Soil Zinc Fertilization of ‘Wichita’ Pecan Trees Growing Under Alkaline Soil Conditions

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Abstract. The effect of soil banding zinc sulfate and zinc (Zn)-EDTA was evaluated over a period of 4 years on established ‘Wichita’ pecans [*Carya illinoensis* (Wangenh.) K. Koch] growing in alkaline, calcareous soil. Treatments evaluated were ZnSO₄ applied at 74 kg Zn/ha and Zn-EDTA at 19 kg Zn/ha. These materials were applied just once on 23 Mar. 2005. Fertilizers were injected in two bands placed 1.2 m from either side of the trunk of the tree and 18 cm deep. Treatments were replicated four times in a randomized complete block design. Data collected included foliar Zn concentrations throughout the season, midseason foliar nutrient concentrations, leaflet growth, nut yield, and nut quality. Significant differences in foliar Zn levels were found 1 month after application of Zn-EDTA. Differences also were noted during the next 3 years on ≈25% of the sampling dates. Yields of in-shell pecans averaged 2800 kg·ha⁻¹ during the 3 years of harvest but were unaffected by treatments. Nut quality also was unaffected. Nut kernel percentage was very high, ranging from 61.2% to 63.6% during the study. Growth, measured as leaflet area and trunk cross-sectional area, was unaffected by Zn application. Chlorophyll index ranged from 47.5 to 48.0 in 2007 and from 44.7 to 45.4 in 2008 and was unaffected by applied treatments. Zn-EDTA increased Zn uptake slightly by ‘Wichita’ pecan trees in alkaline, calcareous conditions during 3 years after one soil band injection. Ongoing research on potted pecan trees (with the same soil used in the present study) suggests that Zn-EDTA can very effectively increase Zn uptake if placed in close proximity to the tree roots. Additional research is needed to refine application and placement methods in these types of soils to produce a more effective and consistent response.

Spraying zinc (Zn) solutions onto the tree canopy is the standard method for supplying this nutrient to pecan trees [*Carya illinoensis* (Wangenh.) K. Koch]. Zinc applied to soil reacts with hydroxyls and carbonates in alkaline and calcareous soils forming compounds of low solubility, limiting its plant availability (Agbenin, 2003; Lindsay, 1979; Udo et al., 1970). Foliar Zn sprays can reliably increase leaf Zn levels over threshold levels of ≈50 µg·g⁻¹, but this method has several disadvantages. Foliar application is time-consuming, requires investment in expensive equipment, uses fuel, repeated traffic through the orchard causes soil compaction, and spray schedules interfere with management in the orchard (mainly with irrigation). Additionally, repeated appli-

cations are required during the growing season as a result of low mobility of sprayed Zn within the tree (Grauke et al., 1982; Wadsworth, 1970). Because of these disadvantages, growers would benefit from an effective and efficient method of applying Zn fertilizers to the soil.

Soil application of Zn has been successful in the acidic soils of the southeast United States (Sparks, 1976; Wood, 2007) but is much less likely to be effective in alkaline and, particularly, calcareous soils.

Response of pecan to soil Zn application can take several years depending on application rate, form of fertilizer, and method of application. On an acid soil in Georgia, using zinc sulfate (35 kg Zn/ha), zinc oxide (35 kg Zn/ha), and Zn-EDTA (3.5 kg Zn/ha), recovery of a Zn-deficient orchard was very slow, and it took 3 to 4 years to reach the optimum Zn levels in the leaf and eliminate deficiency symptoms (Worley et al., 1972). Zinc application rates from 0 to 4224 g Zn/tree (as either ZnSO₄ or ZnO) placed over drip

irrigation lines were evaluated on 4-year-old ‘Desirable’ trees in an acid soil in Georgia. In the first year of evaluation, 4 months after application, trees that received rates higher than 528 g Zn/tree had leaf Zn levels over 50 µg·g⁻¹. In the second year, only those with rates of at least 2112 g Zn/tree had leaf Zn levels over 50 µg·g⁻¹, and in the fourth year after application, treatments with rates higher than 132 g per tree had greater than 50 µg·g⁻¹ of Zn in the leaves (Wood, 2007). In contrast, extremely high rates, as much as 126 kg of ZnSO₄/tree, were needed to provide adequate Zn to pecan trees in a calcareous soil in Texas (Storey et al., 1971).

