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Hass Avocado Nutrition Research In California

A summary of basic information to assist growers in managing their orchards

Concepts reviewed in this summary:

- Optimizing 'Hass' avocado tree nutrient status is fundamental to production.
- 17 elements are essential for plant function and reproduction.
- Strengths and weaknesses of soil and foliar fertilization.
- Concept of the limiting factor.
- Benefit of timing foliar and soil fertilizer applications to meet tree demand.
- Developing a fertilization program that supports your production goals.
- Status of avocado nutrition research in California.
- Future prospects.
- We are all in this together, share results!

Optimizing ‘Hass’ avocado tree nutrient status is fundamental to production

To sustain the California ‘Hass’ avocado (*Persea americana* Mill.) industry in an era of increasingly costly inputs (land, water, labor, fertilizer, etc.) and greater competition within the US avocado fresh fruit market by countries with significantly lower production-related expenses, California avocado growers must increase yield of high quality commercially valuable size fruit per acre, while reducing production costs. Optimizing tree nutrient status, irrigation and canopy management are fundamental to achieving this goal. Properly timing soil and foliar-applied fertilizers to meet the needs of the ‘Hass’ avocado tree during phenological (developmental) stages of high nutrient demand is a cost-effective strategy for optimizing tree nutrient status that can increase yield and fruit size, improve fertilizer use efficiency, and protect the environment.

17 elements are essential for plant function and reproduction

All plants, including avocado trees, require 17 essential elements. These elements include the nine macronutrients required in relatively large quantities – hydrogen (H), carbon (C), oxygen (O), nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and sulfur (S) – and the eight micronutrients required in relatively low amounts – chlorine (Cl), iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), and nickel (Ni) (Table 1). An element is considered “essential” if, in its absence, the plant cannot grow and complete its life cycle (i.e., flower and sexually reproduce to form a viable embryo, representing the next generation, within a seed enclosed within a fruit). The major functions that the 17 essential nutrients have in plants are summarized in Table 1. All plants, including the ‘Hass’ avocado tree, must have adequate amounts of all 17 essential elements throughout the phenology of the tree in order to produce the maximum yield of commercially valuable size fruit.

Table 1. Elements essential to ‘Hass’ avocado tree productivity and their major functions in plant metabolism and physiology.

Element	Chemical symbol	Major functions
Hydrogen	H	Synthesis of a) sugars (carbohydrates) b) amino acids (proteins) c) fatty acids (lipids) d) nucleotides (DNA and RNA) e) hormones
Carbon	C	Synthesis of a) sugars (carbohydrates) b) amino acids (proteins) c) fatty acids (lipids) d) nucleotides (DNA and RNA) e) hormones
Oxygen	O	Synthesis of a) sugars (carbohydrates) b) amino acids (proteins) c) fatty acids (lipids) d) nucleotides (DNA and RNA) e) hormones
Nitrogen	N	Synthesis of a) amino acids (proteins), b) nucleotides (DNA and RNA) c) hormones
Potassium	K	a) role in ionic balance of cells b) role in opening and closing stomata c) cofactor in protein synthesis
Calcium	Ca	a) secondary messenger in hormone signal transduction pathways b) component of the middle lamella (holds plant cells together; important for fruit quality) c) influences permeability of membranes (Ca deficiency results in leaky membranes and loss of cell integrity, leading to cell death) d) role in gravitropism
Magnesium	Mg	a) central ion of the chlorophyll molecule b) ATP-Mg complex (essential for energy transfer in metabolism) c) Stabilizes ribosomes for protein synthesis

Phosphorus	P	Synthesis of <ul style="list-style-type: none"> a) ATP (energy currency of living cells) b) nucleotides (DNA and RNA) c) phospholipids (cell membranes; P deficiency results in leaky membranes, loss of cell integrity and cell death) d) sugar phosphates (stored energy)
Sulfur	S	Synthesis of two amino acids, cysteine and methionine, for protein synthesis
Chlorine	Cl ₂	Required for splitting H ₂ O → 2H + O ₂ , a critical step in photosynthesis
Iron	Fe	<ul style="list-style-type: none"> a) structural component of enzymes in electron transport chains b) required for the synthesis of chlorophyll
Manganese	Mn	<ul style="list-style-type: none"> a) enzyme cofactor b) ATP-Mn complex (essential for energy transfer in metabolism) c) required for splitting H₂O → 2H + O₂ in photosynthesis
Boron	B	<ul style="list-style-type: none"> a) carbohydrate metabolism b) cell division c) pollen germination and pollen tube growth d) ovule viability e) fruit set
Zinc	Zn	<ul style="list-style-type: none"> a) enzyme cofactor b) required for the synthesis of chlorophyll
Copper	Cu	<ul style="list-style-type: none"> a) enzyme cofactor b) electron transport for energy production c) lignin synthesis
Molybdenum	Mo	Enzyme cofactor in the reduction of nitrate to ammonia for protein synthesis (when nitrate is the N source and Mo is deficient, N deficiency occurs)
Nickel	Ni	Cofactor of the enzyme urease, which catabolizes urea to CO ₂ and NH ₃ , important in nitrogen recycling and plant recovery from stress.

Source: Adapted from Taiz and Zeiger (2010).

Strengths and weaknesses of soil and foliar fertilization

Three of the 17 essential elements, carbon, hydrogen and oxygen, are not applied as fertilizers. Hydrogen and oxygen are provided by the water taken up by the roots; carbon and oxygen are available as carbon dioxide and oxygen gases, which enter through the open stomata of leaves to be used in photosynthesis and respiration, including photorespiration, respectively. In addition, significant amounts of carbon dioxide and oxygen are dissolved in the water taken up by the plant's roots.

Soil nutrients. The remaining 14 essential elements (N, K, Ca, Mg, P, S, Cl, Fe, B, Mn, Zn, Cu, Mo and Ni) are found in varying amounts in the soil and are taken up by the roots of the tree. The relative total amounts of

several of these nutrients in an entire 'Hass' avocado tree are given in Table 2. Soil-applied fertilizers are an inexpensive source of these nutrients to supplement the quantity in the soil. If growers are judicious in their

Table 2. Relative amounts of essential nutrients in 'Hass' avocado trees grown in California.

Nutrient	Grams/tree
Nitrogen	1734
Potassium	1665
Calcium	2086
Magnesium	742
Phosphorus	399
Sulfur	345
Iron	33
Manganese	8
Boron	9
Zinc	15

Source: Rosecrance, Faber and Lovatt, unpublished.

selection of fertilizer formulations and soil amendments, a fertilization program can also be used to correct existing soil problems; for example it is possible to improve soil structure, mitigate the negative effects of salinity, correct pH, increase the water-holding capacity of the soil, create a pathogen-suppressive rhizosphere, and even unplug irrigation emitters. Thus, there are many benefits provided by soil-applied fertilizers, but there are also many problems associated with their use.

Many factors affect root uptake of essential nutrients present in or applied to the soil. To be taken up by roots, a nutrient must be in solution, so soil moisture is critical to nutrient uptake. There must also be adequate water available to the roots to compensate for the tree's loss of water through the process of transpiration, the evaporation of water from the inside of the leaf into the atmosphere through open stomata. Transpiration is essential to move nutrients dissolved in water from the

roots to the leaves, flowers and fruit of the canopy. If the water available to the tree is limited, the stomata will close and nutrient uptake and transport will cease. Since nutrients must be in solution to be taken up by the roots, nutrient solubility is an important factor. Some fertilizer formulations are more soluble than others. For example, calcium nitrate $[Ca(NO_3)_2]$ is significantly more soluble (1290 g/L water @ 20 °C) than potassium nitrate (KNO₃) (209 g/L of water @ 20 °C) (<http://www.smart-fertilizer.com/articles/fertilizer-solubility>). Soil temperature is important because temperature influences solubility; nutrients are more soluble when the soil temperature is warmer than when it is colder. The solubility of $Ca(NO_3)_2$ is reduced to 1130 g/L of water @ 10 °C; the solubility of KNO₂ is 170 g/L at this temperature. Soil temperature is also important because it influences root activity. Nutrients are taken up by carrier proteins located in the plasma membrane of the cells of the root. The metabolic process of nutrient uptake, like all other metabolic processes, is faster at warm temperatures than cool temperatures. Too much water can also reduce nutrient uptake. When water is in excess, it fills the air spaces of the soil, displacing oxygen required by roots for

