 2004; Warwick et al., 1998; Zheljazkov and Warman, 2004). Even without incorporation into the soil, use of organic mulch at planting increased the trunk cross-sectional area (TCSA) in young 'Desirable' pecan trees. After 3 years, TCSA was 31 cm^2 in untreated trees versus 39 cm^2 in trees with 10 cm of mulch applied to the soil surface (Foshee et al., 1996). In another study, incorporation of pecan pruning wood chips into the soil improved soil tilth and aggregation and increased volumetric water content 20 d after irrigation (Tahboub et al., 2008) while not affecting nitrogen, phosphorus, or potassium availability (Tahboub et al., 2007).

Increased use of animal manure in pecan orchards has recently accompanied a shift toward ''organic'' production. The purpose of the manure applications is primarily to supply nitrogen in this production system. The relatively large quantities of manure used for this purpose (≈5 to 12 $Mt \cdot ha^{-1}$) might reasonably be expected to have an impact on levels of soil organic matter and metal solubility and bioavailability. Manure fortified with supplemental Zn might provide additional available Zn for trees growing in calcareous soils.

Zinc uptake and pecan tree performance were studied after the application of manure alone or in combination with Zn sulfate. The purpose of this study was to determine the effect of the addition of manure on Zn uptake, growth, yield, and nut quality of pecan trees growing under alkaline and calcareous conditions and to ascertain whether these effects can be enhanced by providing extra Zn with applied manure.

Materials and Methods

A field study was conducted in a commercial pecan orchard in southeast Arizona (lat. 31°55′01.25″ N, long. 110°57′27.56″, elev. 844 m) on 'Wichita' pecan trees (7 years old) from May 2005 to Dec. 2008. The alluvial soil in the orchard is a calcareous Pima clay loam with a soil pH of 7.6 (fine silty, mixed, thermic Typic torrifluvents). This site is semiarid with a mean annual soil temperature from 15 to 22 °C and the area has a mean annual precipitation between 25 and 40 cm (Hendricks, 1985). Table 1 presents general soil characteristics of the orchard site at 0- to 30-cm depth. The soil is typical of many southwestern U.S. soils and therefore many regional pecan orchards. Trees are planted in a square design and the space between trees is 9.15 m. Mowing was used to keep the soil clean of weeds during growing seasons. Trees were flood-irrigated twice each month from April to October. A total of 1.50 m of water depth was applied each year. Standard chemical methods were initially used to control aphids, but in 2007, the orchard was converted to ''organic'' production and pest control methods were changed accordingly. During the winter of

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2006–2007, trees in the buffer rows between experimental plot rows were mechanically hedge-pruned. In the winter of 2007–2008, trees in treatment rows were also hedged. Trees were hedged 3 m from each side of the trunk and 9 m high. Lateral hedge-pruning had an inclination of 5° from the vertical toward the trunk with the top pruned at an angle of 160°.

In 2006, treatments evaluated were: manure (a blend of cattle and horse manure at 12 ton/ha) (M1), manure plus Zn (12 ton/ha of manure plus 129 kg of Zn/ha as $ZnSO_4$) (M1Z1), and an untreated control. The manure application rate is that used commercially to supply nitrogen in this orchard. None of the plots were sprayed with Zn during the study. Two additional treatments were to have received a urea application instead of manure, but were left untreated in 2006 because the block was converted to organic production. Instead, these plots were used to evaluate two more treatments with doubled rates of manure and manure plus Zn in 2007: 24 ton/ha of manure (M2) and 24 ton manure/ha plus 258 kg Zn/ha as $ZnSO_4$ (M2Z2).

Manure was broadcast on the soil in a 2.5-m wide band beginning 2 m from the trunk. Zinc sulfate was broadcast over the manure. All plots were disked to mix the top 10 cm of soil. Manure had a pH of 7.8 and an electrical conductivity of 4.0 and contained ≈0.84% nitrogen, 0.18% P_2O_5, and 1.19% K_2O. Treatments were replicated four times in a randomized complete block design. Each experimental plot consisted of one row containing 15 trees (n = 12 in 2006; n = 20 in subsequent years). Leaf samples and growth measurements were collected from the 11 central trees in each plot row. Experimental plot rows were each separated by one buffer row. Data were analyzed using analysis of variance with mean separation with Tukey's test (SAS Version 9.1; SAS Institute, Cary, NC).

