BORON NUTRITION OF 'SHARWIL' AVOCADO
IN KONA, HAWAI'I

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CHAPTER 1. INTRODUCTION

A. Problem

Poor fruit set and irregular yields are frequent problems for avocado (*Persea americana*) cultivars worldwide. 'Sharwil' avocado is prone to low yields and alternate bearing in both its native Australia (Piccone & Whiley, 1987) and in Kona, the major avocado producing area in Hawai'i. Fertilization practices for avocado in Kona traditionally consist of broadcast applications of inorganic nitrogen (N) - phosphorus (P) - potassium (K) fertilizers. Usually, additions of micronutrients only occurred if growers used certain mixes supplemented with iron, zinc and manganese formulated specifically for use on coffee.

The concern for boron (B) nutrition of 'Sharwil' avocado in Kona first occurred during the 1989-90 harvest season when malformed fruits were observed (Bittenbender, 1990). The majority of fruit symptoms resembled those reported by Piccone & Whiley (1987) and Broadley et al. (1991), which were attributed to B deficiency. Apparently, 'Sharwil' is especially prone to B deficiency and used as an indicator plant to detect B deficiency in Australian orchards (Piccone & Whiley, 1987). Symptoms include indentation on one side resulting in a puckered or hook-shaped fruit, as well as surface lesions that damaged the flesh. Affected fruit is downgraded to one-half its commercial value and becomes unmarketable if the damage is severe, resulting significant economic loss to the grower in either instance.

According to Piccone & Whiley (1987), by the time fruit exhibit deformity symptoms B deficiency is severe and already limiting both plant growth and yield. Tissue analyses revealed typical foliar B levels at 20 mg kg^{-1} throughout Kona (Miyasaka et al., 1992), well below the recommended minimum level of 50 mg kg^{-1} (Embleton & Jones, 1966). Thus, it was hypothesized that B deficiency was seriously affecting yield and quality of 'Sharwil' avocado (Miyasaka et al., 1992).

Although B was identified as an essential micronutrient over sixty years ago, its principal function and mode of action within plants remain unknown (Marschner, 1986). Boron is essential during the reproductive phase of plants, when ample supply in male and female flower parts is necessary for successful fertilization and fruit set (Vasil, 1964). Plant B levels have been correlated positively with fruit- and seed- set in several species, primarily in studies of legumes (Schon & Blevins, 1990) and deciduous fruits (Hanson et al., 1985; Shrestha et al., 1987). However, there is a lack of studies concerning the effect of B on fruit set in non-deciduous subtropical fruits, including avocado (Robbertse et al., 1990).

The issue of boron requirements and recommendations is complicated by the fact that plant species and even cultivars within a given species differ remarkably in their B accumulation, their tolerance of excess B, and their sensitivity to B deficiency (Marschner, 1986). Furthermore, the narrow range of tolerance between B-deficiency and B-toxicity for many plants makes B fertilization decisions difficult (Schon & Blevins, 1990). Recent studies have compounded this problem with evidence that previous leaf B recommendations are inadequate. Results with prune

(Hanson & Breen, 1985; Callan et al., 1978) and hazelnut (Shreshtha et al., 1987) showed increases in fruit set at foliar B levels considerably higher than the range considered sufficient.

B. Significance

When this study began 'Sharwil' avocado was regarded as a crop likely to help diversify Hawai'i's agriculture due to its exceptional quality and imminent clearance for export. However, the export ban was quickly reinstated during the first year of test shipments to the U.S. mainland due to the presence of fruit fly (*Drosophila*) on drought-stressed fruit. Therefore, current export potential is not favorable and depends on development of suitable post-harvest treatments.

A greater understanding of the causes of poor fruit set and fruit deformity is important, however, and will provide immediate benefit to avocado growers in Hawai'i. 'Sharwil' avocado experiences an alternate-bearing habit, in which a "large crop" year is followed by a "small crop" year of very low yields. Boron additions that increase yield may also recover some of the yield loss in the off-year and provide a more even annual bearing. Research with hazelnut (Shrestha et al., 1987) showed foliar B sprays increased fruit set by 30% in a small crop year, compared to 19% in a large crop year.

The deformed fruit symptoms continue throughout the Kona area, though severity varies by farm and by year. Nearly 40% of a recent crop (1993-94) was downgraded due to misshapen appearance (unpublished data). If B additions can correct the fruit deformity problem, the reduced number of off-grade fruit would result in a very significant economic gain to farmers. Research that identifies a cost effective method to increase B levels will provide growers with useful production and management tools and enhance the viability of both the avocado industry and diversified agriculture in general.

C. Objectives

This on-farm study was undertaken to determine whether boron deficiency contributes to low yield and fruit malformation of 'Sharwil' avocado grown on soils low in B in Kona, Hawai'i. The specific objectives are as follows:

Trial 1 Soil Application

1. To determine the effect of soil-applied B on foliar concentration, fruit deformity and yield of 'Sharwil' avocado.
2. To determine the optimal rate of B application to maintain both high yields and good fruit quality.
3. To determine if a relationship exists between leaf B level and fruit production or fruit deformity.
4. To compare the effectiveness of Borax and Solubor fertilizers.

Trial 2 Foliar Application

1. To determine the effect of foliar bloom B-sprays on B concentration of 'Sharwil' leaves and flowers.
2. To determine the effect of B-sprays on fruit set, fruit deformity, and yield.
3. To determine if a relationship exists between flower B level and fruit set.
4. To determine the optimum B-spray concentration.

CHAPTER 2. LITERATURE REVIEW

A. Nutrition and Growth of Avocado

Avocados require careful nutritional management for optimal growth and fruit production (Piccone & Whiley, 1987). Specific nutrient requirements of avocado grown in Hawai'i are not well established, hence most of the local recommendations have been based on production from other parts of the world (Chia et al., 1988). It was noted by Lahav & Kadman (1980) that differences exist in the results of avocado fertilization research conducted in different regions. They (Lahav & Kadman, 1980) claimed that demand for mineral nutrition is greater in places where the avocado is grown on shallow, rocky soils such as those found in Kona, Hawai'i (USDA-SCS, 1973).

Fertility of Kona Soils

Avocado production in Kona occurs in unusual soils on the slopes of Mauna Loa and Hualalai. These Histosols (Tropofolists) are characterized by very shallow, well-drained organic soils underlain by either a'a or pahoehoe lava (USDA-SCS, 1973). Typical profiles consist of 5 - 20cm of dark brown or black surface soil containing loose stones. Below this thin layer is either fragmented a'a or pahoehoe bedrock. Permeability is rapid in both the soil and the fragmented a'a (50+ cm hr^{-1}) (Tamimi, 1978). The pahoehoe lava is very slowly permeable although water penetrates rapidly through the cracks. Soil profiles collected in close proximity to each other can differ markedly in their distribution of fine soil material, loose rocks, gravel-sized particles and organic matter (Tamimi, 1978).

Leaching losses of nutrients and the general fertility of several Histosols on the Big Island were studied by Tamimi (1978). He reported that the fertility status is generally low and depends largely on the amount of organic matter present. Foliar analyses for several plant species grown on these soils showed low levels of micronutrients in most samples, with boron very low in all but one (Tamimi,1978). These soils are relatively young and, therefore, lack accumulations of trace elements caused by more advanced stages of rock weathering. Nitrogen applied to the soil was found to leach very rapidly, whereas potassium (K) leached readily but at a slower rate than N. Leaching loss of phosphorous (P) was minimal.

Fertilizer Requirements

Nitrogen (N) has the greatest influence on tree growth and fruit production (Lahav & Kadman, 1980; Piccone & Whiley, 1987) and is commonly applied every year to maintain yields (Goodall et al., 1981). In Florida, avocado yields declined substantially when trees were not fertilized for several years (Lahav & Kadman, 1980). Embleton & Jones (1966) in California and Koen & du Plessis (1992) in South Africa concluded there was a significant curvilinear relationship between yield and N level in leaves. Conversely, research in Israel (Lahav & Kadman, 1980) provided no clear relationship between yield and N level in leaves. Field studies show that each cultivar has its own particular response to N fertilization (Goodall et al., 1981). For most cultivars, the suggested foliar N level is about 2.0 percent.

In general, P is applied to poor soils although P-deficiency symptoms have not been identified in avocado orchards (Embleton & Jones, 1966). Accumulation of excess P may cause or intensify zinc (Zn) deficiency symptoms (Lahav & Kadman, 1980).

Potassium fertilization is recommended in Florida (Lahav & Kadman, 1980) and other areas where the avocado is grown on soils of volcanic origin (Chia et al., 1988). There are no reports of K-deficiency in California (Embleton & Jones, 1966). Addition of K increased leaf K levels in Israel (Lahav & Kadman, 1980) and South Africa (Koen & du Plessis, 1992), however, tree growth, yield and fruit quality were all unaffected.

Zinc deficiency occurs often on avocado grown in California (Goodall et al., 1981; Chia et al., 1988) and Australia (Piccone & Whiley, 1987), thus routine Zn applications are common. Leaf Zn and iron (Fe) levels in Kona (unpublished data) are frequently below the suggested minimum of 30 mg kg^{-1} and 40 mg kg^{-1}, respectively (Goodall et al., 1981). Iron deficiency occurs only occasionally in avocado orchards in California and is difficult to correct (Goodall et al., 1981).

Growth Characteristics

Avocado trees vary in size, adaptability to climate and soil type, and season of maturity (Chia et al., 1988). The avocado is a subtropical evergreen tree which is never dormant, although its activity is reduced during the winter (Lahav & Kadman, 1980). Ploetz and co-workers (1992) reported in Florida that shoot growth virtually stopped during the late fall and winter, however, root growth continued throughout the year, but at a slower rate. In Australia, Whiley and co-workers (1988) observed that root growth completely ceased during much of the year.

The bearing avocado tree proceeds through a number of distinct growth phases over the course of the year (Piccone & Whiley, 1987). Growth response patterns are dependent on temperature and are more advanced at lower elevations where temperatures are warmer.

The three types of growth are easily distinguishable: root, shoot and reproductive (Whiley et al., 1988). Shoot and root flushes alternate and are cyclical (Ploetz et al., 1992). It is the dependence of roots and shoots on each other that produces the cyclic pattern of vegetative flushing characteristic of avocado trees (Whiley et al., 1988). According to Ploetz and co-workers (1992), root growth flushes followed shoot growth flushes by 30 to 60 days. Whiley and co-workers (1988) observed that root flushes occurred 45 to 60 days after vegetative flushes. Generally, there are two vegetative growth flushes per year (Davenport, 1982), each lasting from 3 to 5 weeks. The first occurs near the completion of flowering and the second during late summer. The growth resulting from this summer flush will eventually produce flowers.

Vegetative - Reproductive Competition

Avocado reproductive growth begins with flowering in mid- to late- winter and is followed by fruit set and development. The timing of reproductive development may vary seasonally as much as one month. Although an avocado tree produces over one million flowers, yields are low compared to other fruits like citrus (Whiley et al., 1988).

The primary cause of low average yields in avocado is vegetative/reproductive competition at the critical period of fruit set (Wolstenholme & Whiley, 1992). The problem is due to incomplete separation of vegetative and reproductive growth, wherein the vegetative terminal bud of the inflorescence resumes growth before completion of fruit set and early fruit development. Since N stimulates vegetative growth it should not be applied during this stage. The other essential nutrients can be applied at any time of the year without concern of inducing competitive vegetative growth (Whiley et al., 1988).

Other Factors Affecting Fruit Set

Flowering Habit

The complex flowering behavior of avocado may account for low yields in some situations (Wolstenholme & Whiley, 1992). Avocado cultivars belong to one of either two flowering types, A and B, which are distinguished by the time of day the flowers open (Chia & Evans, 1987). Each flower opens on two consecutive days, remaining open about half a day each time (Davenport, 1992). The flowers are functionally female on first opening (pollen receptive) and functionally male (pollen shedding) on second opening (Sedgley & Annells, 1981). 'Sharwil' flowers (type B) open first in the afternoon then reopen the following morning (Chia & Evans, 1987); whereas type B flowers open first in the morning then reopen the following afternoon.

There is some overlap between female and male stages on the same tree, but cross pollination between complimentary flowering cultivars, A and B, has been considered the probable mode of pollination (Sedgley & Annells, 1981). In Israel, Guil & Gazit (1992) claimed a significant yield increase in 'Hass' trees planted closest to trees of the pollinator, 'Ettinger'. Isoenzymatic analysis identified a definite cross-pollination with 90 percent of the 'Hass' fruit resulting from 'Ettinger' pollen. Contrary to the conclusion of others, Davenport (1992) found that many flowers were also pollen-receptive during the second opening when pollen shedding occurs. Davenport (1992) concluded self-pollination within avocado flowers results in significant fruit set in Florida.

Temperature

Adverse temperatures during flowering may be responsible for some of the poor or irregular yields often found in avocado (Sedgley & Annells, 1981). Australian researchers identified normal floral development, fertilization and fruit development under temperature conditions of 25°C (77° F) day and 20° C (68° F) night for both 'Fuerte' (Sedgley, 1977) and 'Hass' (Sedgley & Annells, 1981). However, flower or fruitlet abscission occurred at higher temperature conditions of 33°C (91°F) day / 28°C (81°F) night. Low temperature conditions of 17°C (62°F) day and 12°C (52°F) night resulted in either no fertilization or severely inhibited embryo development.

Daytime temperatures in Kona during 'Sharwil' flowering resemble the ideal temperature identified in Australia for optimum performance of both flowers and pollen. However, the night temperatures at this time of year are close to the lowest night temperature condition tested (12°C or 52°F) and could possibly limit fruit set, especially for trees growing at mauka locations (e.g. >350 m elevation). Sedgley

& Annells (1981) proposed that greater tolerance of the flowering stage to a wider range of temperatures may explain more consistent yields of certain avocado cultivars.

Fruitlet Abscission

Avocado trees produce far more flowers than the number of fruits they could carry to maturity (Sedgley, 1980). Soon after fruitset, premature fruit drop is common and can be expected. The resulting set of mature fruit is highly variable in avocado, reported to range from only 0.001 to 0.66 percent, leading to unpredictable and often low yields.

Sedgley (1980) found that both fertilized and unfertilized fruitlets abscissed from avocado trees. Nearly all of the fruitlets which abscissed during the first week after the end of flowering were unfertilized, whereas all fruitlets dropped during the fourth week had been fertilized. Although no anatomical reasons for the high rate of abscission were observed, it was concluded that embryo abortion was not the cause. Sedgley (1980) speculated that premature fruit drop may result from inefficient distribution of water and nutrients to the young fertilized fruitlets.

Degani and co-workers (1986) used isozymes as genetic markers to study the problem of massive abscission of avocado fruitlets. Their analyses identified significant deviations from the expected Mendelian ratio of different genotypes and thus attributed this phenomenon to genetic selection during fruitlet abscission. In their words, out of one million or more flowers, only the "fittest" 100 - 200 fruits will survive.

Boron and Pollen Tube Growth

Sedgley (1977) studied the fertilization process in avocado and reported pollen tube growth in the pistil is highly competitive as only one or two tubes reach the ovary. Tomer & Gottreich (1975) found that pollen tubes penetrated ovules in only 24% of the flowers examined. Sedgley (1977) suggested that perhaps a malfunction of either the penetration process by the pollen or attraction stimulus by the ovary may be limiting fertilization.

Boron is essential for pollen tube growth and successful fruit set. (Robbertse et al., 1990). The elongating pollen tube must be provided B by the stigmatic and stylar tissue of the pistil, otherwise tube growth ceases (Rosen, 1971). Whether fertilization of more flowers would increase the number of mature fruit the tree can support is not known. It is important, however, that the summer vegetative flush matures with optimum levels of B (Whiley et al., 1988) since root activity and uptake of nutrients is limited during the cool winter when B is required by flowers.

B. Boron in the Soil

Mineralogy

Boron is one of the seven essential micronutrients required for the normal growth of plants (Gupta, 1993a). The trace element content of soils is influenced by parent materials at least as much as the macronutrient content (Brady, 1974). Micronutrient deficiencies are often related to low levels of trace elements in the soil-forming rocks and minerals. Likewise, toxicities of micronutrients are frequently related to excessive quantities present in parent materials.

The relatively similar boron levels of soils worldwide may be related to evaporation and condensation of volatile borates from the atmosphere (Bohn et al., 1985). The average B content of the earth's crust is about 10 mg kg^{-1} (Bingham, 1982). The range for igneous rocks is 5-15 mg kg^{-1}, whereas, that of sedimentary rocks varies from 20-100 mg kg^{-1}, and marine shales average 100 mg kg^{-1}. The most common B-containing mineral found in soils is tourmaline, a complex borosilicate comprised of 3% B (Bohn et al., 1985; Goldberg, 1993). Tourmaline is highly resistant to weathering and is virtually insoluble, rendering B unavailable to plants (Goldberg, 1993).

Boron released to solution by weathering interacts with some inorganic clays, primarily Fe- and Al- hydroxides (Bohn et al., 1985). The majority of B in soils is sorbed within the crystalline structure of soil minerals (Bingham, 1982), which may explain further the tendency for the B content of soils to resemble that of their parent materials. Maximum adsorption of B is believed to occur in the tetrahedral layer (Goldberg, 1993) of expanding clay minerals (Offiah & Axley, 1993).

Tamimi (1978) found a dominance of sand particles and very little clay within the fine material of Histosols sampled on the island. However, Fox and Hue (1989) reported B adsorption by certain soils on the Big Island that have high content of aluminosilicates and organic matter.