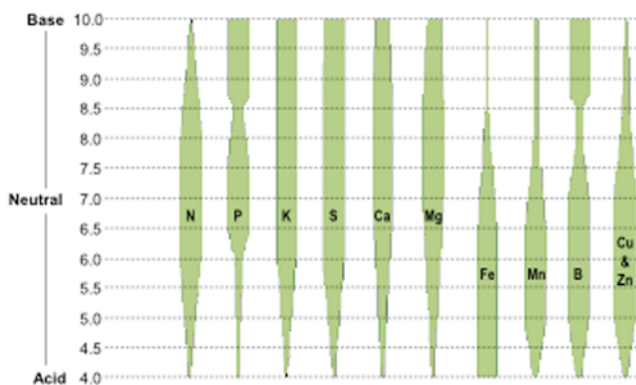


Figure 1. Effect of soil pH on nutrients availability. Maximum availability is indicated by the widest part of the green bar.

energy production by respiration. Soil pH is well known for its effects on the availability of nutrients for root uptake (Fig. 1). Soil pH also influences the composition of microflora (bacteria, fungi, etc), in the soil, which can have both negative and positive effects on the concentrations of nutrients in the rhizosphere available for root uptake. The bacterial conversion of ammonium to nitrate is reduced in acid soils, but increased in soils with a high pH. Mycorrhizal fungi colonize avocado

roots and increase the uptake of P, Zn and Fe (Violi, 2005); soil pH influences the degree of root colonization by mycorrhizal fungi (van Aarle, 2002). The optimum soil pH for 'Hass' avocado roots is between 6.0 and 6.5. Salinity reduces nutrient uptake by roots in several ways, including (i) competition by sodium (Na^+) and chloride (Cl^-) with several essential nutrient ions leading to deficiencies and (ii) an increased expenditure of energy by the tree to maintain water and nutrient homeostasis under osmotic stress. Na^+ competes with K^+ for uptake by both the low- and high-affinity K uptake proteins (Zhu, 2007). Na^+ also competes with K^+ , Ca^{++} , and other cations as they move through nonspecific channels into root cells (Horie and Schroeder, 2004). Cl^- , at the concentrations present under saline conditions, is known to compete with NO_3^- and reduce its uptake (Xu et al., 2000). There is evidence to support both a direct and indirect effect of Cl^- on the N uptake protein and to justify increasing nitrate fertilization as a successful strategy for reducing Cl^- uptake and toxicity of crop plants (Xu et al., 2000), including avocado (Bar et al., 1992). Crop load is an important factor driving the uptake of N, P, K and several other nutrients in avocado; the greater the number of fruit, the greater the uptake and availability of nutrients to other parts of the avocado tree in addition to the fruit (Rosecrance et al., 2012).

The many factors that influence the uptake of soil applied nutrients make it difficult to predict when a nutrient is taken up and how much is taken up over a given period of time. Moreover, the amount of fertilizer being leached past the root zone with each irrigation or rain event is unknown. Thus, with soil fertilization, it can be difficult to know if the tree's nutritional needs are being met during periods of high nutrient demand in the phenology of the tree, especially when periods of high nutrient demand occur when existing soil conditions could compromise nutrient uptake by the roots.

Foliar nutrition. Foliar fertilization is a rapid and efficient method for providing essential mineral nutrients directly to the leaves, where the tree's photosynthetic and metabolic machinery are housed, to overcome the soil's inability to release nutrients to the roots or the roots' inability to take up nutrients and thus, ensure that the tree's physiology and productivity are not compromised. Foliar-applied fertilizers also provide many well-known benefits to the environment. Foliar fertilization reduces nutrient accumulation in the soil, run-off water, surface waters (streams, lakes and oceans) and in the groundwater (our drink-

ing water supply) where they can contribute to eutrophication, salinity and nitrate contamination, which are deleterious to human health and the environment. California avocado growers have always been good stewards of the land. They should, thus, strive to replace soil-applied fertilizers, at least in part, with foliar-applied fertilizers in avocado best management practices (BMPs).

Just as there are problems associated with soil fertilization, there are also problems with foliar fertilization. Some nutrients are taken up more quickly by leaves than others (Table 3). The rates of leaf nutrient uptake reported in

Table 3. Nutrient absorption rates by leaves.

Nutrient	Time for 50% absorption
Urea-nitrogen	½-2 hours
Magnesium	2-5 hours
Potassium	10-24 hours
Calcium	1-2 days
Manganese	1-2 days
Zinc	1-2 days
Phosphorus	5-10 days
Iron	10-20 days
Molybdenum	10-20 days

Source: PureGro (n.d.).

(Table 3) are different for different plant species. Further, the environment in which a plant is growing can influence the rate of nutrient uptake by leaves. For example, mature leaves of ‘Hass’ avocado trees growing in California do not take up foliar-applied urea; uptake is only possible when leaves are less than 2/3-expanded (Nevin et al., 1990). In contrast, mature leaves of ‘Hass’ avocado trees growing in Israel were able to take up foliar-applied urea and studies with N15-labeled urea confirmed that urea, or its metabolites, was transported to the flowers of inflorescences

Table 4. Nutrient mobility in the phloem.

Mobile	Partially Mobile
Urea-nitrogen	Zinc
Phosphorus	Iron
Potassium	Manganese
Chlorine	Molybdenum
Sulfur	Boron
Immobile	
Calcium	

Source: PureGro (n.d.).

(the living transport tissue in plants) from the leaves, to which they are applied, to other leaves, flowers, and fruit in the canopy, and even

and to developing fruit (Zilka et al., 1987). Even if taken up, not all nutrients are phloem mobile (Table 4). Foliar-application of phloem mobile nutrients have the desirable benefit that they are transported in the phloem

to the smallest feeder roots of the tree to prevent nutrient deficiencies throughout the tree. In comparison, foliar-application of nutrients that are not phloem mobile is less efficacious because the nutrient remains in the tissues to which it is applied. Thus, nutrient deficiencies would be prevented or corrected in these tissues only. The efficacy of foliar fertilization, just like soil fertilization, can be improved by using fertilizer formulations with greater solubility. In addition, wetting agents can be included in the spray solution to reduce the surface tension of aqueous fertilizer spray droplets causing them to spread out over a greater portion of the cuticle, the thick waxy layer that covers the outer surface of the leaves and other aerial parts of the plant to prevent water loss. Reducing the surface tension of the aqueous fertilizer spray droplets increases the probability that the fertilizer solution will come in contact with water-filled channels and hydrophylic regions of the cuticle, through which nutrients dissolved in water move into a leaf or other tissue. Applying foliar fertilizers to leaves when they are 1/2 to 2/3 expanded increases nutrient uptake since at this stage of leaf development, the cuticle is not fully formed and the surface area of the leaf is sufficient for adequate nutrient uptake to obtain a physiological response. Targeting foliar fertilizers to organs other than leaves, e.g., buds, inflorescences, flowers or young fruit, is an effective approach for getting a nutrient where it is needed and when it is needed to increase fruit set, yield and fruit size or improve fruit quality. Calcium, which is immobile in the phloem and moves from the roots to the canopy of the tree via the transpiration stream (xylem transport tissue), should be applied in small amounts repeatedly via irrigation or to the soil simultaneously with irrigation. Under California growing conditions, only young developing 'Hass' avocado fruit import Ca (April-October) (Rosecrance et al., 2012). Thus, an adequate supply of Ca needs to be available during this period.

An additional benefit of foliar fertilization being increasingly documented in many plant species is the enhanced uptake of nutrients from the soil in response to foliar fertilization (E. Hard, CDEA-FREP, personal communication). Examples can be found for 'Hass' avocado. Low-biuret urea, urea plus monopotassium phosphate or monopotassium phosphate plus boron applied at the cauliflower stage of inflorescence development significantly increased the Ca concentration in leaves collected for standard leaf analysis in September in the last 2 years of a 3-year experiment (Lovatt, unpublished). For pistachio, foliar applica-

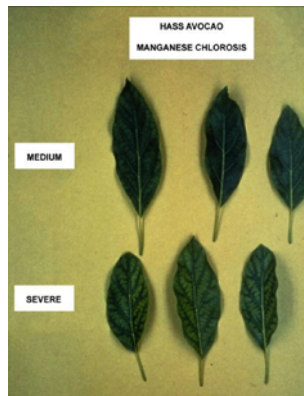
tions of low-biuret urea or urea plus boron made at bud swell significantly increased the Zn concentration of buds 19 days after application in both years of the 2-year experiment. At the conclusion of a 3-year mandarin experiment, low-biuret urea applied in January or July had significantly increased leaf P concentrations by standard leaf analysis compared to control trees receiving only soil-applied urea fertilizer. Urea plus potassium phosphite applied to hardened mandarin foliage in November or December or in April at 2/3-leaf expansion not only increased leaf P concentrations, but also leaf S concentrations by standard leaf analysis. Foliar application of boron at 10% anthesis in the southwest tree quadrant increased mandarin leaf K, Zn and Cu by standard leaf analysis. Taken together, these data support the claim that foliar-applied fertilizers enhance uptake of nutrients from the soil. However, because collection of such data is in its early stages, the broader significance of this phenomenon must await further research.