Twenty-four middle leaflet pairs located in the middle of the current year's shoot growth were collected every 2 or 3 weeks from May to October for Zn analysis. These samples were collected from the branches on the lower part of the trees that could be reached from the ground. Leaflet samples collected in late July were used for complete elemental analysis. Leaves were washed using the following routine: washed in phosphate-free soap, rinsed in tap water, rinsed in distilled water, and rinsed three times in deionized water. Leaf samples were dried at 70 °C, weighed, and then ground in a mortar. During 2008, a rinse with hydrochloric acid (1% v/v) was added between the distilled water and deionized water rinses. Leaf tissue was ashed at 500 °C for 5 h and then dissolved in 2.2 N hydrochloric acid. Complete nutrient analysis was conducted on samples collected in late July or early August each year. Nitrogen was determined by Macro-Kjeldahl (Horowitz, 1980); phosphorus was determined colorimetrically (Olsen and Sommers, 1982); and potassium, calcium, magnesium, S, iron, Zn, copper, and manganese by atomic absorption spectroscopy.

Trunk circumference was measured at 20 cm above the ground in Feb. 2007 and Feb. 2008. Trunk cross-sectional area was calculated from these measurements. Leaflet growth and chlorophyll index were determined on a sample of 60 leaflets collected in late July or early August. Chlorophyll index was obtained using a Konica Minolta SPAD 502 m (Konica Minolta Sensing America Inc., Ramsey, NJ) by optical density difference at two wavelengths (650 and 940 nm). Chlorophyll readings were conducted on the middle part of the leaflet. Leaflets were scanned on a flatbed scanner and leaflet area obtained using Scion Image software (Scion Corp., Frederick, MD). During late July or early August, 20 middle pairs of leaflets were collected from the top half of the trees as described previously for the bottom part of the tree to determine if leaf Zn, leaf area, and leaf weight in the upper half of trees were affected by treatments.

During 2006 and 2007, nut yield and quality were determined. Yield was calculated by mechanically harvesting the complete experimental row. Alternate bearing intensity (I) was determined by the ratio between the absolute difference in yield with the sum of the yields of successive years (Pearce and Dobersek-Urbanc, 1967) according to the formula:

$$I = \frac{1}{n-1} * \left(\left| \frac{Y_1 - Y_2}{Y_1 + Y_2} \right| + \left| \frac{Y_2 - Y_3}{Y_2 + Y_3} \right| + \ldots + \left| \frac{Y_{n-1} - Y_n}{Y_{n-1} + Y_n} \right| \right),$$

where I = alternate bearing intensity, n = total of years, and Y = year. Values are absolute numbers.

Table 1. Orchard soil characteristics at the beginning of the study.

Soil test	Method	Units	Value
pH	Saturated paste	SU	7.5
Electrical conductivity	Saturated paste	$dS \cdot m^{-1}$	0.44
Calcium	NH_4OAc (pH 8.5)	$mg \cdot kg^{-1}$	4000
Magnesium	NH_4OAc (pH 8.5)	$mg \cdot kg^{-1}$	310
Potassium	NH_4OAc (pH 8.5)	$mg \cdot kg^{-1}$	510
Zinc	DTPA	$mg \cdot kg^{-1}$	3.2
Iron	DTPA	$mg \cdot kg^{-1}$	5.1
Manganese	DTPA	$mg \cdot kg^{-1}$	9.4
Copper	DTPA	$mg \cdot kg^{-1}$	2.4
Nickel	DTPA	$mg \cdot kg^{-1}$	0.12
NO_3-N	Cd reduction	$mg \cdot kg^{-1}$	8.8
PO_4-P	Olsen	$mg \cdot kg^{-1}$	9.0
SO_4-S	Hot water	$mg \cdot kg^{-1}$	22
Boron	Hot water	$mg \cdot kg^{-1}$	0.28
Free lime	Effervescence		High
Exchangeable sodium percent	Calculated	%	1.8
Cation exchange capacity	Calculated	$cmol_c \cdot kg^{-1}$	24.3