Organic Matter

Organic matter is an important source of several micronutrients including B (Brady, 1974; Offiah & Axley, 1993). The higher B concentration in the surface soil compared to the subsoil is partially due to B held in the organic fraction. According to Brady (1974), B content of native soils has been highly significantly correlated with the organic carbon content. Boron was shown to combine with several compounds that are produced as organic matter decomposes (Offiah & Axley, 1993). Humus has been reported to adsorb considerable amounts of B, and on a weight basis, it sorbs more B than the mineral soil components (Goldberg, 1993).

Boron Deposits

Boron deposits of economic importance were created by volcanic action that brought B and other volatile elements to the earth's surface (Mortvedt & Woodruff, 1993; Goldberg, 1993). Concentration due to evaporation of B-enriched waters in enclosed basins resulted in alkaline deposits of hydrated sodium borates and hydrated sodium-calcium borates. The high solubility of these minerals prevent their existence in humid regions.

Other Sources of Boron

Fox and Hue (1989) examined both sea water and rain water in Hawai'i for boron content. They found local sea water contained substantial B, 4.2 mg B L^{-1}, while rain water on the Big Island contained 0.05 mg B L^{-1}. They suggested rainwater could supply an appreciable amount of the B required by plants. Moreover, the B concentration of rainwater was much higher on the volcanically active Big Island than on volcanically inactive O'ahu.

Chemistry

Although boron exists in the clay, mineral and organic fractions of soil, it is the water soluble fraction that is of major importance in terms of plant nutrition (Gupta, 1993b). Plant roots acquire water-soluble B from the soil solution, the supply of which is maintained by B in the sorbed phase and organic matter (Offiah & Axley, 1993). Unlike aluminum, B released to the soil solution does not form B^{3+} cations (Goldberg, 1993). Instead, B chemistry is more similar to silicon chemistry, wherein the small, highly charged B^{3+} cation is surrounded by three strongly associated hydroxyls (OH^-) to form boric acid, H_3BO_3 (Bohn et al., 1985). Interestingly, not only is boric acid readily available to plants (Brady, 1975; Bohn et al., 1985), it is the form plant roots absorb most efficiently (Goldberg, 1993).

Boron is unique among the essential mineral nutrients in that it is the only element available to plant roots as an uncharged molecule in the soil solution (Gupta, 1993a). Boric acid dominates the soluble B present in acid soils (Goldberg, 1993). However, as the pH increases, boric acid accepts a hydroxyl to produce the tetrahedral borate anion, $B(OH)_4^-$. Borate polymers such as hydrated sodium borates (i.e. borax) dissociate to monomers in dilute solutions (Bohn et al., 1985).

Highly weathered soils may often result in plant deficiencies of B, while arid and irrigated soils may produce toxicity symptoms (Bohn et al., 1985). Boron concentrations greater than a few mg L^{-1} in bulk solution can be toxic to sensitive plants, and concentrations less than several tenths of a mg L^{-1} may result in deficiency (Bohn et al., 1985). Small variation in extractable B among soils reflects the fact that the range between deficiency and toxicity in soils is narrower for B than for any other esssential element.

Factors Influencing Boron Availability

The overall B content of a soil does not provide a good indication of the need for B fertilization, since normally less than 5% of the total B in soils is in a form available for plant uptake (Offiah & Axley, 1993). One of the best soil testing methods of extracting available B is extraction with boiling water for 5 minutes (Offiah & Axley, 1993). Soil factors such as pH, texture, organic matter and moisture are known to influence the boron availability in soils (Brady, 1974; Goldberg, 1993). Also, plant species and genotypes, environmental factors, and the interaction of B with other nutrients can affect the availability of soil B to crops (Gupta, 1993b).

Soil pH is one of the major factors influencing boron availability (Brady, 1974; Goldberg, 1993). Boron is most soluble and therefore most available to plants under acid conditions. Availability declines with increasing pH and diminishes markedly when pH levels rise above 6.5 (Gupta, 1993b).

Soil texture affects the release of B from soils (Offiah & Axley, 1993). In humid areas, coarser textured soils (e.g. sandy soils) contain less available B than finer textured soils such as silt and clay loams. The lower soluble B level in sandy soils is attributed to lack of B sorption by clay particles and higher losses due to leaching Gupta, 1993b). Boron deficiency in plants is most common on sandy soils. The rocky soils of Kona, Hawai'i (USDA-SCS, 1973) are somewhat comparable to sandy soils in terms of texture (Tamimi, 1978) and, therefore, similar in B availability.

Organic matter is a key soil factor affecting the availability of boron (Brady, 1974; Goldberg, 1993). As previously noted, organic matter is a major source of B, as well as an important B-adsorption site, all of which may be released for plant use. Offiah & Axley (1993) concluded that in humid regions, most of the available B is contained in the organic fraction, with higher amounts of available B found in soils of higher organic matter content. Organic matter content was determined to have a greater effect on B availability than either the pH or the texture of the soil.

Moisture apparently affects the availability of B to a greater extent than other nutrients (Gupta, 1993b). As soil moisture is depleted, available B decreases due to reduced mass flow to the roots (Marschner, 1986). Availability decreases sharply during drought periods due to reduced diffusion rates, polymerization of boric acid, and limited transpiration flow in plants (Gupta, 1993b; Marschner, 1986). Consequently, B deficiency in plants may occur in spite of an adequate supply of available B in the soil.

Finally, B availability to crops was also found to be influenced by temperature (Gupta, 1993b). Boron concentration of plants was positively correlated with both air and root temperatures.

C. Boron Nutrition of Plants

Plants require a greater amount of B (molar basis) than any of the other essential micronutrients (Marschner, 1986). Thus, it is surprising that boron is the least understood of all the essential mineral nutrients. However, there has been a substantial increase in our knowledge of the role of B in plant nutrition, including its distribution and function in plants and the establishment of deficiency and sufficiency levels for various crops (Gupta, 1993a).

Boron Uptake and Translocation

The mechanism of B uptake (passive or active) by plant roots has been the subject of considerable controversy. Shelp (1993) concluded that B enters through passive transport. Overall, results indicate the cell membrane is readily permeable to boric acid and much less to the borate anion. Once inside roots, some B complexes with cell wall components, the magnitude of which depends on genotypical differences in B requirement of plants (Marschner, 1986).

Long distance transport of B from roots to shoots is confined to the xylem (Marschner, 1986). Once in the xylem, the distribution of B is related to the loss of water from shoot organs (transpiration). Because of this control by the transpiration stream, regulation of B uptake and translocation is quite restricted in comparison to that of other mineral nutrients. This often results in steep B concentration gradients within a plant and even within a given leaf when B is supplied in excess (midrib<middle of lamina<margins and tip).

Following accumulation in the leaves, B has typically been thought to undergo limited retranslocation (Shelp, 1993; Marschner, 1986). It is generally believed that a major portion of the total B content of plants is complexed as stable cis-borate esters in the cell wall material of leaf tissue. Although the B concentration in phloem is lower than in source leaves (Epstein, 1973), the difference is not as marked as previously described (Shelp, 1993). The low concentration of B in phloem is also due to a high permeability of cell membranes to B (Shelp, 1993).

Epstein (1973) hypothesized that although immobility of B in the phloem is a detriment in terms of causing local deficiencies at developing sinks it may be an adaptation favoring the maintenance of sieve tubes as open, unstructured conduits through which sugars and other nutrients may flow freely. According to Marschner (1986) and Shelp (1993), there is increasing evidence that the phloem supplies ample B to sustain the growth of developing shoot organs of plants provided with adequate B.

Recent evidence, however, suggests that phloem mobility of B is species dependent (Hanson, 1991; Hu & Brown, 1997). Boron was found to be highly mobile in species producing polyols, due to the co-transport of B-polyol complexes (Hu & Brown, 1997). In contrast, B mobility was very limited in species producing little or no polyols. Species in which B is phloem mobile included, but was not limited to, the tree fruit species *Malus*, *Prunus* and *Pyrus* (Brown & Hu, 1996).

Interactions With Other Nutrients

Marschner (1986) believed that interactions between B and other elements during uptake were of minor importance. However, Gupta (1993b) reported that boron uptake can be affected significantly by the nitrogen level present in the soil. High rates of N to the soil resulted in decreased uptake of B by crops. Gupta (1993b) cited that liberal additions of N have actually been useful in controlling B toxicity in citrus (Chapman & Vanselow, 1955). It was found that excessive K accentuated both B toxicity and B deficiency symptoms under high- and low- B conditions, respectively.

Gupta (1993b) maintained that plant usage of B and calcium (Ca) depends on the correct ratio between them. Apparently, Ca deficiency was found to aggravate B deficiency symptoms, while excessive Ca increased both B and Ca content of plant tissue. Conversely, Marschner (1986) claimed that reports on the significance of the balance between Ca and B in plants are inconclusive. The two elements are related in their limited mobility and extracellular functions.

Boron Complexes

Over the years, various aspects of metabolism have been investigated to determine a function of B in plant growth (Pilbeam & Kirkby, 1983). For a long time the favored hypothesis was that B promoted sugar transport across membranes by forming non-polar sugar borates. This theory was proven unlikely after it was found that B reacts weakly with sucrose and is present in low concentration in the phloem, the main translocation route for sucrose. Instead, B was found to complex with compounds containing pairs of adjacent cis-hydroxyl groups (cis-diols) to form stable esters (Shelp, 1993; Marschner, 1986). Recent explanations of possible functions of B in plants tend to agree on the formation of reversible or irreversible diol-borate complexes with substrates, enzymes, and/or membranes in cell walls. However, there are distinct differences of opinion concerning the major roles of B in metabolism and growth of higher plants.

The Role of B in Cell Wall Biosynthesis

A primary function of boron seems to be regulation of lignin biosynthesis (Pilbeam & Kirkby, 1983; Marschner, 1986). Apparently, B binds with certain phenolic compounds produced during lignin biosynthesis to form stable phenolic acid-borate complexes. Restriction of phenols results in increased availability of cellulose precursors, thus synthesis of hemicellulose and related cell wall material proceed normally.

When B is deficient, phenolic compounds accumulate (Marschner, 1986). Pilbeam & Kirkby (1983) hypothesized that cell damage and metabolic disturbances that develop in B-deficient tissue are caused by accumulation of phenolics. The damaging impact of certain phenols on the permeability of the plasma membrane and membrane-bound enzymes are well known. It is probable that B reacts with other phenols in the plant as well.

The Role of B in the Plasma Membrane

There is increasing evidence associating B with cell membrane stabilization (Shelp, 1993; Marschner, 1986). It is uncertain whether B has a direct effect on the membrane-bound enzyme itself, ATPase, or on the membrane to which it is attached (Shelp, 1993; Pilbeam & Kirkby, 1983). Shelp's (1993) review of the subject included several studies that concluded B was required for the formation and maintenance of electrical potential gradients across membranes. Alternatively, it is possible that membrane behavior is influenced by compounds which are themselves affected by B nutrition. Pilbeam & Kirkby (1983) suggested that when

B is deficient, the reactive hydroxyl groups of phenolic compounds will be free to react with membrane components and possibly cause direct changes in membrane permeability. Impairment of membrane stability and permeability could interfere with enzyme function and the transport of ions, metabolites and hormones required for normal growth and development (Shelp, 1993).

The Role of B in Cell Elongation and Cell Division

Boron is essential for both cell elongation and cell division in apical growing points (Stanley, 1971; Shelp, 1993; Marschner, 1986). It is not known if one process is more sensitive to B deficiency than the other. Research has shown the rapid response of roots to B deficiency, wherein root elongation declined within 3 h after removal of B supply and ceased completely within 24 hr (Marschner, 1986). This rapid stoppage of apical meristem growth as an early symptom of B deficiency led to the suggestion that B is involved in nucleic acid metabolism (Pilbeam & Kirkby, 1983).

The Role of B in Nucleic Acid Metabolism

According to Pilbeam & Kirkby's (1983) review of the subject, several workers found that RNA content was lower in plants grown under B deficiency conditions. Disappearance of B deficiency symptoms following addition of RNA to the nutrient solution led to the conclusion that B is required for RNA synthesis. The synthesis of DNA was also believed to be impaired by B deficiency. Meanwhile, there is evidence that the decrease in RNA content in B deficient plants may also be attributed to enhanced rates of degradation by nuclease enzymes (Shelp, 1993;

Marschner, 1986; Pilbeam & Kirkby, 1983). In fact, Pilbeam & Kirkby (1983) suggested that an increased breakdown of nucleic acids may have more impact on RNA concentration during B deficiency than reduction of RNA synthesis.

The Role of B in Pollen Tube Growth and Fruit Set

Boron is important for flower bud formation and floral development (Kamali & Childers, 1970). The B requirement for seed and grain production is normally greater than that needed for vegetative growth only (Marschner, 1986). This higher B demand is reflected in the increase of B levels found in the reproductive structures of apple, pear and cherry flowers as they open to full bloom (Woodbridge et al., 1971). Close relationships exist between B supply to the plant and B level in pollen grains (Stanley, 1971), pollen production of the anthers, and pollen viability (Marschner, 1986). Moreover, B supply influences both pollen germination and pollen tube growth.

Boron was first reported to stimulate pollen germination in 1932, when high B levels were identified in the fluid of stigmas, which were already known to enhance pollen growth (Stanley, 1971). Since then, it has been shown for most species that the highest B level is found in the stigmas, and not in pollen (Stanley, 1971).

Pollen deposited on the surface of the stigma must germinate and grow through stigma and stylar tissue of the mature pistil enroute to the ovary (Stanley, 1971; Rosen, 1971). Boron, and possibly calcium, are the only essential elements not present in mature pollen at high enough levels to allow normal pollen growth and fertilization (Brewbaker & Kwack, 1964; Stanley, 1971). Therefore, the secretion products of the stigma and style must provide the B required by the elongating pollen tube (Stanley, 1971; Rosen, 1971).

The B levels in flowers and pollen can be increased by externally added sources, a common practice used to assure good fruit production (Stanley, 1971). In vitro studies with pear (Stanley & Loewus, 1964) and avocado (Robbertse et al., 1990) have shown that percent germination and pollen tube length were positively related to the B supply. Although B has been found to improve fruit- and seed- set in various fruit species (Singh & Dhillon, 1987; DeMoranville & Deubert, 1987; Shrestha et al., 1987), there is little information identifying the B requirements for optimal fruit set of subtropical fruits (Robbertse et al., 1990). Robbertse and co-workers (1990) obtained the greatest pollen tube growth in 'Hass' avocado flowers containing 50 to 75 mg kg^{-1} B. Even higher concentrations in the style were necessary for optimal pollen tube growth. They hypothesized that the sufficient B concentration range in the flower is about 50 to 100 mg kg^{-1} for optimal fertilization and fruit set.

In general, hypotheses on the function of B in pollen growth parallel those resulting from research on B in other plant tissues (Stanley, 1971). Repeatedly proposed roles have included sugar uptake during pollen tube growth (Bhandal & Malik, 1985), effects on RNA (Stanley, 1971), and cell wall synthesis (Stanley & Loewus, 1964). Recent advances in pollen research indicate B may be involved in the respiration process (Bhandal & Malik, 1985).

Boron Toxicity

The ratio of toxic to adequate level is smaller for B than for any other essential element (Gupta, 1993c), making it possible for a crop to encounter both toxic and deficient levels in one season. Excessive amounts of B cause severe injury and even plant death; borates are actually included in some herbicides (Kyte, 1987). Sepaskah and co-workers (1988) claimed that B toxicity generally occurs for most species when B concentrations in tissues exceed 200 mg kg^{-1}.

Boron toxicity symptoms are similar for most plants (Gupta, 1993c), with the oldest leaves usually the first to show symptoms (Haas, 1929). Haas (1943) found avocado leaves continued to accumulate B long after they mature, though it tends to concentrate in leaf margins (Gupta, 1993c). Haas (1929) reported burned spots throughout the avocado leaf surface but with a higher incidence along the margins and tip. Severe toxicity leads to necrosis, premature leaf drop and ultimately plant death (Gupta, 1993c; Goldberg, 1993).

Boron toxicity occurs primarily under two conditions: its presence in irrigation water in arid and semi-arid regions with high levels of B in the soil, or excessive applications of B in treating B deficiency (Gupta, 1993c; Goldberg, 1993). Excessive additions would be the likely cause of B toxicity in humid Hawai'i on soils low in B.

D. Boron Deficiency of 'Sharwil' Avocado

Boron deficiency is a widespread nutritional disorder, affecting more plant species worldwide than any other micronutrient deficiency (Marschner, 1986;

Gupta, 1993a). Avocado growth is seriously interfered with when B supply is inadequate (Haas, 1943) and can result in reduced crop yield and/or impaired crop quality (Gupta, 1993a). Although B deficiency in avocado is unknown in California, Florida, and Israel (Lahav & Kadman, 1980), it is a common problem in Australian orchards (Piccone & Whiley, 1987), particularly for the 'Sharwil' cultivar. Trees showing visual symptoms in leaves and fruit have already reached acutely deficient B levels.

Symptoms of Boron Deficiency

As in most physiological disorders there may be several symptoms present, any one of which considered alone may not correctly identify the problem (Haas, 1943). Symptoms of B deficiency generally appear first in actively growing tissues, affecting the terminal buds or youngest leaves at the apical meristems (Haas, 1943; Marschner, 1986). Newly produced lateral shoots are the next tissues affected and death, therefore, proceeds from the most distant youngest portions back toward the base of the trunk (Haas, 1943). This pattern reflects the immobility of B in the phloem, which limits redistribution of B from mature plant parts to growing tissues.

