Correction of Zinc Deficiency in Pecan by Soil Banding

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Abstract. Zinc (Zn) deficiency is common in commercial pecan [*Carya illinoensis* (Wangenh.) C. Koch] orchards. Correction by multiple annual foliar spray applications is expensive but effective in eliminating Zn deficiency. Correction by soil application is also expensive and is usually impractical or noneffective. There is a need for more economical and long-lasting methods for satisfying tree Zn nutritional needs. It is reported here that tree foliar Zn needs [i.e., 50 $\mu\text{g}\cdot\text{g}^{-1}$ dry weight (dw) or greater] are potentially met through one-time “banding” of Zn sulfate ($\text{ZnSO}_4\cdot 7\text{H}_2\text{O}$) or Zn oxide (ZnO) onto orchard floors. Zinc needs of 4-year-old ‘Desirable’ trees growing on acidic soil were satisfied over a 4-year period by a single-banded soil application of either Zn sulfate or ZnO over underground drip irrigation lines at a Zn rate of 2112 g Zn per tree (giving foliar Zn concentrations of 60–115 $\mu\text{g}\cdot\text{g}^{-1}$ dw). Rates of Zn at 264 to 1056 g per tree are occasionally efficacious, but rates less than 264 g Zn per tree (0, 33, 66, and 132) were always ineffective for meeting a leaf sufficiency threshold of 50 $\mu\text{g}\cdot\text{g}^{-1}$ dw. Sulfate and oxide Zn forms were equally effective in meeting tree Zn needs. Foliar Zn concentrations increased quadratically with increasing soil-banded Zn treatments; however, foliar Zn concentrations did not necessarily increase over the 4-year period within each Zn rate treatment. Increasing amounts of banded Zn per tree also increased foliar Mn concentration (from ≈ 150 to 269 $\mu\text{g}\cdot\text{g}^{-1}$ dw) of treated trees the fourth year posttreatment but did not affect foliar concentration of other key micronutrients (i.e., Fe, Co, Cu, or Ni). This fertilization strategy offers an efficacious alternative to annual foliar Zn sprays for orchards established on acidic soils and provides a means of ensuring rapid and long-term Zn absorption through soil application. The approach indicates that soil banding of Zn on certain acidic soils can satisfy the nutritional needs of pecan trees for several years after a single application.

Pecan is a zinc (Zn)-sensitive species possessing a relatively high Zn requirement (Sparks, 1987; Swietlik, 1999). Zinc deficiency is a common, and often major, problem in commercial pecan orchards, especially those established on sandy well-drained acidic soils and on soils from phosphatic rocks. Deficiency is common in the acidic soils of the southeastern United States and the high pH, calcareous soils of the southwestern United States. There has therefore been extensive research, spanning several decades, on methods for correction of Zn deficiency in pecan (Alban, 1955; Alban and Hammar, 1941, 1944; Banin et al., 1980; Harper, 1960; Payne and Sparks, 1982; Sparks, 1976; Worley et al., 1980). Tree and orchard Zn-related requirements are potentially met through several early spring foliar sprays each year (Smith et al., 1979) by broadcast application of relatively large amounts of Zn fertilizers to soils (Brooks, 1964) or by trunk implants or injection (Worley et al., 1980).

Foliar sprays are potentially a rapid method for correction of Zn-deficient foliage, but efficacy depends on complete canopy coverage and repetitive application because foliar canopy expands during the spring. Additionally, foliar sprays probably do not result in sufficient mobilization and transport of endogenous Zn to alleviate deficiency in nonfoliage tree organs such as roots; thus, alleviation on a whole-tree basis is an aspect of Zn management that is often overlooked (Swietlik, 1999; Swietlik and Zhang, 1994). The observation that Zn-deficient trees exude a gummy material (Storey, 2007) is evidence that endogenous Zn needs to be mobilized throughout the tree and that tree needs might be best satisfied through root uptake.

