Soil-applied ZnEDTA: Vegetative Growth, Nut Production, and Nutrient Acquisition of Immature Pecan Trees Grown in an Alkaline, Calcareous Soil

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Abstract. A field study was conducted to evaluate efficacy of soil-applied zinc (Zn) fertilizer on young pecan [*Carya illinoensis* (Wangenh.) K. Koch] trees growing in alkaline, calcareous soils. Chelated Zn ethylenediaminetetraacetic acid (ZnEDTA) was applied at rates of 0, 2.2, or 4.4 kg·ha⁻¹ of Zn via injection into irrigation water (fertigation) in microsprinkler irrigated ‘Western’ and ‘Wichita’ trees. Over the 5-year duration of the study, leaf Zn levels were increased from 22 to 35 µg·g⁻¹ in the highest rate of ZnEDTA treatment compared with 7 to 14 µg·g⁻¹ in unfertilized trees. Zn concentrations in shoot and root tissues were also elevated in Zn-treated trees. Zn treatments largely eliminated visible Zn deficiency symptoms, and increased trunk diameter growth compared with untreated trees. Nut yield (in the third through fifth seasons) were also increased as a result of Zn fertilization. No additional benefit in terms of trunk diameter growth or nut yield was observed by adding a higher rate of Zn (4.4 kg·ha⁻¹) vs. the lower rate (2.2 kg·ha⁻¹). ‘Western’ and ‘Wichita’ trees responded similarly to Zn fertigation.

Pecan (*C. illinoensis*) is the major tree nut crop grown in the desert southwestern states of Arizona, New Mexico, and Texas. Growing conditions vary throughout this region; however, the soils are generally calcareous, with pH levels of 8.0 or above. Pecan trees growing in these soils are prone to Zn deficiency due to limited soil Zn availability (Alloway, 2008; Malstrom and Fenn, 1981; Smith et al., 1980). Fenn et al. (1990) reported that water extractable Zn in a South Texas soil decreased from 394 to 12 µg·g⁻¹ as soil pH increased from pH 4 to 8. Muhammad et al. (2006) found that the majority of Zn in calcareous soils is sorbed to calcium (Ca) carbonate.

Rosetting, a characteristic visual symptom of Zn-deficient pecan trees, occurs when leaf and internode size are reduced. Severe deficiency symptoms also include interveinal chlorosis, eventually developing into necrosis. Terminal growth dieback can occur in severe cases. Zn deficiency can reduce catkin length, number of fruits per shoot, fruit development, and when severe, it can inhibit

production of inflorescences (Hu and Sparks, 1990, 1991). Published literature suggests that pecan leaf Zn concentrations should be greater than 40 to 50 µg·g⁻¹ to avoid deficiency (Payne and Sparks, 1982; Pond et al., 2006; Reuters and Robinson, 1997; Sparks, 1993, 1994).

Foliar application of Zn solutions directly onto tree foliage is the standard method for supplying this nutrient to pecan trees. 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 which requires fuel, and spray schedules may conflict with other management practices in the orchard (mainly with irrigation). Achieving adequate coverage via foliar application is difficult and only leaves actually contacted by spray are affected by foliar treatments (Wadsworth, 1970). Storey et al. (1971) noted that only 0.2% and 1.0% of applied Zn was absorbed by mature and young leaves, respectively. Additionally, repeated applications are required during the growing season as a result of low mobility of sprayed Zn within the tree (Grauke et al., 1982; Wadsworth, 1970). For these reasons, there is considerable interest among pecan producers in the potential of soil-applied Zn.

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

and particularly, calcareous soils. Storey et al. (1971) found that a soil application of 126 kg/tree of zinc sulfate (ZnSO₄) was needed to provide adequate nutrition to mature pecans growing in a calcareous Texas soil. Soluble Zn compounds such as ZnSO₄ applied to alkaline soil react with hydroxyls and carbonates in alkaline and calcareous soils forming compounds of low solubility, limiting its plant availability (Agbenin, 2003; Essington, 2003; Lindsay, 1972, 1979; Sadiq, 1991; Udo et al., 1970). Smith (1934) reported that to correct rosette symptoms on pecan in an “alluvial silt loam soil high in lime” in Uvalde, Texas, a ZnSO₄ rate of 1.8 to 2.3 kg/tree (applied in a trench 60 to 75 cm from the trunk) was necessary. An application of 91 kg/tree of ZnSO₄ failed to bring soil Zn content to a critical level in a study by Lott (1938) because the Zn was converted to insoluble Zn carbonate.

