Timing Citrus and Avocado Foliar Nutrient Applications to Increase Fruit Set and Size

Carol J. Lovatt[1]

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SUMMARY. The goal of this research was to identify the role essential nutrients play in the physiology of tree crops, and then to apply the nutrient as a foliar fertilizer to stimulate a specific metabolic process at phenological stages when nutrient demand is high. This approach has proven successful. A single winter prebloom foliar application of nitrogen as low-biuret urea [0.16 kg N / tree (0.35 lb N / tree)] to 30-year-old ‘Washington’ navel orange (*Citrus sinensis* L. Osbeck) trees during flower initiation significantly increased yield and fruit number per tree for each of 3 consecutive years ($P \leq 0.05$). The number of commercially valuable large-size fruit also increased significantly with yield increases ($r^2 = 0.88$). Sodium tetraborate applied foliarly to ‘Hass’ avocado (*Persea americana* Mill.) trees at the cauliflower stage of inflorescence development (elongation of inflorescence secondary axes, pollen and ovule development) increased the number of pollen tubes reaching the ovule, ovule viability and cumulative yield ($P \leq 0.05$). Additional examples are presented.

Seasonal cycles of flowering, fruit set and fruit development for the ‘Washington’ navel orange and ‘Hass’ avocado growing in California are depicted in Figs. 1 and 2. Fruit set (early fruit drop) is the most critical stage of fruit development from the grower’s point of view. It is during this period that the greatest gains in fruit retention influencing final yield can be made. Events during this period also impact fruit size and quality. In both crops, flowering and fruit set, periods of high nutrient demand, occur when soil temperatures are low. Soil temperatures are generally ≤15 °C (59 °F) from January to April in citrus and avocado growing areas of California (Hamid et al., 1988). Low soil temperature reduces root metabolic activity, solubility of nutrients in the soil solution and nutrient transport in the transpiration stream. Thus, the ability of trees to utilize nutrients applied to the soil is dependent on many factors unrelated to nutrient demand. With increased use of sprinkler, drip or microjet irrigation systems, there is a growing trend to divide the annual amount of fertilizer to be applied into 6 to 12 small monthly applications.

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[1] Professor of plant physiology, Department of Botany and Plant Sciences, University of California, Riverside, CA 92521-0124. E-mail: carol.lovatt@ucr.edu.

While this strategy reduces the potential for groundwater nitrate pollution, it ignores tree phenology and nutrient demand. In foliar fertilization, the nutrient must be taken up by leaves of the crop, or other target organs, and be phloem mobile. Foliar fertilization with nutrients meeting these criteria is considered to be 5 to 30 times more efficient than soil fertilization depending on the nutrient, crop and soil in which the crop is growing (PureGro, n.d.). Moreover, foliar fertilization can be timed to meet the tree's demand for a nutrient. Here we report optimal stages in citrus and avocado tree phenology when foliar application of nitrogen, phosphorus or boron resulted in increased yield and / or fruit size and, in the case of citrus, increased ratio of total soluble solids to acid.

Citrus

Embleton and Jones (1974) demonstrated that regardless of the fertilization method maximum nutritionally attainable yields for sweet oranges annually required between 0.45 and 0.60 kg N / tree (0.99 and 1.32 lb N / tree). Despite this, foliar nitrogen fertilization was not widely adopted commercially. Due to the potential for ammonia toxicity, there is a limit in the amount of nitrogen that can be applied in a single application, necessitating a minimum of three annual sprays to supply the recommended rate of nitrogen. In contrast, earlier results of Sharples and Hilgeman (1969) suggested foliar applications of urea at the appropriate time might increase yield. For 7 years, yields of 'Valencia' orange trees receiving only 0.23 kg N / tree (0.51 lb N / tree) split between two foliar applications of urea, one in early February and a second in late April to early May, produced yields that were statistically equal to those obtained with much higher rates [0.45 or 0.91 kg N / tree (0.99 or 2.01 lb N / tree)] of soil-applied ammonium nitrate. The objective of our research was to identify specific times in the phenology of the navel orange tree when a single foliar application of low-biuret urea at 0.16 kg N / tree (0.35 lb N / tree) could economically increase yield and / or fruit size compared to soil-applied nitrogen. The overall goal is to motivate growers to replace soil-applied nitrogen with foliar nitrogen fertilization to reduce the potential for groundwater nitrate pollution.