The number of foliar sprays in the southeastern United States required to satisfy tree Zn requirements is usually two to four, at 2-week intervals, whereas in the southwestern United States, it is usually four to six, depending on tree vigor and whether trees are hedge-pruned. Zn sulfate and nitrate are the most common Zn sources used in agriculture. Only $\approx 0.2\%$ to 1.0% of the amount of Zn sprayed onto foliage is absorbed by foliage (Wadsworth, 1970), and foliar-applied Zn does not usually remobilize in the fall from foliage to storage tissues at amounts high

enough to substantially offset Zn needs by growing organs the following spring (Walworth and Pond, 2006). The cost of foliar applications is considerable, whether through ground rigs or from aircraft, and is far greater than the cost of the Zn material being applied. This cost, plus timely access to trees in flood-irrigated orchards, is problematic for pecan producers.

Correction of Zn deficiency problems by soil application is potentially advantageous in that the approach can provide trees with available Zn for several years, whereas foliar sprays generally correct deficiency in the season of application (Brooks, 1964; Hunter, 1965; Payne and Sparks, 1982; Wood and Payne, 1987). Ground application options include 1) broadcasting, 2) banding, or 3) trenching. Broadcast application (over the entire orchard floor or only beneath the tree canopy) typically requires 23 to 114 kg (50 to 250 lbs) Zn sulfate per acre; in addition, the first 2 to 3 years (depending on tree and orchard situation) after the ground application may still result in the need for foliar sprays. Application through trenching, even in acidic soils, is generally inferior to broadcast applications, although it can be efficacious and practical (Smith et al., 1934). Problems with satisfactory uptake, expense, or both is problematic for commercial operations applying Zn through broadcast ground application. Banding Zn in a wide band within the perimeter of the canopy dripline potentially reduces the amount of Zn required; however, commercial operations rarely adopt the approach. Success at preventing Zn deficiency by soil application (broadcast and trenching) is erratic and variable among southeast regional orchards and is almost never effective in high-pH southwestern orchards (Walworth and Pond, 2006). Thus, soil application as a means of correction of Zn deficiency remains problematic for commercial-scale orchard operations. Soil Zn application strategies, although potentially efficacious, are unpopular in the southeastern United States where acidic soils are typical and are essentially absent from operations in calcareous alkaline southwestern U.S. soils where efficacy is problematic.

The potential long-term efficacy of a single soil application makes the approach especially attractive if there is a concurrent reduction in the amount of Zn fertilizer needed to satisfy tree needs. The present soil application rate for southeastern soils is typically 2.27 to 4.54 kg Zn sulfate per tree (Brooks, 1964). The most recent study of the banding approach concluded that narrow banding was potentially inferior to broadcasting beneath the tree canopy in that it did not correct Zn deficiency as quickly as broadcasting relatively large amounts of Zn (Payne and Sparks, 1982). This approach used Zn sulfate rates up to 3.2 kg of Zn per tree dispersed in a 15-cm-wide band encircling nonirrigated trees positioned in the middle of a 14.2-m diameter circle. The use of drip irrigation technology in southeastern U.S. pecan orchards has proliferated since the

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1982 study; thus, the situation exists in which tree Zn needs might potentially be more efficiently satisfied by using a more concentrated band in close physical association with irrigation emitters. Additionally, a cost squeeze affecting most farmers reflects a need to reduce production costs. Adoption of a one-time approach to Zn fertilizer application, possible reduction of the amount of Zn used in orchards, and use of the most economical efficacious Zn sources collectively offer potential for a long-term reduction in production costs as well as better tree Zn nutrition. Additionally, because whole-tree Zn nutrition is likely best satisfied through soil application, there is a need for development of efficacious techniques for supplying Zn through the soil (Swietlik, 1999).