In developing a foliar fertilization program, target tissues should be covered just prior to the nutrient spray application and uncovered once the spray has dried. A false impression of successful uptake is frequently obtained when leaves, or other tissues, are not covered during application and poorly washed prior to nutrient analysis. Some foliar-applied ions, such as Zn, Fe and Cu, can only be completely removed from the wax of the cuticle with an acid wash. Target tissues should be collected and analyzed multiple times after treatment. For example B, a partially phloem-mobile nutrient, applied to pistachio trees at bud break was undetectable in bud tissue covered during application and collected 8 days after application, but bud tissue collected 19 days after the foliar fertilizer application had a significantly greater B concentration than buds of untreated control trees (Lovatt and Beede, 2013). Zn, also only partially phloem mobile, applied to pistachio trees when leaves were 2/3 expanded was not detected in leaves that had been covered during application and then collected 7 or 21 days after application. However, six months after application, these leaves had significantly greater Zn concentrations than leaves of untreated control trees.

The classic reason for applying a foliar fertilizer is to rapidly correct a nutrient deficiency when: (i) nutrient deficiency symptoms are visible (Fig. 2); (ii) tissue analysis indicates a nutrient concentration that is at the low end of the optimal range or in the deficient range; or (iii) soil analysis indicates a problem that compromises nutrient availability



Nitrogen sufficient (left) and deficient (right) avocado leaves.



Manganese deficient avocado leaves, moderate (upper) and severe (lower).



Iron sufficient and progressively slight, moderate and severe deficiency upper to low row, respectively.



Severe phosphorus deficiency of mature avocado leaves induced by low soil pH (4.0); no aluminum or manganese toxicity. P deficiency is rare in avocado trees in California. T.W. Embleton commented that he saw it only once!



Zinc deficient (left) and sufficient (right) avocado leaves.



Copper deficient (upper) and sufficient (lower) avocado shoots.

Figure 2. Symptoms of several avocado nutrient deficiencies. Source: T.W. Embleton (n.d.).

and uptake by roots. Foliar fertilization is a rapid and efficient way to improve crop nutrient status during periods of high nutrient demand in the phenology of a tree crop, or when soil conditions (cold wet soils in spring, hot dry soils in summer, salinity, pH) during the growing season render soil nutrients and hence soil-applied fertilizers less available to the tree. Foliar fertilization provides the nutrients required for photosynthesis and other important metabolic functions to prevent restrictions in carbon fixation, metabolism and plant productivity. Even a transient or incipient deficiency, needs to be corrected quickly. The longer the tree's nutrient status remains at the low end or below the optimal range at key stages of tree phenology, the greater the negative effects on yield, fruit size, fruit quality and next year's bloom.

Concept of the limiting factor

Agronomic and horticultural crops can only yield to the level supported by the most limiting factor. This is known as “Leibig’s law of the minimum” after Justus von Liebig. In 1862, Liebig observed that the factor affecting growth the most tends to limit growth independent of the other factors. For example, if all nutrients are available to a tree at optimal levels except nutrient X, which is available at half the optimal rate and at this rate X is known to reduce yield by 60%, the tree will produce only 40% of the yield produced by a tree with all nutrients available at optimal levels. In this scenario, nutrient X is the limiting factor (Fig. 3). Each of the 17 essential nutrients has the potential to be a limiting factor. In a situation where there are multiple limiting factors, the most limiting factor sets the upper limit for yield. When this factor is brought to an optimal level, yield increases to the degree permitted by the next limiting factor.

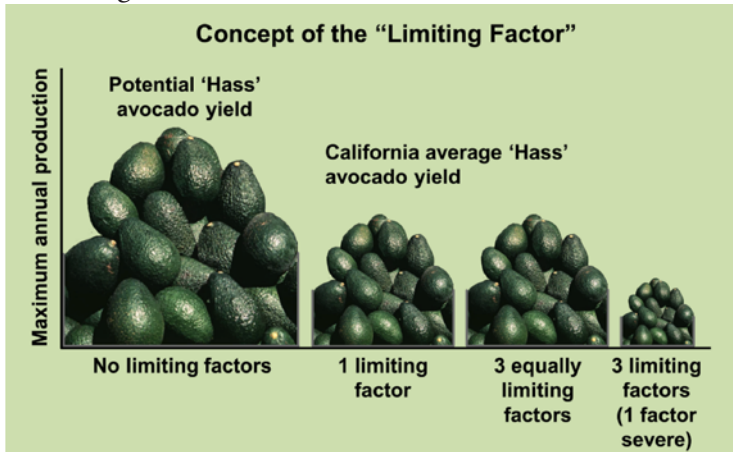


Figure 3. Illustration of Von Liebig’s “Law of the Limiting Factor”.

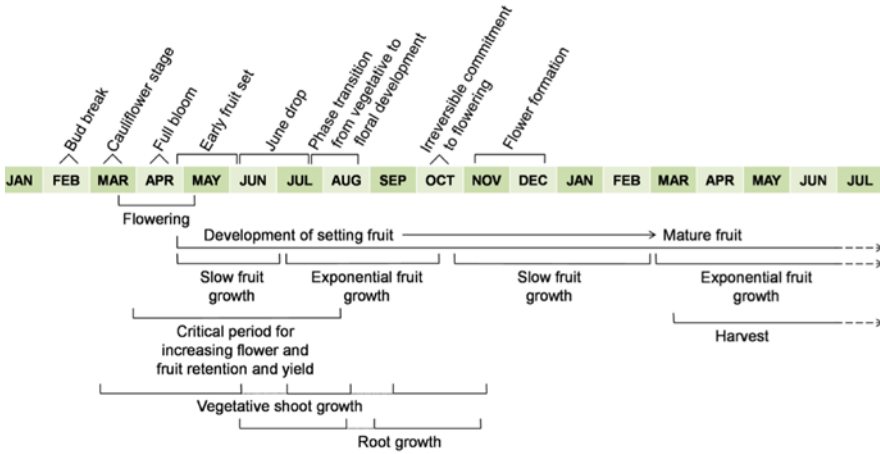


Figure 4. Phenology of the ‘Hass’ avocado tree in Riverside County.†

It is important to recognize that different developmental stages in the phenology of the avocado tree (e.g., flowering, fruit set, June drop, exponential fruit growth, vegetative shoot growth, and root growth) have greater or lesser demands for essential nutrients. Nutrients must be available at each stage of the tree’s phenology at levels sufficient to meet the specific demands of that stage. Thus, a goal of the author’s research program has been to identify the role that the essential nutrient elements play in the physiology of the avocado tree and then to apply the nutrient as a fertilizer to the canopy or to the soil at the appropriate time in the phenology of the tree, i.e., a time when the demand for the nutrient is likely to be high, in order to stimulate a specific physiological process (Lovatt, 1999, 2013). The seasonal cycle of flowering, fruit set and fruit development for the ‘Hass’ avocado in California is depicted chronologically in (Fig. 4). Early fruit set 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. Summer vegetative shoot growth is the most important stage for influencing the intensity of next year’s bloom. Summer vegetative shoots contribute the majority of the inflorescences at spring bloom. In addition, ‘Hass’ avocado trees transition from vegetative to reproductive growth (phase transition) at approximately the end of July through August and into early September (Salazar-García et al., 1998).

In California, avocado flowering and fruit set, periods of high nutrient demand, occur in some years when soil temperatures are low.

Soil temperatures are generally ≤ 15 °C (59 °F) from January to April in avocado growing areas of California (extrapolated from 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. As discussed above, the ability of the roots of ‘Hass’ avocado trees to utilize nutrients applied to the soil is dependent on many factors, i.e., soil temperature, soil moisture, soil pH, salinity, and rhizosphere microflora. With increased use of sprinkler, drip or micro-jet irrigation systems, there is a growing trend to divide the annual amount of fertilizer to be applied into six to 12 small applications. While this strategy protects the environment, it ignores tree phenology and nutrient demand. Thus, it is likely with this approach that transient periods of nutrient deficiency occur during key stages in the tree’s phenology that have a negative effect on yield, fruit size, fruit quality and return bloom.

