Properly Timed Foliar Fertilization Can and Should Result in a Yield Benefit and Net Increase in Grower Income

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Abstract

Foliar fertilization reduces nutrient accumulation in soil, run-off and groundwater, where they contribute to salinity, eutrophication or nitrate contamination, with negative consequences to humans and the environment. Soil-applied fertilizers should be replaced in part with foliar-applied fertilizers. Foliar fertilizers can meet the crop's nutrient demand when soil temperature, moisture, pH, or salinity renders soil-applied fertilizers ineffective. Applying nutrients directly to leaves ensures that the plant's photosynthetic machinery is not compromised by low availability of an essential nutrient. Foliar-applied phloem-mobile nutrients are translocated to all plant parts, even feeder roots. However, not all nutrients are taken up through leaves and, even if taken up, some nutrients are not phloem mobile. Foliar fertilizer rates are typically lower than soil fertilizer rates, but application can be more costly. The goal of our research is to properly time the application of foliar fertilizers at specific stages of tree phenology, when nutrient demand is likely high, to increase yield, fruit size or quality, such that foliar fertilization results in a net increase in grower income even when the tree is not nutrient deficient by standard leaf analysis. A single foliar application of zinc sulphate to *Citrus sinensis,* 'Washington' navel orange, at 10% anthesis significantly increased fruit set through harvest in January, without impact on fruit size or quality. Later applications reduced fruit set. Winter (December) prebloom foliar application of low-biuret urea to *C. reticulata*, 'Nules' Clementine mandarin, increased 2-year cumulative yield of commercially valuable fruit (transverse diameter 63.51-69.85 mm) as both kg and number of fruit per tree with no effect on total yield or fruit quality. Earlier or later applications were without effect. Foliar application of potassium phosphite to *Persea americana*, 'Hass', at the cauliflower stage of inflorescence development significantly increased 3-year cumulative yield (kg and number of fruit per tree) of commercially valuable fruit (178-325 g per fruit) compared to trees receiving foliar- or soil-applied potassium phosphate. All cases resulted in a net increase in grower income.

INTRODUCTION

Foliar fertilization can meet the plant's demand for a nutrient at times when soil conditions (low temperature, low soil moisture, pH, salinity and others) render soil-applied fertilizers ineffective. Thus, foliar fertilization is an effective method for correcting soil deficiencies and overcoming the soil's inability to transfer nutrients to the plant. Nutrients, especially phosphate (PO_4^{3-}), potassium (K) and trace elements can become fixed in the soil and unavailable to plants. Applying nutrients directly to leaves, the major organ for photosynthesis, ensures that the plant's metabolic machinery is not compromised by low availability of an essential nutrient. It is important to note that foliar-applied fertilizers of phloem mobile nutrients are translocated to all parts of the plant, including the smallest feeder roots. Foliar fertilizers reduce the potential for accumulation of nutrients in soil, run-off water, surface water (streams, lakes and the ocean), and groundwater (drinking water supply), where they can contribute to salinity, eutrophication and nitrate contamination, all of which have serious consequences to humans and the environment. Thus, foliar fertilization provides advantages over traditional soil-applied fertilizer and should replace soil-applied fertilizer, at least in part, in crop best management practices (BMPs). Three problems impede adoption of foliar fertilizers. (1) Not all nutrients are taken up through the foliage and, even if taken up, some nutrients are not phloem mobile. Thus, *a priori* knowledge (research) is necessary to know which nutrients are taken up through the leaves of a specific crop in order to develop a foliar fertilization program. This information is not always available to growers and the lack of information compromises a grower's ability to discern which foliar fertilizers are worth using and when to apply them. (2) Standard leaf analyses do not always show the expected increase in nutrient concentration. This can be due to poor nutrient uptake, but also can result from excellent uptake and utilization by tissues typically not analyzed (new shoots, stems, roots and especially fruit). Conversely, leaf analyses can give false information regarding foliar fertilization. Some foliar-applied nutrients persist in the wax of the leaf cuticle. Thus, if the leaves analyzed are not washed properly, a false high reading will be obtained. Frequently, it is considered sufficient to merely demonstrate that a nutrient applied as a foliar fertilizer is taken up. To do this, leaves are typically analyzed within a short period of time after the fertilizer is applied to the foliage. Whereas this approach may confirm that uptake has occurred, benefits of the application are largely presumed. (3) Rates of foliar fertilizer are typically lower than soil-applied fertilizer, but application of foliar fertilizer can be more expensive, especially if a grower does not own his own sprayer. The strategy of tank mixing multiple fertilizers and/or pesticides to save a trip through the orchard should be tested and not simply presumed to be safe. Negative interactions between two compounds that are beneficial when applied separately can result in reduced efficacy or cause negative effects on plant physiology when applied together. For example, individual foliar applications of nitrogen (N) (as low biuret urea) or boron (B) (as sodium tetraborate) during floral ontogeny increased ovule longevity and the number of pollen tubes that reached the ovule of the 'Hass' avocado, respectively, and each treatment significantly increased yield (Lovatt, 1999). In contrast, N and B combined in a single foliar application at the same stage of floral development increased the number of double pistils that developed. With continued treatment, cumulative yield would be significantly reduced after several years. Growers have been proactive in protecting the environment, but with the ever-increasing cost of fertilizers, foliar fertilizers must be proven to be effective for growers to be willing to incur the expense of using them. The key to achieving a yield benefit and net increase in grower income is to properly time the foliar application of fertilizer to specific stages of crop phenology when nutrient demand is likely to be high or when soil conditions are known to restrict nutrient uptake. For citrus (*Citrus sinensis*) and avocado (*Persea americana*) tree crops, this approach is in contrast to the standard application at 2/3-leaf expansion, targeting foliage with a thin cuticle and large surface area, to achieve yields equal to those attained with soil-applied fertilizer (Embleton and Jones, 1974; Labanauskas et al., 1969). With demonstration that properly timed foliar fertilization strategies can be reliably used to increase yield parameters of *C. sinensis* and *P. americana* and grower net income (Ali and Lovatt, 1992, 1994; Lovatt, 1999), growers have replaced soil-applied fertilizer in part with foliar fertilizer, improving fertilizer efficiency and protecting the environment. Winter prebloom foliar applications of low-biuret urea or potassium phosphite (a form of P [HPO_3^{2-}] readily taken up by leaves and translocated through trees to the roots [Lovatt and Mikkelsen, 2006]) have been shown to increase yield, yield of commercially valuable large size fruit and total soluble solids (TSS) of sweet oranges (Albrigo, 1999; Ali and Lovatt, 1992, 1994; Lovatt, 1999); when combined, the yield effects are additive (Albrigo, 1999). Use of urea and potassium phosphite in Clementine mandarin (*C. reticulata*) production in Morocco produced similar beneficial yield results (El-Otmani et al., 2003a,b). Application of potassium phosphite in May (during the cell division stage of fruit development) and again in July (at maximum peel thickness, which marks the end of the cell division stage of citrus fruit development) or a single application of urea in July increased the yield of large size 'Frost nucellar' navel orange fruit (Lovatt, 1999). Fruit size of ‘Sunburst’ tangerine (*C. reticulata* × *C. paradisi*) was increased with foliar application of potassium nitrate (KNO_3) at dormancy (February), post-bloom (~April) and exponential fruit growth (July-August) (Boman, 2002). Foliar application of potassium sulphate (K_2SO_4) at the post-shooting stage of banana (*Musa* spp.) increased yield, fruit quality and post-harvest shelf-life (Kumar and Kumar, 2007). Foliar-applied potassium during cantaloupe (*Cucumis melo*) fruit development and maturation improved fruit market quality by increasing firmness, sugar content, and nutritional value through increased beta-carotene, ascorbic acid and K concentrations in the edible flesh (Lester et al., 2007). For avocado, canopy applications of B or urea-N just prior to avocado inflorescence expansion (cauliflower stage), significantly increased the number of viable ovules, increased the number of pollen tubes that reached the ovules, and increased yield (Lovatt, 1999). Earlier (bud break) applications were not effective, later (full bloom) applications were intermediate in effect. B is also known to stimulate cell division and increase fruit set and fruit size of many crops, even seedless fruit, and even when leaf analyses indicate B is adequate. For all cases cited above, proper timing of the foliar fertilizer application was a factor in increasing commercial yield or improving fruit quality parameters, including increased fruit size. Moreover, these results were attained even though the crops were not deficient based on standard nutrient analysis for the crop.

