Zinc Nutrition of Fruit Crops

Dariusz Swietlik¹

ADDITIONAL INDEX WORDS. apple, deficiency, foliar nutrition, fruit quality, grapefruit, growth, orange, peach, pecan, soil Zn, yield

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SUMMARY. Zinc (Zn) deficiency is widespread throughout the world causing economic losses on a number of crops. Despite the fact that much information was generated during the last 20 years on Zn soil chemistry and its inorganic phase equilibrium, the mechanism controlling the amount of free Zn⁺² present in the soil solution is not yet completely understood. This information is critical for the development of effective techniques of supplying Zn through the soil. As Zn moves very slowly through the soil, however, and a large portion of fruit tree root system occupies deep soil layers, foliar sprays with Zn are generally more effective than soil treatments in alleviating Zn deficiency symptoms. That is why many extension specialists recommend this approach. In view of the poor mobility of foliar-absorbed Zn in plants, however, we may need to reexamine this approach. Zinc foliar sprays may be effective in controlling Zn deficiency in leaves, but not in alleviating Zn deficiency in roots or subsequent flushes of growth. Also, the conditions under which fruit trees are most likely to respond to corrective Zn treatments are not well understood and the critical periods for Zn supply to assure optimal fruit set, fruit growth, and high fruit external and internal quality are not well defined. Field studies on fruit trees suggest that Zn deficiency must be quite severe to make the application of this element economically justifiable. In well-controlled greenhouse studies, however, growth responses were realized on plants only mildly affected by Zn deficiency. If considerable field variability may explain this discrepancy in the data, then future field research must use improved methodologies to properly quantify the impact of various levels of Zn deficiency on tree growth, fruit yield, and fruit quality.

That Zn is essential for the growth of higher plants was discovered at the beginning of the 20th century (Thorne, 1957). During the 1930s, Zn deficiency symptoms such as little leaf or rosette were described for peach (*Prunus persica*) (Chandler et al., 1931) and pecan (*Carya illinoensis*) (Alben et al., 1932). At about the same time, the so called mottle-leaf on citrus (*Citrus* sp.), characterized by yellowing of the areas between leaf veins, was also found to be caused by Zn deficiency (Johnston, 1933; Parker, 1934, 1935).

Chandler et al. (1931, 1932) successfully corrected little leaf on peaches with soil Zn applications whereas Johnston (1933) and Parker (1934, 1935) corrected mottle-leaf of citrus with soil and foliar Zn applications. Zinc nutrition is an important economic factor in the cultivation of fruit trees, especially because most of them are considered sensitive to Zn deficiency (Chapman, 1966). Pecan, peach, citrus, and avocado (*Persica americana*) seem to be particularly sensitive as evidenced by reports of widespread Zn deficiency on these tree species (Chapman, 1966, 1968; Sparks, 1987; Wallihan et al., 1958). Quince (*Cydonia oblonga*) is also sensitive to Zn deficiency, and this is a major problem in areas where quince is an important fruit crop (E. Fallahi, personal communication).

USDA-ARS, Appalachian Fruit Research Station, 45 Wiltshire Rd., Kearneysville, WV 25430.

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¹Plant physiologist.

Zinc deficiencies on various crops are found in Australia, Europe, North and South America, and Asia. The largest contiguous area of Zn deficiency, 8 to 9 million ha (20 to 22.5 million acres), is located in southwestern Australia (see papers cited by Brennan, 1996). Zinc deficiencies are common in plants grown on high pH calcareous soils, as well as highly leached sandy soils. Large areas of Zn deficiency have been reported in the Pacific northwestern U.S., California, southern Texas, and Florida, and in southern British Columbia, Canada (Chapman, 1968; Embleton et al., 1988; Koo, 1988; Neilsen and Neilsen, 1994; Neilsen et al., 1986, 1987; Swietlik, 1989). Zinc deficiency is also widespread on pecans grown in the southeastern and southwestern United States (Sparks, 1987). It is also a major nutritional malady in tree fruit crops grown in the northeastern United States (Stiles, 1980, 1987, 1991, 1992, 1993; Stiles and Goff, 1965).

Zinc in soils

The amount of free Zn^{+2} in the soil solution that is available for plant uptake is in equilibrium with total soil Zn as indicated by the following relationship: $Soil\ Zn \rightleftharpoons Zn^{+2}$. The Zn^{+2} concentrations in the soil solution are expressed in molar concentrations of free Zn^{+2} or Zn^{+2} activity. At low concentrations, free metal activity and its molar concentration are numerically the same. As ionic strength of the solution increases, however, metal activity is depressed by

electrostatic forces to below that of free metal concentration.