Using Zn in combination with sulfuric acid (H₂SO₄) to fertilize pecans growing in alkaline soils was evaluated by acidifying a shallow trench making up less than 1% of the effective root zone of mature Texas pecan trees and applying a mixture of 9 kg ZnSO₄ and 113 L of 36 N H₂SO₄ per tree (Fenn et al., 1990). Leaf Zn did not change in the first 3 years, but 4 years after application, leaves of treated trees contained 54 µg·g⁻¹ Zn vs. 39 µg·g⁻¹ in the untreated control. After 9 years, leaf Zn levels were 58 and 45 µg·g⁻¹ for treated and untreated trees, respectively, and 56 µg·g⁻¹ in trees receiving ZnSO₄ 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.

Chelated Zn fertilizers, such as those made with EDTA, can alter the soil mobility of Zn and more effectively increase levels of bioavailable Zn compared with inorganic Zn fertilizers (Alvarez, 1997). Chelated Zn is less subject to soil fixation reactions (Norvell, 1991). Naik and Das (2010) showed that ZnEDTA was more effective than ZnSO₄ at keeping Zn in solution and Alvarez et al. (1997) found that compared with unamended soil, amendment with ZnEDTA increased soil Zn bioavailability to plants. In an alkaline, calcareous Arizona soil Núñez-Moreno et al. (2009) found that soil-banded application of ZnEDTA (19 kg·ha⁻¹ of Zn) resulted in significant pecan leaflet Zn concentration differences 1, 3, 4, 18, and 30 months after application, but that banded ZnSO₄ (74 kg·ha⁻¹ of Zn) did not.

In a field demonstration study in Texas in 1974, ZnEDTA was applied to pecans through a drip irrigation system at annual rates of 0.8, 1.6, and 2.5 kg·ha⁻¹ of Zn (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 ZnEDTA increased leaf Zn concentrations; however, no unfertilized controls were included, treatments were not replicated, and the data were not statistically analyzed.

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Zn fertilizer placement is also critical. Zinc oxide (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 (Wood and Payne, 1997). A single application of 160 kg·ha⁻¹ of Zn supplied by either ZnO or ZnSO₄ increased leaf tissue Zn above 50 µg·g⁻¹ in the 2nd year after application if the Zn was disked into the soil and in the 4th year if it was not incorporated.

The purpose of this study was to evaluate the efficacy of applying ZnEDTA dissolved in irrigation water to immature pecan trees growing in an alkaline calcareous soil. This study reports on Zn uptake and plant growth response to fertiligated ZnEDTA.

Materials and Methods

Study site and Zn treatments. A field study was conducted in a commercial pecan orchard in San Simon, AZ (32°15'20.2"N; 109°10'29.8"W; elevation 1118 m). The climate is semiarid with an average of <300-mm precipitation annually. The soil in the orchard is a Guest silty clay loam (fine, mixed, super-active, calcareous, and thermic Ustertic Torri-fluents), with pH of 8.1; soil test values at initiation of the study are shown in Table 1.

The main cultivar in orchard block used for this study was 'Wichita' budded onto an open-pollinated seedling 'Ideal' (syn. 'Bradley') rootstock with 25% 'Western' (syn. 'Western Schley') pollinizers, also on 'Ideal' rootstocks. 'Wichita' and 'Western' are the major cultivars grown in Arizona. 'Wichita' is reputed to be more prone to Zn deficiency than many other pecan cultivars when grown in calcareous, alkaline soils (Herrera, 2005). Tree spacing was 6 × 12 m. Each main treatment plot contained at least 15 trees.