The research reported herein had three objectives. The first objective (Experiment 1) was to identify a key time in the phenology of the ’Washington’ navel orange (*C. sinensis* L. Osb.) when applying zinc (Zn) to the foliage would not only improve tree Zn status, but also increase yield or fruit size or improve fruit quality. Application times tested corresponded to the following phenological stages and were selected based on the following rationales (for convenience approximate calendar dates are given in parentheses): 1) 10% open flowers (anthesis; April) to increase flower and fruit retention during early fruit drop; 2) beginning of the fruit drop period (June) to increase fruit set; 3) maximum peel thickness, which marks the end of the cell division stage of fruit development (July), to increase fruit size; and 4) pre-harvest (November) to prevent drop of late-harvested fruit in March. Thus, the overall goal of this first experiment was to maximize the benefit to cost of foliar fertilization with Zn. Zinc is frequently limiting in early spring, especially if the soil is cold and wet, and also limiting to citrus grown in calcareous soil. The second objective (Experiment 2) was to determine the optimal time for a winter prebloom foliar application of low-biuret urea to ‘Nules’ Clementine mandarin (*C. reticulata*) to increase fruit set, total yield, yield of commercially valuable large size fruit, TSS and TSS to acid ratio, as previously achieved with *C. sinensis* (Albrigo, 1999; Ali and Lovatt, 1992, 1994; Lovatt, 1999). The third objective (Experiment 3) was to determine the efficacy of a foliar application of potassium phosphate or potassium phosphite at the cauliflower stage of inflorescence development of the ‘Hass’ avocado to increase yield or fruit size. At the start of each experiment, all trees had adequate nutrition based on standard leaf analyses for the crop.

MATERIALS AND METHODS

Experiment 1

The research was conducted in a commercial orchard in Riverside, California, of 30-year-old ‘Washington’ navel orange trees on ‘Troyer citrange’ rootstock (*C. sinensis* ‘Washington’ navel × *Poncirus trifoliata* L. Raf.). Each treatment, including an untreated control, was applied to a single branch, originally bearing 315 ± 20 flowers, on each of 20 trees per experiment. Flowers or fruit were counted just prior to treatment application on 10 April (Experiment 1a), 1 June and/or 1 July (Experiment 1b), and 1 November (Experiment 1c). In addition, each treatment was duplicated on a second set of 60 trees, which was used for collection of fruit for quality analysis. Treatment solutions of Zn (450 mg L^{-1}) as $ZnSO_4$ (36% zinc) contained 0.1% Silwet L-77® (silicone polyether copolymer) prepared in distilled water and adjusted to a final pH between 5.5 and 6.5.