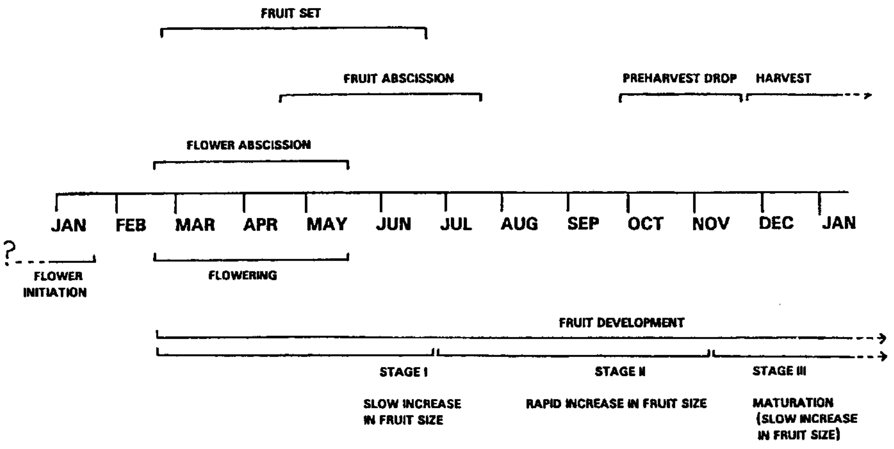

Fig. 1. Phenology model of the navel orange based on 25-year-old 'Washington' navel orange (*Citrus sinensis* L. Osbeck) trees on 'Troyer' citrange [*Poncirus trifoliate* (L. Raf) x *C. sinensis*] rootstock at Riverside, California.

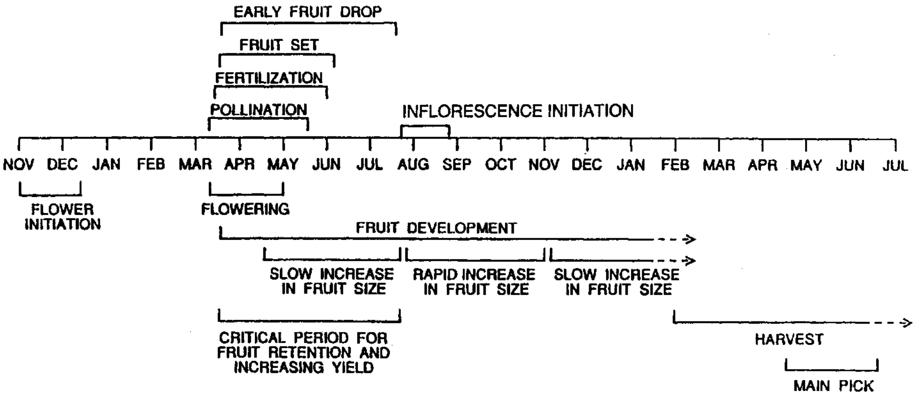

Fig. 2. Phenology model of the 'Hass' avocado (*Persea americana* Mill.) based on environmental conditions for southern California.

The efficacy of a single foliar application of low-biuret urea during one of three phenological stages was tested in four commercial navel orange orchards. The effect of applying urea to the canopy at prebloom (prior to or during flower initiation) or at full bloom was quantified with the objective of increasing fruit set and yield in southern California orchards where yields average 30 $t\cdot ha^{-1}$ (12 ton / acre) (California Agricultural Statistics Service, 1991). Previous research in our lab provided evidence of a relationship between ammonia (a breakdown product of urea), and its metabolites, and flowering and fruit set in citrus. When stress treatments that promote flowering in citrus were reduced in duration (i.e., 4 instead of 8 weeks of low-temperature treatment) or severity (i.e., deficit-irrigated instead of withholding irrigation), foliar-applied low-biuret urea (0.16 kg N / tree) raised the tree ammonia status and increased both the number of inflorescences per tree and flowers per inflorescence, but not the number of vegetative shoots (Lovatt et al., 1988a, 1988b). We subsequently demonstrated that the metabolism of ammonia to arginine and arginine to polyamines were linked in navel orange flowers and developing fruit (Sagee and Lovatt, 1991) and provided evidence of the role of specific polyamines in low-temperature stress-induced flowering in navel orange (Ali and Lovatt, 1995). Developing flowers and