Table 2. Effect of manure and zinc (Zn) application on foliar Zn concentration during the growing season in 'Wichita' pecan trees ($\mu g \cdot g^{-1}$ dry weight).[z]

	Zn ($\mu g \cdot g^{-1}$ dry wt)										
	2006										
Treatment[y]	9 May	1 June	20 June	11 July	27 July	11 Aug.	29 Aug.	21 Sept.	Avg.		
M1	42	36	33	36	30	24	22	27	29		
M1Z1	40	34	29	34	26	20	22	24	31		
Control	44	39	33	37	27	23	24	27	32		
Pr > F	NS[x]	NS	NS	NS	NS	NS	NS	NS	NS		
	2007										
	3 May	22 May	7 June	21 June	10 July	26 July	14 Aug.	5 Sept.	2 Oct.	Avg.	Top
M1	37	43	44	37	32 ab	30	33	27	26	34	32
M1Z1	40	42	40	32	30 a	29	36	30	20	34	33
M2	42	41	37	32	30 a	29	44	27	22	34	29
M2Z2	48	43	43	34	34 ab	37	40	35	26	38	38
Control	44	44	43	33	37 b	30	42	29	28	37	35
Pr > F	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS
	2008										
	15 May	30 May	14 June	2 July	17 July	30 July	14 Aug.	3 Sept.	20 Sept.	Avg.	Top
M1	58 abc	57 ab	37 ab	52	61 ab	67 ab	55 ab	48 ab	46 ab	54 bc	38 a
M1Z1	61 abc	55 ab	37 ab	60	58 ab	63 ab	55 ab	50 ab	54 b	53 b	43 bc
M2	47 a	50 ab	29 ab	38	44 a	50 a	46 a	40 a	41 a	41 a	29 a
M2Z2	72 c	64 b	47 b	54	66 b	86 b	62 b	58 b	60 bc	62 c	45 c
Control	48 ab	48 a	35 a	55	45 a	75 ab	49 ab	50 ab	46 ab	49 ab	34 ab
Pr > F	***	**	**	NS	**	*	*	**	**	***	**

[z]Means followed by different letters are different at $P = 0.05$ through analysis of variance testing.

[y]M1 = manure 12 ton/ha; M2 = manure 24 ton/ha; Z1 = 129 kg Zn as $ZnSO_4$; Z2 = 258 kg Zn as $ZnSO_4$ (manure had a pH of 7.8 and an electrical conductivity of 4.0 and contained ≈0.84% N, 0.18 P_2O_5, 1.19 K_2O).

[x]NS, *, ** = Nonsignificant, significant (Pr > F = 0.05), and highly significant (Pr > F = 0.01).

A sample of harvested nuts was used to determine kernel percent, yield, percent of good nuts, pre-germinated nuts (viviparous), and "stick-tight" nuts. "Stick-tights" are those fruit with shucks that do not separate from the shell at maturity; the shuck remains stuck to the shell after harvest and cannot be separated completely. Yield efficiency was calculated as yield/cm^2 of TCSA. Kernel percent was determined by cracking 10 nuts from each experimental plot and separately weighing shell and kernel. Weight per nut was calculated from the number of nuts in a 1-kg sample.

Results

Leaflet Zn concentration was unaffected during the first year of study in 2006 (Table 2). Significant differences were found in July 2007 with the control having the highest foliar Zn level. In 2008, in eight of the nine leaf sampling dates, significant effects were detected. On all of these sampling dates, trees in the M2Z2 treatment had the highest foliar Zn levels. During the summer of 2008 (17 July), in this treatment, foliar Zn reached 66 $mg \cdot kg^{-1}$, whereas the control treatment had 45 $mg \cdot kg^{-1}$. Only the M2 treatment had lower foliar Zn levels than the control. In 2007, no significant differences were found in foliar Zn between the bottom and top sections of the trees, but in 2008, leaflets from the top had significantly lower values than the bottom leaflets.

Zinc treatments did not affect TCSA, leaflet size and weight, and chlorophyll index (Table 3). Neither TCSA nor its increase in 2 consecutive years was affected by treatments.