Flowers, or fruit, and leaves on each branch were sprayed until runoff (~ 100 ml per branch). The treatment rate is equivalent to 0.84 kg Zn (2.33 kg $ZnSO_4$; 36% Zn) in 1869 liters of water per ha. Neighbouring branches were covered to protect them from drifting treatment sprays. At the start of each experiment all trees had adequate Zn concentrations based on leaf analysis (Embleton et al., 1988). The effect of treatments on fruit number and fruit transverse diameter was determined on 4 August, 15 November, and 6 January for Experiments 1a and 1b, and on 23 March for Experiments 1a, 1b, and 1c. Percent fruit set was calculated as the amount of fruit remaining on each branch for each evaluation date relative to the initial number of flowers or fruit on the branch prior to treatment application. At early harvest in November, TSS and percent acid in the juice were quantified for fruit in Experiments 1a and 1b to determine treatment effects on fruit maturity in terms of TSS to acid ratio. At the final harvest in March, juice mass as a percent fruit fresh mass, TSS and percent acid in the juice were determined. For Experiment 1a, leaves from control and treated branches were analyzed for Zn 4 days after treatment application. For all experiments, leaves from control and treated branches were analyzed for Zn in mid-January, 9 months after the first treatment in April was applied.

Experiment 2

The research was conducted in a commercial orchard in Grapevine, California, of 10-year-old ‘Nules’ Clementine mandarin trees (*C. reticulata* Blanco) on ‘Carrizo citrange’ rootstock (*C. sinensis* ‘Washington’ navel × *P. trifoliata* L. Raf.) in a randomized complete block design with 16 individual tree replicates per treatment. Low-biuret urea (granules, 46% N, 0.25% biuret) was applied to the entire tree at a final concentration of 1.0% N to provide 0.11 kg N per tree in 1869 liters of water (adjusted to a final pH of 5.5) per ha on 15 November, 15 December, 15 January or 15 February. The foliar application made on 15 December approximates the time of irreversible commitment to flowering and flower initiation for this orchard (Lovatt, unpublished). At the start of the experiment all trees had adequate N concentrations based on leaf analysis.

Experiment 3

The research was conducted in a commercial orchard in Somis, California, of 11-year-old ‘Hass’ avocado trees on Duke 7 clonal rootstock (*P. americana* var. *drymifolia*) in a randomized complete block design with 20 individual tree replicates per treatment. All treatments were applied at the cauliflower stage of inflorescence development (~March), which was determined by Salazar-Garcia et al. (1998) to be the time of gametogenesis (pollen, ovule and egg formation). The treatments included: (1) control − soil-applied potassium phosphate (25.2 kg ha^{-1} as P_2O_5 and 25.2 kg ha^{-1} as K_2O); (2) foliar-applied potassium phosphate (Balance®, 4-18-18, 1.8 kg ha^{-1} as P_2O_5 and 1.8 kg ha^{-1} as K_2O) and foliar-applied potassium phosphite (Nutra-Phite®, 0-28-26, 1.8 kg ha^{-1} as P_2O_5 and 1.8 kg ha^{-1} as K_2O). In California, 'Hass' avocado fruit are harvested 10 to 18 months after bloom. Thus, each crop was treated twice-once at the cauliflower stage of inflorescence development and again ~6 months prior to harvest.

Leaf Nutrient Analyses

For both citrus and avocado, spring flush leaves from non-fruiting terminal shoots were collected in September (Embleton et al., 1973). Leaves were washed with soapy water and rinsed thoroughly with distilled water, oven dried at 60°C for 72 h, and ground in a Wiley mill to a size fine enough to pass through a 40-mesh (0.635 mm) screen (Embleton et al., 1973). The ground samples were sent to Albion Laboratories (Clearfield, Utah) for nutrient analysis by atomic absorption spectrometry and inductively coupled plasma atomic emission spectrometry.

Harvest Data

At harvest, treatment effects on yield and fruit size distribution (packout) were determined. For citrus, a subsample of 100 fruit per tree was used to determine fruit diameter and fruit weight to calculate packout, peel colour and external peel quality. A second subsample of 25 fruit per tree was used to determine fruit weight, juice weight, % juice, TSS, percent acidity, TSS to acid ratio. Fruit were mechanically juiced with a commercial juice extractor, the TSS concentration was determined using a refractometer and the percent acidity was determined by titration to pH 8.2 ± 0.1 with 1M NaOH. For avocado, 100 fruit per tree were weighed to calculate packout. Two fruit were randomly selected per tree and allowed to ripen at 18 to 21°C. When ripe, internal flesh quality was evaluated for discoloration, vascularisation (presence of vascular bundles and associated fibres) and stem-end decay. Fruit quality parameters were rated on a scale from 0 (normal) to 4 (high incidence of discoloration, vascularisation and stem-end decay).

Statistical Analyses

For Experiment 1, Duncan's Multiple Range test was used to test for treatment effects at each sampling date. For Experiments 2 and 3, Fisher's Protected LSD Test at $P \leq 0.05$ was used to test for treatment effects. Analyses were performed using the SAS statistical program (SAS Institute, Cary, N.C.)