The orchard owner managed all orchard operations except Zn fertilizer applications. Each tree was irrigated by one microsprinkler with a wetted area ≈2.5 m in diameter. Trees received ≈1 m of irrigation water each season. Weeds in the tree row were controlled with glyphosate (3.5 L·ha⁻¹) four times, carfentrazone (150 mL·ha⁻¹) twice, and glufosinate (3.5 L·ha⁻¹) once per season. Areas between rows were mechanically mowed to suppress weeds. All trees were fertilized uniformly with 16N–3.5P–2.5K–4S fertilizer injected into the irrigation system at annual application rates of 247, 247, 493, 740, and 1232 kg·ha⁻¹ in 2011, 2012, 2013, 2014, and 2015, respectively.

Beginning in 2011 when trees were planted, treatments of ZnEDTA fertilizer (Sequestar 9% Zn Chelate; Monterey Ag Resources, Fresno, CA) were applied by injection through the orchard microsprinkler irrigation system at one of three rates: 0 (control), 2.2, or 4.4 kg·ha⁻¹·yr⁻¹ of actual Zn. Applications were split among irrigation dates (Table 2). No foliar Zn applications were made. The study was a randomized complete block design with four blocks and main plots split into two varieties ('Wichita' and 'Western').

Soil and leaf analysis. Soil cores were collected on 25 June 2013 and separated into 0 to 30 cm, 30 to 60 cm, and 60 to 90-cm

Table 1. Soil test levels before field study initiation.

Soil test	Method	Result	Rating
pH	1:1 soil:water	8.1	High
EC	1:1 soil:water	0.49 dS·m ⁻¹	Low
Calcium	NH ₄ OAc (pH 8.5)	3200 mg·kg ⁻¹	Very high
Magnesium	NH ₄ OAc (pH 8.5)	140 mg·kg ⁻¹	High
Sodium	NH ₄ OAc (pH 8.5)	66 mg·kg ⁻¹	Medium
Potassium	NH ₄ OAc (pH 8.5)	380 mg·kg ⁻¹	High
Zn	DTPA	0.39 mg·kg ⁻¹	Low
Iron	DTPA	1.9 mg·kg ⁻¹	Low
Manganese	DTPA	11 mg·kg ⁻¹	High
Copper	DTPA	0.83 mg·kg ⁻¹	High
Nickel	DTPA	0.14 mg·kg ⁻¹	No standards available
Nitrate-N	Cd reduction	23 mg·kg ⁻¹	Medium
Phosphate-P	Olsen	7.9 mg·kg ⁻¹	Low
Sulfate-S	Hot water	18 mg·kg ⁻¹	High
Boron	Hot water	0.37 mg·kg ⁻¹	Medium
Free lime	Acid test	High	
ESP	Calculated	1.6%	
CEC	Calculated	18.4 cmol _c ·kg ⁻¹	

EC = electrical conductivity; ESP = exchangeable sodium percentage; CEC = cation exchange capacity.

depth fractions from the 4.4 kg·ha⁻¹ treatment only. Cores were located 60, 120, and 240 cm from the trunks of four trees. Zn, copper (Cu), iron (Fe), manganese (Mn), and nickel (Ni) were extracted with diethylenetriaminepentaacetic acid-triethanolamine (DTPA-TEA) (Lindsay and Norvell, 1978) and analyzed with a ThermoFisher iCAP 7000 ICP-OES (Thermo Fisher Scientific Inc., Waltham, MA).

In 2011, leaves from 'Western' and 'Wichita' were combined to obtain a representative foliage sample from the newly transplanted young trees. In subsequent years trees were large enough to sample leaves of cultivars separately. Each year at least 40 leaflets were collected per treatment according to the methods recommended by the University of Arizona and New Mexico State University Extension Services (Heerema, 2013; Walworth and Pond, 2006). First year (2011) sampling was delayed until the end of the growing season (24 Sept.) to avoid damage to the young trees. Other sampling dates were 14 Aug. 2012, 11 July 2013, 24 July 2014, and 3 Aug. 2015.