New leaves of affected avocado shoots are greatly reduced in size and yellowish green in color (Embleton & Jones, 1966). Terminal buds may become discolored and die (Marschner, 1986; Goldberg, 1993). Interveinal chlorosis may occur on mature leaves, as might distorted leaf blades and scorched margins, and early abscission (Haas, 1943; Lahav & Kadman, 1980; Marschner, 1986). The petiole, midrib and other veins on the lower leaf surface often are corky and split (Haas, 1943; Goldberg, 1993). Trees are stunted at more advanced stages of deficiency as internodes shorten and leaves become scale-like (Lahav & Kadman, 1980; Marschner, 1986).

Boron deficiency in trees during the reproductive stage can induce dropping of buds, flowers and developing fruits (Marschner, 1986). In B-deficient fleshy fruits, such as avocado, the size is often reduced and the quality may be severely affected by malformation (Marschner, 1986; Piccone & Whiley, 1987). 'Sharwil' is usually the first cultivar to exhibit fruit symptoms in Australia (Piccone & Whiley, 1987). Boron-deficient avocado fruits show an indentation on one side giving a dumpy, hooked shape. In seriously affected fruits, a lesion similar to the base of a navel orange forms in the indented side. This lesion penetrates inward, damaging the flesh and may reach the seed.

Conditions Influencing B Deficiency in Kona

Boron deficiency in plants is primarily due to naturally low levels of B in the soil (Gupta, 1993b). Generally, soils that developed in humid regions have low amounts of available B because of leaching (Tamimi, 1978; Piccone & Whiley, 1987). Susceptibility to leaching is greater on course-textured, acid soils (Offiah & Axley, 1993), similar to the excessively permeable Histosols found in Kona (USDA-SCS, 1973).

Boron deficiencies are generally found on dry soils where summer or winter drought is severe (Brady, 1974). During the dry season in Kona, the rocky soils lose moisture rapidly between the infrequent winter storms. Shallow-rooted avocado trees obtain B from the surface soil layer and leaf litter, the layers containing most of the available B (Goldberg, 1993). However, during drought periods avocado roots are forced to exploit only the lower soil layers where the B content can be quite low (Brady, 1974).

The problem of reduced B uptake during drought increases the likelihood of deficiency in these low-B soils because it coincides with the period of highest B demand for the avocado tree: during the development of flowers and fruit set (Woodbridge et al., 1971; Robbertse et al., 1990). Moreover, much of the B already in the plant is unavailable to newly developing sinks because of its complexation in leaf cell walls and relative immobility in the phloem (Shelp, 1993; Marschner, 1986). Consequently, B-deficiency may result from reduced uptake even though B concentration may be adequate overall in the tree.

Another factor known to aggravate B deficiency is lime-induced adsorption of this element by clay and other minerals resulting from increases in soil pH (Brady, 1974; Goldberg, 1993). However, lime is rarely applied to avocado orchards in Kona. Two more conditions that can influence B deficiency are depletion of humus (Offiah & Axley, 1993) and diminished soil reserves from years of intensive cropping without addition of B fertilizers (Brady, 1974; Gupta, 1993c). Before the recent problems with fruit deformity, B fertilizers were not applied to avocado orchards in Hawai'i.

Control of Boron Deficiency

Control of micronutrient deficiencies require much more careful consideration than applications of macronutrients because of the narrow range between deficiency and toxicity for a given trace element (Brady, 1974). This statement is especially true for B, which has the smallest toxic/deficient ratio of all the essential micronutrients (Gupta, 1993c). Therefore, B should be added only when the need is certain.

Foliar analysis is the standard method of assessing the internal nutrient levels and needs of avocado trees (Lahav & Kadman, 1980). In scanning the literature on avocado nutrition it becomes apparent that most authors refer to the norms for leaf nutrient requirements first proposed by Embleton & Jones (1966) in California. According to their guidelines, B deficiency occurs if leaf B concentration falls below the optimum range of 50 - 100 mg kg^{-1}. One serious flaw of this diagnostic method is that the B status of leaves may not reflect that of the reproductive structures, due to limited retranslocation of B to developing flowers.

Timing of Application

Since avocado trees respond quickly to B application (Lahav & Kadman, 1980), the time of year B is applied should be planned to best meet the needs of the tree (Brady, 1974). Boron is important for root growth, and it should be added before flushes of root growth in spring and summer (Piccone & Whiley, 1987). Correction of B deficiency should be performed annually because B must be added in small amounts to prevent toxicity, plus its residual effectiveness is rather minimal due to leaching when rainfall is high or irrigation is applied.

Boron Fertilizers

All B fertilizers originate from either sodium- and/or calcium- borate deposits (Mortvedt & Woodruff, 1993). These compounds are characterized by differences in B content and solubility in water. Until recently, the most common B fertilizer was completely soluble, sodium tetraborate, $Na_2B_4O_7 \cdot 10H_2O$ (11.3%B), also known as borax. Fertilizer borate, the generic term for $Na_2B_4O_7 \cdot 5H_2O$ (14.3 - 14.9%B), produced by refinement of borax ores is now more favored because of its higher B content. Borax and fertilizer borate are generally used for soil application.

Boric acid, H_3BO_3 (17.5%B), is completely water soluble and used mainly for foliar sprays (Mortvedt & Woodruff, 1993). This product is more costly so its use is limited. Another B fertilizer produced from further refinement of borax is Solubor, the trade name for $Na_2B_8O_{13} \cdot 4H_2O$, containing 20.5% B. Solubor, the most soluble B fertilizer, especially in cold water, is the preferred B source for foliar sprays.

Two slightly soluble B fertilizers are the calcium borates, colemanite and ulexite (Mortvedt & Woodruff, 1993). Another B source is fritted glass products (borosilicates) containing variable B (2-11%B) (Rhoads et al., 1956). These relatively insoluble materials provide a slow release of B over a long period while also avoiding toxicity. Because they are less soluble, B frits are recommended for maintenance, not for correcting deficiency.

Soil Application

The two main methods of B application are soil application and foliar spray (Gupta, 1993b). In general, direct application of B fertilizer to the soil is most common, broadcast or applied in bands. Orchard trees usually are treated individually, with the fertilizer broadcast around each tree under the canopy (Brady, 1974; Piccone & Whiley, 1987).

Soil application of borax at 112 g (13 g B) three times per year raised leaf B levels from 15 mg kg^{-1} to 25-30 mg kg^{-1} in avocado in Florida (Embleton & Jones, 1966). Single applications of more than 450g (51g B) per tree were required to cause toxicity. The application rate recommended for low B conditions in Australia is borax at 160g $tree^{-1}$ or Solubor at 80g $tree^{-1}$ two times per year (based on borax at 8g m^{-2} and Solubor at 4g m^{-2} of ground area under the canopy) (Piccone & Whiley, 1987). Where B is severely deficient (<20 mg kg^{-1} in leaves) a third application is suggested.

Foliar Application

Foliar spray applications of B have been effective for many fruit crops (Mortvedt & Woodruff, 1993) as a means of quickly correcting a deficiency (McCall, 1980). However, repeated applications may be required due to limited transport of B from older to younger leaves (Mortvedt & Woodruff, 1993). Also, leaf burn is a hazard if B concentration is too high. In addition, the mature avocado leaf has a thick cuticle layer restricting absorption of nutrients (Piccone & Whiley, 1987). Therefore, multiple applications of B on young flush growth is necessary to correct visual symptoms of B deficiency, however, long-term tissue levels will not increase. For this reason, soil application provides the best results for long-term correction of B deficiency.

In spite of drawbacks, foliar sprays can be more successful in supplementing a fluctuating B supply than soil applications when soil conditions are unfavorable for uptake and when a high temporary demand exists in inflorescences (McCall, 1980; Gupta, 1993b). Recent B studies are focusing more on foliar application of B as a method to increase fruit set. Reported studies with cranberry (DeMoranville & Duebert, 1987), mango (Rajput et al., 1976; Singh & Dhillon, 1987), prune (Hanson & Breen, 1985) and avocado (Robbertse et al., 1992; Lovatt, 1994) indicated spray application of B during flowering resulted in increased fruit set and yield.

Robbertse and co-workers (1992) hypothesized that the degree to which foliar applied B is retranslocated from leaves likely influences how effective sprays are in correcting B deficiencies. They found that foliar B-spray treatments significantly increased the B concentration of avocado flowers but did not increase leaf B levels. It was not known whether the B was transported directly to the inflorescences or if it was absorbed by the inflorescences. Meanwhile, Lovatt (1994) found that foliar application at early bloom significantly increased 'Hass' yield, whereas trunk injection of B without spraying the inflorescences raised the B content of leaves but did not increase yield. These results suggest that B must be applied directly on to developing flowers.

Since the function and mode of action of B remain unknown, timing of application for the most efficient uptake and utilization is guesswork (Schon & Blevins, 1990). In most studies with non-deciduous fruit crops (mango, avocado) foliar B sprays were applied at the onset of flowering but before appearance of flowers (Rajput, 1976; Singh & Dhillon, 1987; Littlemore et al., 1991; Robbertse et al., 1990). Robbertse and co-workers (1990) found that B sprays applied at this time did not improve pollen tube growth or fruit set in 'Hass' avocado. They attributed this lack of response to the failure of the sprays to increase the B level of flowers above 30 mg kg^{-1}, far below the desired range of 50-75 mg kg^{-1}.

More recent studies with avocado (Robbertse et al., 1992; Lovatt, 1994) determined the best timing for B application to increase fruit set was during early bloom when mature flowers are opening and B demand is higher (Woodbridge et al., 1971). Since a continuous supply of B is required during the reproductive stage, repeated foliar applications may be more effective than single applications. Two split foliar applications of B during flowering, first at early bloom and the second during mid-bloom increased yield in cranberry (DeMoranville & Deubert, 1987), soybean (Schon & Blevins, 1990), and avocado (Lovatt, 1994).

Finally, foliar B sprays effectively controlled the papaya bumpy-fruit condition in Taiwan (Wang & Ko, 1975). The occurrence of deformed fruit was almost completely eliminated (incidence <1%) by foliar B sprays at locations where deformity previously had affected 100% of the papaya fruits. This fruit deformity is characteristic of B deficiency during periods of drought in the Puna district of the Big Island (Nishina, 1991).

CHAPTER 3. SOIL APPLICATION OF BORON

A. Materials and Methods

An on-farm experiment was conducted on bearing trees of the avocado cultivar 'Sharwil' on the island of Hawai'i.

Locaton

Eight commercial farms located at various elevations throughout the Kona district participated initially; however, two farms dropped out of the study early. Farm elevations ranged from a low of 260 m to the highest at 610 m (Table 3.1). The three soil series represented were Histosols. These rocky, organic soils belong to the Kaimu series, extremely stony peat; Puna series, extremely stony muck; and Punalu'u series, extremely rocky peat (USDA-SCS, 1973).

Design and Field Operations

The experiment ran from February, 1990 to June, 1994. Initial treatment design consisted of four boron treatments applied to single tree plots at each of the eight locations. Each farm served as a replicate. However, after the first season, one additional replicate of treatments was installed at four locations. By the end of year two, six farms remained, half with one replicate of treatments and half with two replicates.

Three rates of Solubor, 0-, 110-, and 220- g tree^{-1} (0-, 23-, and 46- g B tree^{-1}) were dissolved each in 1 L water and applied as a spray on the ground under the tree canopy in February, 1990. The fourth treatment was a broadcast application of 158 g Borax tree^{-1}, equivalent in B to the middle Solubor treatment (23 g B).

These treatments were repeated in August and December, 1990; however, beginning in 1991 the B treatments were applied in April, July and October of each year when basal fertilizers were broadcast. Thus, annual additions were: Solubor at 0, 330, and 660 g tree^{-1}; and Borax at 474 g tree^{-1}. Boron rates and timing were based on recommendations for avocado in Australia (Piccone & Whiley, 1987).

At the same time that B was applied, N-, P- and K- fertilizers were broadcast under each tree canopy at the most commonly applied rates for avocado in Kona (Mills-Packo et al., 1990). Application rates were as follows: N at 180 g tree^{-1} as urea, K at 240 g tree^{-1} as sulfate of potash, and P at 30 g tree^{-1} as treble superphosphate. Nitrogen and potassium rates were reduced in half for the October applications as recommended by Piccone & Whiley (1987). Beginning in 1991, iron was provided as 50 g $FeSO_4$ tree^{-1} in spring and summer, but was omitted from autumn applications. Farmers continued their own management regimes throughout the trial. Cultural practices consisted mostly of weed control, ground cover maintenance, and occasional pruning.

Collection of Samples and Data

Soil samples were collected at each site, first in year 1 to identify initial B levels and fertility status, and then again for B analysis one-year following the final B applications in year 4. Leaf samples for B analysis were collected annually in October. A total of 10 to 12 leaves were taken from all sides of the tree on non-fruiting, non-flushing branches, at least two nodes below the terminal bud of the matured summer growth flush. Leaf blades and petioles were washed thoroughly in deionized water, dried at 65^{0}C, and ground in a Wiley mill. Boron was determined colorimetrically by the azomethine-H method (Wolf, 1974) at the University of Hawai'i's Agricultural Diagnostic Service Center.

Yields for each tree were determined as fruits matured and were harvested by the cooperating farmers, usually beginning in late October/November at the lower elevations and continuing until about late March/early April at the higher elevations. Fruit quality was assessed by grading fruits into the following categories: grade 1- no damage, grade 1- slight deformity, grade 2- severe deformity, grade 2- other causes, and grade 3- unmarketable- (i.e. rat bites, overripe drops). Fresh weight, number of fruits, and mean fruit weight were determined for each grade, then summed for total per tree yields.

Statistical Analysis

Data were analyzed as a split-plot experiment with boron treatments (4 levels) as the main plots, locations as the replicates and years as the sub-plots. Three locations had two replicates of treatments during years 2 thru 4. Averages of the two replicates within farms were utilized for data analysis. Only six farms had data over two years. Due to the alternate bearing habit of avocado trees, cumulative yields of two-year periods were used. Data also were analyzed as randomized complete block experiments for each individual year to determine initial treatment effects and to identify trends over time.

Statistical analyses were by ANOVA using SAS computer programs (SAS Institute, Inc., Cary, NC). Regression analysis was used to examine treatment effects over time; and to determine relationships between leaf B level and yield or fruit deformity. Single degree of freedom contrasts were utilized to compare the effectiveness of Solubor and borax fertilizers; and to evaluate linear and quadratic models on all parameters. All data were examined for differences at the P=0.05 level of significance.

B. Results and Discussion

Soil Characteristics

Some soil chemical attributes (0 to 30 cm) are listed for each location in Table 3.2. Initial soil pH ranged from 5.5 to 6.5 at all but one site (MA 7.3). Organic carbon was characteristically high for these organic soils, ranging from 7.2 to 11.6 %. Exchangeable cations P, Mg, and Ca were generally in the adequate levels suggested by Tamimi et al. (1994), whereas K was considerably below the minimum level of 400 µg g^{-1}. Initial soil B levels ranged from 0.9 to 1.5 µg g^{-1}, revealing the low B status of Kona soils.

Soil Boron

Soil tests taken one-year following final application of treatments indicated that soil B levels ranged from ~3.5 to 11 µg g^{-1} across the middle- and high- rates, respectively, and from ~1.0 to 4.5 µg g^{-1} at control trees (Table 3.3). Boron leaches readily from Kona soils, as evidenced by lower B levels at the farm (KA) located in a relatively high rainfall area (Table 3.1). The farmer at the ME location applied B to all trees during the year following completion of the trial, resulting in higher soil B levels compared to the control trees at the other sites.

Foliar B Concentration

Soil-applied boron increased foliar B concentration in 'Sharwil' leaves compared to leaves from untreated trees (Fig. 3.1) (Table 3.4). A highly significant, positive, linear relationship occurred between Solubor rate and foliar B level each of years 1 thru 4. Three split-applications of either 110 g or 220 g Solubor tree^{-1} in year 1 increased average foliar B levels to the accepted sufficiency range of 50 to 100 mg kg^{-1} (Fig. 3.1). This rapid response of avocado to B additions is common and expected (Lahav & Kadman, 1980). In Florida, soil-applied B added three times per year, at approximately half our middle rate (13 g B tree^{-1}), increased avocado leaf B an average of 10-15 mg kg^{-1} (Embleton & Jones, 1966).

Foliar B concentration of untreated trees was relatively constant and remained below the recommended minimum level of 50 mg kg^{-1} throughout the study (Fig. 3.1). In contrast, leaf B levels at the middle- and high- rates increased linearly over time ($P=0.11$ and 0.05, respectively), resulting in a highly significant Years effect (Table 3.4). The different responses over time, between the control and B- treated trees, resulted in a significant interaction between B treatment and Years (Table 3.4).

By year 3, average foliar B concentration of trees at the high rate far exceeded (>125 mg kg^{-1}) the upper limit of the sufficiency range (Fig. 3.1.) Not surprisingly, B toxicity symptoms were observed in two trees at this time. Further, B toxicity kills roots of 'Sharwil' avocado (S. Miyasaka, pers. comm.) and this may have allowed root rot organisms (e.g. *Phytopthera*) to enter the affected trees. Symptoms included interveinal chlorosis and tip burn of fully expanded leaves as described by Haas (1944). Premature leaf drop and stunted new growth progressed to marginal and interveinal necrosis, total defoliation, and ultimately death for both trees. The first tree defoliated before collection of leaf samples, but produced only 8 kg of fruit through year two and set zero fruit in the year of its demise. The second tree accumulated leaf B to a very excessive level of 375 mg kg^{-1} prior to its death. Results are consistent with observations reported by Haas (1944), in which excessive B resulted in severe damage and death of previously healthy avocado seedlings.