Table 1. Effects of a winter prebloom foliar application of low-biuret urea on yield of the 'Washington' navel orange, 3-year average and 3-year cumulative yield.^{z}

Month urea applied	Yield (kg/tree)^{y}	Fruit no./tree		3-year cumulative yield (kg/tree)
		All sizes	7.0–8.0 cm^{x}	
None (control)	85 b^{w}	542 b	172 a	256 b
November	102 a	657 a	188 a	305 a
December	103 a	661 a	211 a	308 a
January	113 a	761 a	190 a	338 a
February	107 a	708 a	198 a	321 a
Significance	$P \leq 0.001$	$P \leq 0.01$	NS	$P \leq 0.001$

^{z}Ali and Lovatt (1994).
^{y}1 kg = 2.2 lb.
^{x}1 cm = 0.39 inches.
^{w}Means within a column followed by different letters are significantly different by Duncan's multiple range test at $P \leq 0.05$.
^{NS}Nonsignificant at $P \leq 0.05$.

Table 2. Effect of a winter prebloom foliar application of low-biuret urea on yield of the 'Washington' navel orange.^{z}

Month urea applied	Yield (kg fruit/tree)^{y}		
	Year 1	Year 2	Year 3
None (control)	109 b^{x}	32 c	116 b
November	125 a	42 abc	140 a
December	129 a	38 bc	143 a
January	132 a	48 a	159 a
February	127 a	46 ab	150 a
Significance	$P \leq 0.05$	$P \leq 0.05$	$P \leq 0.01$

^{z}Ali and Lovatt (1994).
^{y}1 kg = 2.2 lb.
^{x}Means within a column followed by different letters are significantly different by Duncan's multiple range test at $P \leq 0.05$.

postpetal fruit borne on leafy inflorescences were characterized by significantly higher polyamine concentrations, faster growth rates and a greater percent fruit set than those borne on leafless inflorescences (Lovatt et al., 1992). Foliar application of low-biuret urea at full bloom significantly increased concentrations of ammonia, arginine and polyamines and fruit growth rate and size by June for fruit of leafy inflorescences (Corona, 1994). Last, based on the well established role of polyamines in promoting growth by cell division and on our finding that foliar-applied urea stimulated polyamine biosynthesis, we hypothesized that a foliar application of low-biuret urea at the end of the cell division stage of fruit growth might increase the cell division rate or extend the length of the cell division period of fruit growth, and thus increase fruit size without increasing fruit set. The end of the cell division stage of fruit growth in navel orange is associated with the time the peel is at its maximum thickness. The effect of a foliar application of urea at the end of the cell division stage of fruit growth (time of maximum peel thickness) was tested with the goal of stimulating cell division to increase fruit size in two orchards in the San Joaquin Valley of California, where yields average 60 $t \cdot ha^{-1}$ (24 ton / acre) (California Agricultural Statistics Service, 1991).

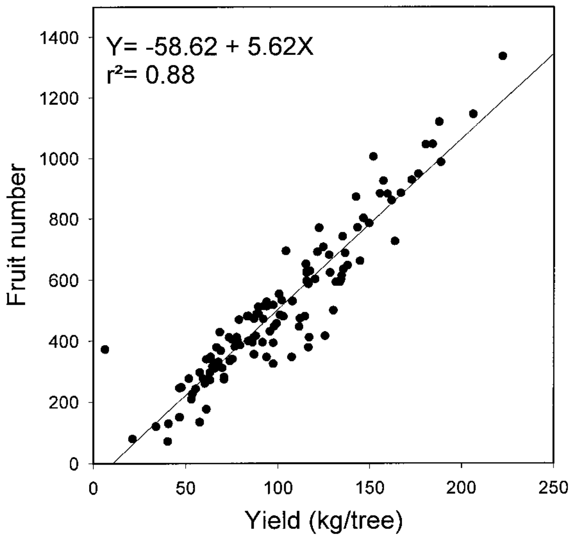

Fig. 3. Yield (kg/tree) vs. number of navel orange fruit with diameters of 6.1 to 8.0 cm (2.4 to 3.1 inches) per tree averaged over 3 years of the study (1 kg = 2.2 lb).