Heavy rainfalls during 2006 prevented the use of the hydraulic lift needed to sample the top part of the trees. In 2007 and 2008, specific leaflet areas from the top and bottom parts of the trees were unaffected by manure or Zn applications. Chlorophyll index varied from 46.5 to 47.3 in 2007 and from 46.8 to 45.4 in 2008. Manure treatments had the highest values, but differences were not significant.

Yield of whole nuts and kernel were affected by applied treatments (Table 4). In 2006, both treatments receiving manure outyielded the control treatment, but differences were not significant. In contrast, in 2007, the highest yield of nuts was obtained in the control treatment (3852 $kg \cdot ha^{-1}$), whereas other treatments had yields between 2891 and 3010 $kg \cdot ha^{-1}$. In 2008, the control treatment had the lowest yield, and it was significantly lower than M2Z2, which had the highest yield. Kernel yields and yield efficiency reflected overall yields. Differences in cumulative yields and cumulative efficiency were not significantly different, although control plots ranked highest in both. Alternate bearing intensity ranged from 0.15 to 0.7. The control treatment had the highest alternate bearing intensity, but differences were not significant.

Nut filling and nut weight were unaffected by treatments (Table 5). Nut fill was excellent both years, over 61% in 2006 and over 62% in 2007 and 2008. Nut weight was larger

Table 3. Effect of manure and zinc (Zn) application on growth parameters in 'Wichita' pecan trees.

Treatments[z]	2006	2007	2008	
	Trunk cross-sectional area ($cm^2 \cdot ha^{-1}$)			*Increase (2007–2008)*
M1	387.4	456.8	514.2	58.3
M1Z1	393.7	447.5	544.5	97.0
M2		417.1	480.7	63.6
M2Z2		403.3	466.5	63.2
Control	354.6	405.7	482.2	76.5
Pr > F	NS[y]	NS	NS	NS
	Leaflet area bottom (cm^2)			
M1	23.2	31.4	20.4	
M1Z1	23.7	32.7	20.4	
M2		29.9	19.9	
M2Z2		30.0	20.3	
Control	22.4	30.1	21.8	
Pr > F	NS	NS	NS	
	Leaflet area top (cm^2)			
M1		23.0	26.5	
M1Z1		22.3	24.3	
M2		21.9	24.7	
M2Z2		21.4	25.9	
Control		20.7	22.5	
Pr > F		0.895 NS	0.44 NS	
	Leaflet weight bottom (g)			
M1		0.253	0.139	
M1Z1		0.275	0.130	
M2		0.247	0.125	
M2Z2		0.235	0.136	
Control		0.265	0.129	
Pr > F		NS	NS	
	Leaflet weight top (g)			
M1		0.224	0.223	
M1Z1		0.221	0.208	
M2		0.217	0.212	
M2Z2		0.217	0.234	
Control		0.193	0.195	
Pr > F		NS	NS	
	Chlorophyll index (SPADs)			
M1x		46.5	45.4	
M1Z1		46.5	44.4	
M2		47.1	44.9	
M2 Z2		47.3	45.1	
Control		46.5	43.8	
Pr > F		NS	NS	

[z]M1 = manure 12 ton/ha; M2 = manure 24 ton/ha; Z1 = 129 kg Zn as $ZnSO_4$; Z2 = 258 kg Zn as $ZnSO_4$ (manure had a pH of 7.8 and an electrical conductivity of 4.0 and contained ≈0.84% nitrogen, 0.18 P_2O_5, and 1.19 K_2O).
[y]NS, *, ** = Nonsignificant, significant (Pr > F = 0.05), and highly significant (Pr > F = 0.01).