In a study of several forms of Zn fertilizer, ZnSO₄, ZnO, and Zn-EDTA were broadcast or placed in holes (six holes, each 2.5 cm in diameter × 30 cm depth) in a Georgia soil that had been limed to a pH of 7.4 (Worley et al., 1972). Broadcast applications of either ZnO (applied at 22 g·cm⁻¹ of trunk circumference, applied annually over 5 years) or Zn-EDTA (3.3 g·cm⁻¹) increased leaf Zn relative to the untreated control; ZnSO₄ placed in holes did not. Response to broadcast Zn-EDTA was significant in Year 2, whereas ZnO effects were not apparent until Year 5. Zinc sulfate had no significant effect regardless of placement. Extractability of Zn²⁺ in soils treated with EDTA at rates of 0.1 and 0.2 mg·kg⁻¹ soil was increased as EDTA rate was increased (Karaca et al., 2000). DTPA-extractable Zn was 6.29 for the 0.1 mg·kg⁻¹ rate and 7.57 mg·kg⁻¹ for the 0.2 mg·kg⁻¹ rate versus 2.07 mg·kg⁻¹ in the control. In a field demonstration study in Texas, Zn-EDTA was applied through a drip irrigation system in 1974 at annual rates of 0.8, 1.6, and 2.5 kg Zn/ha (Lindsey and Condra, unpublished data). Resulting leaf Zn levels were 39, 53, and 68 µg·g⁻¹, respectively. In 1975, the corresponding leaf Zn levels were 49, 54, and 70 µg·g⁻¹, respectively. These data suggest that drip irrigation-applied Zn-EDTA elevated leaf Zn levels; however, no unfertilized controls were included, and the data were not statistically analyzed.

Zinc fertilizer placement is also critical. ZnO and ZnSO₄ were broadcast on a limed Georgia soil with a pH of 7.3 in the top 2.5 cm and 6.2 in the 2.5 cm below that. A single application of 160 kg Zn/ha of either material increased tissue Zn above 50 µg·g⁻¹ in Year 2 when disked into the soil and in Year 4 when not incorporated (Wood and Payne, 1997). In another study, an application of ZnSO₄ was banded (0 to 391 kg·ha⁻¹) or broadcast (0 to 448 kg·ha⁻¹) on a Georgia soil with pH ranging from 4.8 to 5.2 in a single application. Leaf Zn levels increased over the next 5 years. Applications of at least 112 kg ZnSO₄/ha broadcast or 391 kg ZnSO₄/ha banded increased Zn levels to over 50 µg·g⁻¹. Greater broadcast application rates increased leaf Zn sooner; 448 kg ZnSO₄/ha increased Zn above the 50 µg·g⁻¹ threshold in the second year, 224 kg ZnSO₄/ha in Year 4 to 5, and 112 kg ZnSO₄/ha in Year 5. In banded treatments, 391 kg ZnSO₄/ha raised leaf Zn to 50 µg·g⁻¹ in Year 5 (Payne and Sparks, 1982b).

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There is a lack of studies of Zn applied to irrigated calcareous soils. We evaluated Zn uptake, tree growth, and nut yield after a one-time band application of ZnSO₄ and Zn-EDTA in a calcareous soil over a period of 4 years. The objective was to determine if these fertilizers can effectively enhance Zn uptake in young ‘Wichita’ pecan trees in an irrigated, alkaline desert soil.