Leaflet samples were first washed in a water bath with a phosphorus (P)-free detergent (0.05% detergent), followed by two rinses in deionized water and a rinse in dilute hydrochloric acid (1% HCl), and finally one additional rinse with ultrapure water. Leaflets were spun to remove excess water, then dried in an oven for 3 d at 65 °C, and mechanically ground to a 20-mesh particle size.

Root and dormant shoot tissues were collected on 21 Jan. 2015 and 15 Jan. 2016. One to four root sections and six shoot segments (previous-season growth only), each ≈1 cm in diameter were collected from each of four 'Wichita' trees in each plot. These were handled and analyzed for Zn concentration using the procedure for leaflet samples.

Tissue samples were dry ashed in a muffle furnace by placing 0.5 g aliquots into 30-mL porcelain crucibles, ramping the temperature to 500 °C over 3.5 h, and maintaining the temperature for 5.5 h. Cooled ash was dissolved in 10 mL of 2.0 N HCl, allowed to sit for several hours, diluted to 50 mL with H₂O and allowed to sit overnight (Jones and Case, 1990).

Table 2. Dates of zinc ethylenediaminetetraacetic acid application. Annual zinc applications were evenly split among application dates.

2011	2012	2013	2014	2015
18 Apr.	25 Apr.	3 May	14 Apr.	14 Apr.
11 May	7 May	24 May	28 Apr.	24 Apr.
25 May	21 May	7 June	12 May	8 May
6 June	5 June	21 June	31 May	22 May
20 June	13 June	27 June	13 June	29 May
5 July	21 June	5 July	3 July	5 June
18 July	26 June	11 July	11 July	12 June
1 Aug.	3 July	19 July	18 July	19 June
15 Aug.	8 July	25 July		26 June
29 Aug.	3 Aug.	2 Aug.		3 July
12 Sept.	23 Aug.	9 Aug.		
26 Sept.	7 Sept.	16 Aug.		
10 Oct.	18 Sept.	23 Aug.		
	9 Oct.	30 Aug.		
		6 Sept.		
		13 Sept.		

Zn concentration was analyzed with a PerkinElmer 3100 Atomic Absorption Spectrophotometer (PerkinElmer, Waltham, MA) at a wavelength of 213.86 nm. Complete nutrient analyses were conducted on leaflets collected on 14 Aug. 2012, 11 July 2013, 23 July 2014, and 3 Aug. 2015. Samples were analyzed for N by combustion using a Leco™ TruSpec (Leco Corp., Saint Joseph, MI). Following digestion with nitric acid/hydrogen peroxide, samples were analyzed for potassium, P, Ca, Mg, sulfur, boron, Cu, Fe, Mn, Ni, and Zn using a ThermoFisher iCAP 7000 ICP-OES (Thermo Fisher Scientific Inc.).

Trunk diameters were measured with a caliper at 45 cm above the ground in both north-south and east-west directions. The two directions were averaged to obtain trunk diameters. Measurements were made on 11 May 2011, 26 Sept. 2011, 9 Oct. 2012, 28 Sept. 2013, 11 Jan. 2015, and 4 Dec. 2015. Differences between measurements were used to estimate annual tree growth.

Visual ratings of severity of Zn deficiency symptoms were made using a scale of one to five, where five represented trees with no visible symptoms, and one represented trees with severe symptoms including limb dieback.

Visual ratings were conducted on 21 Aug. 2012, 19 July 2013, and 24 July 2014.

Nuts were harvested manually on 21 Nov. 2013, 24 Nov. 2014, and 19 Nov. 2015. Nuts were graded to determine percentages of nuts with vivipary, and shelled to determine relative weights of kernels and shells. Kernel Zn concentration was determined using the methods described above for leaf tissue.

Analyses of variance were conducted using a split-plot analysis where Zn treatments were the main plots and variety the split plots, except where data were collected from just one variety (e.g., stem and root samples) or from both varieties combined (leaf samples in 2011). In those cases, data were analyzed as a randomized complete block. Means were separated using least significant difference (LSD, $\alpha = 0.05$).