Table 4. Effect of manure and zinc (Zn) application on yield of nut and meat of 'Wichita' pecan trees.[z]

Treatment[y]	2006	2007	2008
	Yield of nut ($kg \cdot ha^{-1}$)		
M1	863	2,993 ab	1,844 b
M1Z1	850	2,891 ab	1,676 ab
M2		3,086 ab	1,567 ab
M2Z2		2,910 a	2,154 b
Control	597	3,852 b	745 a
Pr > F[x]	NS	*	*
	Nut yield efficiency ($g \cdot cm^{-2}$)		
M1	19.0	56.1 ab	29.9 ab
M1Z1	18.0	54.1 a	26.2 ab
M2		62.3 ab	26.9 ab
M2Z2		61.1 ab	37.9 b
Control	14.0	80.6 b	12.8 a
Pr > F	NS	*	*
	Yield of kernel ($kg \cdot ha^{-1}$)		
M1	467	1,904 ab	1,155 ab
M1Z1	448	1,794 ab	1,042 ab
M2		1,960 ab	988 ab
M2Z2		1,843 a	1,363 b
Control	322	2,417 b	473 a
Pr > F	NS	*	*
Least significant difference (0.05)		583	747

	Alternate bearing intensity (I)	
	2006–2007	2007–2008
M1	0.55	0.24 ab
M1Z1	0.53	0.27 ab
M2		0.32 ab
M2Z2		0.15 a
Control	0.73	0.67 b
Pr > F	NS	**

[z]Means followed by different letters are different at $P = 0.05$ through analysis of variance testing.
[y]M1 = manure 12 ton/ha; M2 = manure 24 ton/ha; Z1 = 129 kg Zn as $ZnSO_4$; Z2 = 258 kg Zn as $ZnSO_4$ (manure had a pH of 7.8 and an electrical conductivity of 4.0 and contained ≈0.84% nitrogen, 0.18 P_2O_5, 1.19 K_2O).
[x]NS, *, ** = Nonsignificant, significant (Pr > F = 0.05), and highly significant (Pr > F = 0.01).

during 2006, when nut harvest was small. In 2007, nuts from the control treatments were lighter than nuts from other treatments, but differences were not significant.

The percentage of nuts exhibiting vivipary and the percentage of stick-tights were unaffected by treatments (Table 5). The percentage of pregerminated (viviparous) nuts percent ranged from 6.0 to 12.7. Values were highest in 2007. Stick-tight percentages varied from 3.2% to 8.8%, and the highest values occurred in 2006, the year of low nut production.

Table 5. Effect of manure and zinc (Zn) application on nut quality of adult 'Wichita' pecan trees.

Treatment[z]	2006	2007	2008
	Nut filling (kernel %)		
M1	61.9	63.6	62.7
M1Z1	61.4	62.2	62.2
M2		63.3	62.8
M2Z2		63.3	63.3
Control	61.6	62.8	63.5
Pr > F	NS[y]	NS	NS
	Nut weight (g)		
M1	8.7	8.0	7.3
M1Z1	8.2	7.4	7.0
M2		7.7	7.0
M2Z2		7.9	7.2
Control	8.6	7.5	7.2
Pr > F	NS	NS	NS
	Vivipary (%)		
M1	6.1	8.7	3.3
M1Z1	8.8	12.0	4.2
M2		11.4	3.6
M2Z2		11.2	3.8
Control	6.0	12.7	3.8
Pr > F	NS	NS	NS
	Stick tights (%)		
M1	8.8	4.8	4.9
M1Z1	7.3	4.8	3.7
M2		4.0	4.4
M2Z2		5.4	3.2
Control	8.2	3.2	4.3
Pr > F	NS	NS	NS

[z]M1 = manure 12 ton/ha; M2 = manure 24 ton/ha; Z1 = 129 kg Zn as $ZnSO_4$; Z2 = 258 kg Zn as $ZnSO_4$ (manure had a pH of 7.8 and an electrical conductivity of 4.0 and contained ≈0.84% nitrogen, 0.18 P_2O_5, 1.19 K_2O).

[y]NS, *, ** = Nonsignificant, significant (Pr > F = 0.05), and highly significant (Pr > F = 0.01).

Leaf mineral composition of pecans was unaffected by manure or Zn applications in the first year of study but was affected during 2007 and 2008 (Table 6). In 2007, leaflet potassium levels were higher in the control and M1Z1 treatments. In 2008, 2 years after the start of the study, significant differences were found in foliar calcium (Ca) and magnesium (Mg) concentrations, which were highest in manure and manure plus Zn treatments. The control treatment had foliar Ca and Mg concentrations of 21.8 $g\cdot kg^{-1}$ and $g\cdot kg^{-1}$, respectively, compared with 25.8 $g\cdot kg^{-1}$ and 4.9 $g\cdot kg^{-1}$ in the M1Z1 treatment.