Zinc sulfate has traditionally been the preferred source for correction of deficiency through soil application on acidic soils (O'Barr, 1989). This is because of its relatively high water solubility ($1.67 \text{ g}\cdot\text{mL}^{-1} \text{ H}_2\text{O}$), indirect source of sulfur (S), and ease of use (Worley et al., 1972). Conversely, Zn oxide is generally a more economical source per unit, or mole, of Zn; yet, it has exceedingly low water solubility (less than $0.00001 \text{ g}\cdot\text{mL}^{-1} \text{ H}_2\text{O}$). This solubility differential is likely of little practical significance, because most ground-applied Zn sulfate eventually converts to Zn oxide in soils (Viets, 1962), thus largely neutralizing a perceived advantage of Zn sulfate over Zn oxide in orchards. A study of a wide variety of Zn-sensitive agronomic and horticultural crops concludes that Zn oxide is at least as good as Zn sulfate in correcting Zn deficiency (Murphy and Walsh, 1972). Worley et al. (1972) came to the same conclusion for pecan after comparing the ability of several Zn sources for correcting foliar deficiencies. However, after more than three decades since Worley's report, Zn sulfate remains the overwhelmingly used source by the southeastern U.S. pecan industry. Because Zn oxide is usually a more economical source per unit of Zn than Zn sulfate, and appears to be as effective as Zn sulfate for correcting deficiency through broadcast soil applications, there is a need to compare the efficacy of these two Zn sources when applied as a highly concentrated band to soils supporting orchard trees. This study assesses the efficacy of correcting Zn deficiency of young drip-irrigated pecan orchards on an acidic mineral southeastern U.S. soil using a single concentrated band of either Zn oxide or Zn sulfate applied over drip irrigation emitters.

Materials and Methods

Orchard and soil situation. The study orchard is comprised of 'Desirable' trees grafted to open-pollinated 'Elliott' rootstocks and is located at Byron, GA (lat. $32^\circ 39' 54''$ N, long. $83^\circ 44' 31''$ W). Trees are spaced 9.1 m between rows and 4.6 m within rows. The experimental orchard soil is a Faceville fine sandy loam (FoA; fine, kaolinitic, thermic Typic Kandiodult). Belowground drip irrigation lines with drip emitters rising to the soil surface at 1-m intervals along the line provide trees with supplemental water. Parallel irrigation lines run the length of tree rows positioned 1.2 m on either side of trunks. Drip emitters delivered water at a rate of 3.78 L per hour, for ≈ 8 to 12 h per day, depending on water needs throughout the growing season. The irrigation lines were within an herbicide strip maintained in a bare state using glyphosate.

Trees were entering their fourth year of growth at the time of the initiation of the study. Table 1 presents general soil characteristics of the orchard site. In general, the soil is typical of many southeastern U.S. soils and therefore many regional pecan orchards. The orchard received uniform annual broadcast soil applications of nitrogen, phosphorus, and potassium, calcium, and magnesium based on University of Georgia Extension Service recommendations; however, trees did not receive ground or foliar applications of Zn and other trace elements during the study period.

Zinc treatments. Trees within the previously described 'Desirable' orchard exhibited moderate Zn-deficiency symptoms beginning the third growing season after orchard establishment with deficiency exhibited by control trees in all subsequent years. This orchard was therefore used to evaluate the potential for correction of deficiency through application of either Zn sulfate ($\text{ZnSO}_4\cdot 7\text{H}_2\text{O}$) or Zn oxide (ZnO) as a concentrated band of Zn fertilizer placed in a 10 cm $\times$ 4-m band exactly over the drip irrigation lines on each side of the trees. Zn application treatments were at equivalent rates of actual Zn, for each of the Zn sulfate and ZnO sources, over a concentration range of 0, 33, 66, 132, 264, 528, 1056, 2112, and 4224 g of actual Zn per tree. Treatments were established as a randomized complete block (RCB) consisting of four blocks. The experimental unit was comprised of single trees separated from neighboring trees by at least one tree or by a tree row. The concentrated

band treatments were applied to soils in mid Mar. 2003. The experiment was a factorial consisting of two-factors ($\text{ZnSO}_4\cdot 7\text{H}_2\text{O}$ versus ZnO) at nine levels (g Zn per tree) structured as a RCB with foliage annually analyzed for Zn concentration over the following four growing seasons.