Materials and Methods

A field study was conducted on a commercial pecan orchard in southeast Arizona (lat. 31°55'01.25" N, long. 110°57'27.56", elev. 844 m) on ‘Wichita’ trees (7 years old) from May 2005 to Nov. 2008. The trees are growing in an alkaline and calcareous Pima clay loam soil with a soil pH of 7.6 (fine clayed, mixed, thermic, Typic Hapliargid). The soil is thermic and semiarid with mean annual soil temperatures from 15 to 22 °C and a mean annual precipitation between 25 to 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. The area between tree rows was mowed to keep the soil clean of weeds during the growing season. Trees were level basin flood-irrigated twice each month from April to October. A total of 1.50 m of water depth was applied annually. Beginning in 2007, the orchard was converted to organic production and pest control methods were changed accordingly. Before the block was converted to organic production, imidacloprid was soil-applied at a rate of 480 g a.i. per ha. After conversion to organic production, an insecticide–fungicide composed by potassium salts of fatty acids (49% w/w), propanol–glycol (specimen label for M-Pede®; Dow AgroSciences, Indianapolis, IN), was sprayed at least twice a year to the foliage at a rate of 1% v/v to reduce aphid populations. During the winter of 2006–2007, the trees in buffer rows between experimental plots were mechanically hedge-pruned. In the winter of 2007–2008, tree rows within plots were 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°.

Treatments evaluated were ZnSO₄ applied at a rate of 74 kg Zn/ha and Zn-EDTA at 19 kg Zn/ha and an untreated control treatment that did not receive any Zn application. Zinc materials were applied once only, on 23 Mar. 2005. Zinc sulfate was applied in 840 L H₂O/ha with 0.0026 mL H₂SO₄/L to increase solubility. Zn-EDTA was applied in 380 L H₂O/ha. Fertilizer solutions were injected using a single shank in bands placed 1.2 m from the trunk of the trees and 18 cm depth. Each tree row received two fertilizer bands, one on each side of the row. Treatments were replicated four times in a randomized complete block design. Each plot consisted of one row of 15 trees (n = 12). Every experimental plot was separated by one buffer row. Leaf sampling and growth measurements were collected from the 11 central trees in each plot row. Analysis of variance was conducted with SAS (Version 9.1; SAS Institute, Cary, NC). Mean separation was conducted with Tukey’s honestly significant difference.

Trunk circumferences were measured 20 cm above the ground for calculation of trunk cross-sectional area (TCSA) measurements. Trunk cross-sectional area was calculated from trunk circumferences in Feb. 2007 and Feb. 2008.

During 2005, 2006, 2007, and 2008, nut yield and quality were measured. Yield was calculated by mechanically harvesting the complete experimental plot. Cumulative nut yield was determined from the 4 years of harvest. Alternate bearing intensity was determined by the deviation of yield in successive years (Pearce and Dobersek-Urbanc, 1967) according to the formula:

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

where I = alternate bearing intensity, n = total

of years, and Y = year. Values are absolute numbers.

A subsample of ≈5 kg of the harvested nuts was used to determine meat yield, percent of good nuts, and stick-tight nuts (fruit with shuck remaining stuck to the shell after harvest). Yield efficiency was determined by calculating yield of nuts per square centimeter of tree TCSA. Kernel percent was determined by cracking 10 nuts from each experimental plot and separately weighing the shell and kernel. Weight per nut was calculated by counting the number of nuts per kilogram.

Twenty middle pairs of exterior leaflets from the leaves located in the middle part of the current season’s shoot growth on lower limbs (1.5 to 2.0 m height) from all the cardinal directions were collected every 2 or 3 weeks from May to October for Zn analysis. Complete nutrient analyses were conducted on leaflet samples collected in late July to determine the nutritional composition of the leaves. Immediately after sampling, leaves were washed using the following routine: washed in phosphate-free soap, rinsed in tap water, rinsed in distilled water, followed by three rinses in deionized water. Leaves were dried at 70 °C and ground with a mortar and pestle. During 2008, a rinse with hydrochloric acid (1% v/v) was added between the rinse with distilled water and rinse with deionized water. Complete analysis was conducted as follows. Nitrogen was determined by macro-Kjeldahl (Horowitz, 1980). For additional analysis, leaf tissue was ashed in a muffle furnace for 5 h at 500 °C. Hydrochloric acid (2.2 N) was used to dissolve the ash. Phosphorus was determined colorimetrically (Olsen and Sommers, 1982). Potassium, calcium, magnesium, sulfur, iron, Zn, copper, manganese were assayed by atomic absorption spectroscopy (Motz Laboratory, Inc., Tempe, AZ).