Results

Soil samples collected from the 4.4 kg·ha⁻¹ treatment in 2013, during the third season of ZnEDTA fertigation, show that available Zn levels were above background levels (indicated by samples collected 240 cm from the tree trunks, located well outside the fertigated zone; Table 3). Surface (0 to 30 cm) soil nearest the tree contained 5.65 µg·g⁻¹

Table 3. DTPA-TEA extractable soil zinc (Zn) (µg·g⁻¹) on 25 June 2013 in plots fertigated with 4.4 kg·ha⁻¹ of Zn.

Soil depth	Distance from tree trunk		
	60 cm	120 cm	240 cm
0–30 cm	5.65	2.06	0.70
30–60 cm	4.53	1.32	0.44
60–90 cm	3.95	1.23	0.42
LSD _{0.05}		2.03	

LSD = least significant difference.

of Zn compared with 0.70 µg·g⁻¹ in the untreated soil. Suggested interpretations of DTPA-TEA soil Zn are as follows: low = 0 to 0.5 µg·g⁻¹, marginal = 0.5 to 1.0 µg·g⁻¹, and adequate >1 µg·g⁻¹ (Cox and Kamprath, 1972), indicating that the available Zn levels were increased from low to adequate as a result of ZnEDTA fertigation. Other micro-nutrients tested (Cu, Fe, Mn, and Ni) were not altered by fertigation treatments (data not shown).

Foliar Zn concentrations increased proportionally to the amount of ZnEDTA applied (Fig. 1). In 2011, the highest application rate (4.4 kg·ha⁻¹) resulted in leaf Zn concentrations of 21.9 µg·g⁻¹. By 2014, after four seasons of ZnEDTA application, the leaf Zn concentration associated with this treatment had risen to 35.3 µg·g⁻¹, but in 2015 it decreased to 23.6 mg·kg⁻¹. Leaf Zn in the untreated trees dropped from 14.5 µg·g⁻¹ in 2011 to 7.4 µg·g⁻¹ and over the duration of the study averaged 10.7 µg·g⁻¹, considerably lower than the 40 or 50 µg·g⁻¹ minimum sufficiency levels frequently recommended (Sparks, 1994; Worley et al., 1972).

Differences in foliar Zn concentrations between varieties were inconsistent, and generally nonsignificant. In 2015, levels were slightly higher in ‘Western’ than in ‘Wichita’ (17.4 vs. 15.6 µg·g⁻¹). In other years, differences were not significant: in 2014 ‘Wichita’ had higher leaf Zn concentrations (24.2 vs. 22.0 µg·g⁻¹), whereas in 2012 and 2013, levels were higher in ‘Western’ than in ‘Wichita’ (20.8 vs. 17.9 µg·g⁻¹ and 18.2 vs. 14.9 µg·g⁻¹, respectively). The variety by Zn-application interaction was not significant, indicating that Zn uptake response to treatment levels was not different in ‘Western’ and ‘Wichita’.

In contrast to foliar Zn concentrations, Zn deficiency symptoms were significantly more severe in untreated ‘Wichita’ than untreated ‘Western’ in both 2012 and 2013 (Table 4). In 2014, the cultivar × Zn treatment was not significant. By 2013, the second season of the study, Zn fertigation nearly eliminated visible deficiency symptoms (only some slight symptoms remained) in both ‘Western’ and ‘Wichita’, although even the highest treatment level did not result in leaf Zn concentrations above suggested minimum sufficiency levels of 40 to 50 µg·g⁻¹. By 2014, differences in Zn deficiency symptom severity between varieties were no longer apparent. Application of either 2.2 or 4.4 kg·ha⁻¹ eliminated most deficiency symptoms (Tables 4 and 5).

Shoot, root, and kernel Zn concentrations, measured only on ‘Wichita’ trees, closely mirrored leaf Zn concentrations (Table 6). Shoot, root, and kernel Zn concentrations in untreated trees were 14.92, 16.99, and 25.96 µg·g⁻¹, respectively, in 2014 and 12.95, 24.53, and 10.09 µg·g⁻¹ in 2015. In trees treated with 4.4 kg·ha⁻¹ of Zn the corresponding levels were 35.08, 44.01, and 43.40 µg·g⁻¹ in 2014 and 29.57, 45.26, and 31.91 µg·g⁻¹ in 2015. In contrast to foliar application where tissue Zn is elevated only in close proximity to Zn solution droplets (Wadsworth, 1970), fertigation with chelated Zn increased Zn concentrations in all plant parts tested.