Von Liebig’s law of the minimum has been expanded beyond optimal plant nutrition to include water, sunlight, temperature, pathogens, insects, nematodes, salinity, nutrient toxicities (over-fertilization can be as detrimental to productivity as under-fertilization), tree size and architecture, all of which have the potential to become factors limiting productivity. When yield is reduced by a limiting factor, all other factors supplied at the high rate required for maximum yield, fruit size and quality, are, in part, wasted. The goal of a well-managed orchard is for all these factors to be optimal. It makes good economic sense for growers to optimize all factors within their control, such as tree nutrient status, irrigation, pest, and canopy management. A healthy, well-balanced tree can tolerate and recover from climatic stress better than one that is not.

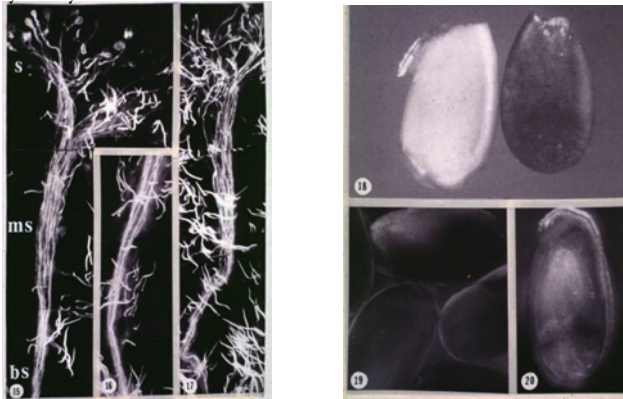
Benefit of optimally timing foliar and soil fertilizer applications to meet tree demand

Foliar nutrition. Examples of the yield benefits derived from optimally timing the application of foliar or soil fertilizers to key stages of avocado tree phenology are presented in this section. The first examples fall under the broad category of foliar fertilization, but due to the poor uptake of foliar-applied fertilizers by mature leaves of ‘Hass’ trees avocado under California-growing conditions, all of the successful foliar fertilization strategies we have developed target the cauliflower stage of inflorescence development. At the cauliflower stage, meiosis has occurred in the anther of the stamen (male reproductive structure).

Pollen grains are evident but have not completed development. At this stage, the ovule is undergoing the final stages of development leading to the formation of the egg (Salazar-García et al., 1998). This stage of floral development has proven very responsive to both foliar-applied fertilizers and plant growth regulators. A cauliflowerer stage application is made when 50% of the trees in the block have 50% of the bloom at the cauliflowerer stage, 25% will be at an earlier stage of inflorescence development and 25% will be approaching or at full bloom (open flowers).

Our first foliar fertilizer research was based on the well-established role of B to stimulate pollen germination and pollen tube development, which are required to deliver the sperm to the egg for syngamy, the critical first step in seed and fruit development (Lovatt and Dugger, 1984; Robertse et al., 1990). Nitrogen was also included in the study based on a single report of its ability to increase ovule viability, fruit set and yield in apple (Williams, 1965). Boron (1.3-1.4 lb/acre B as sodium tetraborate; 6.3-6.8 lb/acre Solubor™ 20 Mule team Borax™, 20.5% B)

Table 5. Foliar applied boron or urea at the cauliflowerer stage of inflorescence development of the ‘Hass’ avocado increased the number of pollen tubes reaching the ovule, ovule viability and yield.



Treatment	Pollen tubes (no.) penetrating the ovule	Viable ovules (%)	3-year cumulative yield lb/110 trees/acre
Boron	2.29 a ^z	81 a	58686 ^y
Urea	1.48 b	88 a	57474
Boron + Urea	2.10 a	78 a	45106
Control	0.77 c	70 b	46561

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

^y Means within a column followed by different letters are significantly different by Duncan's MRT at $P \leq 0.05$.

15 s= pollen germinating on the stigma

ms = pollen tubes growing through the mid-style

bs = pollen tubes at the base of the style

16 and 17 pollen tubes at the opening to the ovule

18 a dead ovule (left) stained with a fluorescent dye; a viable ovule (right) preventing dye uptake

19 viable ovules

20 a dying ovule partially infiltrated with fluorescent dye

Source: Jaganath, 1993; Lovatt, 1999.

and nitrogen (23-26 lb/acre N as 50-54 lb/acre low-biuret urea, 46% N, $\leq 0.25\%$ biuret) were applied at bud break, the cauliflower stage of inflorescence development, and at full bloom. Both fertilizers applied to cauliflower stage inflorescences significantly increased ovule viability and the number of pollen tubes penetrating the ovule (Table 5). There was a concomitant increase in total yield per tree in response to both the foliar-applied boron and urea fertilizer treatments that resulted in a net increase in total yield of 12, 125 and 10, 913 lb based on 110 trees/acre over the 3 years of the research, respectively (Table 5) (Jaganath and Lovatt, 1998; Lovatt, 1999).

There were no significant negative effects due to fertilizer treatment on any fruit quality parameter analyzed in any year of the experiment. The applications made at bud break were not effective, but the full bloom applications produced intermediate increases in yield and therefore applying B or urea as late as full bloom is better than not making any application at all. The spray should target the inflorescences.

Boron is more effective when applied directly to the flowers. In this research we trunk-injected trees with B. Despite the fact that we



Figure 5. Double carpel (left) and four carpels (right) of flowers of ‘Hass’ avocado trees in California (left) and Mexico (right) treated with a combined foliar-application of boron and urea. Source: Jaganath, 1993; Salazar-García, personal communication.

could increase the B concentration of the leaves to a greater degree by trunk injecting B than with the foliar spray, yield was not increased. In addition, urea is not taken up by mature leaves of avocado trees grown in California (Nevin et al., 1990) but is taken up by flowers. It is important to note that, unlike apple (Stover et al., 1999) and date palm (Khayyat et al., 2007) for which a combined bloom spray of boron plus urea increases yield, for avocado the combined treatment increases the number flowers with multiple carpels (Fig. 5). In California, this effect did not significantly reduce 3-year cumulative yield (Table 5) (Jaganath and Lovatt, 1998; Lovatt, 1999). In Mexico, the combined B and urea spray resulted in as many as four carpels per

flower (Fig. 5) and reduced yield by 2,600 lb/acre in a single year (S. Salazar-García, personal communication). Boron is preferred over urea-N due to the potential negative effects that can occur when air temperatures exceed 90 °F on the day of application. Late afternoon or early evening sprays are best; morning sprays are fine as long as the temperature remains moderate throughout the day. Boron 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. In Mexico, foliar-applied B during Stage I of fruit development when growth is predominantly by cell division (the period associated with early fruit set) at 1.9 lb/acre B in March or 1 lb/acre B in March and again in April, respectively, increased the net yield of fruit equal to or larger than fruit of packing carton size 60 by 27, 888 lbs/110 trees/acre with no increase in total yield (March) or increased total yield by 6, 062 lb/110 trees/acre and yield of fruit of packing carton size 60 or larger by 4,123 lb/100trees/acre (March + April) (Table 6) (Cossio-Vargas et al., 2009).

Table 6. Foliar-applied boron during Stage I of fruit development (fruit set) increased the yield of large size fruit (1 application) and total yield (2 applications) of the ‘Hass’ avocado in Nayarit, Mexico.

Treatment	Rate	Timing	Total yield	Fruit of packing carton sizes	
				≤ 70	≥ 60
				----- lb/110 trees/acre -----	
Boron	1.9 lb/acre	Mar	47289 ab ^z	17945 b	29343 a
Boron	1 lb/acre	Mar + Apr	50926 a	45349 a	5578 b
Control			44864 b	43409 a	1455 c

^z Means within a column followed by different letters are significantly different by Duncan’s multiple range test at $P \leq 0.05$. Calculated from Cossio-Vargas et al. (2009).