Leaflet size and chlorophyll index were determined on samples of 60 leaflets each summer. 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 pair of leaflets. Leaflets were scanned on a flatbed scanner and leaflet area obtained using Scion Image software (Scion Corp., Frederick, MD). Weights of dried leaves were also measured. During late July or early August, 20 middle pairs of leaflets were collected from the upper part of the canopy to compare leaf Zn concentration and leaf area with the ground level samples described previously.

Results

Zinc concentration in leaf tissue collected during the study is shown in Table 2. Significant differences were found as early as 1 month after injection of Zn fertilizers, although differences were not consistent over the duration of the study. Significant differences were found in ≈25% of the samples collected from 2005 through 2007, but not at all in 2008.

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·m ⁻¹	0.44
Calcium	NH ₄ OAc (pH 8.5)	mg·kg ⁻¹	4000
Magnesium	NH ₄ OAc (pH 8.5)	mg·kg ⁻¹	310
Potassium	NH ₄ OAc (pH 8.5)	mg·kg ⁻¹	510
Zinc	DTPA	mg·kg ⁻¹	3.2
Iron	DTPA	mg·kg ⁻¹	5.1
Manganese	DTPA	mg·kg ⁻¹	9.4
Copper	DTPA	mg·kg ⁻¹	2.4
Nickel	DTPA	mg·kg ⁻¹	0.12
NO ₃ -N	Cd reduction	mg·kg ⁻¹	8.8
PO ₄ -P	Olsen	mg·kg ⁻¹	9.0
SO ₄ -S	Hot water	mg·kg ⁻¹	22
Boron	Hot water	mg·kg ⁻¹	0.28
Free lime	Effervescence		High
Exchangeable sodium percent	Calculated	%	1.8
Cation exchange capacity	Calculated	cmol _c ·kg ⁻¹	24.3

Foliar Zn levels were consistently lower than the critical level of 50 $\mu\text{g}\cdot\text{g}^{-1}$ for pecans (Sparks, 1993, 1994) until 2008, when this level was reached in all treatments. Throughout the study, trees never exhibited visual Zn deficiency symptoms. During most of this study, the Zn-EDTA-treated trees had higher leaf Zn concentrations than the other two treatments; however, even in this treatment, leaflet Zn concentrations did not reach 50 $\mu\text{g}\cdot\text{g}^{-1}$ until the fourth year after treatment application. In 2005, leaf Zn concentrations were significantly higher in the leaves on the upper half of the trees as compared with the lower canopy leaves, although in 2007, there was no difference in leaf Zn concentration in the two parts of the trees. In 2008, differences in leaf Zn between lower and upper leaflets were not significant for the control treatment, but leaf Zn levels in the Zn-EDTA and zinc sulfate treatments were lower in the upper canopy compared with the lower part of the tree.

Zinc treatments did not affect growth of pecan trees (Table 3). Trunk cross-sectional area was unaffected and growth from 2006 to 2008 was unaffected by treatments. The increase in TCSA was slightly higher for the Zn-EDTA treatment than the rest of the treatments; however, differences were not significant. Chlorophyll indices ranged from 47.5 to 48.0 in 2007 and from 44.7 to 45.4 in 2008. No significant differences were found among treatments.

In the 4 years after soil Zn application, no effect was found on nut yield or quality (Table 4). The 2005 season was a high-yielding “on” year. This was followed by a low-yielding “off” year and then another high/low yield cycle. Variations in yields in consecutive years were quite similar in all treatments. Cumulative yield among Zn treatments over the 3 years of the study also was not significantly different, but Zn-EDTA had the highest yield. Notably, the annual nut yields of the Zn-EDTA-treated trees increased relative to that of the other treatments each yield cycle.

Nut quality was unaffected by treatments (Table 5). Kernel percentage was over 61.2 in all the years of evaluation. Nut weight ranged from 7.0 to 8.4 g per nut. The percentage of nuts exhibiting vivipary was between 2.6% and 11.0% and the percentage of stick tights ranged from 2.6% to 11.2%. Neither disorder was affected by Zn treatments.