Leaf concentrations of nutrients other than Zn were generally inconsistent, and few effects of Zn application or pecan variety were observed over all years in which complete leaf analyses were conducted (data not shown). There were, however, two notable exceptions. In 2012, 2013, 2014, and 2015,

Fig. 1. Average leaf zinc (Zn) concentration of ‘Wichita’ and ‘Western’ pecan trees fertigated with varying levels of Zn. Mean totals with a common letter within each year are not different ($\alpha = 0.05$) by analyses of variance least significant difference.

Table 4. Visual rating of zinc (Zn) deficiency symptoms (5 = no symptoms; 1 = severe symptoms) of 'Western' and 'Wichita' pecan trees fertigated with various rates of Zn ethylenediaminetetraacetic acid.

Zn treatment level	Yr		
	2012	2013	2014
Western			
0 kg·ha ⁻¹	4.10	3.53	2.91
2.2 kg·ha ⁻¹	4.40	5.00	5.00
4.4 kg·ha ⁻¹	4.30	4.93	5.00
LSD _{0.05}			
0.24 0.30 NS			
Wichita			
0 kg·ha ⁻¹	3.65	3.03	2.86
2.2 kg·ha ⁻¹	4.38	4.80	4.91
4.4 kg·ha ⁻¹	4.35	4.98	4.92
LSD _{0.05}			
0.24 0.30 NS			

LSD = least significant difference.

Table 5. Average visual rating of zinc (Zn) deficiency symptoms (5 = no symptoms; 1 = severe symptoms) of 'Western' and 'Wichita' pecan trees fertigated with various rates of Zn ethylenediaminetetraacetic acid.

Zn treatment level	Yr		
	2012	2013	2014
0 kg·ha ⁻¹	3.88	3.28	2.89
2.2 kg·ha ⁻¹	4.39	4.90	4.97
4.4 kg·ha ⁻¹	4.33	4.95	4.96
LSD _{0.05}			
0.17 0.21 0.20			

LSD = least significant difference.

Table 6. Zinc (Zn) concentrations (μg·g⁻¹) of 'Wichita' shoots, roots sampled in the dormant season, and harvested nut kernels in trees fertigated with Zn.

Zn treatment level	Plant part		
	Shoot	Root	Kernel
2014			
0 kg·ha ⁻¹	14.92	16.99	25.96
2.2 kg·ha ⁻¹	25.32	24.71	37.73
4.4 kg·ha ⁻¹	35.08	44.01	43.40
LSD _{0.05}			
10.70 10.81 11.07			
2015			
0 kg·ha ⁻¹	12.95	24.53	10.09
2.2 kg·ha ⁻¹	19.70	25.27	15.41
4.4 kg·ha ⁻¹	29.57	45.26	31.91
LSD _{0.05}			
4.16 11.96 9.91			

LSD = least significant difference.

fertigation with ZnEDTA reduced foliar Ca and Mg concentrations (Table 7). The leaf Ca concentrations were within or above the adequate concentration range for pecans (Heerema, 2013). Magnesium concentrations; however, fell below the adequate concentration range of 3.0 to 6.0 mg·g⁻¹ in the trees fertigated with the higher rate of ZnEDTA, although no visible symptoms of Mg deficiency were observed. In 3 of the 4 years, foliar Ni levels also declined in trees fertigated with ZnEDTA.

Growth of trees, reflected in annual and cumulative increase in trunk diameter, was consistently greater in 'Western' than 'Wichita' (Table 8). Trunk diameter growth was affected by Zn application level to a smaller degree than tissue Zn concentrations. The Zn application rate × variety interaction was not

Table 7. Foliar calcium (g·kg⁻¹), magnesium (g·kg⁻¹), and nickel (μg·g⁻¹) concentrations in 'Western' and 'Wichita' pecans combined resulting from various levels of fertigation with zinc (Zn) ethylenediaminetetraacetic acid.