Foliar analysis. Leaf Zn concentration was determined annually from 2003 through 2006 from leaf samples collected from individual trees in late July by standard sampling methods with samples collected from all four cardinal directions of the midcanopy. Individual samples were rinsed according to Smith and Storey (1976), oven-dried at 55°C to a constant weight, ground, and stored in airtight containers until analysis. Samples [0.5 g dry weight (dw)] were ashed at 500°C , dissolved in 20% nitric acid (TraceSelect; Sigma-Aldrich, St. Louis), and diluted with 2% nitric acid to 50 mL. Aliquots were then appropriately diluted and analyzed for Zn using a PerkinElmer ELAN 9000 ICP-Mass Spectrometer (Concord, Ontario, Canada) interfaced with a CETEC ASX-510 Auto-sampler (CETEC Technologies, Omaha, NE) through monitoring of the Zn^{67} mass [4% natural abundance (n.a.)]. Additionally, foliage sample analysis of individual trees during the fourth growing season enabled assessment of the influence of Zn treatments on key trace metals by monitoring the following masses: Ni^{60} (26% n.a.), Cu^{63} (69% n.a.), Fe^{57} (2% n.a.), Mn^{55} (100% n.a.), and Co^{59} (4% n.a.).

Data analysis. All differences among treatment effects compounded throughout the experimental periods (all years after treatment); thus, analysis was by repeated measures and multivariate analysis of variance using JMP (JMP-SAS, Cary, NC). Additionally, because of the need to assess treatment effects yearly, effects were analyzed by "year" (for each year separately) using analysis of variance (ANOVA) and Student-Newman-Keuls test using JMP. ANOVA analysis using standard least squares was based on the previously described factorial design and performed for each year. The alpha level for all statistical tests was ≤ 0.05 .

Results and Discussion

Repeated-measures analysis using the Wilks' lambda test indicated differences in foliar Zn concentration based on "year" ($P < 0.0001$), "year*block" ($P < 0.0075$), "zinc rate" ($P < 0.00001$), and "year*Zn

Table 1. Soil characteristics of a Desirable pecan orchard before implementation of the present study involving application of zinc through a narrow concentrated band to the orchard floor over drip-irrigation lines on each side of trees.

Soil depth (cm)	pH	CEC (meq/100 g)	P (kg·ha ⁻¹)	K (kg·ha ⁻¹)	Mg (kg·ha ⁻¹)	Ca (kg·ha ⁻¹)	B (kg·ha ⁻¹)	Zn (kg·ha ⁻¹)	Mn (kg·ha ⁻¹)	Fe (kg·ha ⁻¹)	Cu (kg·ha ⁻¹)	Ni (kg·ha ⁻¹)
0–2.5	5.2	9.6	67 M ^c	486 VH	430 VH	1911 VH	1.2 A	39 VH	137 VH	15 A	0.7 L	1.0
2.6–5.1	5.1	6.6	43 L	300 H	179 A	893 A	0.9 M	9 A	109 VH	19 A	0.7 L	0.9
5.2–10.2	5.8	5.5	27 L	300 A	162 A	833 A	0.8 M	3.2 L	85 VH	20 A	0.7 L	0.7
10.3–20.3	5.9	5.4	12 L	209 A	185 A	758 M	1.0 M	1.5 L	72 VH	20 A	0.7 L	0.6

^cAccording to Georgia Extension Service recommendations: L = low; M = medium; A = adequate; H = high; VH = very high. CEC = cation exchange capacity (i.e., total number of negative charge available to attract positively charged ions in solution).

source*Zn rate" ($P < 0.0272$). Subsequent ANOVA analysis by "year" provided the following model characteristics: For 2003, model $R^2 = 0.74$ with a "Zn rate" effect at $P < 0.0001$; for 2004, model $R^2 = 0.74$, with a "Zn rate" effect at $P < 0.0001$; for 2005, model $R^2 = 0.81$, with a "Zn rate" effect at $P < 0.0001$; and for 2006, model $R^2 = 0.83$, with a "Zn rate" effect at $P < 0.0001$. Because "Zn source" and the "Zn source*Zn rate" interaction are not significant, and for the purpose of clarity, data are combined regarding "Zn source" and plotted for "Zn rate" for each "year" with mean separation by Tukey's honestly significant difference (HSD) test (Fig. 1). ANOVA analysis of Mn concentration in foliage, during the fourth year posttreatment (i.e., 2006), provided the following model characteristics: model $R^2 = 0.92$, with "Zn source" effect at $P < 0.0001$, "Zn rate" at $P < 0.0001$, and at $P < 0.0001$. Manganese means for the "Zn source*Zn rate" effect, as separation by Tukey's HSD test, is presented in Figure 2.