RESULTS

Experiment 1

On 10 April 10% of the flowers on branches on the south-facing side of 'Washington' navel orange trees had reached open petals (anthesis). In Experiment 1a, branches sprayed with Zn on this date retained a significantly greater number of fruit and had a higher percent fruit set at the end of the June drop period (August) than untreated control branches (Table 1). In addition, branches receiving a foliar application of Zn at this stage of tree phenology retained more fruit and had a higher percent fruit set through both early harvest (November) and mid-harvest (January) compared to untreated control branches. Increased yield was not accompanied by a reduction in fruit size (Table 1). The effect of foliar-applied Zn on fruit retention did not persist through late harvest in March. In contrast, in Experiment 1b, foliar application of Zn on 1 June and then again 1 July significantly reduced the number of fruit retained and percent fruit set at the end of the June drop period (August) compared to untreated control branches (Table 2). Fruit number and percent fruit set for branches receiving the two applications of Zn remained significantly lower than for untreated control branches through late harvest in March. The yield reduction did not result in a significant increase in fruit size at any harvest (Table 2). In contrast, a single foliar application of Zn on 1 July had no significant effect on fruit number, percent fruit set or fruit size at the end of the June drop period compared to untreated control branches (Table 2). However, by early harvest branches sprayed with Zn on 1 July had a significantly lower percent fruit set than untreated control branches. This difference remained significant through late harvest. Reduced yield at harvest was not accompanied by increased fruit size (Table 2). In Experiment 1c, a single foliar application of Zn (450 mg L^{-1}) to branches pre-harvest (1 November) to prevent drop had no effect on fruit retention, percent fruit set, or fruit size compared to untreated control branches when navel orange trees were harvested in March (data not shown). The capacity of mature, hardened leaves of *C. sinensis* to take up Zn was determined 4 days after the first application of Zn at 10% open flowers in April. The Zn concentration of leaves from branches receiving a foliar application of Zn was 57 µg g^{-1} dry mass (DM) compared to 27 µg g^{-1} DM leaves from untreated control branches. By January, spring flush leaves from untreated control branches for Experiments 1a through 1c had more than adequate levels of Zn: 22, 21 and 29 µg g^{-1} DM, respectively (Labanauskas et al., 1969; Embleton et al., 1988). Zn concentrations of spring flush leaves analyzed in January were on average 16.3 ± 5.7 µg g^{-1} DM greater for Zn-treated branches than untreated control branches. This result was independent of whether branches received one or two foliar applications of Zn. Foliar application of Zn to branches of the navel orange at 10% open flowers had no negative effect on fruit maturity (TSS to acid ratio) at early harvest or late harvest (Table 3). Furthermore, there was no effect on any external fruit quality parameter measured during early or late harvest, including albedo breakdown, puff, split or fruit colour development (data not shown). In contrast, Zn applied to the foliage of navel orange trees during the June drop period, either as two sprays on 1 June and 1 July or a single spray on 1 July, significantly reduced fruit TSS at early harvest compared to fruit from untreated control branches (Table 4). Two foliar applications of Zn also reduced the percent acid of the fruit compared to fruit from branches receiving only a single Zn application or untreated control branches. Despite these results, no treatment affected TSS to acid ratio at early harvest. For navel orange trees harvested in March, fruit from branches receiving two foliar applications of Zn during June drop had greater fresh mass and percent acid in the juice compared to fruit from branches receiving only a single application of Zn to the foliage on 1 July (Table 4). For fruit from control branches harvested in March, these fruit quality parameters were intermediate to and not significantly different from fruit receiving either Zn treatment. There was no treatment effect on TSS to acid ratio (Table 4) or on any external fruit quality parameter evaluated (data not shown). A single foliar application of Zn pre-harvest (1 November) had no effect on fruit fresh mass, percent juice in the fruit, TSS or percent acid in the juice, TSS to acid ratio, or any external fruit quality parameter evaluated in this study compared to fruit from untreated control branches at the late harvest in March (data not shown).

Experiment 2

Alternate bearing, production of a heavy on-year crop followed by a light off-year crop, is a problem associated with the production of 'Nules' Clementine mandarin. Thus, yield results for two successive years (one complete alternate bearing cycle) are required to determine the efficacy of a treatment designed to increase yield or fruit size. Winter prebloom foliar applications of low-biuret urea made monthly from November through February to different sets of trees had no effect on total yield per tree in either year of the experiment and no effect on 2-year cumulative yield per tree (Table 5). The January application of low-biuret urea significantly reduced 2-year cumulative yield of fruit less than 44.45 mm in diameter (packing carton size tiny), which have no commercial value, compared to the November and December foliar applications but not the February treatment or the control receiving only soil-applied fertilizer. December application of low-biuret urea significantly increased yield of fruit of packing carton size jumbo in both years of the experiment and significantly increased the 2-year cumulative yield of jumbo size fruit per tree compared to the control (Table 5). The December application of low-biuret urea also increased the 2-year cumulative yield of mammoth size fruit in kg per tree compared to all treatments, except the January foliar application of low-biuret urea. The December foliar application of low-biuret urea also increased the yield of the combined pool of commercially valuable large size fruit of packing cartons sizes large+jumbo+mammoth compared to all other treatments, except the November application of low-biuret urea ($P = 0.077$) (Table 5). At standard planting densities of 480 to 900 trees per ha, the net increase in yield of jumbo size fruit equalled 5,026 and 9,423 kg per ha for two years, respectively, for trees receiving the December application of low-biuret urea, resulting in a net increase in grower income. Repeated measures analysis with year as the repeated measure was performed to determine which treatments were effective across both years of the experiment. The December foliar application of low-biuret urea significantly increased the yield of jumbo size fruit as both kg ($P = 0.0340$) and number ($P = 0.040$) of fruit per tree averaged across the two years of the experiment (Data not shown). The December foliar application of low-biuret urea also increased the yield of the combined pool of fruit of packing carton sizes large+jumbo+mammoth as both kg ($P = 0.0675$) and number ($P = 0.0584$) of fruit per tree averaged across the two years of the experiment (Data not shown). The winter prebloom foliar applications of low-biuret urea had no negative effect on any fruit quality parameter evaluated in this experiment (Table 6). The application of 0.11 kg of N per tree as a winter (November-February) prebloom foliar application of low-biuret urea had no significant effect on leaf N concentration at the time of standard leaf analysis in September relative to control trees receiving soil-applied N (data not shown).