Based on toxicity symptoms observed and average foliar B concentrations (Fig. 3.1), it appears that B accumulated to toxic levels beginning in year 3. However, individual tree data revealed that excessive foliar B levels (e.g. 101-, 111-, and 156-mg kg^{-1}) first occurred for some trees in year 2. Interestingly, one of those trees (101 mg kg^{-1}) received the middle B rate. Furthermore, the first tree that died contained excessive leaf B (114 mg kg^{-1}) as early as year 1.

There were no significant differences between Solubor and Borax on leaf B levels (Table 3.4). Figure 3.2 illustrates the similar foliar B concentrations that occurred when the two fertilizers were applied at equal rates of B (23 g B).

Location Effect

The wide variation in tree response (Fig. 3.1) at both the middle- and the high-B rates in years 3 and 4 can be explained by examining the very highly significant (P=0.0001) location effect that occurred (Table 3.4).

An attempt was made at the inception of this study to select experimental trees uniform in age, size, and vigor, both within and between farms. Considering the small size of avocado farms in Kona, the uniformity of trees within farms was quite good with initial trunk diameters varying only 2 to 5 cm at all but one location. However, due to the limited number of potential cooperators, uniformity of trees between locations was more difficult to achieve (Table 3.1). For example, initial trunk diameters at Farm MC ranged from nearly 2- to almost 3- times greater than those at three locations with much younger and smaller trees (Farms MA, NO, KA) (Table 3.1). In general, trees at the remaining sites (Farms BE, LA, ME) were intermediate in age and size.

Much of the large variation found in leaf B concentration between locations is due to the decrease (P=0.08) in B concentration in leaves as initial trunk diameter increased (Fig. 3.3). For instance, the middle rate (330 g Solubor) generally resulted in optimal foliar B levels, however, by year 3 even this rate proved to be excessive for some of the smallest trees (Fig. 3.3). A similar relationship occurred at the high B rate (660 g Solubor) except that toxic leaf B levels generally occurred sooner than at the middle rate: either year 1 or 2 in small trees, and year 3 or 4 in intermediate trees (data not shown). Foliar B concentration over time, therefore, was affected by both the B rate applied and the relative size/age of the tree; which explains the highly significant (P=0.0008) interaction between location and year that occurred (Table 3.4).

Poorly growing trees often exhibit a lack of response to nutrient additions. This effect may be caused by: competition from unchecked weeds and/or ground cover, presence of *Phytopthora* (root rot), and inherent variability of non-clonal rootstock. Furthermore, the large variability in the ratio of rocks to soil in Kona soils, both within and between locations (Tamimi, 1978), accounts for a great deal of variability in tree growth and vigor.

Fruit Yield

Year 1

Although not significant (P=0.126), a linear trend existed between boron rate and fruit yield per tree for the first crop (Fig. 3.4 - 3.5). Average yield increased nearly 70%, from 29 kg tree^{-1} in controls to 49 kg tree^{-1} at the high rate (Fig. 3.4). The number of fruits harvested per tree increased (P=0.149) from an average of 84 per untreated tree to 144 fruits per tree at the high rate (Fig.3.5).

Since initial B application occurred after the flowering period, B could not have improved fruit set. Therefore, the increase in number of fruits must be attributed to a decrease in premature fruit drop that is known to be a B-deficiency symptom (Marschner, 1986). There was no significant B effect on average weight of individual fruits for any of the fruit grades (data not shown). In contrast, significant increases in fruit size were reported in mango (Singh & Dillon, 1987; Rajput et al., 1976), possibly due to the known promotory effect of B on cell division and elongation processes (Shelp, 1993; Marschner, 1986).

Despite increases in number of fruit per tree at both B rates, a clear relationship between foliar B concentration and yield was not evident (data not shown). Neither was there a relationship between leaf B and individual fruit weight, either for deformed- or normal- fruit, respectively (data not shown). This result is not surprising when the alternate-bearing habit of avocado is considered. Weinbaum and co-workers (1994) found B uptake in pistachio was higher in off-years (11%) than in on-years, suggesting it was probably due to both higher transpiration that accompanies the larger leaf area per tree and increased root growth. Furthermore, avocado trees in Kona are not synchronized in their on-year, off-year patterns.

Year 2

A major change in yield response to B fertilization occurred in year 2. A significant quadratic relationship occurred between B rate and number of fruits per tree (P=0.045). For example, the total number of fruits harvested (Fig. 3.6) increased 53%, from 108- to 165- fruits per tree from controls to the middle rate, but declined 18% below controls to 89 fruits per tree at the high rate. A similar, nearly significant relationship (P=0.08) occurred for total fruit weight, which increased 45% at the middle rate, from 39- to 57 kg tree^{-1} (Fig. 3.7). However, at high B, yield declined below controls, from 57 kg tree^{-1} to 36 kg tree^{-1}. The decrease in average yields and number of fruits compared to untreated trees indicates the presence of B toxicity in some trees given the highest B rate during year 2.

Cumulative Two-Year Yield

Annual analyses were useful for identifying initial trends and their changes; however, cumulative two-year yields are more appropriate for analyses of yields in alternate-bearing avocado.

Nearly significant quadratic relationships occurred between B rate and cumulative yield per tree (Table 3.4). On average, the middle B rate increased yield 42% for the first two-year period and 29% in years 3 + 4 (Table 3.5) compared to no B treatment. Meanwhile, the high B rate also increased yield during years 1 and 2, but to a lesser degree (24%) compared to no B treatment. However, during the second half of the trial, yields at the high rate declined 16% below controls. These results differed from those of Robbertse and co-workers (1990), in which soil-applied B increased avocado leaf B levels from nearly 50 mg kg^{-1} to 60 mg kg^{-1}, but had no effect on yield. The authors concluded that the leaf B increase, although significant, was insufficient for optimal pollen tube growth and fruit set, reflected by flower B levels (~ 30 mg kg^{-1}) well below the desirable level. Further, control trees were not B deficient in the study of Robbertse et al. (1990), whereas control leaf B levels in our study indicated severe deficiency. Therefore, B was probably more of a limiting factor in our study, hence the yield gain when leaf B levels were increased to the recommended level.

Although no significant (P=0.12) relationship existed between 2-year average leaf B and 2-year cumulative yield (Fig. 3.8), highest yields were related to leaf B levels ~50 mg kg^{-1}. Large variability in fruit yields per tree requires a greater number of trees, either due to replicates or more treatments, to clearly identify the relationship between leaf B and yield. Nonetheless, these results are in agreement with the current recommendation of maintaining leaf B levels beteen 50 to 100 mg kg^{-1} for optimal fruit production (Piccone & Whiley, 1987).

There were no significant differences between Solubor and Borax in terms of overall yield per tree (Table 3.4). Likewise, weight of individual fruits at each grade (data not shown) were not statistically different between B sources.

Location Effect

Highly variable fruit yield at both B rates, over all 4 years, reflects a very highly significant location effect (Table 3.4). Much of this variability was related to the large difference in tree size between some sites. Avocado yield, therefore, was increased significantly by both the B rate applied (Table 3.4) and the size/age of the tree as indicated by initial trunk diameter (P=0.0004) (Fig. 3.9). For example, after year 1, the high B rate resulted in lower yields compared to the middle rate at all but one site (MC) that contained trees nearly 2 - 3 times larger than trees at other locations. In fact, at this site the high B rate resulted in optimal leaf B levels (53 to 67 mg kg^{-1}) and a four-year yield 61% higher than the middle rate. When data from this site was excluded from analysis, the quadratic treatment effect on 2-year yields (fruits per tree) increased from nearly significant (P=0.09) (Table 3.4) to very highly significant (P=0.0002). Other factors probably contributed to variable yields between locations, including ratio of soil to rocks, nutritional status of trees, rootstocks, temperature and rainfall patterns, as well as cultural practices.

Years Effect

Cumulative yields were significantly lower for years 3 + 4 than for years 1 + 2 on trees receiving boron (Tables 3.4 - 3.5). Although avocado yields often decrease from one year to the next due to the alternate-bearing habit of this species, it is uncharacteristic for yield to decrease in successive two-year intervals for trees as young as those in this study. Most trees were 5 to 8 years old when the trial began.

Much of this yield decline is attributed to unusually severe drought conditions in Kona during years 2 through 4, particularly during the flowering and early fruit development period, when avocado trees were most susceptible to water stress (Fig. 3. 10 - 3.11). Actual drought periods exceeding 6 weeks occurred in each of those years; the most severe was 9 - 10 weeks in year 4. Water stress symptoms occur after 4 to 5 weeks of drought on these excessively permeable a'a soils, composed of broken lava rocks containing some fine soil particles and organic matter (Tamimi et al., 1994). Many avocado trees throughout Kona experienced either zero fruit-set or massive premature fruitlet drop during years 3 and 4. Figure 3.12 illustrates both the typical alternate-bearing habit, and with one notable exception (ME), the decline in yield to dismal levels in years 3 and 4.

The substantially higher yields at that one location (ME) is attributed primarily to cultural practices. This farmer was the only one that irrigated during the droughty flowering period in years 3 and 4. Water was hauled in by pickup truck and applied to each tree via a garden hose. It is uncertain how much water was applied, but it was added weekly throughout the critical water stress period during flowering.

Yields at this location (ME) were far superior, at the middle B rate, compared to most other sites. Cumulative yield at this farm was 75% higher than the overall mean for all locations in years 1 & 2, and 250% higher in years 3 & 4. Further, it was the only location where similar yields occurred, as expected, in the second two-year period. It accounts for the significant Location x Year interaction found for yield (number of fruits per tree).

Fruit Deformity

There was no effect of soil-applied B on avocado fruit deformity at any time; however, incidence of fruit deformity varied significantly by location and by year (Table 3.4.). In general, average total incidence of deformity ranged from 21- to 27% during years 1 thru 3, but increased to 43% in year 4. Fruit deformity affected an alarming 60 to 80% of fruit at some locations in year 4, causing a substantial economic loss to growers. Further, there was no significant relationship between leaf B and percentage of undeformed Grade-1 fruit per tree (data not shown).

Meanwhile, early in the study larvae of the Mexican leafroller (*Amorbia emigratelia*) insects were observed at several locations feeding on small fruitlets within 1 month of fruit set. Results are consistent with observations on strawberry (Riggs & Martin, 1988), wherein the authors believed that damage caused by feeding insects was responsible for most of the deformity. A similar theory was presented for avocado in Florida (Fisher & Davenport, 1989). In contrast, no insects were found to be associated with deformed papaya fruits grown in B-deficient conditions (Wang & Ko, 1975).

The lack of treatment effect, the possiblility of insect damage, and the marked increase in deformity in year 4 suggest that deformity data may have been confounded by other causes, including Zn-deficiency. However, drought is known to cause B deficiency by limiting B uptake. For instance, papaya fruit deformity, caused by B deficiency, was most serious during the dry winter, both in Taiwan (Wang & Ko, 1975) and the Puna district of the Big Island (Nishina, 1991). Furthermore, B demand in avocado is highest in flowers, during winter, when B availability is lowest. Boron, essential for pollen tube growth and fruitset, must be provided by the stigma and style of the pistil (Rosen, 1971). Boron deficiency during flowering is known to result in malformation of certain fleshy fruits (Marschner, 1986).

After reviewing the literature, it was hypothesized that severe drought and limited B redistribution from leaves cause B-deficiency in flowers, and hence, deformity in developing fruitlets, despite optimal foliar B levels. On the basis of these findings, a field trial was designed to test the hypothesis that foliar B sprays applied strategically during flowering may provide sufficient B for normal fruit development. Foliar bloom B sprays resulted in increased fruit set on 'Hass' avocado (Robbertse et al., 1992; Lovatt, 1994).

C. Conclusion

The current results confirm the hypothesis that B deficiency is a problem for 'Sharwil' avocado grown in Kona, Hawai'i. Foliar B concentration of untreated trees remained considerably below the recommended minimum level during the entire four-year trial period. Tree response to soil-applied B fertilizer was quite rapid, since low foliar B levels were corrected within the first 6 to 8 months of the study. Likewise, a small but not significant yield response to B addition was observed with the first crop, which was in the early stage of development when the trial began.

The lack of correlation of yield with leaf B concentration indicates that even though B is required for healthy tree growth, its concentration has no significant effect on yield provided it is adequate and not toxic. The quadratic relationship occurring after year-1, between B rate and yield, reflects the narrow range of tolerance between B-deficiency and B-toxicity common to most plants. Therefore, tissue analysis for B is suggested to growers and B application is recommended if leaf B levels are below 50 mg kg^{-1}. Although B rate was an important factor in causing B toxicity, the other main factor was tree size. Boron application rates, therefore, should consider tree size, in addition to foliar B levels.

There were no significant differences between the two sources of boron tested in their effect on foliar B levels, yield, or fruit deformity. Nearly all avocado growers in Kona broadcast granulated fertilizers, therefore, Borax is recommended at ~316 g $tree^{-1}$ per year on bearing trees with trunk diameters in the range of 10 to 20 cm. Solubor, a fine powder and highly soluble, is recommended at ~220 g $tree^{-1}$ per year, for growers with fertigation capability. Two split-applications per year are recommended, one prior to the spring- and one prior to the summer- vegetative flushes, respectively. Higher rates are only recommended for large trees (trunk diameters >20 cm) with severely deficient foliar B concentration (<25 mg kg^{-1}), in which case a third application may be required. However, applications should be reduced to the standard rate if leaf B levels increase to or above 75 mg kg^{-1}. In all cases, B additions should be terminated if leaf B levels increase above 75 mg kg^{-1}. Additional application may lead to serious B toxicity problems.

Application of Borax and Solubor at the recommended rates, assuming 50 trees planted to the acre, would result in a materials cost of \$19- and \$34- acre^{-1}, respectively. Assigning labor costs at \$8 per hour, and allowing one-hour to fertilize one acre would result in a total annual cost of \$35- and \$50- acre^{-1}, respectively. The annual yield gain required to pay for the added costs would be 90 pounds per acre (2 to 4 fruits per tree), assuming an average return of \$0.40/lb. Since boron applications increased yield ~35% on average, or 1,290 pounds per acre, it is concluded that yield gains outweigh the nominal costs.

Table 3.1. Elevation of 7 cooperating farms, initial size of 'Sharwil' trees, and rainfall in years -1 (June 1 - Dec. 31, 1990) and -2 (1991).

Farm	Elevation,	Trunk diameter	Canopy diam.	Rainfall yr 1	 yr 2
	--m--	-----cm [z]-----	-----m------	--------cm---------	
BE	610	17.2 (0.9)	4.4 (0.2)	92	123
KA	430	14.2 (1.0)	4.7 (0.4)	82	m
LA	550	17.6 (0.7)	4.4 (0.3)	m	m
MA	400	12.2 (0.6)	4.3 (0.2)	60	91
MC	260	25.5 (1.2)	7.3 (0.1)	73	112
ME	370	16.2 (1.9) [y]	6.2 (0.7)	60	88
NO	430	11.0 (0.4)	3.6 (0.1)	56	m

[z] Means are followed by standard errors of the mean, in parentheses.
[y] Only the largest stem was measured, when multiple stems occurred.
m Data either incomplete or not recorded.

Table 3.2. Initial soil characteristics at 7 cooperating farms.

Farm	pH H_20	pH KCl	N %	0C %	P	K ----------------$\mu g\ g^{-1}$-----------------	Ca	Mg	B
BE	6.5	5.8	0.5	7.2	117	160	2900	490	1.5
KA	5.6	5.1	0.9	11.1	9	112	4900	830	1.5
LA	6.4	5.8	0.7	11.2	349	197	6000	700	0.8
MA	7.3	6.5	0.6	8.5	173	520	6500	850	0.9
MC	5.6	5.0	0.8	9.9	86	171	4200	580	1.2
ME	5.6	5.0	0.7	9.2	445	170	5500	490	1.5
NO	6.3	5.6	0.6	11.6	55	225	6200	1000	0.5

* NH_4OAc extractable K, Ca, Mg; modified Truog extractable P.

Table 3.3. Soil boron levels, at 3 locations, one-year following final B applications (Oct. 1994).

B source: Solubor	B source: Borax	B applied per year	Farm: KA	Farm: ME	Farm: NO
------------g tree^{-1}		------------	------------------μg g^{-1}		------------------------
0	0	0	0.9 (0.16)	4.7 (0.18)^{y}	2.1 (0.01)
110	0	69	3.6 (0.64)	4.9 (1.17)	8.7^{z}
0	158	69	5.1 (0.56)	6.8 (0.77)	6.4 (1.07)
220	0	138	3.5 (1.08)	7.3 (2.56)	10.8 (0.97)

Means followed by standard error in parentheses.

^{z} Data represents one sample.

^{y} Farmer applied B during the year.

Table 3.4. Analysis of variance of boron treatment effects at six locations, over 4-year period, on foliar B concentration, cumulative yield, and fruit deformity.