In 2 of 4 years, leaflet manganese (Mn) concentration was significantly lower in Zn-EDTA-treated trees than in other treatments (Table 6). The decrease in Mn level in Zn-EDTA trees was 14% in 2006 and 10% in 2007. The same relationship was noted in 2008, but the difference was not significant. Concentrations of other nutrients in leaflet tissues were unaffected by treatment.

Discussion

Leaflet Zn levels below 50 $\mu\text{g}\cdot\text{g}^{-1}$ did not cause visual deficiency symptoms in this study. In the first season after soil Zn application (2005), late July leaflet Zn concen-

trations ranged from 15 to 22, in 2006 from 33 to 38, in 2007 from 39 to 42, and in 2008 from 44 to 58 $\mu\text{g}\cdot\text{g}^{-1}$. Leaflet Zn concentration below the critical level of 50 $\mu\text{g}\cdot\text{g}^{-1}$ (Sparks, 1993, 1994; Wood, 2007) during the first years of the study could be the result of rapid growth of the young ‘Wichita’ trees.

Leaflet Zn concentrations increased as the study progressed, even in the untreated control plots. The reasons for this are not clear. However, in 2007, manure applications were started as part of a switch from “conventional” to “organic” production. This may be related to the high Zn concentrations in 2008,

although it does not explain the increase from 2005 to 2006. In 2008, numerous fruiting bodies of the ectomycorrhizal fungi *Pisolithus tinctorius* and *Scleroderma bovista* were found in the orchard. Development of mycorrhizal fungi is known to enhance uptake of several nutrients, including Zn. It is not known whether these fungi were a factor in data obtained in the current study.

Nut yield and quality did not appear to be related to leaflet Zn, although lack of response of foliar Zn concentrations to soil Zn fertilizer treatments made this relationship difficult to assess. It is possible that all trees

Table 2. Effect of soil zinc (Zn) fertilization on leaflet Zn concentration during the growing season in ‘Wichita’ pecan trees ($\mu\text{g}\cdot\text{g}^{-1}$ dry weight).

2005										
Zn source	18 May	20 June	11 July	5 Aug.	2 Sept.	30 Sept.	5 Aug. top?			
Control	36	15 b	21 b	20	18 b	16	28			
Zinc sulfate	35	21 ab	23 ab	25	18 b	20	27			
Zn-EDTA	36	23 a	29 a	29	29 a	27	35			
Pr>F	NS	*	*	NS	**	NS	NS			
2006										
	9 May	9 June	26 June	11 July	27 July	11 Aug.	29 Aug.	21 Sept.		
Control	45	30	32	32	29	30	29	25 b		
Zinc sulfate	62	35	35	33	33	33	35	32 ab		
Zn-EDTA	64	39	37	42	42	35	36	35 a		
Pr>F	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.	top
Control	45	37	35	32	29	29	32 ab	24 ab	24	29
Zinc sulfate	50	39	38	33	31	35	29 b	22 b	28	30
Zn-EDTA	50	42	38	37	32	42	41 a	29 a	30	33
Pr>F	NS	NS	NS	NS	NS	NS	*	*	NS	NS
2008										
	30 May	14 June	2 July	17 July	30 July	14 Aug.	3 Sept.	20 Sept.	14 Aug. top	
Control	48	61	50	50	56	52	45	43	40	
Zinc sulfate	56	64	44	58	63	56	46	45	34	
Zn-EDTA	56	74	53	71	67	62	46	48	36	
Pr>F	NS	NS	NS	NS	NS	NS	NS	NS	NS	
Most significant difference (0.05)	—	—	—	—	—	—	—	—	—	

²Leaves from the upper half of the tree canopy.

NS, *, ** = Nonsignificant or significant at $P \leq 0.05$ or 0.01, respectively.

Table 3. Effect of soil zinc (Zn) fertilization on growth parameters of ‘Wichita’ pecan trees.