WINTER PREBLOOM FOLIAR N. For the three successive harvests, from 1990 through 1992, Ali and Lovatt (1994) successfully increased fruit set and yield of the 'Washington' navel orange with a single foliar winter prebloom application of low biuret urea. A final concentration of 0.5% N [as Unocal Plus (Unocal, Brea, Calif.), 20% N, 0.1% biuret], provided 0.16 kg N / tree (Table 1). Control trees received 0.5 kg N / tree (1.10 lb N / tree) as urea (granules, 0.25% biuret) applied to the soil in winter (November to January). Single foliar applications of urea were made on 15 Nov., 15 Dec., 15 Jan. or 15 Feb. The foliar applications made on 15 Jan. or 15 Feb., the approximate time of irreversible commitment to flowering and flower initiation for the southern California orchard in which the research was conducted (Lord and Eckard, 1987), significantly increased yield all 3 years of the study ($P \leq 0.05$) (Table 2). Applications of foliar urea made on 15 Nov. or 15 Dec. increased yield 2 of the 3 years ($P \leq 0.05$). Yield increases were not accompanied by a decrease in fruit size. As the total weight of fruit per tree increased in response to foliar-applied urea, the number of fruit of commercially valuable size also increased (Fig. 3). Yield increases were not due to improved nitrogen status of trees receiving a foliar application of low-biuret urea. All trees had optimum levels of N and other nutrients throughout the experiment according to annual September leaf analyses. There was no significant relationship between tree nitrogen status and yield (Table 3). Time of foliar urea application significantly affected cumulative yield. In each year of this study, the winter prebloom foliar application of low-biuret urea was cost-effective (Ali and Lovatt, 1992). Janu-

Table 3. Linear regression analysis of leaf nitrogen content (%) and fruit weight (kg) per tree.

Independent variable (X)	Dependent variable (Y)	*P* value	Coefficient of linear correlation
Nitrogen	Fruit weight per tree	0.78	0.026

[z] Ali and Lovatt (1994).

ary or February foliar-applied urea resulted in net cumulative (3 years) increases in yield over the control of 20.6 and 16.4 t·ha^{-1} (8.3 and 6.6 ton / acre), respectively.

FULL-BLOOM FOLIAR N. At full bloom low-biuret urea (as Unocal Plus, 20% N, 0.1% biuret) was applied to fully cover the canopy of ‘Washington’ navel orange trees at a final concentration of 1.3% N providing 0.16 kg N / tree. All trees had optimum levels of N and other nutrients throughout the experiment according to annual September leaf analyses. The treatment significantly increased both total weight and number of fruit per tree in the “on” year ($P \le 0.10$), but not in the “off” year (Table 4). Combining the full bloom application of urea with an application of cytokinin (proprietary material) at full bloom and 30 d later significantly increased total weight of fruit per tree both years of the study ($P \le 0.10$). As yield increased so did the number of commercially valuable large-size fruit [transverse diameter 7.0 to 8.0 cm (2.8 to 3.1 inches)] ($P \le 0.05$) (Fig. 4). The two treatments resulted in a net increase in cumulative yield (2 years) over the control of 7 and 11 t·ha^{-1} (2.8 and 4.4 ton / acre), respectively. Both treatments were cost-effective.