The Zn concentration in 'Desirable' foliage increased proportionally as the amount of soil-banded Zn increased (Fig. 1). This increase occurred in these 'Desirable' trees within 4 months after application (Fig. 1A). The absence of a "year*Zn source" interaction ($P = 0.69$) is evidence that the relatively poor water solubility of ZnO (less than $0.00001 \text{ g}\cdot\text{mL}^{-1} \text{ H}_2\text{O}$) did not pose a significant disadvantage with regard to Zn uptake by pecan from this particular acidic soil situation. Conversely, $\text{ZnSO}_4\cdot 7\text{H}_2\text{O}$ possesses relatively high water solubility ($1.67 \text{ g}\cdot\text{mL}^{-1} \text{ H}_2\text{O}$), being greater than 10^5 -fold greater. Thus, under conditions of this study, the relatively insoluble ZnO is as effective during the first 4 years as is soluble $\text{ZnSO}_4\cdot 7\text{H}_2\text{O}$ in satisfying foliar tree needs. The increase in foliar Zn concentration during the first growing season, as a consequence of increasing amounts of soil-banded Zn per tree, reflected both linear and curvilinear relationships; however, the relationship best approximates a quadratic $f(x) = y_0 + ax + bx^2$ polynomial. Thus, foliar Zn concentration increased curvilinearly in a quadratic manner ($y = 29.05 + 0.040x - 0.00000517x^2$; $R^2 = 0.65$; $P \leq 0.0001$), resulting in maximum foliar Zn concentration at $\approx 115 \text{ }\mu\text{g}\cdot\text{g}^{-1} \text{ dw}$. Midsummer Zn concentration in foliage of nontreated trees was $\approx 20 \text{ }\mu\text{g}\cdot\text{g}^{-1} \text{ dw}$ with foliage exhibiting typical visual symptoms of Zn deficiency. The generally accepted Zn sufficiency level of $50 \text{ }\mu\text{g}\cdot\text{g}^{-1} \text{ dw}$ (Sparks and Payne, 1982) was achieved during the first year of application by either the sulfate or oxide sources applied at a rate 528 g Zn or greater per tree (Fig. 1A) with foliage of trees treated with these treatments being free of visual Zn-deficiency symptoms. The highest Zn treatment of 4224 g Zn per tree elevated foliar Zn concentration to $\approx 115 \text{ }\mu\text{g}\cdot\text{g}^{-1} \text{ dw}$ during the first year after application.

During the second posttreatment growing season (2004), the early season was very dry and the irrigation system failed. Thus, the

Fig. 1. Leaflet zinc (Zn) concentrations of 'Desirable' pecan trees in response to a single soil application of Zn as a concentrated band over drip-irrigation lines on each side of the trees. Zinc was applied Mar. 2003. Foliar Zn concentrations reflect Zn present in foliage in late July 2003 and each July of for 3 years afterward. Treatment means with different letters are statistically significant by Tukey's honestly significant difference test at $\alpha = 0.05$. The horizontal dashed line is the standard extension service recommendation of $50 \text{ }\mu\text{g}\cdot\text{g}^{-1}$ dry weight for whole-canopy leaf Zn concentration.

drier soil conditions required banded Zn at 2112 g or greater per tree to exceed the $50 \text{ }\mu\text{g}\cdot\text{g}^{-1} \text{ dw}$ sufficiency threshold, this being a fourfold greater amount of Zn than was required under more normal soil moisture circumstances. During this dry spring, the high 4224 g per tree Zn rate treatment elevated foliar Zn to only $\approx 63 \text{ }\mu\text{g}\cdot\text{g}^{-1} \text{ dw}$, with the untreated control being $\approx 16 \text{ }\mu\text{g}\cdot\text{g}^{-1}$

dw (Fig. 1B). Zinc concentration in foliage quadratically increased ($y = 20.5 + 0.0240x - 0.00000324x^2$; $R^2 = 0.68$; $P \leq 0.0001$) as the amount of soil-applied Zn increased. A much greater amount of banded Zn was therefore required to satisfy tree needs when soil moisture was more limiting.