The mechanisms controlling the amount of free Zn^{+2} present in the soil solution are not yet completely understood. Some of the processes involved include Zn adsorption and desorption, precipitation and dissolution, biological processes, and the flow of soluble Zn in soil due to gravitational forces, evapotranspiration, and diffusion. Sorption and precipitation are the chief reasons why Zn does not readily move in the soil and thus has limited availability to plants.

Soil pH is the single most important factor affecting the amount of free Zn^{+2} in the soil solution. Ma and Lindsay (1990) developed a model describing this relationship as $\log(Zn^{+2}) = 5.7 - 2\ pH$, where (Zn^{+2}) indicates Zn^{+2} activity. This solubility equation indicates that the activity of Zn decreases 100-fold for each unit of pH increase. Ma and Lindsay reported that Zn^{+2} activities in 10 arid calcareous soils ranging in pH from 6.75 to 8.22 varied from $10^{-7.9}$ to $10^{-10.9}$ M [800 to 0.8 parts per trillion (ppt)]. The solubility of soil Zn found in this and another study (Ma and Lindsay, 1993) matches the solubility of Zn from franklinite ($ZnFe_2O_4$), suggesting that this mineral may control Zn solubility in alkaline soils.

Several studies attempted to determine the critical concentration of free Zn^{+2} in the rhizosphere needed for the normal growth of various plant

species. In these studies, nutrient solutions were used in which the activity of Zn^{+2} was controlled by the addition of a strong Zn chelator, e.g., DTPA (diethylenetriamine-pentaacetic acid). The critical Zn^{+2} concentrations found were $10^{-10.8}$ M (1.0 ppt) for soybean (*Glycine max*) (Chaney et al., 1989), $10^{-10.6}$ M (1.6 ppt) for corn (*Zea mays*) and tomato (*Lycopersicon esculentum*) (Halvorson and Lindsay, 1977; Parker et al., 1992), $10^{-10.52}$ M (1.9 ppt) for barley (*Hordeum vulgare*) (Norvell and Welch, 1993) and $10^{-9.8}$ M (10 ppt) for sour orange (*Citrus aurantium*) (Swietlik and Zhang, 1994). Coupled with Ma and Lindsay's model, these results explain why many plant species frequently develop Zn deficiencies when grown on alkaline soils.

Zn deficiency and normal tissue concentrations

Rosetting and little leaf are the most characteristic symptoms of Zn deficiency in fruit trees. These symptoms are the result of strong inhibition of internode elongation and leaf expansion. When the deficiency is very severe, the plants may exhibit shoot dieback, defoliation, and partial or total chlorosis (Embleton et al., 1973; Marschner, 1986; Sparks 1987, 1994; Stiles, 1966; Swietlik, 1989). In citrus, Zn deficiency is accompanied by the condition called mottle-leaf, which is characterized by yellowing of the areas between leaf veins, while the leaf tissue adjacent to the midrib and main veins

Table 1. Normal Zn tissue concentrations in selected fruit and nut crops.

Crop	Tissue	Zn [mg·kg ⁻¹ (ppm) dry wt]	Reference
Apple	Leaves	15–200	Shear and Faust, 1980
		35–50	Stiles and Shaw Reid, 1991
Apricot	Leaves	12–?? ^z	Shear and Faust, 1980
Cherry	Leaves	15–70	Shear and Faust, 1980
		35–50	Stiles and Shaw Reid, 1991
Grapefruit	Leaves	20–110	Swietlik, 1996b
Orange	Leaves	20–110	Swietlik, 1996b
Peach	Leaves	12–50	Shear and Faust, 1980
		35–50	Stiles and Shaw Reid 1991
Pear	Leaves	20–60	Shear and Faust, 1980
		35–50	Stiles and Shaw Reid, 1991
Pecan	Leaflets (shoot basis)	≥14	Hu and Sparks, 1991
	Leaflets (orchard basis)	50–200	Sparks 1993
Pistachio	Leaves	10–15	Uriu and Pearson, 1986
Sour Orange	Leaves	23–??	Swietlik and Zhang, 1994
Walnut	Leaves	20–200	Shear and Faust, 1980

^z?? = unknown.

remains green (Swietlik, 1989). Leaf size usually remains normal unless deficiency is very severe.