Discussion

The relatively low concentrations of foliar Zn during 2006 and 2007 did not cause visible deficiency symptoms in 'Wichita' pecan trees. Foliar Zn concentration ranged from 20 to 24, 33 to 44, and 46 to 62 ppm during 2006, 2007, and 2008, respectively. Leaflet Zn concentrations generally were below the widely accepted critical level for the southeast conditions of 50 $\mu g\cdot g^{-1}$ (Sparks, 1993, 1994; Wood, 2007) during the first 2 years of the study. These low levels of Zn apparently did not affect fruit set, yield, or quality of pecans in 2007 because a large crop with very high quality was produced.

In Georgia, high-yielding pecans (greater than 58 kg nuts per tree) had an average of 126 $\mu g\cdot g^{-1}$ Zn in leaves (Beverly and Worley, 1992), in Mexico 65 $\mu g\cdot g^{-1}$ (Medina, 2004), and in the southwest United States 174 $\mu g\cdot g^{-1}$ (Pond et al., 2006). Zinc critical levels have been established for pecans ranging from 20 to 60 $\mu g\cdot g^{-1}$, and several authors have noticed no difference in tree growth development within this range (Lane et al., 1965; Obarr et al., 1978; Sparks, 1976; Storey et al., 1971; Worley et al., 1972). Seedlings of 'Curtis' grown in nutrient solution without Zn had 24 to 37 $\mu g\cdot g^{-1}$ and seedlings showed mild Zn deficiency symptoms (Sparks, 1978). Pecans grown in sand culture under hydroponic conditions with a nutrient solution lacking Zn had intervenial necrosis in leaves with 7.2 $\mu g\cdot g^{-1}$, mottling at 9.8 $\mu g\cdot g^{-1}$, and no symptoms in leaves with 11.2 $\mu g\cdot g^{-1}$ (Kim et al., 2002).

Size of leaflets in this study were larger than those reported from 'Choctaw' pecan trees in spring flush shoots growing in Georgia, where leaflets had 18.5 cm^2/leaflet (Andersen and Brodbeck, 1988).

Published data regarding chlorophyll indices of pecan leaves are uncommon, but it is known that leaf chlorophyll content, stomatal conductance, and net photosynthesis are all positively related to leaf Zn concentration (Hu and Sparks, 1991). Chlorophyll content rose from 0.5 to 3.0 $mg\cdot g^{-1}$ fresh leaflet in pecan as Zn leaflet concentration increased from 4 to 9 $\mu g\cdot g^{-1}$ dry matter (Hu and Sparks, 1991). The lack of chlorophyll in Zn-deficient leaves is related with the characteristic interveinal chlorosis in Zn-deficient pecan trees. Because the nut yield and quality from the trees in this study were relatively good, chlorophyll indices from these trees may be considered to represent acceptable readings for established 'Wichita' pecan trees in the irrigated southwestern United States. In several other crops, a SPAD index reading of 50 to 52 represented chlorophyll concentrations of 4 to 5 mg of total chlorophyll per gram of (fresh weight) leaf (Uddling et al., 2007). Thus, in our study, 1 g of fresh leaflet was estimated to have

Table 6. Effect of manure and zinc (Zn) application on mineral composition of pecan 'Wichita' trees.[z]