"Zn rate" was the only significant ($P < 0.0001$) treatment effect in either the third or

Fig. 2. Influence of soil-banded zinc (Zn) treatments from $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ and Zn oxide sources on foliar Mn concentration the fourth year after Zn application. Treatment means with different letters are statistically significant by Tukey's honestly significant difference test at $\alpha = 0.05$.

fourth growing season. Thus, this banding approach to Zn fertilization resulted in tree Zn needs being satisfied for at least 4 years after application (Fig. 1). The critical Zn threshold for foliage was satisfied during the third growing season by the 1056 g or greater Zn per tree treatment applied 3 years earlier (Fig. 1C), whereas the threshold during the fourth growing season was satisfied by the 264 g Zn per tree treatment (Fig. 1D). Zn concentration in foliage increased quadratically in both the third ($y = 35.4 + 0.025x - 0.00000165x^2$; $R^2 = 0.72$; $P \leq 0.0001$) and fourth ($y = 54.9 + 0.014x - 0.00000128x^2$; $R^2 = 0.58$; $P \leq 0.0001$) years with maximum foliar Zn concentration being ≈ 110 and $95 \mu\text{g}\cdot\text{g}^{-1}$ dw, respectively. The application of a concentrated band of Zn to drip-irrigated soil has the potential to, directly or indirectly, influence the concentration of metabolically important transition metals in foliage through competitive inhibition of divalent cation uptake by the ever-increasing abundance of soil Zn. Subsequent analysis of Fe, Mn, Co, Cu, and Ni in fourth growing season foliage found no significant effects of “Zn rate” or “Zn source” on any measured transition element except for Mn. Foliar Mn concentration increased quadratically ($y = 165.6 + 0.061x - 0.00000927x^2$; $R^2 = 0.88$; $P \leq 0.05$) as Zn sulfate applied to the soil increased (Fig. 2). The increase likely indicates that either Mn uptake was positively influenced by acidification of soil by the S component of the SO_4 anion or because the commercial Zn sulfate used in this study contained Mn as a trace contaminate. In either case, foliar Mn

concentration ranged from ≈ 151 to $269 \mu\text{g}\cdot\text{g}^{-1}$ dw depending on Zn sulfate treatment amount and never approached foliar concentrations that might cause Mn toxicity (i.e., greater than $1000 \mu\text{g}\cdot\text{g}^{-1}$ dw). Although the ZnO source also influenced Mn uptake, the relative impact was small and not tightly linked to Zn treatments (Fig. 2).

Attempts at correction of Zn deficiency by soil banding previously found the approach to be inferior to broadcasting (Payne and Sparks, 1982), but the present study adopting a different banding approach appears to result in an efficacious strategy for certain soil situations. The observation that ZnO is as efficacious as Zn sulfate agrees with previous observations by Worley et al. (1972), and Wood and Payne (1987) as postulated by Viets (1962). The amount of change in foliar Zn concentration is very small relative to the amounts of Zn applied to the soil (Fig. 1, note the quadratic equations). Depending on year, foliar leaf Zn concentration roughly increased from 14 to $61 \text{ ng}\cdot\text{g}^{-1}$ dw for each gram of Zn applied to the soil through banding. Thus, the soil-banding fertilization approach results in a relatively small change in foliar Zn concentration per unit of Zn applied to the soil. It is possible that much less Zn would be required if it were chiseled into the soil so as to potentially increase root access; however, this approach is problematic in existing orchards with drip irrigation already installed as a result of likely damage to existing lines and emitters. An alternative approach is injection of Zn into the drip irrigation system; however, this approach is

probably riskier for micronutrients such as Zn, because of the potential for excessive exposure of a large mass of emitter-associated feeder roots to a potentially toxic concentration of metals.