Experiment 3

Foliar application of potassium phosphate or potassium phosphite at the inflorescence cauliflower stage of the 'Hass' avocado had no significant effect on 3-year cumulative total yield (Table 7). However, foliar-applied potassium phosphite significantly increased the 3-year cumulative yield of commercially valuable large size fruit weighing 213 to 269 g per fruit (packing carton size 48) compared to trees receiving potassium phosphate applied to the foliage, but not to the soil (Table 7). Foliar-applied potassium phosphite also increased the yield of commercially valuable large size fruit in the combined pool of fruit of packing carton sizes 60+48+40 (fruit weighing 178-325 g) (Table 7) compared to trees receiving potassium phosphate either to the canopy or to the roots. Based on a standard 240 trees per ha, foliar-applied potassium phosphite produced a net increase of commercially valuable large size fruit (packing carton sizes 60+48+40) of 4,224 or 3,770 kg per ha for the three crop years of the experiment compared to trees receiving foliar-applied potassium phosphate or control trees receiving soil-applied potassium phosphate, respectively. The net increase in yield of commercially valuable fruit produces a net increase in grower income, making the treatment cost-effective. Foliar-applied potassium phosphite significantly increased total yield (P = 0.0640) and yield of fruit of packing carton sizes 60 (P = 0.0534) and 48 (P = 0.0644) and the combined pool of fruit of packing cartons sizes 60+48+40 (P = 0.0595) as both kg and number of fruit per tree in the off-crop year but had no significant effect in the on-crop years (data not shown). Neither foliar fertilizer had a significant effect on any yield parameter relative to trees receiving soil-applied potassium phosphate when analyzed across years by repeated measures analysis with year as the repeated measure. Foliar-applications of potassium phosphate or potassium phosphite had no effect on internal fruit quality in any year of the experiment relative to the control. In general, the fruit were of excellent quality. Discoloration of the flesh was ≤ 1 in all years of the experiment. Vascularisation averaged 1.2, 1.3 and 1.1 for each year of the experiment, respectively. Stem-end decay reached a maximum value of 0.6, 1.3 and 0.07 for the 3 years of the experiment. Foliar-applications of potassium phosphate or potassium phosphite had no effect on leaf concentrations of nutrients analyzed in this experiment (N, S, P, K, Mg, Ca, Fe, Mn, B, Zn, and Cu) in any year relative to trees receiving soil-applied potassium phosphate. For all 3 years of the experiment, trees had high levels of N (2.5%, 2.6% and 2.4%, respectively). The California Avocado Commission recommends 2.1% leaf N (Guy Witney, California Avocado Commission, personal communication). Leaf P concentrations were always at the high end of the adequate range for avocado (0.10%-0.25% P) at 0.25%, 0.20% and 0.20% annually. Leaf K concentrations gradually decreased over the 3 years of the experiment from 1.3% to 1.1% to 1.0%, respectively, but remained within the optimal range (0.75%-2.0% K) each year. Yield was not significantly correlated with leaf N, P or K in any year of the experiment (Data not shown).

DISCUSSION

To our knowledge this is the first demonstration that foliar-applied zinc sulphate at 10% open flowers increased fruit set of *C. sinensis* through harvest in January. Although the results must be considered preliminary in nature because the research was conducted as a branch study, the strategy of applying zinc sulphate to the canopy of citrus trees at 10% anthesis to increase fruit set and yield warrants further investigation with whole trees in a commercial orchard. Trees in Experiments 1a through 1c had adequate concentrations of Zn throughout the course of the study. The Zn concentration of leaves from untreated control branches was 22, 21 and 29 $ug \cdot g^{-1}$ DM of spring flush leaves for Experiments 1a through 1c, respectively, at the mid-season harvest in January. A Zn concentration of 20