The normal range of Zn concentration shown in Table 1 indicates an adequate supply of the element that supports optimal tree growth, productivity, and fruit or nut quality. In most fruit and other crops, the critical Zn deficiency levels are below 15 to 20 mg·kg⁻¹ (ppm) dry weight of leaves. However, Stiles and Shaw Reid (1991) considered normal leaf Zn concentrations for apple (*Malus domestica*), cherry (*Prunus avium*), peach, and pear (*Pyrus communis*) grown in the northeastern U.S. to be >35 mg·kg⁻¹ dry weight of leaves, i.e., much higher than those reported by other authors. Apricot (*Prunus armeniaca*) and pistachio (*Pistacia vera*) seem to require lower Zn concentrations than the other plant species for normal growth (Table 1).

Effect of Zn on vegetative growth

Stunted shoot growth is frequently observed on pome and stone fruit trees suffering from severe Zn deficiency (Stiles, 1966, 1987; Stiles and Shaw Reid, 1991). There are, however, very little quantitative data describing this relationship for fruit trees.

Neilsen and Hogue (1983) reported elevated shoot growth of Zn-deficient 'McIntosh' apple seedlings treated with one foliar spray containing Zn in the form of lignosulfonic chelate or hydrated zinc sulfate (ZnSO₄·7H₂O). The two chemical forms produced similar responses at identical Zn concentrations in the spray solution. Interestingly, however, Zn applications did not produce higher leaf Zn concentrations in treated plants

due to dilution effect resulting from the increased growth.

Swietlik and Zhang (1994) demonstrated that various tissues of sour orange seedlings have different sensitivity to Zn deficiency, i.e., root dry weight < leaf number = white roots dry weight < stem dry weight < leaf dry weight < shoot elongation = leaf area. Activities of free Zn⁺² in the rhizosphere coincident with the observed maximum response of sour orange seedlings for a given growth variable are indicated in Table 2. Below these values, growth was restrained. It is of interest to note that at Zn⁺² activities higher than 10^{-10.2} M (4 ppt) no visible shoot Zn deficiency symptoms were noted, yet growth increases were observed with further increases in Zn⁺² concentration in the rhizosphere.

Swietlik and Zhang (1994) showed that foliar sprays are less effective than applying Zn to the rhizosphere in terms of maximizing plant growth. Poor mobility of foliar-absorbed Zn prevented the correction of this element deficiency in the roots. This disadvantage of foliar Zn sprays may possibly be the reason why several experiments using foliar sprays with Zn on mildly deficient orange (*Citrus sinensis*) or grapefruit (*Citrus paradisi*) trees, were unable to induce any growth responses in field trials (Griffiths and Enzor, 1953; Swietlik and LaDuke, 1991; Wutscher and Obreza, 1987). Considerable field variability, however, may be another reason why different results were obtained in the greenhouse and field trials.

Based on several experiments conducted on alkaline soils in Texas and Arizona and acid soils in Georgia, Sparks (1993, 1994) reported vegetative growth of pecan to increase with

the increasing level of leaf Zn until the threshold value of 49 mg·kg⁻¹ dry weight was reached. The rate of the increase for vegetative growth was less than that for nut yield indicating that vegetative growth may be less responsive to Zn deficiency in this crop.

Effect of Zn on yield

There is ample evidence of a strong relationship between Zn nutrition and yield of fruit trees. For example, Stiles and Goff (1965) and Stiles (1966) reported a strong positive relationship between leaf Zn concentrations and yield of 'McIntosh' apple trees whose leaf Zn levels were within the range of 5.9 to 14.4 mg·kg⁻¹ dry weight. This range is indicative of severe Zn shortage but no description of deficiency symptoms was provided.

Sparks (1993) reported that pecan yields increase with increasing leaf Zn concentrations until the threshold value of 50 mg·kg⁻¹ dry weight. This threshold coincided with the disappearance of Zn deficiency symptoms, thus illustrating that the occurrence of leaf Zn symptoms was a prerequisite for yield reduction. This point is further illustrated by a strong relationship between the percent of leaves with Zn-deficiency chlorosis and yield of 'Rio Red' grapefruit trees (Swietlik, 1996a) (Fig. 1). In the latter example, however, significant yield reductions were only observed when more than 15% to 20% of foliage was affected by Zn deficiency whereas Sparks' (1993) data seem to indicate that pecan trees respond with yield reductions to even mild Zn deficiencies.

A number of trials concerned with the effect of soil and foliar Zn applications to various fruit crops are summarized in Table 3. A common characteristic of the experiments in which there were substantial increases in yield on apple and citrus trees was the presence of severe Zn deficiency symptoms. This underscores the importance of the severity of Zn deficiency symptoms as a criterion for predicting trees' response to corrective Zn treatments and for assessing a tree's Zn nutritional status. However, one must not lessen the importance of leaf chemical analysis as the most reliable diagnostic tool, particularly when dealing with complex, multielemental deficiency symptoms.