Both foliar and broadcast Zn application strategies introduce substantial amounts of metallic Zn into the orchard environment over a period of several decades. Zinc accumulation in old orchards is such that uptake and physiological availability of Ni (and possibly Cu) are suppressed such that Zn-induced Ni deficiency became increasingly common in southeastern U.S. orchards, causing “mouse-ear” (“little-leaf”) and “orchard replant” maladies (Wood et al., 2004a, 2004b, 2006). Although the soil-banding approach still puts a lot of metallic Zn into the orchard environment, it is concentrated in a relatively small zone. An alternative approach that potentially increases Zn use efficiency, mobilization within the plant, and reduces the amount of Zn going into the orchard environment is a slow-release Zn material applied to the root collar (Swietlik, 2007). This latter approach merits further investigation for pecan.

Conclusion

The soil-banding approach to Zn fertilization demonstrates that Zn requirements of young pecan trees in drip-irrigated commercial orchards established on certain acidic soils can be satisfied for several years through a single banded application of either Zn sulfate or ZnO fertilizer sources. The approach enables tree Zn needs to be satisfied through root absorption rather than through foliar absorption. Therefore, the root absorption avenue provided by this approach is likely superior to standard foliar Zn application in that it increases the likelihood of Zn mobilization to nonfoliar organs (e.g., roots) also suffering from Zn deficiency. The approach is potentially a viable alternative to multiple foliar Zn applications as is typical of most commercial orchard on acidic soils. It is unknown how many years the single application of soil-applied Zn will meet tree needs; however, it appears that under moist soil situations, tree Zn needs will be satisfied for at least 4 years and potentially for several years thereafter as applied Zn moves deeper into the soil profile with passage of time and more feeder roots penetrate the Zn-enriched zone. Results indicate that because of the usually lower cost, but equal efficacy, ZnO may potentially prove preferable to Zn sulfate. Associated cost savings may be small in orchard situations where several spring sprays are required for control of pests; however, savings may be substantial in orchard or yard situations where spring spraying of pests is minimal or absent such as dry springs that make it unnecessary to apply scab disease control sprays until after canopy development is nearly complete. The banding of Zn onto the soil surface over irrigation lines is a simple, rapid, and efficacious approach to correction of Zn deficiency. The concentration

of Zn above drip irrigation lines does not appear to affect adversely foliar concentrations of other key transition metal micronutrients (i.e., Fe, Mn, Co, Cu, or Ni).