END OF CELL DIVISION STAGE OF FRUIT GROWTH. About 1 week or 3 weeks past petal fall low-biuret urea (as Unocal Plus, 20% N, 0.1% biuret) was applied to provide full coverage of ‘Frost nucellar’ navel orange trees at a final concentration of 1.5% N to provide 0.16 kg N / tree. Both treatments significantly increased the number of large-size fruit [transverse diameter 8.1 to 8.8 cm (3.2 to 3.5 inches)] in a single, but different, year of the 3-year study ($P \le 0.05$). In an attempt to improve the efficacy of the treatment, the time of maximum peel thickness, which marks the end of the cell division stage for navel oranges, was determined experimentally for orchards from southern coastal California to the northern citrus region of the San Joaquin Valley for both “on” and “off” crop years. Maximum peel thickness occurred between 17 June and 27 July. Based on this result, low-biuret urea (granules, 46% N, 0.25% biuret) was applied to ‘Frost nucellar’ navel orange trees at a final concentration of 1.5% N to provide 0.16 kg N / tree during mid-May or mid-July. This study included phosphorus, another nutrient that would be in high demand during cell division, and, a nutrient known to increase fruit quality by increasing soluble solids per hectare and the ratio of total soluble solids to acid in the juice (Embleton et al., 1973). Phosphorus was applied to the foliage as potassium phosphite [Nutri-Phite (Biagro, Visalia, Calif.), 0–28–26] at a rate of 6 L·ha^{-1} (0.64 gal / acre) in mid-May or mid-July or as two applications at 4.6 L·ha^{-1} (0.49 gal / acre) in mid-May and mid-July. All trees had optimum nutrient concentrations according to annual September leaf analyses. The July application of urea and the double application of potassium phosphite in May and July were the only treatments that significantly increased the number of commercially valuable large-size fruit [transverse diameter 6.9 to 7.4 cm (2.7 to 2.9 inches), 7.5 to 8.0 cm (3.0 to 3.1 inches), and 8.1 to 8.8 cm (3.2 to 3.5 inches), packing carton sizes 88, 72, and 56, respectively] (Table 5). In addition, these two treatments had higher total weight (nonsignificant) and number of fruit ($P \le 0.10$) per tree. The double-application of potassium phosphite also significantly increased total soluble solids ($P \le 0.001$) and the ratio of total soluble solids to acid ($P \le 0.01$) by early November compared to control fruit. By this date, fruit from trees receiving the two foliar applications of potassium phosphite had a ratio of 8.1 compared to a ratio of 7.2 for control fruit. A minimum ratio of 8.0 is required for navel harvest in California. Total soluble solids ($P \le 0.04$) and the ratio of total soluble solids to acid ($P \le 0.01$) remained significantly higher in fruit from trees treated with potassium phosphite than control fruit 30 d later.

Avocado

Research using boron to increase fruit set and yield of crops requiring pollination and fertilization has been extensive. Reports in the literature document the positive effect of boron on pollen germination; growth of the pollen tube to the ovule; gametogenesis; and cell division during the early stages of fruit development (Lovatt and Dugger, 1984). Yield increases were achieved in response to added boron even for trees with adequate boron levels (Hanson, 1991). Boron sprays were most effective when cool, wet weather predominated during flowering, conditions that reduce bee activity and pollination (Hanson, 1991). In South Africa, Robbertse et al. (1990, 1992) demonstrated that when pistils harvested from avocado trees receiving a boron foliar application were pollinated with pollen from trees also sprayed with boron, pollen germination and pollen tube

Table 4. Effect of foliar applications of low-biuret urea (full bloom) and cytokinin (full bloom + 30 d later) on the yield of ‘Washington’ navel orange.[z]

Urea applied at full bloom	Cytokinin applied at full bloom + 30 d	Yield			
		“On” year		“Off” year	
		kg/tree[y]	no./tree	kg/tree	no./tree
Control (untreated)		157 b[x]	981 b	53 b	336 b
+	–	182 a	1198 a	57 b	380 b
+	+	181 a	1146 ab	73 a	448 a

[z] Ali and Lovatt (1994).

[y] 1 kg = 2.2 lb.

[x] Means within a column followed by different letters are significantly different by Duncan’s multiple range test at $P \le 0.10$.