Based on earlier success targeting foliar-applied fertilizers to the cauliflower stage of inflorescence development, we compared the efficacy of a cauliflower stage foliar-application of potassium phosphate (4N-7.7P-14.9K, 0.7 lb/acre as P and 1.3 lb/acre as K) and potassium phosphite (Nutra-Phite® 0-28-26 at 0.69 gallons/acre, Verdesian Life Sciences, LLC, Cary, NC, 0N-12.2P-21.6K, 0.7 lb/acre as P and 1.25 lb/acre as K) with a control receiving soil-applied potassium phosphate (10.0 lb/acre as P and 19.1 lb/acre as K). Foliar-applied potassium phosphite at the cauliflower stage of inflorescence development significantly increased the 3-year cumulative yield of commercially valuable size fruit (packing carton sizes 60 + 48 + 40) as pounds ($P = 0.0068$) and number of fruit per tree ($P = 0.0211$), without reducing total yield. On a per acre

basis, foliar-applied potassium phosphite resulted in a net increase of 4,653 lb (9,130 fruit) and 4,268 lb (8,140 fruit) of commercially valuable size fruit/110 trees/acre over the 3 years of the research compared to foliar- and soil-applied potassium phosphate, respectively (Table 7). When averaged across the 3 years of the experiment by repeated measure analysis, foliar-applied potassium phosphite increased the yield of commercially valuable size fruit as pounds, but not number, of fruit per tree ($P = 0.070$). This provides evidence that the treatment increased fruit size, not fruit set, and that the effect was independent of the large differences in annual crop load (fruit number per tree) in the severely alternate bearing orchard [alternate bearing index (ABI) for the three consecutive crops was 0.88]. Despite the significant increase in the yield of larger size fruit, foliar-applied potassium phosphite did not significantly increase 3-year cumulative total yield as number or pounds of fruit per tree (Table 7). There were no significant effects due to fertilizer treatment on any fruit quality parameter analyzed in any year of the experiment.

Table 7. Foliar-applied potassium phosphite at the cauliflower stage of inflorescence development increased the 3-year cumulative yield of commercially valuable size fruit of the ‘Hass’ avocado compared to foliar- and soil-applied potassium phosphate.

Treatment	3-year cumulative yield			
	Total yield		Fruit of packing carton sizes 60+48+40	
	lb	no.	lb	no.
	----- 110 trees/acre -----			
Potassium phosphate	33369 a ^z	75680 a	23540 b	49280 b
Potassium phosphite	35212 a	78870 a	28193 a	58410 a
Control – soil applied potassium phosphate	32811 a	77220 a	23925 b	50270 b
<i>P</i> -value	0.5463	0.9246	0.0068	0.0211

^z Mean values within a column followed by different letters are significantly different at the *P*-value specified by Fisher’s protected least significance difference test. Source: Lovatt (2013).

In Mexico, Salazar-García (unpublished) significantly increased total yield and the yield of commercially valuable size fruit equivalent to packing carton sizes 60 + 48 with two applications of potassium phosphite (Nutra-Phite® 0-28-26, Verdesian Life Sciences, LLC, Cary, NC, 0.32-0.42 gallons/acre) at the beginning and during Stage II of fruit development (exponential fruit growth) (Table 8). One application was made in May and the second was made approximately 30 days later in June. This foliar fertilizer treatment resulted in a net increase in total yield equivalent to 11,446/110 trees/acre, a net increase in the yield of fruit equal to or larger than packing carton size 60 by 14,963 lbs/110 trees/acre, and reduced the yield of fruit smaller than packing carton size 60 by 3,516 lb/110 trees/acre.

Table 8. Foliar-applied potassium phosphite at the beginning and midway through Stage II of fruit development (May and June, respectively; June drop) increased total yield and yield of large size fruit of the ‘Hass’ avocado in Nayarit, Mexico.

Treatment	Total yield	Fruit of packing carton sizes	
		≤ 70	≥ 60
----- lb/110 trees/acre -----			
Potassium phosphite	38946 a ^z	7712 b	31235 a
Control	27500 b	11228 a	16272 b

^z Means within a column followed by different letters are significantly different by *t*-test at $P \leq 0.05$. Source: Samuel Salazar-Garcia, Nayarit, Mexico.

Soil Nutrition. Matching fertilizer rates and application times to periods of high nutrient demand by the fruit, strong canopy growth (floral and vegetative) and when roots are active and growing makes sense based on tree phenology and physiology. Under soil conditions that support nutrient uptake by the roots, application of fertilizers to the soil during periods of nutrient high demand increases fertilizer-use efficiency. This in turn, improves the benefit derived per unit of fertilizer-cost and contributes to protecting the environment by reducing nutrient accumulation in the soil and nutrient loss in the leachate or run-off. To test this hypothesis, all trees received nitrogen (N) at 125 lb/acre annually applied to the soil at the rate of 25 lb/acre N as ammonium nitrate in January, February, April, June and November. Control trees received only this amount of N fertilizer, whereas separate sets of trees received an extra 25 lb/acre N in January, February, April, June or November, respectively. Extra N was applied in November, January or February to determine the optimal time to preload the tree with N to increase flowering, flower retention, fruit set of the new crop while meeting the nutrient demand of the exponentially growing mature fruit. Extra N was applied in April to specifically test the idea that N supplied at this time would stimulate the growth of the vegetative shoot apex of indeterminate floral shoots and cause fruit abscission due to competition between the growing shoot and the setting fruit. This well-known idea was based on the discussion in a publication by Kamar and Lahav (1976) and not on actual research results. However, the idea that competition exists between the apical vegetative shoot and setting fruit of an indeterminate floral shoot is valid. Inhibiting the growth of the vegetative shoot apex of indeterminate floral shoots with paclobutrazol or by completely removing the bud increased fruit set and yield (Köhner and Kremer-Köhner, 1987) and fruit size, (Cutting and Bower, 1992). Clearly, the

degree of competition for a resource increases as the resource becomes limiting. Thus, we tested the hypothesis that supplying extra N would reduce or eliminate the competition between the vegetative shoot apex and the setting fruit and meet the nutrient demand of both organs and increase fruit retention, yield and fruit size. The June extra N application was also designed to mitigate competition between the developing fruit, shoot growth and root growth to reduce June drop. Providing extra N (total 50 lb/acre) to trees in April or November significantly increased total yield equivalent to a net increase of 16, 272 and 20, 686 lb/110 trees/acre over the 4 years of the experiment, respectively, compared to the control trees receiving only 25 lb/acre N each month (Table 9). In addition, providing extra N in April or November increased the yield of commercially valuable size fruit (packing carton sizes 60 + 48 + 40) by 16, 952 and 18, 116 lb/110 trees/acre for the 4 years of the research, respectively, compared to the control not receiving extra N. A third benefit was that the application of extra N in April reduced the severity of alternate bearing over the 4-year period.

Table 9. Matching soil-applied nitrogen fertilizer time and rates to meet ‘Hass’ avocado tree demand increased 4-year cumulative total yield and yield of commercially valuable size fruit.

Month extra N applied	4-year cumulative yield	
	Total yield	Fruit of packing carton sizes 60+48+40
	----- lb/110 trees/acre -----	
None (control)	53545 c ^z	34484 b
January	53085 c	32617 b
February	51630 c	30823 b
April	69817 ab	51436 a
June	56140 bc	36085 b
November	74231 a	52600 a
<i>P</i> -value	0.01	0.01

^z Mean values within a column followed by different letters are significantly different at the *P*-value specified by Fisher’s protected least significance difference test. Source: Lovatt (2001).

In a subsequent experiment, we demonstrated that when N is applied to the soil at multiple optimal times, a single dose of N is sufficient. Thus, trees receiving 25 lbs/acre N in April, July, August and November produced a 3-year cumulative total yield and yield of commercially valuable size fruit (packing carton sizes 60 + 48 + 40) equal to trees receiving a double dose (50 lb/acre N) in April or November. Last, we asked the question of whether yield could be increased further by supplying P and K with N to eliminate the potential that P or K were factors limiting the tree’s response to soil-applied N. Due to its

immobility in the soil P is commonly limiting. K can also be limiting in the due to its restricted mobility by adsorption onto clay particles (Hinsinger, 2006). Moreover, avocado trees have a high demand for K because avocado fruit have a high K concentration. Compare 1, 800 mg K to 1, 100 mg N to only 225 mg P per fruit (Rosecrance et al., 2012). If P or K, or other nutrient, is limiting at a key stage of ‘Hass’ tree phenology, the response to added N would be diminished. To test this possibility, trees received a single or double dose of soil-applied N (25 or 50 lb/acre, respectively) with or without P and K at 3.75 and 22.5 lb/acre, respectively. Soil applications of N (single dose) with P and K in April, July, August and November significantly reduced 3-year cumulative total yield and yield of commercially valuable size fruit of packing carton sizes 60 + 48 + 40 compared to supplying trees with only N at these times (Table 10). Supplying P and K with a double dose of N in April or November had a negative, but nonsignificant effect on yield and fruit size compared to providing only N. In contrast, supplying P and K (3.75 and 22.5 lb/acre, respectively) with N (25 lb/acre) in July and again in August had positive effect on yield and fruit size compared to trees receiving only N. Comparison of the yield results for all soil-applied NPK treatments readily identifies July and August as a beneficial time to apply P and K.