	Year				
Zn source	2005	2006	2007	2008	
Trunk cross-sectional area (cm ² /tree)					Growth 2006–2008
Control	—	440	497	562	125
Zinc sulfate	—	444	499	552	112
Zn-EDTA	—	416	477	536	122
Pr>F		NS	NS	NS	NS
Leaflet area top (cm ² /leaflet)					
Control	19.4	—	24.3	23.5	
Zinc sulfate	19.4	—	22.3	23.5	
Zn-EDTA	19.7	—	24.1	24.5	
Pr>F	NS		NS	NS	
Leaflet area ground (cm ² /leaflet)					
Control	23.2	28.4	25.0	19.0	
Zinc sulfate	27.8	24.3	24.5	20.4	
Zn-EDTA	26.5	24.4	23.3	20.0	
Pr>F	NS		NS	NS	
Chlorophyll index (SPAD)					
Control	—	—	47.8	45.6	
Zinc sulfate	—	—	48.0	45.4	
Zn-EDTA	—	—	47.5	44.7	
Pr>F			NS	NS	

NS, *, ** = Nonsignificant or significant at $P \leq 0.05$ or 0.01, respectively.

Table 4. Effect of soil zinc (Zn) application on yield and alternate bearing of 'Wichita' pecan trees.

Zn source	Year				Cumulative
	2005	2006	2007	2008	
Yield of nut (kg·ha ⁻¹)					
Control	3,789	1,297	3,415	1,693	10,195
Zinc sulfate	3,935	1,141	3,422	1,688	10,187
Zn-EDTA	3,415	1,382	3,932	1,928	10,658
Pr>F	NS	NS	NS	NS	NS
Cumulative alternate bearing intensity (Cum. I)					
Control	—	0.49	0.46	0.43	
Zinc sulfate	—	0.45	0.51	0.46	
Zn-EDTA	—	0.52	0.44	0.44	
Pr>F		NS	NS	NS	
Nut yield efficiency (g·cm ⁻²)					Cumulative
Control	73	25	57	42	151
Zinc sulfate	75	22	57	45	154
Zn-EDTA	69	28	69	41	166
Pr>F	NS	NS	NS	NS	NS
Yield of kernel (kg·ha ⁻¹)					Cumulative
Control	2,079	692	2,127	1,071	5,902
Zinc sulfate	2,077	612	2,160	1,061	5,916
Zn-EDTA	2,411	719	2,498	1,221	6,270
Pr>F	NS	NS	NS	NS	NS

NS, *, ** = Nonsignificant or significant at $P \leq 0.05$ or 0.01 , respectively.

contained adequate Zn for optimal production. Varying critical levels have been established for pecans and several researchers noticed no difference in pecan performance when Zn levels were above 36 to 35 $\mu\text{g}\cdot\text{g}^{-1}$ (Sparks, 1976). Other reported critical levels are: 20 $\mu\text{g}\cdot\text{g}^{-1}$ (Lane et al., 1965), 40 $\mu\text{g}\cdot\text{g}^{-1}$ (Worley et al., 1972), and 60 $\mu\text{g}\cdot\text{g}^{-1}$ (Storey et al., 1971). A sufficiency range of 50 to 100 $\mu\text{g}\cdot\text{g}^{-1}$ has been proposed (Sparks and Payne, 1982). The preferred leaf level of Zn for pecans in Louisiana is 50 to 150 $\mu\text{g}\cdot\text{g}^{-1}$ (O'Barr et al., 1978). Seedlings of 'Curtis' growing in nutrient solution without Zn contained 24 to 37 $\mu\text{g}\cdot\text{g}^{-1}$ of Zn, at which levels seedlings showed mild Zn deficiency symptoms (Sparks, 1978). In Georgia, high-yielding pecans (greater than 58 kg nuts per tree) had an average of 126 $\mu\text{g}\cdot\text{g}^{-1}$ Zn in leaves, and the cv was 60% (Beverly and

Worley, 1992). Optimum concentration in Mexico was determined to be 65 $\mu\text{g}\cdot\text{g}^{-1}$ (Medina, 2004) and in the southwestern United States 174 $\mu\text{g}\cdot\text{g}^{-1}$ (Pond et al., 2006). In our study, average annual yield 3 years after application was over 2800 kg·ha⁻¹, which is considered very acceptable, nut quality was excellent, and kernel yield was over 61%.