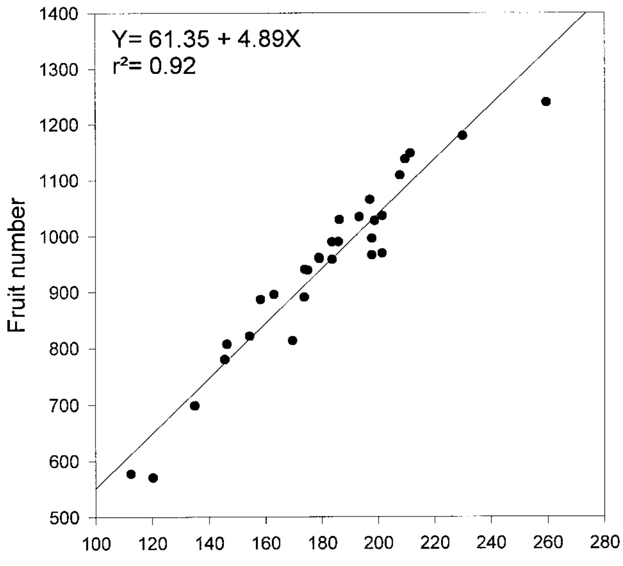

Fig. 4. Yield (kg/tree) vs. number of navel orange fruit with diameters 6.4 to 8.8 cm (2.5 to 3.5 inches) per tree averaged over 2 years of the study (1 kg = 2.2 lb).

growth were significantly better than in flowers from untreated trees. However, statistically significant yield increases in response to foliar-applied boron were only achieved in some orchards and in some years (Coetzer et al., 1993). Evidence that nitrogen increased ovule viability of apple was reported by Williams (1965).

CAULIFLOWER STAGE FOLIAR B AND N. During the cauliflower stage of avocado inflorescence development, boron (sodium tetraborate, Solubor, 20.5% B), and / or low-biuret urea (Unocal Plus, 20% N, 0.1% biuret), was applied to commercial 'Hass' avocado trees to provide 6 g B / tree (0.2 oz B / tree), or 0.16 kg N / tree (Jaganath and Lovatt, 1998). All trees had optimum nutrient levels based on annual September leaf analyses. The cauliflower stage is characterized by elongation of the secondary inflorescence axes of the inflorescence and pollen and ovule development within the flowers (Salazar-Garcia et al., 1998). Boron significantly increased the number of pollen tubes that reached the ovule for open-pollinated 'Hass' avocado trees in a commercial orchard, and increased ovule viability and cumulative yield in the commercial orchard ($P \leq 0.05$) (Tables 6 and 7) (Jaganath and Lovatt, 1998). Urea significantly increased the number of viable ovules and number of pollen tubes that successfully reached the ovule and increased cumulative yield ($P \leq 0.05$) (Tables 6 and 7) (Jaganath and Lovatt, 1998). Foliar-applied boron or urea resulted in a net increase in cumulative (3 years) yield over the control of 12.2 and 11.0 t·ha^{-1} (4.9 and 4.4 ton / acre), respectively. (This research will include five harvests when completed.) The increased cumulative yield was accompanied by an increase in the number of commercially valuable large-sized fruit. Treatments were cost-effective. The combined foliar application of boron plus urea, despite having positive effects on the number of pollen tubes that successfully reached the ovule and on ovule viability (Table 6), significantly increased the number of flowers with double pistils ($P \leq 0.05$) and had no effect on yield (Table 7). At the cauliflower stage of inflorescence development, foliar fertilization is more effective than a soil application. Robbertse et al. (1992) reported that root absorption of boron was restricted in spring. The results of Jaganath and Lovatt (1998) indicate that it is necessary to spray the developing inflorescence. They obtained yield increases with foliar-applied boron, but could not increase yield with trunk injections of boron at the cauliflower stage even though trunk injections increased tree boron status to a greater degree than foliar sprays. Urea also must be applied directly to inflorescences because mature leaves of the 'Hass' avocado under southern California conditions do not take up urea (Nevin et al., 1990). Based on our results (Jaganath and Lovatt, 1998) and those of Robbertse et al. (1992), boron is used as a foliar bloom spray by growers to increase yield in years in which adverse climatic conditions might reduce pollen tube growth and ovule viability.