Table 10. Matching soil-applied nitrogen, phosphorus and potassium fertilizer time and rates to meet ‘Hass’ avocado tree demand increased 4-year cumulative total yield with no reduction in yield of commercially valuable size fruit.

Month N or NPK applied	3-year cumulative yield	
	Total yield	Fruit of packing carton sizes 60+48+40
	----- lb/110 trees/acre -----	
1xNPK April +July + August + November	23445 c ^z	15860 c
1xN April +July + August + November	32316 ab	21697 ab
2xN + 1xPK April	26714 bc	19141 abc
2xN April	30931 ab	22087 a
1xNPK July + August	33608 a	22475 a
1xN July + August	28077 abc	19481 abc
2xN 1xPK November	24032 c	19613 abc
2xN November	26339 bc	16988 bc
P-value	0.0035	0.0109

^z Mean values within a column followed by different letters are significantly different at the P-value specified by Fisher’s protected least significance difference test.

Developing a fertilization program that supports your production goals

Several principles will assist in developing a fertilization program to support your production goals. The first two principles are discussed

without the added complication of alternate bearing, which is discussed further below. **Principle 1:** It is critical that your fertilization program include plans for three crop years: the current crop (Year 1), the next crop (Year 2) and the following crop (Year 3) (Fig. 6). For example, if we start in January of Year 2, the Year 1 mature crop will enter a period of exponential fruit growth at the end of February-beginning of March, which continues through harvest. During this period the potential for preharvest fruit drop increases; meeting the nutrient needs of the Year 1 crop is important to increase fruit size and to reduce fruit drop. In addition, February is when bud break for the Year 2 spring bloom occurs. Flowering is a period of high nutrient demand. Adequate nutrition is essential to support inflorescence development, including the growth of the vegetative shoot apex of indeterminate floral shoots, for flower retention, fruit set and fruit retention of the Year 2 crop and also to support the development of the Year 2 spring vegetative shoots, which will contribute inflorescences at spring bloom in Year 3. Although decisions about the intensity of the up-coming Year 2 spring bloom were actually made the previous summer, adequate fertilization will increase the number of fruit set by the existing flowers, improve fruit size, and reduce alternate bearing by increasing spring vegetative shoot growth (Table 5) (Jaganath and Lovatt, 1998; Lovatt, 1999) and (Table 9) (Lovatt, 2001).

The number of inflorescences at spring bloom is determined by the amount of spring and summer vegetative shoot growth that occurred the previous year. Each node (point of leaf attachment to the shoot) along a shoot bears a bud in the axil of the leaf. At the end of July-beginning of August through September, a proportion of these buds transition from vegetative buds to floral buds, a developmental process called

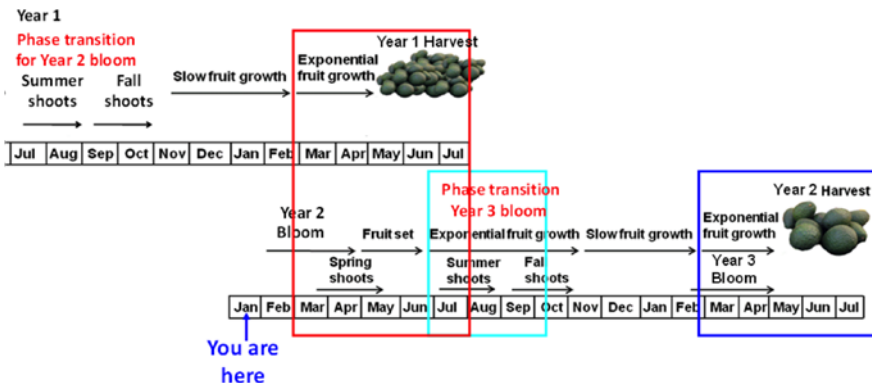


Figure 6. Periods of high nutrient demand of the ‘Hass’ avocado.†

phase transition. In a strong bloom, the previous year's spring shoots contribute ~30% of the inflorescences, summer shoots, ~60%, and fall shoots, 0%-10%. Thus, fertilization during the spring and summer will influence the floral intensity of the following year's spring bloom, fruit set and yield. In addition, adequate fertilization through summer is essential to support exponential fruit growth of the setting crop to attain commercially valuable fruit size.

By the end of October-early November, all the buds that are going to be floral are committed to floral development. In November individual flowers start to develop at the base of the inflorescence; development of flowers within an avocado inflorescence progresses from base to apex. At the cauliflower stage of inflorescence development (~March), critical final steps in the development of the pollen in the male reproductive structure (stamen) and egg in the female reproduction structure (carpel) are occurring. To provide nutrients for these stages of development, trees can be fertilized in fall, as late as is deemed safe to prevent growth of a late vegetative shoot flush that would be sensitive to frost damage, to preload the trees for floral development and bloom. Alternatively, foliar fertilizers as discussed above can be used when spring soil conditions compromise nutrient uptake to increase yield (Table 5) or fruit size (Table 7).

Principle 2: Fertilize to meet tree demand. Keep your production goals in mind throughout the year and modify them as required. Fertilize the mature crop on the tree (Year 1), flowering, fruit set and fruit development of the next crop (Year 2), and the spring and summer vegetative shoot flushes for the following crop (Year 3) (Fig. 6). The pattern of accumulation of a specific nutrient during the development of individual fruit identified the periods of high crop nutrient demand, when fertilizer applications should be made, and how the annual amount of fertilizer for a given crop year should be divided for application (Rosecrance et al., 2012). For example, the accumulation of N by developing fruit increased steadily from April through the end of October (500 mg N/fruit), with ~300 mg N/fruit taken up during the period of exponential fruit growth from July to October (Fig. 7). During the second period of exponential fruit growth the following spring, the fruit, which are nearly mature, took up an additional 500 mg N/fruit from April through June. A pattern of nutrient uptake similar to N was identified for P, Mg, S, Fe and Zn. Thus, 1/2 of the total annual amount of each of these nutrients should be applied from spring through autumn for the

setting fruit and 1/2 from spring through summer the following year to support the growth of the now mature fruit. The uptake of K by young developing fruit was similar to N; 600 mg K/fruit was taken up from April to October, with 400 mg/fruit during the first period of exponential fruit growth (July to October) (Fig. 7). However, during the second period of exponential fruit growth the following spring, the nearly mature fruit took up 2-fold more K (1200 mg/fruit) than young developing fruit. The results of this research confirmed that avocado trees in California require more K than N, almost 1.8-fold more and demonstrated that the greater ratio of K to N was required during exponential growth of the mature fruit. The uptake pattern of B was similar to that of K, with the mature fruit exhibiting greater B accumulation than the young developing fruit. Thus, 1/3 of the total annual amount of K and B fertilizer for a given crop year should be applied to support the growth of the young developing fruit (April-October) and 2/3 to support the growth of the mature fruit from April through June. The uptake pattern of Ca is also of interest (Fig. 7). Only young developing fruit accumulated Ca. Thus, for good fruit quality, the Ca requirements of the fruit must be met during early development (April-October).

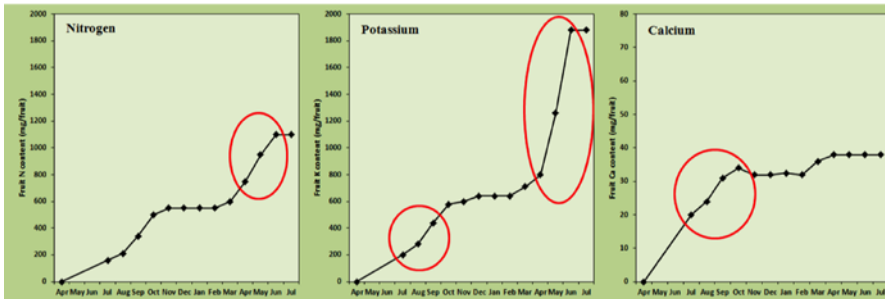


Figure 7. Pattern of N, K and Ca uptake by individual 'Hass' avocado fruit. Source: Rosecrance et al., 2012.

Leaf analyses done annually (because it is easier to correct an incipient deficiency than a severe deficiency) and soil analyses performed every 2 to 4 years (unless the results of the leaf analyses indicate a problem), and estimates of the current mature crop and young developing crop should be used to calculate the total annual amount of fertilizer to be applied. At a minimum the amount of each nutrient that the fruit will remove from the soil by harvest should be supplied to that crop during its development. Nutrient removal values in the literature (Avilan et al., 1979; Dirou and Huett, 2001; Lahav and Kadman, 1980; Rosecrance

et al., 2012; Salazar-Garcia, and Lazcano-Ferrat, 2001; Lovatt and Whitney, 2001) or generated with the “Total Nutrient Removal Calculator” (Hofshi and Hofshi, 2003) are valuable resources.