Zn treatment level	Ca				Mg				Ni			
	2012	2013	2014	2015	2012	2013	2014	2015	2012	2013	2014	2015
0 kg·ha ⁻¹	22.0	21.8	22.8	27.5	3.5	3.1	3.5	3.0	1.49	1.91	1.22	2.48
2.2 kg·ha ⁻¹	17.5	17.6	19.0	20.5	2.9	2.6	3.1	2.6	1.04	1.06	0.81	1.68
4.4 kg·ha ⁻¹	16.5	15.4	18.1	18.3	2.8	2.3	2.7	2.3	1.05	1.05	1.17	1.22
LSD _{0.05}												
1.6 2.3 2.9 2.8 0.3 0.3 0.2 1.7 0.12 0.41 NS 0.42												

LSD = least significant difference.

significant so data are presented of both varieties combined (Table 9). Growth differences between treatments became more pronounced over time. In 2012, no significant growth response was observed. In 2014 and 2015, trees that were fertigated with ZnEDTA exhibited significantly more growth than untreated trees. The same was true of cumulative growth from 2012 to 2015. Although growth differences between trees treated with 2.2 or 4.4 kg·ha⁻¹ were not significant, those trees that received the lower of the two Zn levels exhibited slightly more rapid growth than those that received the higher Zn application.

Although 'Western' trees grew slightly faster than 'Wichita' trees, they did not bear nuts in 2012, whereas 'Wichita' did (Table 10). This was the only year there was a nut yield difference between 'Western' and 'Wichita'. Average yields of the two varieties increased in the Zn-fertigated trees relative to untreated trees (Table 11). Interestingly, and mirroring trunk diameter growth patterns, 2013 and 2015 nut yields were significantly greater in trees fertigated with 2.2 kg·ha⁻¹ than those that received 4.4 kg·ha⁻¹. The same pattern was observed in 2014, although in that year differences were non-significant.

Neither the percentage of nuts exhibiting vivipary, nor the size of individual nuts was affected by Zn application in 2013, 2014, or 2015 (data not presented). Vivipary was greater in 'Wichita' than in 'Western' (2.95% vs. 0.40%, LSD_{0.05} = 0.87%) in 2015. 'Wichita' nuts were larger than 'Western' in 2014 (8.07 vs. 6.96 g/nut, LSD_{0.05}) and 2015 (9.03 vs. 8.30 g/nut, LSD_{0.05} = 0.16), respectively.

Discussion

In pecan orchards irrigated with pressurized irrigation systems, nutrient application via fertigation is being adopted. The industry standard for treating Zn deficiency in pecans growing in calcareous soils has been through the use of foliar sprays; however, the research described here shows that chelated Zn fertigation can be effective for young trees. Fertigation of 4.4 kg·ha⁻¹ of Zn in the form of ZnEDTA raised levels of available soil Zn from a low to an adequate range, while increasing leaf, stem, root, and nut kernel Zn concentrations. Plant responses were already measurable and significant in the first year of Zn application. Leaf tissue Zn concentrations were not raised to the 40 or

50 μg·g⁻¹ frequently cited as a minimum sufficiency level, but reached ≈22 to 35 μg·g⁻¹ with the higher Zn application rate tested (4.4 kg·ha⁻¹) and eliminated most visible deficiency symptoms. In 2015, leaf tissue Zn levels declined from those observed in 2014, even though application rates were not decreased, perhaps suggesting that tree Zn was diluted in a larger biomass as the trees grew larger or that the tree crop load was beginning to compete for Zn with the foliage. In contrast to leaf tissue Zn applications, fertigated ZnEDTA elevated Zn levels of all plant tissues, suggesting that this application method could positively impact root growth and function; however, this was not measured in the current study.