Literature Cited

- Alban, A.O. 1955. Preliminary results of treating rosetted pecan trees with chelated zinc. *Proc. Amer. Soc. Hort. Sci.* 66:28–30.
- Alban, A.O. and H.E. Hammar. 1941. Progress report on soil applications of zinc sulfate in the control of rosette of pecan. *Proc. Texas Pecan Growers Assn.* 21:63–70.
- Alban, A.O. and H.E. Hammar. 1944. The effect of pecan rosette from application of zinc sulfate, manure, and sulfur on heavy textured alkaline soils. *Proc. Amer. Soc. Hort. Sci.* 45:27–32.
- Banin, A., J. Navrot, and Y. Ron. 1980. Tree implanted zinc-bentonite paste as a source of slow-release zinc for Delmas pecan. *HortScience* 15:182–184.
- Brooks, O.L. 1964. Yield response of Stuart pecan to zinc sulfate. *Proc. Southeastern Pecan Growers Assn.* 57:23–25.
- Harper, R.E. 1960. A chelate for controlling zinc deficiency in pecan trees. *New Mexico Agr. Expt. Sta. Res. Rpt.* 36:1–10.
- Hunter, J.H. 1965. Effects of lime and zinc on the pH of the soil, yield of pecans, and zinc content of leaves. *Proc. Southeastern Pecan Growers Assn.* 58:6–11.
- Murphy, L.S. and L.M. Walsh. 1972. Correction of micronutrient deficiencies with fertilizers, p. 347–381. In: R.C. Dinauer (ed.). *Micronutrients in agriculture*. Soil Sci. Soc. Amer., Madison, WI.
- O'Barr, R.D. 1989. Pecan nutrition, p. 61–72. In: W.D. Goff, J.R. McVey, and W.S. Gazeway (eds.). *Pecan production in the southeast: A guide for growers*. Alabama Coop. Ext. Serv. Circ. ANR-459.
- Payne, J.A. and D. Sparks. 1982. Zinc level in pecan leaflets from broadcast and band application over a six-year period. *HortScience* 17:235–236.
- Smith, C.L., A.O. Alban, and J.R. Cole. 1934. Progress report of pecan rosette control experiments in Texas. *Proc. Texas Pecan Growers Assn.* 14:41–46.
- Smith, M.W. and J.B. Storey. 1976. The influence of washing procedures on surface removal and leaching of certain elements from pecan leaflets. *HortScience* 11:50–52.
- Smith, M.W., J.B. Storey, and P.N. Westfall. 1979. The influence of two methods of foliar application of zinc and adjuvant solutions on leaflet zinc concentration of pecan trees. *HortScience* 14:718–719.
- Sparks, D. 1976. Zinc nutrition and the pecan—a review. *Pecan South* 3:304–334.
- Sparks, D. 1987. Apparent effect of zinc treatment on the growth rate of pecan production and yield. *HortScience* 22:899–901.
- Sparks, D. and J.A. Payne. 1982. Zinc concentration in pecan leaflets associated with zinc deficiency symptoms. *HortScience* 17:670–671.
- Storey, J.B. 2007. Zinc, p. 411–436. In: A.V. Barker and D.J. Pilbeam (eds.). *Handbook of plant nutrition*. Taylor and Francis Group, New York.
- Swietlik, D. 1999. Zinc nutrition in horticultural crops. *Hort. Rev. (Amer. Soc. Hort. Sci.)* 23: 109–178.
- Swietlik, D. 2007. A new method of applying zinc to apple plants. *Proc. 27th International Horticultural Congress and Exhibition, Seoul, Korea*, 13–20 July. p. 106 (abstr.).
- Swietlik, D. and L. Zhang. 1994. Critical zinc activities for sour orange determined with chelator-buffered nutrient solutions. *J. Amer. Soc. Hort. Sci.* 119:693–701.
- Viets, F.G., Jr. 1962. Chemistry and availability of micronutrients in soils. *Agr. Food Chem.* 10:174–178.
- Wadsworth, G. 1970. Absorption and translocation of zinc in pecan trees [*Carya illinoensis* (Wangenh.) K. Koch]. Texas A & M University, Masters Thesis.
- Walworth, J.L. and A.P. Pond. 2006. Zinc nutrition of pecans growing in alkaline soils. *Pecan South* 39:14–22.
- Wood, B.W. and J.A. Payne. 1987. Comparison of Zn oxide and Zn sulfate for correcting severe foliar Zn deficiency in pecan. *HortScience* 32:53–56.
- Wood, B.W., C.C. Reilly, and A.P. Nyczepir. 2004a. Mouse-ear of pecan: I. Symptomatology and occurrence. *HortScience* 38:87–94.
- Wood, B.W., C.C. Reilly, and A.P. Nyczepir. 2004b. Mouse-ear of pecan: A nickel deficiency. *HortScience* 39:1238–1242.
- Wood, B.W., C.C. Reilly, and A.P. Nyczepir. 2006. Field deficiency of nickel in trees: Symptoms and causes. *Acta Hort.* 721:83–98.
- Worley, R.E., S.A. Harmon, and R.L. Carter. 1972. Effect of zinc sources and methods of application on yield and leaf mineral concentration of pecan, *Carya illinoensis* Koch. *J. Amer. Soc. Hort. Sci.* 97:364–369.
- Worley, R.E., R.H. Litrell, and J.D. Dutcher. 1980. A comparison of zinc injection and implantation of zinc capsules for correction of zinc deficiency in pecan trees. *J. Arboric.* 6:253–257.