These data imply that a critical level of 50 $\mu\text{g}\cdot\text{g}^{-1}$ is probably too high. Pecans grown in hydroponic sand culture with nutrient solution omitting Zn exhibited interveinal necrosis in leaves with 7.2 $\mu\text{g}\cdot\text{g}^{-1}$, mottling at 9.8 $\mu\text{g}\cdot\text{g}^{-1}$, and no symptoms in leaves with 11.2 $\mu\text{g}\cdot\text{g}^{-1}$ (Kim et al., 2002).

The size of the leaflets (23.5 to 24.5 cm²/leaflet) was larger than those reported for 'Choctaw' pecan trees in shoots from the spring flush with 18.5 cm²/leaflet (Andersen and Brodbeck, 1988).

Table 5. Effect of soil zinc (Zn) fertilization on nut quality of 'Wichita' pecan trees.

Zn source	Year			
	2005	2006	2007	2008
Kernel (%)				
Control	62.3	61.5	62.0	63.3
Zn sulfate	62.5	62.3	63.2	62.8
Zn-EDTA	62.4	61.2	63.6	63.4
Pr>F	NS	NS	NS	NS
Nut weight (g)				
Control	8.0	8.2	7.8	7.2
Zinc sulfate	8.1	8.1	8.4	7.4
Zn-EDTA	7.9	7.7	8.0	7.0
Pr>F	NS	NS	NS	NS
Vivipary (%)				
Control	8.3	6.0	7.3	2.6
Zinc sulfate	11.0	8.4	9.2	4.4
Zn-EDTA	7.0	6.5	6.4	3.7
Pr>F	NS	NS	NS	NS
Stick tights (%)				
Control	6.5	9.6	3.3	4.4
Zinc sulfate	4.3	7.1	2.6	3.9
Zn-EDTA	7.0	11.2	4.5	3.7
Pr>F	NS	NS	NS	NS

NS, *, ** = Nonsignificant or significant at $P \leq 0.05$ or 0.01 , respectively.

There are few previously published chlorophyll index values for pecan leaves with which to compare our data. A previous study positively related leaf chlorophyll content to leaf Zn concentration (Hu and Sparks, 1991). Because the yield and quality of nuts from the studied trees were excellent in this study, the chlorophyll indices of these trees can be considered acceptable for 'Wichita' pecan trees in the irrigated southwestern United States. 'Pawnee' leaflets in Texas had similar values as those obtained for 'Wichita' in our study (Lombardini et al., 2005). In several crops as birch, wheat, and potato, soil plant analysis development (SPAD) indices of 50 to 52 represent chlorophyll concentrations of 4 to 5 mg of total chlorophyll per gram (fresh weight) of leaf (Uddling et al., 2007). We calculated that 1 g of fresh leaflet tissue in our

Table 6. Effect of soil zinc (Zn) fertilization on leaf mineral composition of adult pecan 'Wichita' pecan trees (July leaf samples, dry matter).

	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sulfur	Iron	Zinc	Copper	Manganese	Boron
	(g·kg ⁻¹)						(mg·kg ⁻¹)				
Treatment	2005										
Control	25.0	0.9	10.8	13.8	3.1	1.9	58.5	15	4.6	262	112
Zn sulfate	25.0	1.0	11.8	14.8	3.2	2.0	75	22	5.2	290	125
Zn-EDTA	24.0	0.9	11.0	13.8	3.1	2.0	66	20	4.7	265	112
Pr>F	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	2006										
Control	26.5	1.2	11.5	22.0	4.5	2.5	81	33	14.8	298 a ^z	109
Zn sulfate	27.3	1.1	11.5	21.3	4.4	2.5	86	34	14.8	295 a	109
Zn-EDTA	27.3	1.1	11.5	20.0	4.3	2.5	88	38	15.5	255 b	99
Pr>F	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
	2007										
Control	24.7	1.2	12.6	25.5	5.4	3.0	76	39	9.6	275 a	98
Zn sulfate	24.4	1.2	12.9	26.2	5.3	2.8	71	32	9.0	281 a	100
Zn-EDTA	24.3	1.2	12.9	24.8	5.6	3.0	76	42	9.8	246 b	98
Pr>F	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
	2008										
Control	22.0	1.1	13.5	24.3	4.9	2.0	86	44	8.7	267	98
Zn sulfate	21.5	1.0	13.0	24.0	4.6	2.0	98	48	8.5	247	105
Zn-EDTA	21.3	1.0	13.5	24.0	4.8	2.0	90	58	8.5	210	106
Pr>F	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