		Leaf B, mg kg^{-1}	Yield, no. fruits tree^{-1}	Yield, kg tree^{-1}	Deformity, incidence tree^{-1} (%)
ANOVA	--df--	------------------------PR > F			------------------------------
B treatments	3				
Solubor, linear	(1)	0.0001	0.67	0.67	0.69
Solubor, quad.	(1)	0.46	0.09	0.12	0.88
Sol.$_{110}$ vs Borax $_{158}$	(1)	0.96	0.25	0.32	0.50
Location	5	0.0001	0.00004	0.00001	0.0001
Year	3^{z}	0.0001	0.04	0.01	0.0001
B x Year	9	0.04	0.20	0.18	0.57
Location x Year	15	0.0008	0.05	0.16	0.002

^{z} Degrees of freedom = 1 for yield data (2 - year cumulative yields).

Table 3.5. Effect of boron additions on cumulative 2-year avocado yield.

B source		B applied	Cumulative Yield	
Solubor	Borax	per year	Years 1+2	Years 3+4
--------------g tree^{-1}---------------			----------------kg tree^{-1}-----------------	
0	0	0	68.3 (16.4)	62.3 (27.5)
110	0	69	96.9 (20.2)	80.5 (44.5)
0	158	69	100.8 (28.3)	51.2 (27.4)
220	0	138	85.1 (32.8)	52.1 (26.3)

Means followed by standard error in parentheses.

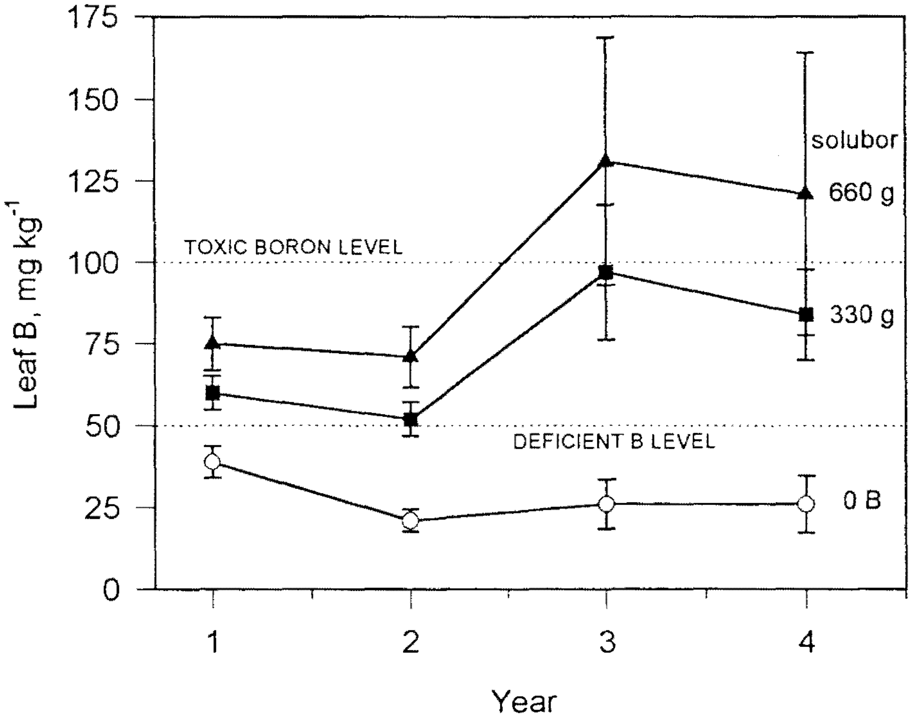

Fig. 3.1. Effect of soil-applied B on 'Sharwil' leaf B level over time. Solubor applied in 3 split-applications. Control trees were untreated. Leaves were sampled each October.

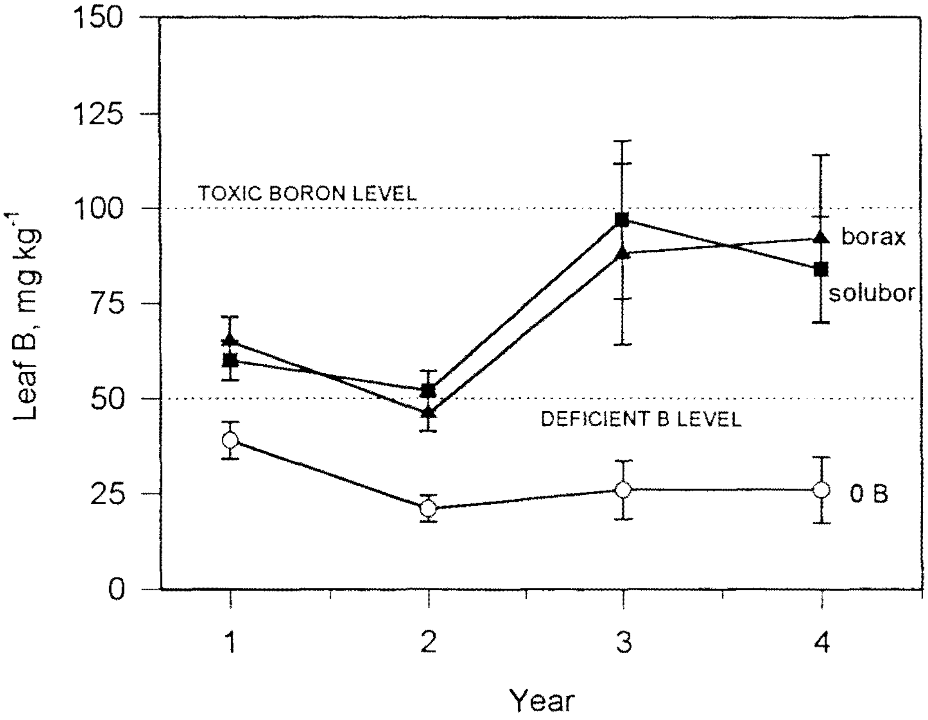

Fig. 3.2. Effect of borax and Solubor fertilizers on 'Sharwil' leaf B level over time, when applied at the rate of 23 g B per application.

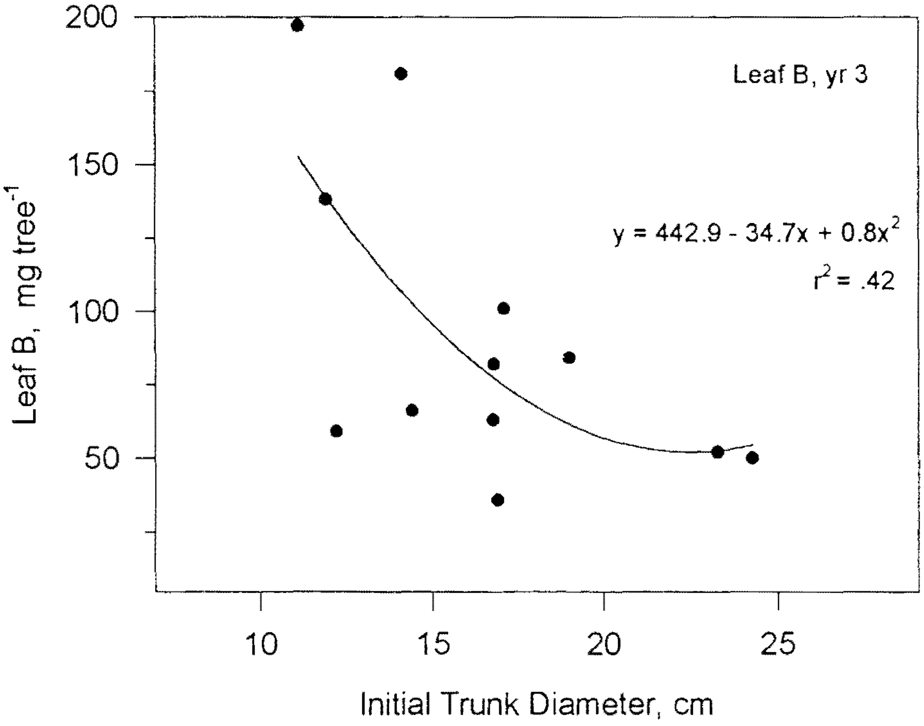

Fig. 3.3. Relationship between initial trunk diameter and leaf B concentration at year 3, in trees receiving either 110 g Solubor or 158 g Borax, 3 times per year (69 g B per year).

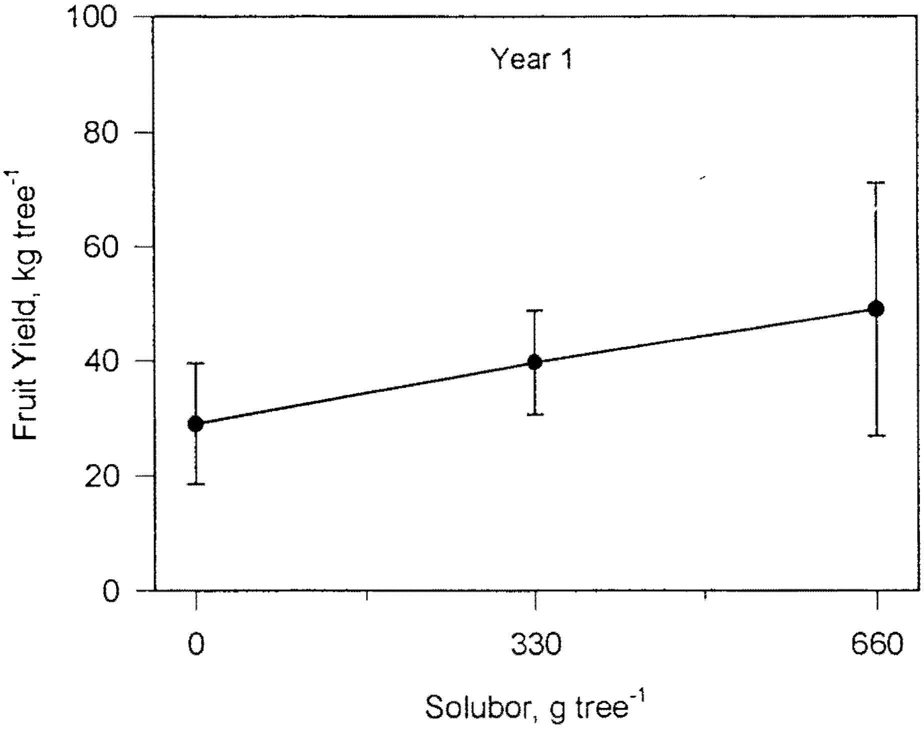

Fig. 3.4. Effect of soil-applied B on per tree yield of 'Sharwil' avocado in year 1. Solubor applied in 3 split-applications. Control trees were untreated.

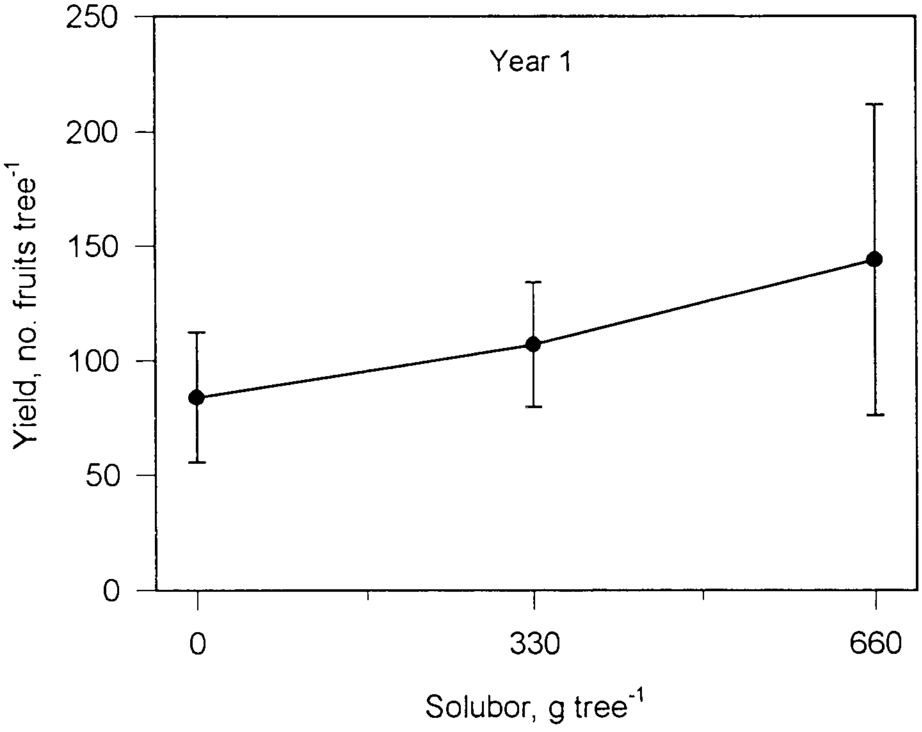

Fig. 3.5. Effect of soil-applied B on per tree yield of 'Sharwil' avocado in year 1. Solubor applied in 3 split-applications. Control trees were untreated.

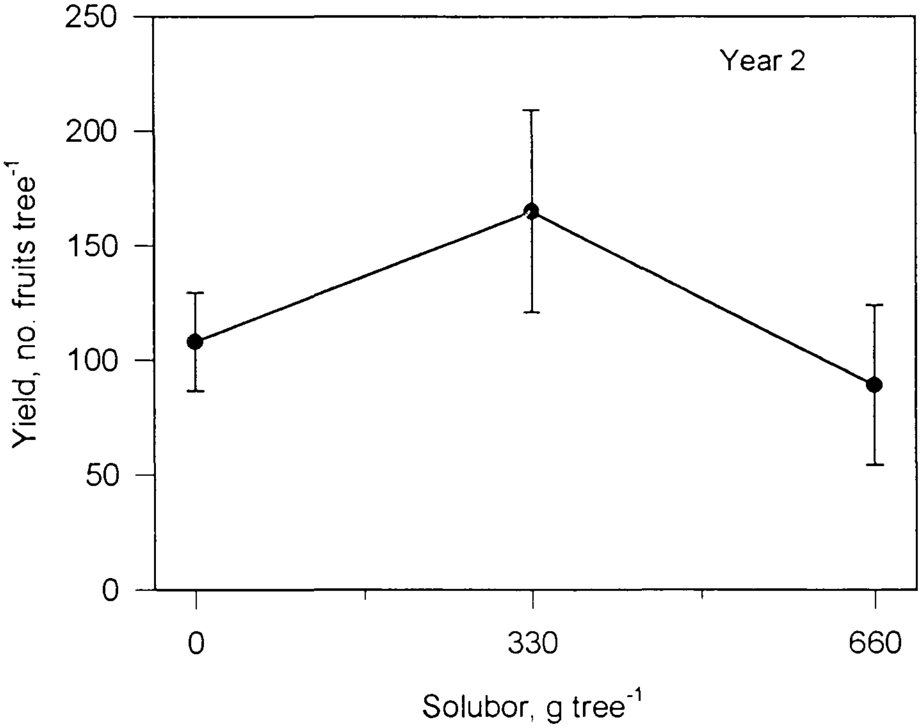

Fig. 3.6. Effect of soil-applied B on per tree yield of 'Sharwil' avocado in year 2. Solubor applied in 3 split-applications. Control trees were untreated.

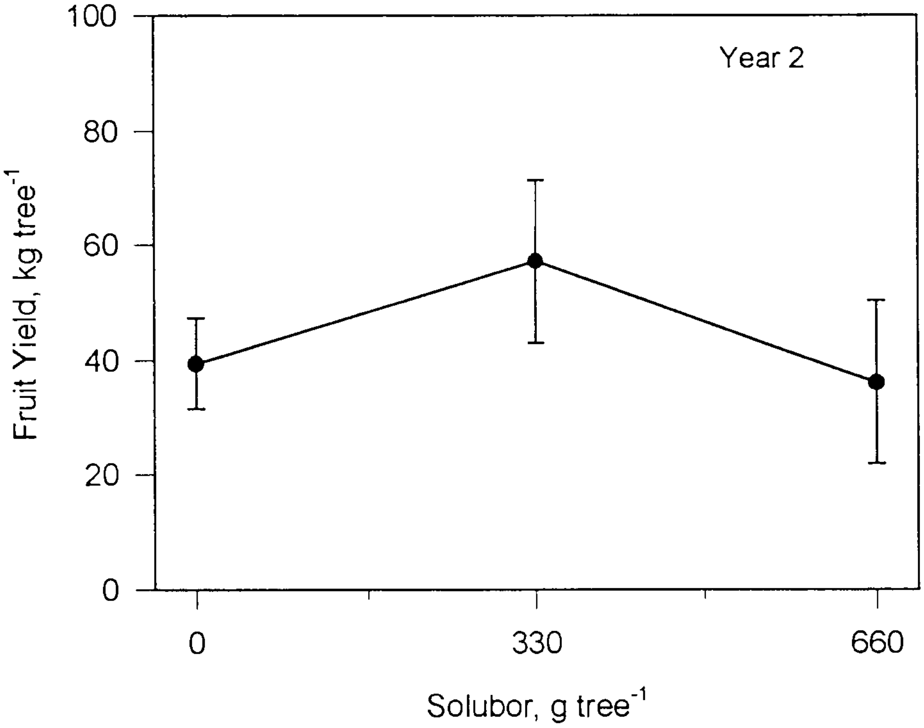

Fig. 3.7. Effect of soil-applied B on per tree yield of 'Sharwil' avocado in year 2. Solubor applied in 3 split-applications. Control trees were untreated.