$\mu g \cdot g^{-1}$ DM of spring flush leaves collected from non-fruiting terminals in September was confirmed in a 4-year study to be adequate for commercial production of the 'Washington' navel orange (Embleton et al., 1988). Despite this, Zn applied to the foliage of 'Washington' navel orange trees at 10% anthesis in the present study resulted in a significant increase in fruit retention through June drop (August) and yield at mid-harvest (January) compared to untreated control branches. Flowering and early fruit set are periods of high nutrient demand. Since 10% open flowers occurred on 10 April, soil temperatures were likely still below 15°C (Hamid et al., 1988). Zn uptake through leaves is known to be relatively fast, 1 to 2 days, and Zn is also known to be partially phloem mobile (PureGro, n.d.). In this experiment, a significant increase in Zn leaf concentration was documented 4 days after foliar application. In addition, flowers have proven to be effective organs for uptake of foliar-applied nutrients, resulting in positive effects on fruit set and yield (Jaganath and Lovatt, 1998). For 'Washington' navel orange trees, peak abscission of reproductive structures occurs in April (Erickson and Brannaman, 1960), at which time more than 18,000 floral buds, 8,000 flowers and 10,000 small fruit abscise per tree. Only 23.8% of the total flowers on Zn-deficient 'Shamouti' orange (*C. sinensis*) trees reached the stage of young fruit, whereas 45.1% of flowers on Zn-sufficient trees produced young fruit (Shavit, 1956). In the research presented herein, Zn applied at 10% open flowers increased fruit set per branch 6% or 3% at harvest in November and January, respectively, compared to the untreated control. Thus, this Zn treatment has the potential to translate into a significant net increase in yield per tree and per ha. Furthermore, this application time and rate caused no negative effects on fruit maturity or on any fruit quality parameter evaluated. The results confirmed the findings of Embleton et al. (1988) that Zn nutrition had no effect on albedo breakdown. Use of winter and spring foliar fertilizer applications likely increases fruit set, yield and fruit size because nutrients essential for flowering, fruit set and fruit growth are limiting due to reduced transpiration and/ or nutrient uptake by roots when air and/ or soil temperatures are low. Our previous research provided evidence that foliar application of urea during or after a low temperature or water-deficit period increased citrus flowering by elevating the ammonia status of the tree (Lovatt et al., 1988a,b) and increasing the polyamine content, growth rate, and size of developing citrus fruit, as well as their potential to set (Lovatt et al., 1992). Thus, increased yield of commercially valuable large size fruit achieved with the December foliar application of low-biuret urea to *C. reticulata* was not unanticipated. The properly timed winter prebloom foliar application of low-biuret urea to *C. sinensis* increased the yield of commercially valuable large size fruit in addition to increasing total yield (Ali and Lovatt, 1992, 1994). The mechanism by which foliar-applied potassium phosphite increases fruit size remains unclear. Research has shown that phosphite is more readily absorbed into plant tissues than phosphate, including citrus and avocado leaves that are notoriously impervious to phosphate, and that foliar applications of phosphite can replace phosphate in citrus and avocado through chemical oxidation or by the action of oxidizing bacteria and fungi associated with the leaves (Lovatt and Mikkelsen, 2006). Additionally, phosphite up regulates the shikimic acid pathway, which produces three essential amino acids, indole-3-acetic, salicylic acid, a broad spectrum of phenols, antioxidants and secondary metabolites and lignin.

CONCLUSIONS

Taken together, the results of this research provide strong evidence that specific nutrients applied to the foliage, including flowers, can efficiently meet crop nutrient demand and stimulate specific metabolic and physiological processes resulting in increased yield of commercially valuable large size fruit and, hence, grower net income. The foliar fertilization strategies reported herein were all cost-effective and have the potential to reduce nutrient accumulation in the soil, run-off water, surface water and groundwater. With the increasingly high cost of fertilizer, replacing soil-applied fertilizers in part with properly timed foliar fertilizers provides growers with a tool to reduce fertilizer use and expense while increasing yield and revenue and protecting the environment.

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Literature Cited

Albrigo, L.G. 1999. Effects of foliar applications of urea or Nutri-Phite on flowering and yields of Valencia orange trees. Proc. Fla. State Hort. Soc. 112:1-4.

Ali, A.G. and Lovatt, C.J. 1992. Winter application of foliar urea. Citrograph 78:7-9.

Ali, A.G. and Lovatt, C.J. 1994. Winter application of low-biuret urea to the foliage of 'Washington' navel orange increased yield. J. Amer. Soc. Hort. Sci. 119:1144-1150.

Boman, B.J. 2002. KNO_3 foliar application to 'Sunburst' tangerine. Proc. Fla. State. Hort. Soc. 115:6-9.

El-Otmani, M., Ait-Oubahou, A., Taibi, F.-Z., Lmfoufid, B., El-Hila, M. and Lovatt, C.J. 2003a. Prebloom foliar urea application increases fruit set, size, and yield of Clementine mandarin. Proc. Intl. Soc. Citriculture 1:559-562.

El-Otmani, M., Ait-Oubahou, A., Gousrire, H., Hamza, Y., Mazih, A. and Lovatt, C.J. 2003b. Effect of potassium phosphite on flowering, yield, and tree health of 'Clementine' mandarin. Proc. Intl. Soc. Citriculture 1:428-432.

Embleton, T.W. and Jones, W.W. 1974. Foliar-applied nitrogen for citrus fertilization. J. Environ. Quality 3:388-392.

Embleton, T.W., Matsumura, M. and Kahn, I. 1988. Citrus zinc and manganese nutrition revisited. Proc. 6th Int. Citrus Congr. 1:681-688.

Embleton, T.W., Jones, W.W., Labanauskas, C.K. and Reuther, W.J. 1973. Leaf analysis as a diagnostic tool and guide to fertilization, p.183-211. In: W.J. Reuther (ed.), The citrus industry. Vol. 3. Univ. of California, Div. of Agr. Sci., Berkeley.