^cNumbers in a column followed by different letters are significantly different at $P < 0.05$.

NS, *, ** = Nonsignificant or significant at $P \leq 0.05$ or 0.01 , respectively.

study contained ≈ 4 to 5 mg of chlorophyll. Hu and Sparks (1991) found that fresh 'Mohawk' leaflets contained 3.2 mg of chlorophyll/g of fresh leaves.

Alternate bearing intensity (I) measured as a variation in yield in consecutive years was very high, over 0.45 in 2 years of study, over 0.44 in 3 years, and more than 0.43 over 4 years. In Sonora, Mexico, I for 'Wichita' pecan trees has been reported to be 0.26 over seven seasons (Nunez, 2001) and in Georgia 0.51 in young trees and 0.67 in mature trees (Conner and Worley, 2000).

Yield efficiency was high in the "on" years and very low in the "off" years. It increased in the Zn-EDTA plots over the course of the study, and this treatment had the highest cumulative yield efficiency, but no differences could be attributed to treatments.

Zn-EDTA application decreased Mn leaflet levels. This could be the result of an antagonism between Zn and Mn, which has previously been reported (Mengel and Kirkby, 1987). It has also been noted that low leaf Zn is accompanied by high leaf Mn concentrations (Kim et al., 2002). Additionally, increasing the Mn concentration in a nutrient medium from 0 to 14.78 g·L⁻¹ decreased leaf Zn levels in 'Desirable' pecan seedling leaflets from 137 to 43.5 $\mu\text{g}\cdot\text{g}^{-1}$ (O'Barr et al., 1987). Leaflet Mn increased from 187 to 4525 $\mu\text{g}\cdot\text{g}^{-1}$.

In our study, leaflet Zn levels were not consistently affected by banding Zn in a calcareous soil. Similarly, banding a comparable rate of Zn (69 kg Zn/ha as zinc sulfate) in an acidic soil (pH 4.8 to 5.2) did not increase leaflet Zn levels above 50 $\mu\text{g}\cdot\text{g}^{-1}$ (Payne and Sparks, 1982a). In that study, leaflet Zn levels above this critical level were obtained by only applying 138 kg Zn/ha, and these concentrations were reached 6 years after Zn was banded. Banding 63 kg Zn/ha as ZnSO₄ over a drip-emitter irrigation system did not raise leaf Zn levels above 50 $\mu\text{g}\cdot\text{g}^{-1}$ until 4 years after application in young 'Desirable' trees (Wood, 2007).

Four years after the initiation of this study in a calcareous soil with a pH of 7.6, all treatments, including the control treatment, had leaflet Zn levels above the critical level. Reasons for the increase in foliar Zn concentration over the course of the study could be related to the conversion of this orchard to organic production, which included a shift to mowing for weed control instead of the previously used soil cultivation. Extensive earthworm and mycorrhizae activity is now much more apparent than at the beginning of the study. Also, increased presence of feeder roots was noted in the shallow surface soil and in the leaf litter. These conditions can affect nutrition of plants (Sharpe and Marx, 1986).

Zn-EDTA occasionally increased Zn uptake by 'Wichita' pecan trees in alkaline, calcareous soil over the 4 years after a single band application. Yield, nut quality, and growth were unaffected by any of the experimental treatments. At this time, this Zn fertilization method cannot be recommended for established pecans in the southwestern United States. Additional research to evaluate application methods and Zn sources is needed to find appropriate methods for soil Zn application in southwestern pecan orchards.

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