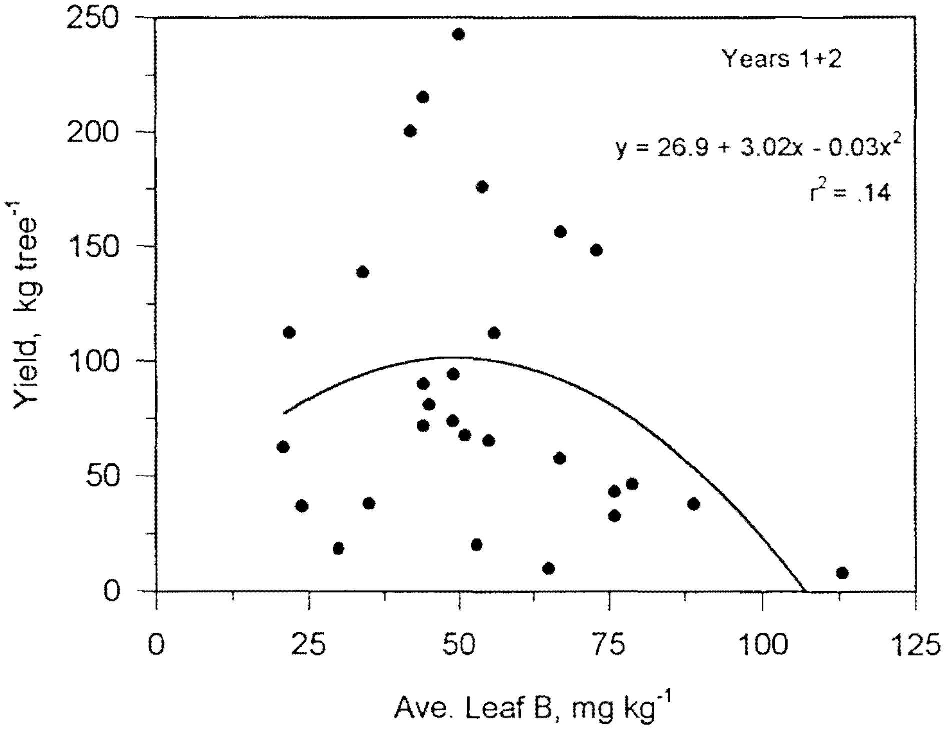

Fig. 3.8. Relationship between average leaf-B level for years 1 & 2 and cumulative yield per tree for years 1 & 2.

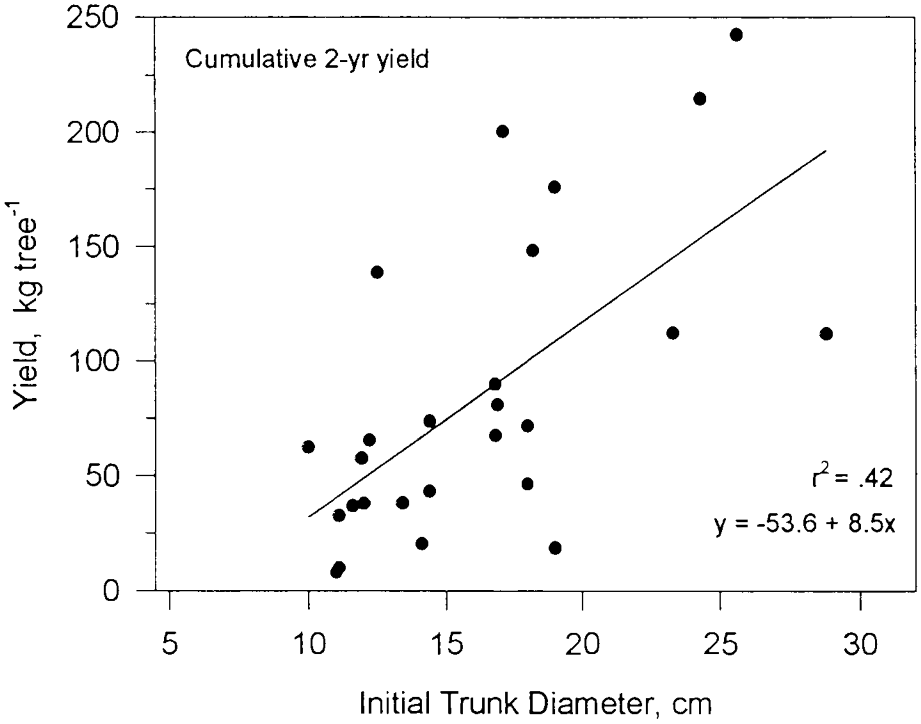

Fig. 3.9. Relationship between initial trunk diameter and total cumulative yield per tree for years 1 and 2.

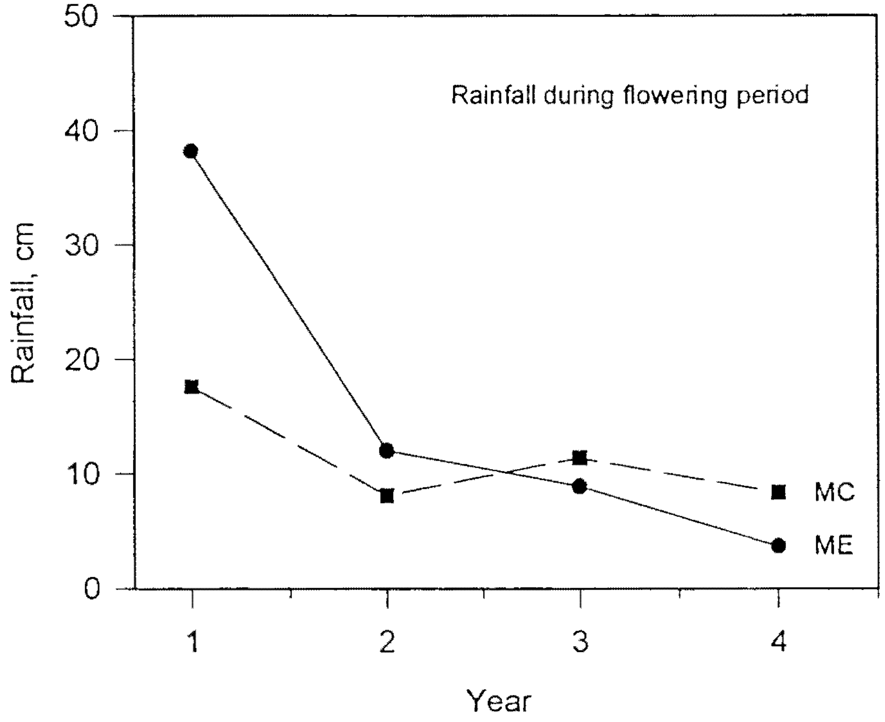

Fig. 3.10. Rainfall patterns during the critical water stress period of flowering and early fruit development (January through March). Data from two representative locations (MC, ME).

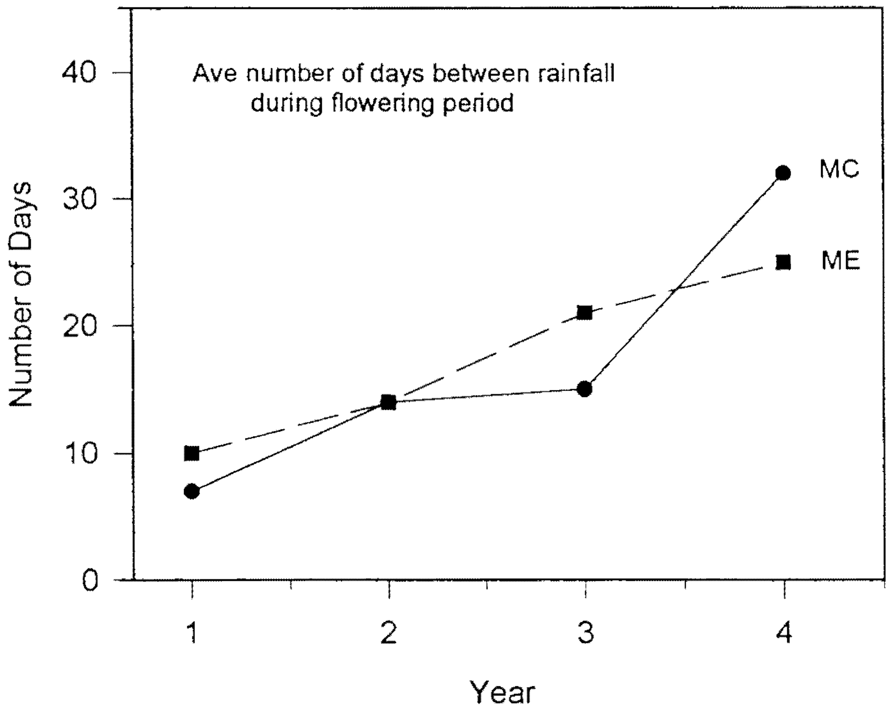

Fig. 3.11. Average number of days between significant rainfall (>0.6 cm) during flowering and early fruit development (January through March). Data from two representative locations (MC, ME).

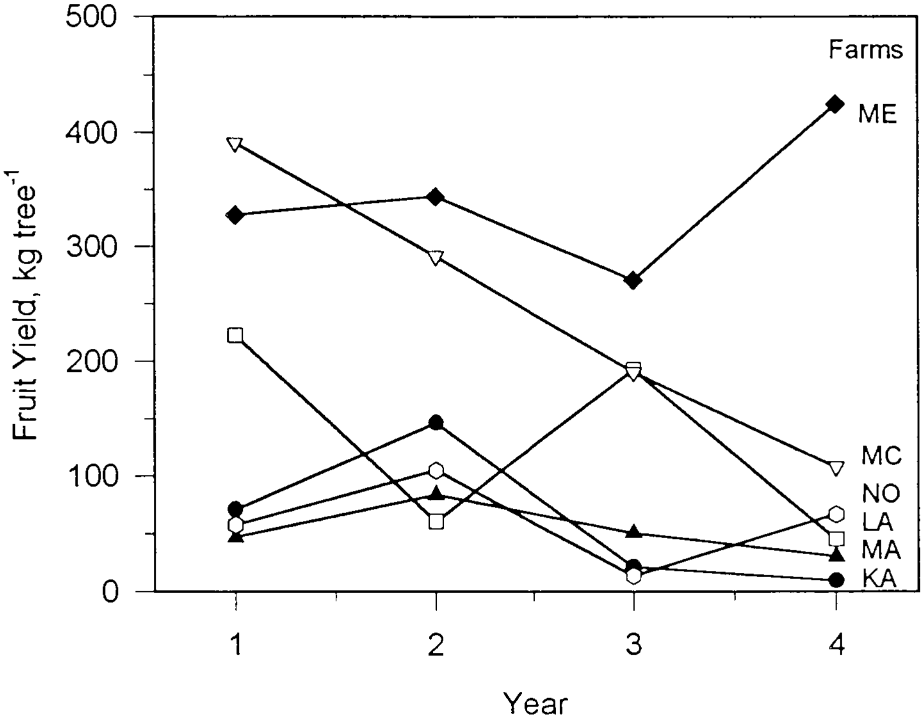

Fig. 3.12. Total yield over time, of experimental trees combined at each of six locations.

CHAPTER 4. FOLIAR APPLICATION OF BORON

A. Materials and Methods

A preliminary field trial was conducted to determine the effects of foliar B sprays on avocado leaf- and flower- B concentration, fruit set, yield, and fruit deformity.

Location

The trial was conducted using six-year old 'Sharwil' avocado trees at site KA from Trial 1 (Table 3.1). The farm was located in Honaunau, at 430 m elevation, where uniformly selected trees were maintained under rainfed conditions.

Design and Field Operations

The trial ran from February, 1994 to October, 1994. Treatments included an unsprayed control and three levels of Solubor (5-, 10-, and 15- g L^{-1}), replicated 6 times in a completely randomized design. Since B is required continuously during flowering a split-application was included, wherein one treatment (10 g L^{-1} Solubor) was repeated at the same concentration 9 days following initial application. Foliar sprays were applied with a hand-held sprayer to the point of run-off, using 6 L per tree. Thus, total B applied was 0, 6, 25, and 18 g $tree^{-1}$, respectively.

Treatments were applied when most trees in the orchard were between the early- and mid- bloom stage (February 19, 1994). Sharwil flowers (type A) are pollen receptive when they open during the afternoon on the first day of their two-day lifespan (Chia & Evans, 1987). Thus, trees were sprayed in the afternoon to allow for direct absorption by flower structures. Trees were observed for 10 days after each application to detect spray damage.

Collection of Samples and Data

Leaf samples were collected for B analysis at 2-, 7-, and 35- days after treatment. Samples were prepared for analysis as described in Trial 1; leaves were rinsed three times in deionised water to ensure removal of B-spray residue from their surfaces. Flower samples were collected for B analysis at 2- and 7- days after treatment and consisted of 100 open blossoms randomly selected from the perimeter of each tree. Although these mature flowers were not open when the B-spray was applied, they were rinsed and prepared for analysis similar to the leaf samples to remove residues from their outer surfaces.

Fruit set measurements were made one month after treatment by counting fruit on 5 previously selected branches per tree. Branches were selected randomly around the perimeter of each tree between 1 to 2.5 m above ground level. Fruit retention was measured throughout the season by counting the remaining fruit 2-, 4-, and 8- months after treatment. Deformity observations were recorded 4- and 8-months after treatment by counting the number of slightly deformed- and severely deformed- fruit per branch for each tree. Fruit deformity was assessed in the same manner as in trial 1 (Chapter 3), even though certain deformity symptoms are characteristic of B deficiency.

Statistical Analysis

Statistical analyses were conducted using SAS computer programs (SAS Institute, Inc., Cary, NC). Analysis of variance (ANOVA) was utilized to determine treatment effects. Regression analysis was used to examine treatment effects over time; and to determine relationships between flower B concentration and fruit set, yield, and fruit deformity. General linear models (GLM) procedure was utilized to evaluate linear and quadratic models on all parameters. Single degree of freedom contrasts were used to compare flower B levels between sample dates at each treatment; and to compare fruit set between treatments. All data were examined for differences at the P= 0.05 level for significance.

B. Results and Discussion

Foliar B Concentration

Boron sprays were absorbed readily by avocado leaves, resulting in up to a 3-fold increase in B concentration 2 days after application (Table 4.1). Leaf B increased linearly (P=0.0001) with Solubor rate, from 33 mg kg^{-1} in control trees to 94 mg kg^{-1} in trees at the highest rate. However, only the two highest concentrations (10- and 15- g L^{-1}) elevated leaf B above the recommended minimum level of 50 mg kg^{-1} (Piccone & Whiley, 1987) (Fig.4.1).

Results were consistent with 3-fold increases in leaf B concentration found with prune (Hanson et al., 1985) and hazelnut (Shrestha et al., 1987). Results differed from those found on avocado in South Africa and California, where leaf B concentration either did not increase significantly (Robbertse et al., 1992), increased only 10 mg kg^{-1} (Lovatt, 1994), or increased 15 to 20 mg kg^{-1} (Robbertse et al., 1990). However, the Solubor concentrations (1- and 2- g L^{-1}, respectively) utilized in those studies were 5 to 15 times lower than the rates applied in this trial.

Boron concentrations in treated leaves decreased rapidly between 2- and 7-days after application (Fig. 4.1). Foliar B at the lowest rate decreased linearly (P=0.03) over 35 days to levels similar to untreated leaves, whereas leaf B concentration at the highest rate decreased quadratically (P=0.09) and remained above the minimum requirement for 35 days. Trees at the middle rate (10 g L^{-1}), however, exhibited a slight increase in leaf B between day 7 and day 35, possibly due to the second B split-application applied on day 9, thus resulting in no significant decline overall (P= 0.89). This rapid decline in leaf B concentrations, similar to that reported for apple, pear, and plum (Hanson, 1991), suggests applied B was translocated readily from leaves, possibly to developing flowers.

Flower B Concentration

In control trees B concentration of flowers was higher than that of leaves, perhaps reflecting the high B demand in flowers (Table 4.1). Foliar B-sprays resulted in very highly significant increases in B concentration of 'Sharwil' inflorescences that first opened either 2 days - or 7 days - after application (Table 4.1). However, at both the 10- and 15- g L^{-1} rates, flowers maturing 7 days after treatment contained significantly lower B levels (P=0.03 and 0.04, respectively) compared to the flowers sampled at day 2. The decrease in B level reflects both the need for a continuous supply of B to flowers and the temporary benefit of B-sprays. Although B-spray effects diminished over time, average B level in flowers 7 days after application at the highest two rates were 50 to 70 mg kg^{-1} higher than untreated flowers and above the target level of 100 mg kg^{-1}, the level considered necessary for optimal pollen tube growth in avocado flowers (Robbertse et al., 1992). Flower B concentrations at the low rate, however, were similar to controls.

Results were consistent with those reported in 'Hass' avocado (Robbertse et al., 1990). Although foliar B sprays significantly increased B concentration of 'Hass' flowers, they were unable to increase the B level above 30 mg kg^{-1}. The dramatically higher B level in flowers (and leaves) in our trial is ascribed to the use of much higher B-spray concentrations (5 -15X) and different application timing.

In similar studies, B-sprays were applied prior to bud break for mango (Singh & Dillon, 1987; Rajput et al., 1976), at bud break and/or opening of the first flowers on the panicles for avocado in South Africa (Robbertse et al., 1990; Robbertse et al., 1992), and between budbreak and first flower opening for avocado in California (Lovatt, 1994). It is presumed these timings were chosen to specifically avoid direct spray contact on inflorescences, probably due to the concern in causing tissue damage to floral structures. In these instances, researchers relied on the ability of sprays to increase foliar B to levels high enough to supply free boron for transport to the developing flowers. After reviewing the literature, we concluded differently, that foliar B-sprays should be applied during bloom when B demand is greatest and flowers are present to absorb B directly from the spray solution.