Conclusions

Winter and spring foliar fertilizer applications likely increase fruit set and yield because nutrients essential for flowering and fruit set are limiting due to reduced transpiration and / or nutrient acquisition by roots when air and / or soil temperatures are low. The key has been, however, to identify the specific nutrient elements to be applied and the role each plays in fruit set and development in order to determine the optimal time to apply the nutrient to stimulate a specific physiological process. Our previous research provided evidence that foliar urea applied 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, 1988b) and increased the polyamine content, growth rate, and size of developing citrus fruit, as well as their potential to set (Corona, 1994; Lovatt et al., 1992). The mechanism by which fruit size was increased by foliar application of urea or potassium phosphite

Table 5. Effect of low-biuret urea and potassium phosphite applied to the foliage of 'Frost nucellar' navel orange in July or May and July, respectively, on yield and number of fruit per tree of packing carton sizes 88, 72, and 56.

Treatment	Fruit/tree[z] (kg)	Fruit/tree (no.)	Fruit/tree of packing carton size (no.)[y] 88	72	56	88+72	88+72+56
Control	126	487 b[x]	51 b	83 b	113 b	134 b	247 b
Urea (July)	148	629 a	81 a	140 a	156 a	222 a	378 a
Potassium phosphite (May and July)	150	621 a	84 a	140 a	166 a	224 a	390 a
Significance	NS	$P \leq 0.10$	$P \leq 0.10$	$P \leq 0.05$	$P \leq 0.10$	$P \leq 0.05$	$P \leq 0.05$

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[z] 1 kg = 2.2 lb.

[y] Packing carton sizes 88, 72 and 56 correspond to fruit with transverse diameters 6.9–7.4 cm (2.7–2.9 inches), 7.5–8.0 cm (3.0–3.1 inches), and 8.1–8.8 cm (3.2–3.5 inches), respectively.

[x] Means within a column followed by different letters are significantly different by Duncan's multiple range test at $P \leq 0.05$.

Table 6. Effect of boron and/or urea applied to the foliage of 'Hass' avocado trees in the field at the cauliflower stage of inflorescence development on number of pollen tubes penetrating the ovule and percent viable ovules.[z]

Treatment	Pollen tubes (no.) penetrating the ovule[y]	Viable ovules[x] (%)
Control	0.77 c[w]	70 b
Boron	2.29 a	81 a
Urea	1.48 b	88 a
Boron +urea	2.10 a	78 a

[z] Jaganath and Lovatt (1998).

[y] Data are the average for 30 samples per treatment.

[x] Data are the average for 20 samples per treatment.

[w] Means within a column followed by different letters are significantly different by Tukey's HSD at $P \leq 0.05$.

Table 7. Effect of boron and/or urea applied to the foliage of 'Hass' avocado trees at the cauliflower stage of inflorescence development on yield.[z]

Treatments	Yield (kg fruit/tree)[y] Year 1	Year 2	Year 3	Cumulative
Control	69 a	82 b	41 a	192 b
Boron	67 a	134 a	41 a	242 a
Urea	99 a	89 b	47 a	237 a
Boron+urea	56 a	87 b	43 a	186 b

[z] Jaganath and Lovatt (1998).

[y] Data are the average value for 16 individual tree replicates per treatment. Values in each vertical column followed by different letters are significant by Tukey's HSD at $P \leq 0.05$ (1 kg = 2.2 lb).

at the end of the cell division stage of fruit growth (identified by maximum thickness of peel) remains to be determined. The increased ratio of total soluble solids to acid in juice of fruit from trees treated with foliar sprays of potassium phopshite is the reported response of citrus fruit to increased phosphorus nutrition (Embleton et al., 1973). The results of our research identified three stages in the phenology of the citrus tree when foliar applied urea N can be used to increase yield or fruit size. In general, low-biuret urea applied during the period from flower initiation through fruit set significantly increased yield without reducing fruit size, whereas applications made at the end of the cell division stage of fruit development (time of maximum peel thickness, mid-June through end of July in California) significantly increased fruit size without affecting yield. Each foliar urea application provided 25 to 33% of the annual N required by sweet oranges for maximum yield (Embleton and Jones, 1974). The treatments were cost-effective and reduced the potential for nitrate pollution of the groundwater. Either boron or urea, as a foliar spray at the cauliflower stage of inflorescence development of 'Hass' avocado trees, increased the number of pollen tubes penetrating the ovule and the number of viable ovules. Taken together, these results provide evidence that specific nutrients applied foliarly can efficiently meet tree nutrient demand and stimulate specific physiological processes resulting in increased yield, fruit size and quality.

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