Growth of trees, measured by change in trunk diameter, was increased by application of fertigated ZnEDTA, as were nut yields of both 'Western' and 'Wichita' trees. Although leaf Zn concentrations were greater in trees fertigated with 4.4 kg·ha⁻¹ than in those receiving 2.2 kg·ha⁻¹ of Zn, neither trunk diameter growth nor nut yield increased along with the elevated leaf Zn concentrations. Trunk diameter growth and nut yield were actually numerically lower in trees receiving 4.4 kg·ha⁻¹ vs. 2.2 kg·ha⁻¹ of Zn, although differences were not statistically significant. Top growth and nut yields were associated with leaf Zn concentrations ranging from 16 to 23 μg·g⁻¹, suggesting that current sufficiency levels may be higher than necessary for immature pecan trees. However, ZnEDTA application reduced leaf Mg concentrations below the sufficiency levels for that nutrient and, although no Mg deficiency symptoms were noted, low Mg concentrations resulting from ZnEDTA application could adversely impact pecan growth and yield. No explanation is offered for this phenomenon. Nutrient dilution as a result of accelerated plant growth was not noted for nutrients other than Ca, Mg, and, perhaps Ni, so this is not a likely explanation. Neither Ca nor Mg form strong bonds with EDTA and, if they did, one would expect increased rather than decreased plant uptake. This interaction warrants additional investigation.

Our data show that soil application of ZnEDTA by fertigation may be a commercially acceptable alternative to foliar Zn spray applications in immature pecan orchards with alkaline and calcareous soils. Nevertheless, additional research is needed. Information about nut yield and quality effects of ZnEDTA application by fertigation

Table 8. Annual and cumulative trunk diameter (mm) growth of 'Western' and 'Wichita' pecans.

Variety	Yr(s)				
	2012	2013	2014	2015	2012–15
'Western'	12.92	21.24	17.70	24.90	76.75
'Wichita'	9.20	18.10	12.94	19.99	60.22
LSD _{0.05}	2.08	1.97	2.07	1.55	6.02

LSD = least significant difference.

Table 9. Average annual and cumulative trunk caliper growth (mm) of 'Western' and 'Wichita' pecans combined.

Zinc treatment level	Yr(s)				
	2012	2013	2014	2015	2012–15
0 kg·ha ⁻¹	10.38	18.09	13.48	19.49	61.42
2.2 kg·ha ⁻¹	12.24	20.80	16.40	24.08	73.52
4.4 kg·ha ⁻¹	10.57	20.12	16.07	23.76	70.51
LSD _{0.05}	NS	2.41	2.54	1.90	7.37

LSD = least significant difference.

NS = not significant ($\alpha = 0.05$).

Table 10. In-shell nut yield (kg·ha⁻¹) of 'Western' and 'Wichita' pecans fertigated with zinc (Zn).

Zn treatment level	Yr		
	2012	2013	2014
Western			
0 kg·ha ⁻¹	0.0	68.3	155.9
2.2 kg·ha ⁻¹	0.0	96.5	554.1
4.4 kg·ha ⁻¹	0.0	67.7	338.7
Wichita			
0 kg·ha ⁻¹	18.0	34.3	90.8
2.2 kg·ha ⁻¹	39.7	109.4	396.5
4.4 kg·ha ⁻¹	28.0	94.7	323.2
LSD _{0.05}	7.7	NS	NS

LSD = least significant difference.

NS = not significant ($\alpha = 0.05$).

Table 11. Combined average in-shell nut yield (kg·ha⁻¹) of 'Western' and 'Wichita' pecans fertigated with zinc (Zn).

Zn treatment level	Yr		
	2013	2014	2015
0 kg·ha ⁻¹	9.0	51.3	123.4
2.2 kg·ha ⁻¹	19.8	103.0	475.3
4.4 kg·ha ⁻¹	14.0	81.2	330.9
LSD _{0.05}	5.5	25.5	99.9

LSD = least significant difference.

in more mature pecan orchards with alkaline soils, especially, in comparison with the standard foliar Zn applications, is of particular interest. Furthermore, there remain several important unanswered questions regarding soil application of other Zn chelates, other soil-application techniques, and effects of timing and placement of soil-applied ZnEDTA fertilizers.

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