Since mature avocado leaves are covered by a waxy cuticle and leaf absorption of B was limited in the studies cited above, we further decided that considerably higher B spray concentrations are necessary to increase tissue B levels to the desirable range. In addition, it should be noted that 'Sharwil' is especially prone to

B-deficiency, whereas the 'Hass' avocado trees in the other studies were not B deficient. We speculated, therefore, that higher B-spray concentrations may be required to increase 'Sharwil' flower B levels compared to 'Hass' flowers. In fact, the two highest treatments each increased the B concentration in flowers above 100 mg kg^{-1}, the level considered to be necessary for optimal pollen tube growth in avocado flowers (Robbertse et al., 1992).

Fruit Set and Yield

Foliar application of increasing boron rates resulted in a significant linear increase in fruit set compared to unsprayed trees (Table 4.2). Fruit set increased more than 3-fold, from 105 fruits per five stems in control trees to 369 fruits per five stems in trees at the highest Solubor rate. The low (5 g L^{-1})- and middle (10 g L^{-1})-rates increased fruit set more than 2-fold, however, they were not statistically different from each other (P=0.21). Similar increases due to B sprays in fruit set were reported in mango (Rajput et al., 1976), in which fruit set increased up to 40% compared to controls. Studies with avocado did not report initial fruit set data (Lovatt, 1994; Robbertse et al., 1992).

Regression analysis revealed a significant (P=0.017), but not particularly strong (r^2=.25), relationship between flower B level at 7 days after treatment and fruit set (Fig. 4.2). Results suggest that flower B levels do, in fact, influence pollen tube growth and fertilization in 'Sharwil' avocado. In general, lowest fruit set was related to flower B levels between 50 to 75 mg kg^{-1}, and highest fruit set occurred on trees with flower B at 100 to 150 mg kg^{-1}. It is interesting to note that the flower B concentration in the tree that set the highest number of fruit was 100 mg kg, the level considered optimal (Robbertse et al., 1992). However, other important factors are involved in fruit set, including general nutritional status of trees, whether its an on-year or an off-year for fruit-bearing, and presence of environmental stresses.

Avocado trees typically set far more fruit than they can carry to maturity and, thus, fruit set is normally followed by a several month period of fruit drop. The B-spray effect on fruit set diminished during this time and fruit retention per tree approached that of control trees within 2 months of application (Fig. 4.3). By the time the fruit were near maturity (8 months) there were no significant (P=0.33) differences in the number of avocados per shoot. This result may be misleading, however, due to inadequate sampling methods. Total fruit yields per tree were not measured, due to previous termination of the on-farm trials. Lack of yield response due to B sprays was similarly reported for 'Hass' avocado in South Africa (Robbertse et al., 1992). In contrast, Lovatt (1994) observed a 50% increase in yield over control trees when a single application of B spray occurred during early bloom, and a 25% yield gain when 2 split-applications were applied.

Fruit Deformity

Foliar B-sprays significantly decreased deformity of 'Sharwil' fruit (Table 4.2). The total incidence of deformity per tree decreased from 64% in controls to 42% at 5 g L^{-1}, 28% at two applications of 10 g L^{-1}, and 33% at the highest rate (15 g L^{-1}). Most of the improvement was due to a marked reduction in severely-deformed fruit, which declined from a 32% incidence in controls to affecting only 10% or less of the fruit at either of the two highest rates (Fig. 4.4). A highly significant (P=0.01) quadratic relationship existed between flower B level and overall incidence of deformity (Fig. 4.5), providing further evidence that B deficiency in some flowers contributed to the development of malformed fruit. In general, fruit deformity decreased as flower B level increased from 50- to 125 mg kg^{-1}.

Results are similar to those reported on papaya (Wang & Ko, 1975), however, they found that B-sprays corrected nearly 100% of the fruit malformation. It is interesting to note, that all 'Sharwil' trees with incidence of deformity >60% contained flower B near 50 mg kg^{-1} and all trees with less than 20% affected fruits contained flower B at approximately 100 mg kg^{-1} (Fig. 4.4). The fact that deformity still affected ~30% of avocado fruits suggests that ample B may not have been supplied continuously throughout flowering. Another possible explanation is that other factors may have contributed to fruit malformation, such as zinc-deficiency and damage due to feeding insects.

C. Conclusion

Although additional replicated work needs to be done, it is concluded that B-deficiency in flowers contributes to avocado fruit deformity in Kona, Hawaii. Results also indicate that foliar B-sprays are an effective method of supplying B to 'Sharwil' flowers and reflect favorably on our hypothesis that application should occur during bloom. In a similar study, Lovatt (1994) found that trunk injections increased B content of leaves but did not increase yields, whereas early bloom sprays successfully increased both leaf B and yield, providing strong evidence that B must be applied directly onto the developing flowers.

Solubor, applied either twice at 10 g L^{-1} or once at 15 g L^{-1} reduced incidence of deformity by 50 percent. The high concentration (15 g L^{-1}), however, was more effective in increasing leaf B, flower B, and fruit set, respectively. Both treatments increased flower B above 100 mg kg^{-1}, the level considered optimal for best pollen tube growth and fruit set. Results are in agreement with our hypothesis that Solubor concentration should be considerably higher than that utilized in previous studies (1 - 2 g L^{-1}) with avocado (Lovatt, 1994; Robbertse et al., 1992).

Finally, although fruit retention data indicated no significant increase due to B-sprays, we suggest that total yields per tree (had they been measured) may have shown otherwise. Fruit retention 8 months after spraying was 4 fruit per shoot at the highest Solubor rate (15 g L^{-1}) versus 2 fruits per shoot at all other treatments. If this relationship occurred throughout the tree then a significant yield increase would have resulted. More importantly, deformed fruits are reduced to one-half the value of grade-1 fruits (~$0.50/lb.) and become unmarketable when damage is extremely severe, resulting in significant income loss. Therefore, B-sprays that result in up to 50 percent reduction in off-grade fruit would provide welcome economic relief to current 'Sharwil' avocado growers in Kona.

Table 4.1. Effect of foliar B sprays applied during bloom (19 Feb. 1994) on B concentration of leaves and flowers. Data are means from 6 trees.

Solubor	B applied	Leaf B			Flower B	
		2 days	7d	35d	2 days	7d
g L^{-1}	g tree^{-1}	----------------mg kg^{-1}------------------			-----------mg kg^{-1}------------	
0	0	33 (9.6)	33 (8.9)	43 (13.4)	75 (25.6)	57 (4.0)
5	6	44 (1.6)	40 (4.2)	32 (11.2)	90 (11.2)	77 (8.4)
10[z]	25	66 (5.6)	57 (6.0)	64 (6.8)	156 (23.3)	106 (8.9)
15	18	94 (10.1)	70 (6.0)	69 (9.5)	232 (43.3)	128 (15.8)
<u>ANOVA: PR>F</u>						
B, linear		0.0001	0.0002	0.0169	0.0002	0.0001
B, quad.		0.2400	0.6300	0.4500	0.2500	0.9500

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* Means are followed by standard errors of the mean, in parentheses.

[z] Repeated 9d after initial application at same Solubor concentration (10 g L^{-1}).

Table 4.2. Effect of foliar B sprays applied during bloom (19 Feb. 1994) on fruit set and incidence of deformity. Stem data are totals from 5 stems tree^{-1}.

Solubor	B applied	Fruit set[x]	Incidence of Deformity[y]		
			Slight	Severe	Total
g L^{-1}	g tree^{-1}	no.of fruits tree^{-1}	---------------------%------------------------		
0	0	105 (25.0)	32 (4.8)	32 (3.8)	64 (7.3)
5	6	273 (82.8)	27 (5.4)	15 (3.5)	42 (3.7)
10[z]	25	251 (56.6)	18 (6.5)	10 (4.8)	28 (6.9)
15	18	369 (88.4)	24 (8.5)	9 (3.4)	33 (7.2)
ANOVA: PR>F					
B, linear		0.0170	0.2500	0.0006	0.0018
B, quad.		0.2400	0.4200	0.0426	0.0450

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* Means are followed by standard errors of the mean, in parentheses.

[x] Recorded 1 month after treatment (26 Mar. 1994).

[y] Recorded 4 m after treatment.

[z] Repeated 9d after initial application at same Solubor concentration (10 g L^{-1}).

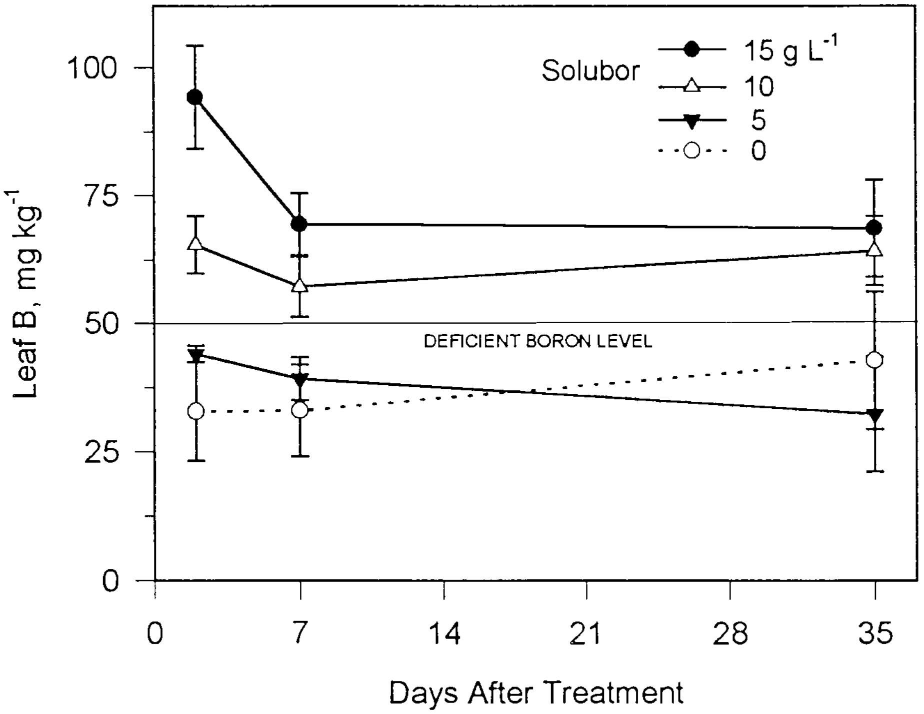

Fig. 4.1. Change in B levels over time of 'Sharwil' leaves treated with foliar bloom B-sprays on 19 Feb. 1994 compared to unsprayed controls.

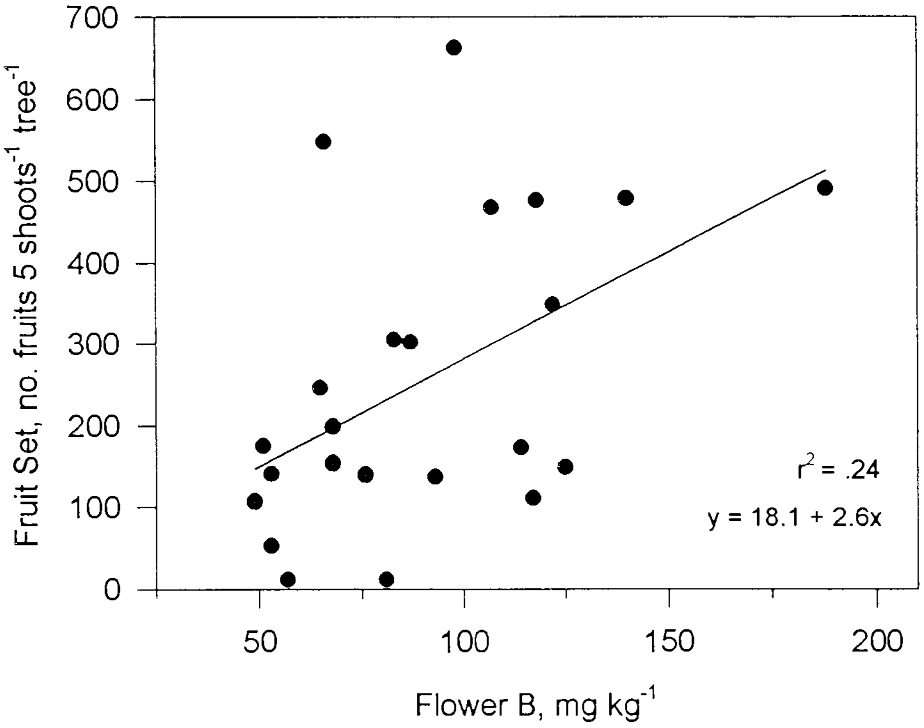

Fig. 4.2. Relationship between flower B level of mature flowers, sampled seven days after treatment, and fruit set observed one month later.

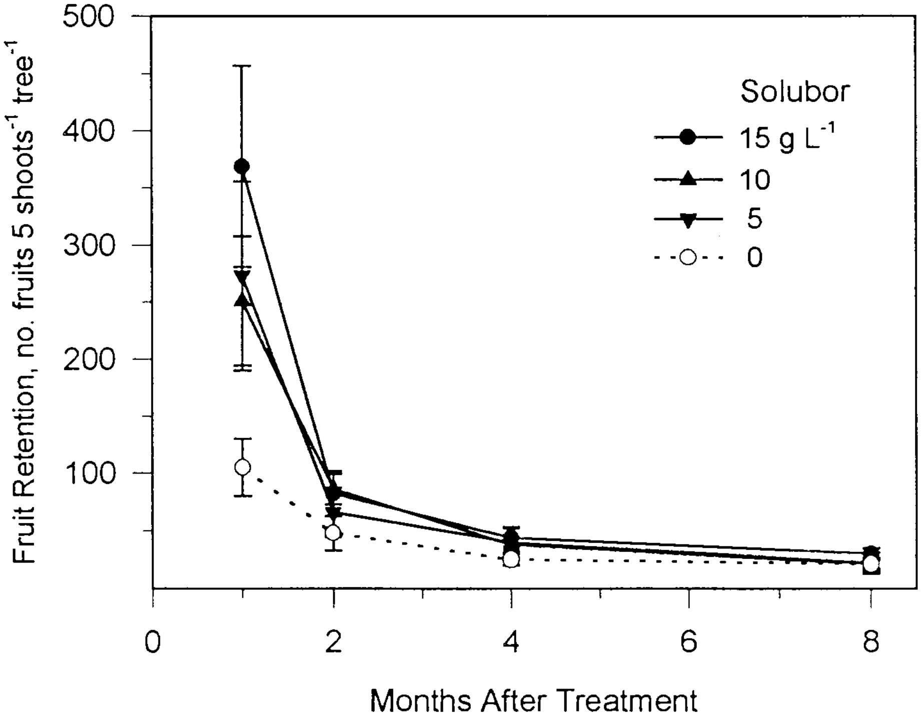

Fig. 4.3. Effect of foliar bloom B-sprays on fruit set and yield. Fruit set recorded 1mo. (26 Mar. 1994) after treatment. Fruit retention recorded at several intervals as the total number of fruits retained on five shoots tree^{-1}.

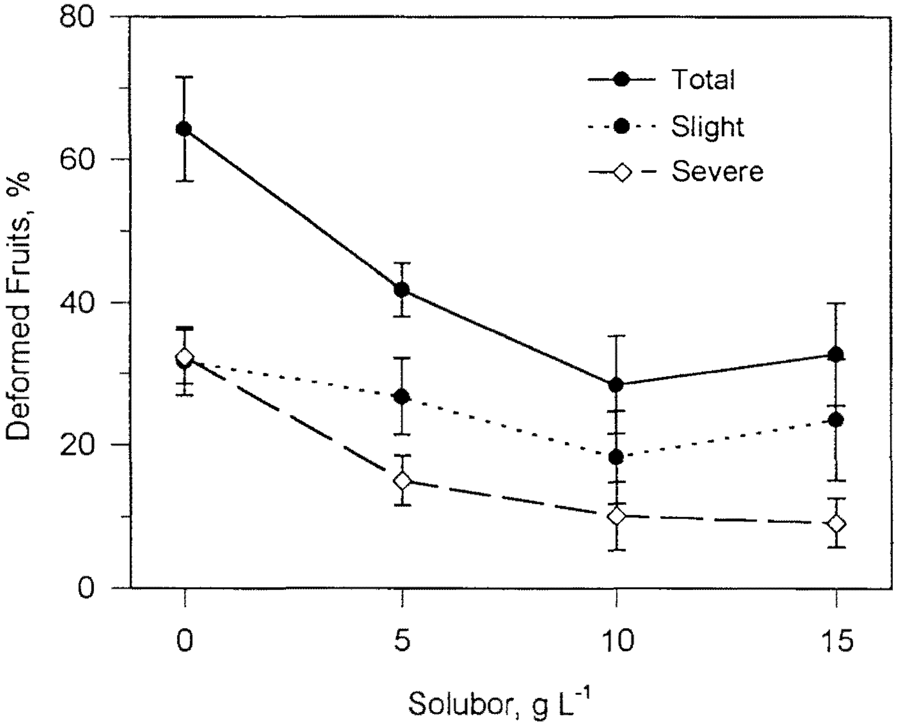

Fig. 4.4. Effect of foliar bloom B-sprays on incidence of deformed 'Sharwil' fruits recorded 4 m after treatment. Total is the sum of percentages of slightly- and severely- deformed fruits tree^{-1}. Points represent the means of six trees.