Erickson, L.C. and Brannaman, B.L. 1960. Abscission of reproductive structures and leaves of orange trees. Proc. Amer. Soc, Hort. Sci. 75:222-229.

Hamid, G.A., Van Gundy, S.D. and Lovatt, C.J. 1988. Phenologies of the citrus nematode and citrus roots treated with oxamyl. Proc. 6th Intl. Citrus Congr. 2:993-1004.

Jaganath, I. and Lovatt, C.J. 1998. Efficacy studies on prebloom canopy applications of boron and/or urea to Hass avocado. Proc. 3rd World Avocado Congr. 1:181-184.

Kumar, A.R. and Kumar, N. 2007. Sulphate of potash foliar spray effects on yield, quality and post-harvest life of banana. Better crops 91:22-24.

Labanauskas, C.K., Jones, W.W. and Embleton, T.W. 1969. Low residue micronutrient sprays for citrus. Proc. 1st Intl. Citrus Symp. 3:1535-1542.

Lester, G.E., Jifon, J.L. and Stewart, W.M. 2007. Foliar potassium improves cantaloupe marketable and nutritional quality. Better Crops 91(1):24-25.

Lovatt, C.J. 1999. Timing citrus and avocado foliar nutrient applications to increase fruit set and size. HorTechnol. 9:607-612.

Lovatt, C.J., Sagee, O. and Ali, A.G. 1992. Ammonia and/or its metabolites influence flowering, fruit set, and yield of the 'Washington' navel orange. Proc. Intl. Soc. Citricult. 1:412-416.

Lovatt, C.J. and Mikkelsen, R.L. 2006. Phosphite fertilizers: What are they? Can you use them? What can they do? Better Crops. Vol. 90: p.11-13.

Lovatt, C.J., Zheng, Y. and Hake, K.D. 1988a. Demonstration of a change in nitrogen metabolism influencing flower initiation in citrus. Isr. J. Bot. 37:181-188.

Lovatt, C.J., Zheng, Y. and Hake, K.D. 1988b. A new look at the Kraus-Kraybill hypothesis and flowering of citrus. Proc. 6th Intl. Citrus Congr. 1:475-483.

PureGro Company. n.d. Soil vs. foliar. PureGro Co., Sacramento, Calif.
Salazar-Garcia, S., Lord, E.M. and Lovatt, C.J. 1998. Inflorescence and flower development of the 'Hass' avocado (*Persea americana* Mill.) during "on" and "off" crop years. J. Amer. Soc. Hort. Sci.123:537-544.
Shavit, A. 1956. An investigation into the process of flower and fruit abscission of the Shamouti orange. Bul. Res. Coun. Israel, Sect. D., Bot. 5:189-199.

Tables

Table 1. Effect of Zn (450 mg L^{-1}) as $ZnSO_4$ (36% Zn) applied to the foliage of 'Washington' navel orange trees at 10% open flowers (April) in the southwest tree quadrant on fruit set and size (transverse diameter – diam.).

Treatment	Initial flower No.	August			November			January			March		
		Fruit set		Fruit diam. (mm)	Fruit set		Fruit diam. (mm)	Fruit set		Fruit diam. (mm)	Fruit set		Fruit diam. (mm)
		No.	%		No.	%		No.	%		No.	%	
Zn-April	329	4.9 a	1.6 a	34	4.8 a	1.6 a	54	4.7 a	1.4 a	55	4.0	1.2	56
Control	312	3.2 b	1.1 b	34	3.2 b	1.0 b	54	3.3 b	1.1 b	55	3.3	1.1	55
P-value	NS	0.04	0.07	NS	0.04	0.04	NS	0.07	0.06	NS	NS	NS	NS

No.-Number. Means within a column followed by different letters are different by Duncan's Multiple Range test at $P \leq 0.05$. NS-not significant.

Table 2. Effect of Zn (450 mg L^{-1}) as $ZnSO_4$ (36% Zn) applied to the foliage of 'Washington' navel orange trees during June drop (the period of fruit drop from approximately mid-June through the end of July) and/ or at maximum peel thickness on fruit set and size (transverse diameter – diam.).

Treatment	Initial flower No.	August			November			January			March		
		Fruit set		Fruit diam. (mm)	Fruit set		Fruit diam. (mm)	Fruit set		Fruit diam. (mm)	Fruit set		Fruit diam. (mm)
		No.	%		No.	%		No.	%		No.	%	
Zn-June 1+July 1	330	2.7 b	1.0 b	35	2.5 b	0.9 b	59	2.6 b	0.9 b	59	2.7 b	1.1 b	60
Zn- Jul 1	326	4.4 ab	1.4 ab	34	3.6 ab	1.1 b	56	3.4 ab	1.1 b	56	3.3 ab	1.0 b	57
P-value	NS	0.007	0.01	NS	0.02	0.03	NS	0.03	0.04	NS	0.04	0.06	NS

No.-Number. Means within a column followed by different letters are different by Duncan's Multiple Range test at $P \leq 0.05$. NS-not significant.

Table 3. Effect of Zn (450 mg·L^{-1}) as $ZnSO_4$ (36% Zn) applied to the foliage of 'Washington' navel orange trees at 10% open flowers in the southwest tree quadrant on fruit quality at early and late harvest.