Our knowledge on how timing and number of Zn foliar applications may affect yield responses in fruit trees

Table 2. The activities of free Zn⁺² in the nutrient solutions coincident with the observed maximum response of sour orange seedlings for a given growth variable (Swietlik and Zhang, 1994).

Growth variable	Free Zn ⁺² activity	
	(M)	ppt ^z
Root dry weight	10 ^{-10.2}	4.1
Leaf number	10 ^{-10.1}	5.2
White root growth	10 ^{-10.1}	5.2
Stem dry weight	10 ^{-10.0}	6.5
Leaf dry weight	10 ^{-9.9}	8.2
Shoot elongation	10 ^{-9.8}	10.3
Leaf area	10 ^{-9.8}	10.3

^zppt = parts per trillion.

Fig. 1. The relationship between the percent of leaves with Zn deficiency chlorosis in Jan. 1992 and total yield in 1992–93 season for ‘Rio Red’ grapefruit trees untreated or foliar- or soil-treated with Zn (Swietlik, 1996a); 1 kg = 2.2 lb.

is very limited. This is, however, an important consideration because foliar sprays have only a short term effect

on leaf Zn concentrations due to limited translocation of absorbed Zn to new growing tissues. This is exempli-

fied by the failure of postharvest or dormant Zn sprays on apples to affect next year’s midterminal leaf Zn concentrations (Nielsen and Nielsen, 1994) and by the inability of foliar Zn sprays on citrus to elevate Zn levels in new flushes of growth formed after treatment (Swietlik and LaDuke, 1991). The results of Swietlik’s (1996a) study on ‘Rio Red’ grapefruit showed that, under the condition of severe Zn deficiency, only foliar sprays before but not after anthesis were effective in increasing yield (Table 3). However, as Zn deficiency became less severe in later years of this study, foliar sprays before and after anthesis were not able to affect fruit yield.

Effect of Zn on fruit quality

Information on the effect of Zn nutrition on fruit quality is very limited and often inconsistent. Deficient apple trees were reported to produce small

Table 3. The effect of Zn application on yield of selected fruit and nut tree crops.

Crop	Zn application ^z	Leaf Zn [mg.kg ⁻¹ (ppm)]	Deficiency symptoms	Yield response ^y	Reference
Apple					
‘Red Delicious’	Three foliar sprays: petal fall, 1 st and 2nd cover	2.8–7.4	Severe	++	Stiles, 1966
‘McIntosh’	Soil: 340 kg.ha ⁻¹ ZnSO ₄	13.4	Not given	+	Stiles, 1966
‘Red Delicious’	Dormant	117	Absent	0	Stang et al., 1978
‘Cox’s Orange Pippin’	Two foliar sprays: before bloom and petal fall	12–13	Absent	0	Yogarathnam and Greenham, 1982
‘Discovery’	Two foliar sprays: before bloom and petal fall	14–28	Absent	0	Yogarathnam and Greenham, 1982
Grapefruit					
‘Rio Red’	Two foliar sprays: December and January (before bloom)	6.8–12.7	Severe	++	Swietlik, 1996a
	Two foliar sprays: March and June (after bloom)			0	
	Soil: 30 g/tree Zn as Zn EDTA (once in January)			++	
	Soil: 10 g/tree Zn as Zn EDTA or Zn DTPA (once in January)			0	
‘Ruby Red’	One to three foliar sprays bloom until June	12–46	Mild	0	Swietlik and LaDuke, 1991
Orange					
‘Valencia’	One to three foliar sprays: bloom until June	13–26	Mild	0	Swietlik and LaDuke, 1991
Pecan					
Cultivar not given	Three foliar sprays: April, May and June	23–42	Not given	++	Smith and Storey, 1979
‘Stuart’	Soil: 0.82 kg/tree Zn as ZnSO ₄ or Zn 0.082 kg/tree Zn as Zn HEDTA or Zn EDTA	42–76	Moderate	0	Worley et al., 1972
‘Stuart’	Soil: 0.82 kg/tree Zn as ZnSO ₄	25–60	Moderate	+	Worley et al., 1972

^z1.0 kg.ha⁻¹ = 0.89 lb/acre; 1.0 g = 0.035 oz; 1.0 kg = 2.2 lb.

^y++ = large yield increase (≥37%); + = small yield increase (≤17%); 0 = no yield response.