Treatment[y]	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sulfur	Iron	Copper	Manganese	Boron
	($g\cdot kg^{-1}$)						($mg\cdot kg^{-1}$)			
	2006									
M1[y]	27.2	1.0	12.2	21.5	4.2	2.5	74	13	307	118
M1Z1	27.0	0.9	11.5	20.5	4.0	2.4	78	12	312	118
Control	27.0	1.0	12.0	19.0	3.6	2.4	70	12	300	115
Pr > F	NS[x]	NS	NS	NS	NS	NS	NS	NS	NS	NS
	2007									
M1	26.6	1.2	10.6 ab	24.6	5.3	3.3	141	11.8	232	108
M1Z1	24.7	1.2	12.2 b	26.0	5.2	3.3	87	12.6	355	104
M2	22.8	1.1	10.5 a	24.3	5.2	3.5	77	11.0	340	99
M2Z2	24.9	1.2	11.4 a	23.3	4.8	3.8	91	12.5	301	104
Control	24.8	1.2	12.2 b	26.2	5.3	3.4	78	12.3	334	104
Pr > F	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
	2008									
M1	22.0	1.1	14.0	25.8 ab	4.9 b	2.0	108	8.8	265	108
M1Z1	21.8	1.1	13.8	23.8 ab	4.3 a	2.0	104	8.3	307	102
M2	20.8	1.0	14.0	23.0 ab	4.4 ab	1.9	100	4.4	257	98
M2Z2	21.0	1.0	13.2	24.2 ab	4.5 ab	2.0	100	8.1	270	102
Control	21.5	1.0	13.2	21.8 a	4.2 ab	1.9	98	7.7	245	102
Pr > F	NS	NS	NS	**	*	NS	NS	NS	NS	NS

[z]Means followed by different letters are different at $P = 0.05$ through analysis of variance testing.

[y]M1 = manure 12 ton/ha; M2 = manure 24 ton/ha; Z1 = 129 kg Zn as $ZnSO_4$; Z2 = 258 kg Zn as $ZnSO_4$ (manure had a pH of 7.8 and an electrical conductivity of 4.0 and contained ≈0.84% nitrogen, 0.18 P_2O_5, 1.19 K_2O).

[x]NS, *, ** = Nonsignificant, significant (Pr > F = 0.05), and highly significant (Pr > F = 0.01).

contained ≈4 to 5 mg of chlorophyll. For comparison, healthy fresh 'Mohawk' leaflet had 185 mg chlorophyll per leaflet (Andersen and Brodbeck, 1988). Hu and Sparks (1991) found that 'Stuart' fresh non-Zn-deficient leaflets contained 3.2 mg of chlorophyll/g fresh leaves and 10 μg Zn/g in dry leaflets.

Yield was very low in 2006 but quite high in 2007. High nut yield coupled with low observed foliar Zn levels in 2007 suggests that the critical level of 50 $\mu g \cdot g^{-1}$ may be too high. The fact that the highest yield in 2007 was in the control treatment could be a result of the very low yield in this treatment the previous year. This is apparent from the alternate bearing intensity, which is very high for this treatment (although not significantly different from other treatments). In other studies, 'Wichita' pecans have had lower alternate bearing intensities than those we observed in the control plots (Conner and Worley, 2000; Nunez, 2001).

A higher incidence of vivipary in 2007 than in 2006 could be the result of stress caused by the high crop load in 2007. In previous studies conducted in Arizona and Texas, it was reported that 'Wichita' exhibited increased vivipary when large crop load was present (Kilby and Gibson, 2000; Sparks et al., 1995).

Manure and Zn affected foliar Zn levels in the plant. These results agree with research with other crops: rice (Battacharyya et al., 2006); sorghum (Pinto et al., 2004); basil, chard, dill, and peppermint (Zheljazkov and Warman, 2004). Additionally, foliar Zn concentrations have also been increasing in control treatment since the beginning of the study. Possible explanations for this may be related to conversion of this orchard to "organic" production and a change from a traditional tillage system for eliminating weeds to mowing. A qualitative increase in activity of earthworms has been observed. Also, mycorrhizae activity is now apparent, because fruiting bodies of ectomycorrhizal *Pisolithus tinctorius* and *Scleroderma bovista* are now found in the orchard. Mycorrhizae can have a profound effect on uptake of soil-immobile nutrients such as Zn (Sharpe and Marx, 1986). A proliferation of feeder roots has been noted in the surface soil and in the leaf litter.

Application of manure and particularly manure plus Zn increased foliar Zn levels in pecan trees after 2 years of annual applications. Additional research on the effects of manure on Zn behavior would help provide understanding concerning the processes involved and management practices to enhance Zn uptake by pecan trees.

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