	November			March				
Treatment	TSS (ºBrix)	Acid (%)	TSS/ acid	Fruit mass (g)	Juice mass (%)^z	TSS (ºBrix)	Acid (%)	TSS/ acid
Zn – 10% open flowers	11.4	1.7	6.7	97	40	14.8	1.2	12.6
Control–none	11.6	1.7	6.7	102	40	14.9	1.2	12.3
P-value	NS	NS	NS	NS	NS	NS	NS	NS

Means within a column followed by different letters are different by Duncan's Multiple Range test at $P \leq 0.05$.
^{z}Percent juice = juice fresh mass/fruit fresh mass.

Table 4. Effect of Zn (450 mg·L^{-1}) as $ZnSO_4$ (36% Zn) applied to the foliage of 'Washington' navel orange trees during June drop or at maximum peel thickness on fruit quality at early and late harvest.

	November			March				
Treatment	TSS (ºBrix)	Acid (%)	TSS/ acid	Fruit mass (g)	Juice mass (%)^z	TSS (ºBrix)	Acid (%)	TSS/ acid
Zn – June 1 + July 1	11.1 b	1.6 b	6.9	121 a	41	15.8	1.39 a	10.9
Zn – July 1	10.9 b	1.8 a	6.0	100 b	39	15.2	1.28 b	11.7
Control–none	11.6 a	1.8 a	6.4	107 ab	39	15.3	1.31 ab	11.5
P-value	0.05	0.05	NS	0.05	NS	NS	0.05	NS

Means within a column followed by different letters are different by Duncan's Multiple Range test at $P \leq 0.05$.
^{z}Percent juice = juice fresh mass/fruit fresh mass.

Table 5. Effect of timing of a winter prebloom foliar application of 1% low-biuret urea on 2-year cumulative total yield (kg fruit per tree) and 2-year cumulative yield of fruit in different size categories (based on transverse diameter) for 'Nules' Clementine mandarin trees.

		Categories based on transverse diameter (mm)									
		T	S	T+S	M	L	J	MA	L+J+MA	C	SC
Treatment	Total yield	<44.45	44.45-50.80		50.81-57.15	57.16-63.50	63.51- 69.85	69.86-76.20		76.21-82.55	82.56-101.59
	---------- kg fruit per tree ----------										
Control	217.2	0.9 ab	15.8	16.7	84.9	84.3	23.6 b	5.7 b	113.6	1.3	0.7
1% urea Nov.	224.2	1.5 a	14.6	16.0	86.3	85.1	30.4 ab	4.6 b	120.1	1.5	0.3
1% urea Dec.	209.9	1.3 a	14.1	15.4	71.6	78.4	34.1 a	9.6 a	122.1	0.9	0.00
1% urea Jan.	210.6	0.4 b	16.4	16.8	85.8	72.1	27.1 ab	6.8 ab	106.0	1.3	0.6
1% urea Feb.	211.28	0.9 ab	12.2	13.1	84.7	83.3	23.6 b	5.0 b	111.9	1.4	0.00
P-value	NS	0.0456	NS	NS	NS	NS	0.0502	0.0532	NS	NS	NS

T-Tiny, S-Small, M-Medium, L-Large, J-Jumbo, MA-Mammoth, C-Colossal, and SC-Supercolossal. Means followed by different letters are significantly different by Fisher's Protected LSD Test at $P \leq 0.05$. NS-Not significant.

Table 6. Effect of timing of a winter prebloom foliar application of 1% low-biuret urea on fruit quality parameters of 'Nules' Clementine mandarin trees in a commercial orchard for the 2 years of the experiment.

	Fruit weight (g)		Juice weight (g)		Percent acid		TSS (ºBrix)		TSS/acid	
Treatment	Year1	Year2	Year1	Year2	Year1	Year2	Year1	Year2	Year1	Year2
Control	86.9	89.9	34.0	28.2	0.8	0.80	12.6	11.9	15.4	15.0
1% urea Nov.	84.8	90.0	32.8	32.1	0.8	0.8	12.5	11.6	14.8	15.1
1% urea Dec.	86.7	93.9	32.6	30.2	0.8	0.8	13.0	11.9	15.4	14.9
1% urea Jan.	87.8	87.7	34.2	30.8	0.8	0.8	12.9	11.9	15.2	14.5
1% urea Feb.	88.0	88.8	33.3	29.9	0.8	0.8	12.8	11.8	15.1	14.7
P-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Means followed by different letters are significantly different by Fisher's Protected LSD Test at $P \leq 0.05$. NS- Not significant.

Table 7. Effect of foliar potassium phosphate or potassium phosphite applied at the cauliflower stage of inflorescence development of the 'Hass' avocado on 3-year cumulative total yield and 3-year cumulative yield of fruit of in different fruit size categories (based on the weight of individual fruit) compared to control trees receiving soil-applied potassium phosphate.

		Packing carton size							
		84	70	84+70	60	48	40	60+48+40	36
Treatment	Total	99-134g	135-177g		178-212g	213-269g	270-325g		326-354g
	kg fruit/tree								
Potassium phosphate	137.6	4.96	29.3	34.3	50.9	38.0 b	9.5	98.7 b	1.2
Potassium phosphite	145.2	3.15	26.6	28.6	53.4	51.0 a	11.6	116.0 a	0.5
Control – soil applied Potassium phosphate	135.3	2.02	32.3	35.4	48.2	43.1 ab	8.7	100.2 b	0.7
P-value	NS	NS	NS	NS	NS	0.0045	NS	0.0093	NS

Means followed by different letters are significantly different by Fisher's Protected LSD Test at $P \leq 0.05$. NS-Not significant.