Principle 3: Use your fertilization program to manage alternate bearing. Alternate bearing in an orchard dictates that adjustments be made to avoid under-fertilizing on-crop trees or over-fertilizing off-crop trees. This will avoid exacerbating the severity of alternate bearing. Since the amounts of N and K fertilizer used are large relative to other nutrients, their application should be well planned to ensure the desired outcome is achieved. The nutrient demand of the setting on-crop should be met from bloom through the first period of exponential fruit growth (April-October) in order to increase fruit size and also to support the development of spring and summer vegetative shoots, which will bear next spring’s inflorescences, to mitigate alternate bearing. N fertilizer is an especially valuable tool for achieving this goal. Nitrate and ammonium increase the expression of the key gene regulating cytokinin (CK) biosynthesis in both roots and leaves (Sakakibara, 2006). Moreover, N and CK transport from roots to shoots are coordinated to support shoot growth. The following year, the nutrient demand of the mature on-crop must be met simultaneously with the nutrient demands of spring bloom and fruit set of the next crop to avoid further reducing the crop set by the off-bloom. Foliar-applied B can be used increase the number of fruit set. Harvest an on-crop of mature fruit earlier rather than later so that it does not inhibit spring and summer vegetative shoot growth for a second year and cause back-to-back off-crop years (Lovatt, 2011). In addition, harvesting the mature on-crop before summer (earlier is better) will save money since the on-crop no longer requires fertilization and will make managing the off-crop year easier. Removal of the on-crop before summer will increase summer vegetative shoot growth when the setting crop is an off-crop. Less fertilizer, especially N, should be used in order to reduce the intensity of this flush and the following on-bloom to even out alternate bearing. In addition, due to the setting light crop, less fertilizer is needed to support exponential fruit growth.

Status of avocado nutrition research in California

Efforts of California avocado growers to optimize the nutrient status of ‘Hass’ avocado trees continue to be compromised by the lack of a reliable diagnostic tool. Specifically, for the ‘Hass’ avocado in

California, experiments to determine the optimal leaf nutrient concentrations for maximum yield have been conducted for only N (Arpaia et al., 1996; Embleton et al., 1968; Embleton and Jones, 1972; Lovatt, 2001, 2006; Lovatt and Witney, 2001; Lovatt et al., 2009; Salvo, 2005), Zn and Fe (Crowley, 1992; Crowley and Smith, 1996; Crowley et al., 2001). Eight studies to determine optimal N fertilization of the 'Hass' avocado have been completed. Alarming, each experiment provided clear evidence that leaf N concentration was not related to yield and likely not to fruit size. Nitrogen fertilization had an inconsistent effect on fruit size (Arpaia et al., 1996; Lovatt 2006; Lovatt et al., 2009). The results suggest that a factor other than N is the determinant of total yield, fruit size and grower income.

Failure of leaf nutrient concentrations to correlate with avocado yield is not limited to N (Lovatt et al., 2009). The time when soil P and K fertilizer was applied influenced yield and fruit size in a manner unrelated to leaf concentrations of either nutrient (Lovatt, 2006). Jaganath and Lovatt (1998) demonstrated that foliar-applied B increased yield compared to untreated control trees despite the fact that all trees had leaf B concentrations considered optimal by current standards. Further, trees injected with B had greater leaf concentrations of B than those sprayed with B, but yield was not increased. Yield of large size fruit is increasingly critical to grower net profit. The California avocado industry desperately needs a diagnostic tool that relates tree nutrient status to the yield of commercially valuable size fruit. Avocado fruit are strong sinks for not only N, but also K (Rosecrance et al., 2012). The optimal leaf concentration ranges for this important nutrient and all other essential nutrients are not known for the 'Hass' avocado. Since the optimal ranges for most nutrients are not known, current ranges for N, Zn and Fe are likely inaccurate, since they were determined under conditions where the availability of one or more of the other essential nutrients might have been limiting production.

Preferred ranges for nutrients, other than N, Fe and Zn, were borrowed from citrus and although modified over the years, they are not related to any avocado yield parameter. Moreover, it should be noted that modifications made to the ranges prescribed as optimal by various testing laboratories were based on their experience with local growers. As a result, the leaf nutrient concentration ranges now prescribed as optimal by various analytical laboratories are different! Last, avocado leaf analyses were developed to guide replacement fertilization for the next

year's crop. With the increased incidence of alternate bearing, careful management is required to prevent under-fertilization of on-crop trees and over-fertilization of off-crop trees!

Future prospects

Presently, researchers at the University of California, Riverside, are using a combination of statistical analyses to “mine” a comprehensive data set that includes: total yield, yield for individual packing carton size categories (84, 70, 60, 48, 40, 36, 32), and fruit quality for more than 700 trees, for which there are industry standard leaf analyses for each tree. These data sets in some cases are for only 1 year per orchard, but in most cases include more than 2 years up to 10 years and more than 15 orchards in the Irvine, Pauma Valley, Rancho California, Fillmore, Somis, Santa Paula, Carpinteria, Santa Barbara and San Luis Obispo growing areas, enabling us to determine the degree to which tree nutrient status, climate and/or soil factors influence ‘Hass’ avocado total yield, yield of commercially valuable size fruit and fruit quality. The project's objectives are: (1) to identify predictors for yield, fruit size and fruit quality parameters, especially yield of commercially valuable size fruit of the ‘Hass’ avocado, among leaf nutrient concentrations (N, P, K, CA, S, Mg, Fe, Zn, Mn, B, Cu), climate (max. and min. temperatures and precipitation), and/or soil factors (soil composition, e.g., percent clay; excess boron) that are effective across large growing areas, varying irrigation water quality, rootstocks, and cultural practices; and (2) to provide growers with a tool to optimize tree nutrient status to increase the yield of commercially valuable size fruit of high quality and their income.

As part of this project, a smaller data set that not only includes total yield, yield for individual packing carton size categories, fruit quality and leaf nutrient concentrations but also nutrient concentrations for cauliflower and full bloom inflorescences, pedicels (stems) from fruit at different stages of development for trees in orchards in Pauma Valley, Somis, Santa Paula, Carpinteria, Santa Barbara and San Luis Obispo for two crop years is being analyzed. The objective is to identify the best tissue and nutrients that predict yield parameters with the goal of being able to identify nutritional problems sufficiently early in the season that corrective fertilization actions can be taken that will result in increased yield and/or fruit size and improved fruit quality. An additional goal,

which will require further research, is to be able to confirm that successful changes in tree nutrient status were achieved as a result of corrective fertilization through nutrient analysis of leaves or pedicels sampled at a later time.

We are all in this together

In this day of social networking, it is hoped that growers will share the outcomes obtained with changes in their fertilization management. The outcomes of the data “mining” efforts described above will benefit from additional field-testing. While the data sets being used represent a broad range of producing areas in the State, they are not exhaustive. Grower experience is invaluable and it might prove to be the best means to gain knowledge that adequately reflects the differences in yield potential under the various growing conditions and management practices used in avocado production in California.

† Phenological stages are provided when possible to assist growers in understanding the timing of developmental events independent of the effects of local climates. Months, typically provided in parentheses, are approximations of when phenological events occur but unfortunately are not applicable to all avocado-growing areas of the state of California.

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Literature Cited.