(Stiles, 1966) or poor-flavored fruit (Stiles and Shaw Reid, 1991). Soil applications of zinc sulfate (ZnSO_4) to Zn deficient 'McIntosh' apple trees, containing Zn at $13.4 \text{ mg}\cdot\text{kg}^{-1}$ leaf dry weigh, improved fruit red color (Stiles, 1966). However, foliar Zn sprays did not affect red color of 'Discovery' apple fruit produced on trees whose leaf Zn concentrations varied from 14 to $28 \text{ mg}\cdot\text{kg}^{-1}$ dry weigh (Yogarathnam and Johnson, 1982). In that same study, foliar sprays did not affect fruit cracking and senescent breakdown. Similar results were reported for 'Cox's Orange Pippin' apples produced on trees whose leaf Zn concentration was only 12 to $13 \text{ mg}\cdot\text{kg}^{-1}$ dry weigh (Yogarathnam and Johnson, 1982).

Zn foliar sprays had a positive effect on apple fruit Ca concentrations that resulted in less bitter pit (Schmitz and Engel, 1973). The positive effect of Zn on fruit Ca, however, was not confirmed by studies conducted by Martin et al. (1976) and Yogarathnam and Johnson (1982).

Hu and Sparks (1990) reported that as Zn deficiency in pecan increased from none to very severe, there was a reduction in nut volume, nut and kernel weight, percent of kernel in nut, and percent of shuck dehiscence.

Trials concerned with grapefruit Zn nutrition in California in the 1930s indicated that trees with severe Zn deficiency produced small fruit of abnormal shape, thick rind with resin like formations in the albedo, and low juice content (Parker, 1937). However, later studies with mildly deficient orange and grapefruit trees produce no changes in external and internal fruit quality in response to foliar or soil Zn treatments (Embleton et al., 1988; Koo, 1988; Swietlik and LaDuke, 1991).

Technology of Zn application to fruit trees

Soil Zn treatments frequently produce poor and inconsistent effects in terms of improving Zn nutritional status of fruit trees due to poor Zn mobility in soils, particularly in those with neutral and alkaline reaction. Despite the poor mobility, however, a number of studies reported an improved Zn nutritional status of fruit tree species such as apple, avocado, citrus, and pecan in response to soil Zn applications. To be effective, however, such

treatments required the application of large amounts of Zn materials (Crowley et al., 1996; Embleton et al., 1965; Leonard et al., 1958; Smith et al., 1980; Stiles et al., 1995), application within concentrated bands (Crowley et al., 1996; Embleton et al., 1965; Neilsen and Neilsen, 1994; Smith et al., 1980), piles (Leonard et al., 1958), in peat plugs containing Zn inserted into the soil (Neilsen and Neilsen, 1994), application beneath trickle irrigation emitters (Crowley et al., 1996; Neilsen and Neilsen, 1994), with Zn materials injected directly into the irrigation water (Stiles et al., 1995; Zekri and Koo, 1992), applying Zn into shallow trenches acidified with sulfuric acid (Fenn et al., 1990), or using chelated forms of Zn (Crowley et al., 1996; Swietlik, 1996a). When successful, soil Zn treatments usually provide long lasting benefits. However, the large amounts of Zn used or applications in highly concentrated bands may cause serious phytotoxicity (Neilsen and Neilsen, 1994; Orphanus, 1982). That is why soil applications are not generally recommended for fruit trees.

Foliar sprays have the ability to rapidly alleviate Zn-deficiency symptoms. However, they must be repeated at frequent intervals due to poor mobility of foliar-absorbed Zn from sprayed to nonsprayed new leaves, (Crowley et al., 1996; Embleton et al., 1988; Labanauskas et al., 1969; Neilsen and Neilsen, 1994; Swietlik and LaDuke, 1991).

Neilsen and Neilsen (1994) reported that in apple there is little difference in effectiveness of various forms of foliar Zn materials. The work reported by Smith et al. (1972), Smith and Storey (1979), and Storey et al. (1979), however, indicated better absorption of Zn from the mixture of zinc nitrate [$\text{Zn}(\text{NO}_3)_2$], urea [$\text{CO}(\text{NH}_2)_2$], and ammonium nitrate (NH_4NO_3) rather than from ZnSO_4 and other forms of Zn.

Dormant or postharvest Zn sprays are recommended in the Pacific northwest U.S. and British Columbia, Canada as a means of alleviating Zn deficiency on fruit trees (Neilsen and Neilsen, 1994). A foliar application of ZnSO_4 may cause severe russetting of the fruit surface, but this response may be avoided by using chelated forms of Zn. Foliar zinc ethylenediamine tetraacetate (ZnEDTA) applications

are recommended in New York State as being most effective for pome and stone fruit trees (Stiles, 1992).

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