- Arpaia, M.L., J.L. Meyer, G.W. Witney, G.S. Bender, D.S. Stottlemeyer, and P.R. Robinson. 1996. The Cashin Creek nitrogen fertilization trial — What did we learn? Calif. Avocado Soc. Yrbk. 80:85-98.
- Avilan, R.L., A. Chirinos and M. Figueroa. 1979. Quantification of some minerals extracted from the soil by an avocado crop. Proc. Of the Trop. Region Amer. Soc. Hort. Sci. 27:108-113.
- Bar, Y., U. Kafkafi, and E. Lahav. 1992. Reducing chloride toxicity in avocado by nitrate. In: Lovatt, C.J. (Ed.), Proc. II World Avocado Congress, Orange, CA. April 21–26, 1991, p. 373.
- Cossio-Vargas, L.E., S.Salazar-García, and I.J.L. González-Durán. 2009. Respuesta del aguacate ‘Hass’ a la fertilización con boro en huertos sin riego. III Congreso Latinoamericano del Aguacate. Medellín, Colombia. 11-13 de Noviembre. Memorias, p.4-17.
- Crowley, D.E. 1992. Soil fertility and the mineral nutrition of avocado: the physical, chemical, and biological properties of soil and their importance in the culture of avocado. California Avocado Development Organization and The California Avocado Society, Circular No. CAS-92/1. 26p.
- Crowley, D.E. and W. Smith. 1996. Zinc fertilization of avocado trees. HortScience 31:224-229.
- Crowley, D.E., W. Smith, B. Faber, and M.L. Arpaia. 2001. Trace metal nutrition of avocado. AvoResearch 1(3):5-7, 12.
- Cutting, J.G.M. and J.P. Bower 1992. The effect of vegetative pruning on fruit mineral composition and postharvest quality in ‘Hass’ avocado. In: Lovatt, C.J. (Ed.), Proc. II World Avocado Congress, Orange, CA. April 21–26, 1991, p. 403-407.
- Dirou, J. and D. Huett. 2001. Crop nutrient replacement for avocado. Talking avocados 12:25-27.
- Embleton, T.W. and W.W. Jones. 1972. Development of nitrogen fertilizer programs for California avocados. Calif. Avocado Soc. Yrbk. 56:90-96.
- Embleton, T.W., W.W. Jones, M.J. Garber, and S.B. Boswell. 1968. Nitrogen fertilization of the Hass avocado. Calif. Avocado Soc. Yrbk. 52:131-134.

- Hamid, G.A., S.D. Van Gundy, and C.J. Lovatt. 1988. Phenologies of the citrus nematode and citrus roots treated with oxamyl. *Proc. 6th Int. Citrus. Congr.* 2:993-1004.
- Hinsinger, P. 2006. Potassium. In: Lal, R. (Ed.), *Encyclopedia of Soil Science*. Taylor and Decker Group, LLC, New York. 1354-1358.
- Hofshi, R. and S. Hofshi. (2003). Total nutrient removal calculator. <http://www.avocadosource.com/tools/NutRemCalc.htm>.
- Horie, T. and J.I. Schroeder. 2004. Sodium transporters in plants: Diverse genes and physiological functions. *Plant Physiol.* 136(1): 2457–2462.
- Jaganath, I. 1993. Effect of boron and/or nitrogen on pollen tube growth, ovule viability and yield in ‘Hass’ avocado. Univ. Calif., Riverside, MS Thesis.
- Jaganath, I. and C.J. Lovatt. 1998. Efficacy studies on prebloom canopy applications of boron and/or urea to ‘Hass’ avocado. *Acta Hort.* 1:181-184.
- Kalmar, D. and E. Lahav. 1976. Water requirement of the avocado tree in the Western Galilee (1968-1074). Pamphlet 157. Div. Sci. Publ., Bet Dagan, Israel.
- Khayyat, M., E. Tafazoli, S. Eshghi, and S. Rajaei. 2007. Effect of nitrogen, boron, potassium and zinc sprays on yield and fruit quality of date palm. *American-Eurasian J. Agr. and Environ. Sci.* 2:289-296.
- Köhne, J.S. and S. Kremer-Köhne. 1987. Vegetative growth and fruit retention in avocado as affected by a new plant growth regulator (Paclobutrazol). *South African Avocado Growers’ Assoc. Yrbk* 10:64-66.
- Lahav, E., and A. Kadman. 1980. Avocado fertilization. *Bull. Intern. Potash Inst. No. 6* Worblaufen-Bern, Switzerland.
- Lovatt, C. J. 2010. Alternate bearing of ‘Hass’ avocado. *Calif. Avocado Soc Yrbk.* 93:125-140.
- Lovatt, C.J. 1999. Timing citrus and avocado foliar nutrient applications to increase fruit set and size. *HortTechnology* 9:607-612.
- Lovatt, C.J. 2001. Properly timed soil-applied nitrogen fertilizer increases yield of ‘Hass’ avocado. *J. Am. Soc. Hort. Sci.* 126:555-559.

- Lovatt, C.J. 2006. Increasing yield of 'Hass' avocado by adding P and K to properly timed soil N applications. Proc. 14th Annual California Department of Food and Agriculture Fertilizer Research & Education Program Conference. November 29, 2006, Monterey, California pp.35-44. http://www.cdfa.ca.gov/is/fldr/frep/FREP_Conference_Proceedings.html.
- Lovatt, C.J. 2013. Properly timing foliar-applied fertilizers increases efficacy: A review and update on timing foliar nutrient applications to citrus and avocado. *HortTechnology* 23:536-541.
- Lovatt, C.J. and R. Beede. 2013. Towards development of foliar fertilization strategies for pistachio to increase total yield and nut size and protect the environment. Proc. 21st Annual California Department of Food and Agriculture Fertilizer Research & Education Program Conference. October 29-30, 2013, Modesto, California pp.29-32. http://www.cdfa.ca.gov/is/fldr/frep/FREP_Conference_Proceedings.html.
- Lovatt, C.J., R. Rosecrance, and B. Faber. 2009. Can a better tool for assessing 'Hass' avocado nutrient status be developed? Proc. 17th Annual California Department of Food and Agriculture Fertilizer Research & Education Program Conference. November 17-18, 2009, Visalia, California pp.41-45. http://www.cdfa.ca.gov/is/fldr/frep/FREP_Conference_Proceedings.html.
- Lovatt, C.J. and W.M. Dugger. 1984. Boron. In: Friedan, E. (Ed.). *The Biochemistry of the Essential UltraTrace Elements*. Plenum Publishing Corp. New York. p.389-421.
- Lovatt, C.J. and G. Witney. 2001. Nitrogen fertilization of the 'Hass' avocado in California. *AvoResearch* 1(3):1-4, 11.
- Nevin, J.M., C.J. Lovatt, and T.W. Embleton. 1990. Problems with urea-N foliar fertilization of avocado. *Acta Hort.* 2:535-541.
- PureGro Company. n.d. Soil vs. foliar. PureGro Co., Sacramento, Calif.
- Robertse, P.J., L.A. Coetzer, M. Slabbert, and J.J. Bezuidenhout. 1990. The influence of boron on fruit set in avocado. *Acta Hort.* 275:587-594.
- Rosecrance, R., B. Faber and C. Lovatt. 2012. Patterns of nutrient accumulation in 'Hass' avocado fruit. *Better Crops* 96 (11):12-13.
- Sakakibara, H. 2006. Cytokinins: Activity, biosynthesis, and translocation. *Annu. Rev. Plant Biol.* 57:431-449.

- Salazar-Garcia, S. and I. Lazcano-Ferrat. 2001. Identifying fruit mineral removal differences in four avocado cultivars. *Better Crops* 15(1):28-31.
- Salazar-Garcia, S., E.M. Lord, and C.J. Lovatt. 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.
- Salvo, J. 2005. The effect of nitrogen and plant growth regulators on sylleptic and proleptic shoot development of 'Hass' avocado (*Persea americana* Mill.) – Relationship to yield. Univ. Calif., Riverside, PhD Diss.
- Stover, E., M. Fargione, R. Risio, W. Stiles, and K. Iungerman. 1999. Prebloom foliar boron, zinc and urea applications enhance cropping of some 'Empire' and 'McIntosh' apple orchards in New York. *HortScience* 34:210.
- Taiz, L. and E. Zeiger. 2010. *Plant Physiology* (5th edition). Sinauer Assoc., Inc. Sunderland, MA.
- van Aarle, I.M., P.A. Olsson and B. Söderström. 2002. Arbuscular mycorrhizal fungi respond to the substrate pH of their extraradical mycelium by altered growth and root colonization. *New Phytol.* 155: 173–182.
- Violi, H. 2005. Interactions among root colonizing fungi and *Persea* spp. (Lauraceae): Impact on carbon allocation to plant and fungi. Univ. Calif., Riverside, PhD Diss.
- Williams, R.R. 1965. The effect of summer nitrogen applications on the quality of apple blossom. *J. Hort. Sci.* 40:31-41.
- Xu, G., H. Magen, J. Tarchitzky, and U. Kafkafi. 2000. Advances in chloride nutrition of plants. *Adv. Agron.*, 68:97–150.
- Zhu, J-K. 2007. Plant salt stress. *Encyclopedia of Life Sciences*. John Wiley & Sons, Ltd.
- Zilkah, S., I. Klein, S. Feigenbaum and S.A. Weinbaum. 1987. Translocation of foliar-applied urea 15N to reproductive and vegetative sinks of avocado and its effect on initial fruit set. *J. Amer. Soc. Hort. Sci.* 112(6):1061-1065.