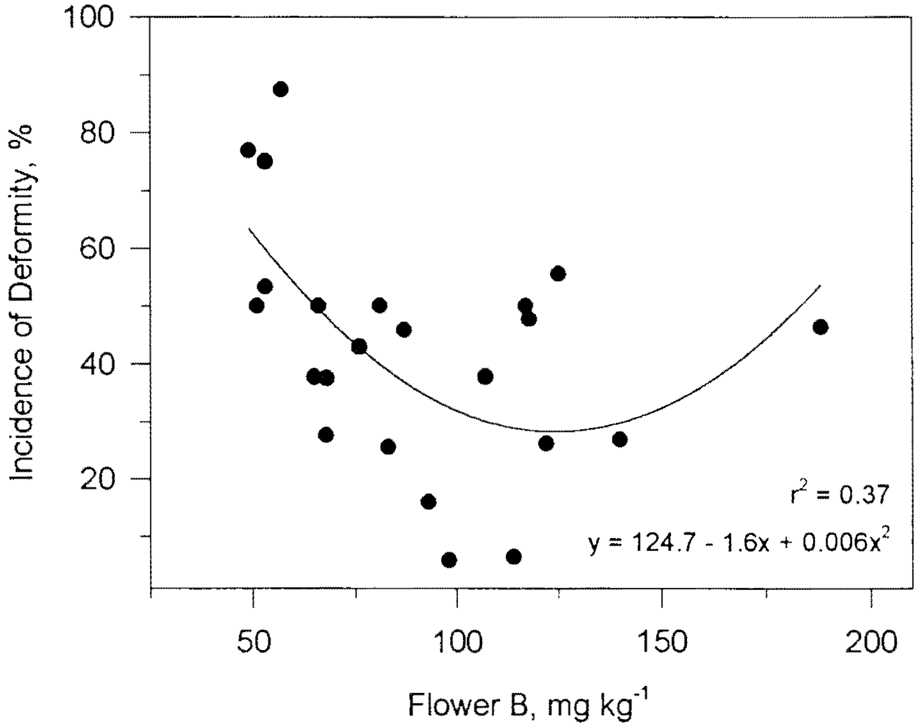

Fig. 4.5. Relationship between flower B level of mature flowers, sampled seven days after treatment and incidence of fruit deformity, observed four months later.

SUMMARY

Results from this study affirmed several previously known characteristics of boron nutrition of plants. For instance, we found that not only do avocado trees respond rapidly to B additions, but the range between deficient- and toxic- plant B levels is indeed narrow; and that repeated B additions may result in tree fatality. Thus, tree B levels should be monitored annually through leaf tissue analysis and B should only be added when the need is certain. Further, we found that drought does seem to influence B deficiency symptoms in 'Sharwil' avocados in Kona.

Results also confirmed our hypothesis that B deficiency seriously affected production and quality of 'Sharwil' avocados grown in low-B soils in Kona. In general, B applied to the soil during the rainy season (spring/summer) provided sufficient B for normal vegetative growth and fruit development, and increased yields, but did not influence fruit deformity. In contrast, foliar bloom B sprays were more effective in providing B during the peak B demand period of flowering/fruit set in the winter dry season when soil conditions were unfavorable for uptake. Foliar bloom B sprays significantly reduced fruit deformity and thus showed promise as a valuable tool for avocado growers in rainfed conditions, particularly during severe winter droughts.

APPENDIX

A. Data, Trial 1: Soil-applied Boron

Year 1					G1		G1_DEF		G2_DEF		G2_OTHE		G3		Total / tree	
Loc	Yr	Tre	Trt	Lf B	No.	lbs	No.	lbs	No.	lbs	No.	lbs	No	lbs	No.	lbs
BE	1	10	0	59	21	17.44	10	8.50	26	19.44	7	5.63	6	5.44	70	56.44
KA	1	10	0	45	15	13.38	1	1.06	2	1.63	0	0.00	1	1.75	19	17.81
LA	1	10	0	49	62	38.00	4	2.56	0	0.00	0	0.00	1	0.44	67	41.00
MA	1	10	0	37	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
MC	1	10	0	28	125	93.75	0	0.00	23	5.88	9	6.69	0	0.00	157	106.31
ME	1	10	0	33	167	144.38	5	4.50	15	11.25	14	11.06	12	8.94	213	180.13
NO	1	10	0	23	30	24.38	11	7.38	12	7.63	11	6.50	0	0.00	64	45.88
BE	1	5	110	76	24	21.38	16	14.88	29	24.63	21	19.50	0	0.00	90	80.38
KA	1	5	110	66	46	38.69	14	4.38	25	18.8	4	2.56	0	0.00	89	64.38
LA	1	5	110	38	79	75.13	5	3.94	1	0.94	4	2.81	3	2.31	92	85.13
MA	1	5	110	52	10	9.13	0	0.00	5	4.00	0	0.00	2	1.63	17	14.75
MC	1	5	110	73	186	128.81	17	10.25	33	19.56	5	3.50	0	0.00	241	162.13
ME	1	5	110	51	111	109.38	2	2.03	8	6.47	18	17.13	18	17.4	156	152.38
NO	1	5	110	67	35	30.00	19	15.38	6	4.25	6	4.00	0	0.00	66	53.63
BE	1	13	220	79	1	0.88	2	1.94	0	0.00	1	0.94	3	2.75	7	6.50
KA	1	13	220	86	11	12.06	2	1.81	4	3.88	1	0.94	0	0.00	18	18.69
LA	1	13	220	60	109	73.06	52	40.50	108	75.56	25	16.50	2	1.38	296	207.00
MA	1	13	220	114	12	11.13	0	0.00	1	0.88	0	0.00	7	6.00	20	18.00
MC	1	13	220	47	384	279.75	8	5.00	57	34.31	5	3.44	0	0.00	454	322.50
ME	1	13	220	62	192	166.88	3	3.25	14	10.63	2	1.31	0	0.00	211	182.06
NO	1	13	220	74	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
BE	1	14	brx	88	0	0.00	0	0.00	0	0.00	2	1.25	2	1.38	4	2.63
KA	1	14	brx	58	54	40.75	4	2.94	9	6.44	11	4.81	2	1.25	80	56.19
LA	1	14	brx	58	136	98.25	31	22.69	23	16.00	29	19.00	2	1.56	221	157.50
MA	1	14	brx	65	52	38.81	0	0.00	2	8.75	2	1.50	24	21.50	80	70.56
MC	1	14	brx	51	373	231.56	0	0.00	37	20.63	25	16.19	3	1.81	438	270.19
ME	1	14	brx	45	209	178.81	2	1.69	10	9.69	14	12.38	5	4.31	240	206.88
NO	1	14	brx	89	23	22.38	0	0.00	0	0.00	6	5.31	0	0.00	29	27.69

Key:

Loc= Location; Tre= tree #; Yr= Year, 1-4; Trt= 0, 110, 220 g Solubor or 158 g Borax tree^{-1};

Lf B= Leaf B concentration, mg kg^{-1}; No.= number of fruits tree^{-1}; lbs= pounds tree^{-1};

G1= grade 1, undeformed fruit; G1_DEF= grade1, slightly deformed fruit;

G2_DEF= grade 2, severely deformed fruit; G2_OTHE= grade 2 fruit not due to deformity;

G3= grade 3, unmarketable fruit; Total / tree= all grades combined.

Year 2					G1		G1_DEF		G2_DEF		G2_OTHE		G3		Total / tree	
Loc	Yr	Tre	Trt	Lf B	No.	lbs	No.	lbs	No.	lbs	No.	lbs	No	lbs	No.	lbs
BE	2	10	0	28	41	27.75	58	37.50	16	9.75	42	26.38	0	0.00	157	101.38
KA	2	10	0	25	47	43.31	18	16.38	4	3.19	1	0.56	6	3.53	75	66.97
LA	2	10	0	11	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
MA	2	10	0	11	60	52.63	31	24.13	6	4.38	0	0.00	0	0.00	97	81.13
MC	2	10	0	16	131	125.75	13	11.00	2	1.19	3	2.75	0	0.00	149	140.69
ME	2	10	0	35	124	105.91	22	14.32	8	5.40	0	0.00	0	0.00	153	125.63
NO	2	10	0	19	62	49.13	27	19.00	7	4.63	17	11.75	11	6.81	124	91.31
BE	2	5	110	69	146	100.63	84	50.88	24	14.88	130	79.88	0	0.00	384	246.25
KA	2	5	110	32	58	43.44	53	38.06	14	9.50	2	1.06	9	6.06	135	98.13
LA	2	5	110	49	144	104.25	12	7.81	1	0.75	0	0.00	0	0.00	157	112.81
MA	2	5	110	54	16	16.75	12	11.25	2	2.00	0	0.00	0	0.00	30	30.00
MC	2	5	110	38	101	72.69	12	8.25	4	2.81	2	1.50	0	0.00	119	85.25
ME	2	5	110	56	203	195.29	19	32.33	9	7.79	0	0.00	0	0.00	230	235.41
NO	2	5	110	67	34	29.47	33	28.25	11	7.75	6	5.44	3	2.56	86	73.47
BE	2	13	220	78	64	59.25	26	22.38	6	4.19	11	9.75	0	0.00	107	95.56
KA	2	13	220	91	56	50.00	14	10.56	6	4.06	0	0.00	0	0.00	75	64.63
LA	2	13	220	37	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
MA	2	13	220	111	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
MC	2	13	220	53	207	187.75	24	21.50	3	2.75	0	0.00	0	0.00	234	212.00
ME	2	13	220	72	174	153.83	12	8.36	0	0.00	0	0.00	0	0.00	186	162.19
NO	2	13	220	57	13	12.38	9	7.81	0	0.00	2	2.00	0	0.00	24	22.19
BE	2	14	brx	63	55	45.25	30	23.00	6	3.75	27	20.75	0	0.00	118	92.76
KA	2	14	brx	43	55	44.44	35	26.69	13	10.06	3	2.09	10	9.16	114	92.44
LA	2	14	brx	32	20	17.50	4	3.50	0	0.00	0	0.00	0	0.00	24	21.00
MA	2	14	brx	44	67	54.50	25	19.00	0	0.00	0	0.00	0	0.00	92	73.50
MC	2	14	brx	37	218	187.75	17	13.50	0	0.00	3	2.50	0	0.00	238	203.75
ME	2	14	brx	40	103	226.83	8	7.74	0	0.00	0	0.00	0	0.00	262	234.56
NO	2	14	brx	63	14	14.75	12	14.44	8	7.31	6	6.69	2	1.00	42	44.19

Year 3					G1		G1_DEF		G2_DEF		G2_OTHE		G3		Total / tree	
Loc	Yr	Tre	Trt	Lf B	No.	lbs	No.	lbs	No.	lbs	No.	lbs	No	lbs	No.	lbs
KA	3	10	0	22	12	10.69	9	7.00	1	0.38	1	0.75	0	0.00	22	18.81
LA	3	10	0	13	28	19.75	15	11.38	0	0.00	7	3.75	0	0.00	50	34.88
MA	3	10	0	18	18	15.75	13	10.63	4	3.63	1	0.88	0	0.00	36	30.88
MC	3	10	0	15	154	137.88	26	24.13	14	10.13	14	12	1	1.25	209	185.38
ME	3	10	0	63	139	120.72	7	5.31	5	3.69	9	7.63	1	1.31	160	138.66
NO	3	10	0	27	6	5.38	0	0.00	0	0.00	2	1.31	0	0.00	7	6.69
KA	3	5	110	66	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
LA	3	5	110	63	130	95.00	32	23.75	8	5.25	10	8.13	0	0.00	180	132.13
MA	3	5	110	181	57	42.63	24	16.75	11	7.50	5	3.00	0	0.00	97	69.88
MC	3	5	110	52	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
ME	3	5	110	84	300	255.25	8	6.88	1	1.06	18	16.09	1	0.50	327	279.78
NO	3	5	110	138	6	6.81	1	0.56	0	0.00	0	0.00	0	0.00	7	7.38
KA	3	13	220	101	32	23.44	2	1.50	2	0.81	2	1.44	0	0.00	37	27.19
LA	3	13	220	52	0	0.00	41	28.25	0	0.00	9	5.88	0	0.00	50	34.13
MA	3	13	220	.	.	.	.	.	.	.	.	.	.	.	.	.
MC	3	13	220	67	146	133.69	21	21.00	12	9.50	11	10.25	0	0.00	190	174.44
ME	3	13	220	253	116	78.00	1	0.69	1	0.75	4	2.56	0	0.00	121	82.00
NO	3	13	220	180	16	13.13	2	1.50	1	0.44	1	0.50	0	0.00	19	15.56
KA	3	14	brx	82	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
LA	3	14	brx	36	145	126.13	92	73.38	25	17.25	9	6.88	0	0.00	271	223.63
MA	3	14	brx	59	10	10.00	1	1.13	0	0.00	0	0.00	0	0.00	11	11.13
MC	3	14	brx	50	50	47.13	4	4.13	0	0.00	4	4.50	4	4.19	62	59.94
ME	3	14	brx	101	103	89.94	3	2.44	0	0.00	4	3.31	0	0.00	109	95.69
NO	3	14	brx	197	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00

Year 4					G1		G1_DEF		G2_DEF		G2_OTHE		G3		Total / tree	
Loc	Yr	Tre	Trt	Lf B	No.	lbs	No.	lbs	No.	lbs	No.	lbs	No	lbs	No.	lbs
KA	4	10	0	26	3	3.25	3	3.50	0	0.00	0	0.00	0	0.00	6	6.75
LA	4	10	0	14	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
MA	4	10	0	13	16	13.88	7	6.13	20	15.13	0	0.00	0	0.00	43	35.13
MC	4	10	0	14	33	26.50	15	12.00	3	1.88	2	1.75	3	2.13	56	44.25
ME	4	10	0	68	210	134.63	121	78.59	70	42.66	6	3.31	2	1.00	408	260.19
NO	4	10	0	18	43	28.19	21	12.13	9	5.25	10	5.31	16	11.06	98	61.94
KA	4	5	110	99	8	7.19	4	3.75	2	1.91	2	1.50	0	0.00	15	14.34
LA	4	5	110	54	41	32.50	32	24.25	25	16.25	15	10.56	4	1.50	117	85.06
MA	4	5	110	132	15	14.25	7	6.75	10	8.63	1	0.88	0	0.00	33	30.50
MC	4	5	110	38	17	13.88	1	0.75	0	0.00	0	0.00	0	0.00	18	14.63
ME	4	5	110	79	224	158.38	180	123.66	114	69.91	12	7.44	6	3.69	534	363.06
NO	4	5	110	99	55	41.81	21	15.25	13	7.75	4	2.56	0	0.00	93	67.38
KA	4	13	220	130	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
LA	4	13	220	63	1	0.50	11	7.25	4	1.81	1	0.25	7	2.25	24	12.06
MA	4	13	220	.	.	.	.	.	.	.	.	.	.	.	.	.
MC	4	13	220	61	168	119.56	36	27.19	11	6.88	6	3.69	2	1.38	223	158.69
ME	4	13	220	286	16	12.81	15	11.81	40	24.63	3	1.56	2	0.88	76	51.69
NO	4	13	220	64	14	9.94	5	3.19	5	2.44	6	3.00	0	0.00	29	18.56
KA	4	14	brx	125	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
LA	4	14	brx	33	0	0.00	2	1.50	3	1.81	0	0.00	0	0.00	5	3.31
MA	4	14	brx	48	1	1.00	0	0.00	0	0.00	0	0.00	0	0.00	1	1.00
MC	4	14	brx	63	20	16.13	5	4.38	0	0.00	0	0.00	0	0.00	25	20.50
ME	4	14	brx	177	182	131.44	118	78.59	48	36.72	13	8.41	11	6.56	371	261.72
NO	4	14	brx	104	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00

APPENDIX

B. Data, Trial 2: Foliar-applied Boron

	B, %	Leaf B, mg/kg				Flower B, mg/kg			Fruit set per shoot, March				
TREE	TRT	LF1	LF2	LF3	*	FL1	FL2	*	CT1a	CT1b	CT1c	CT1d	CT1e
1	0.2	60	53	49		115	83		85	82	19	58	61
2	0.1	49	45	51		132	118		141	38	181	60	57
3	0.2	56	61	57		144	140		177	53	53	109	87
4	0.3	97	76	80		396	188		132	103	134	78	44
5	0.3	75	59	45		150	122		97	49	43	100	60
6	0.1	44	28	28		54	68		6	44	55	56	38
7	0.1	43	47	23		85	66		105	200	52	65	126
8	0.2	47	31	47		77	87		57	14	158	49	24
9	0.3	63	48	49		201	98		140	209	139	80	95
10	0	18	20	28		201	51		45	7	67	39	17
11	0	21	23	26		33	49		62	0	28	15	2
12	0.1	48	52	38		80	68		10	37	50	56	1
13	0.3	117	73	71		178	107		59	44	45	260	60
14	0.3	86	70	59		237	125		52	2	10	77	8
15	0	80	77	109		66	76		53	37	7	34	9
16	0.2	69	64	72		181	114		120	24	14	5	10
17	0.2	80	75	91		179	117		28	17	31	33	2
18	0	30	28	36		48	53		6	12	6	3	26
19	0	27	27	34		57	57		0	7	2	1	2
20	0.2	81	59	70		240	93		58	18	42	12	7
21	0.1	41	35	29		77	65		58	118	57	10	3
22	0.1	39	28	25		110	81		1	0	4	5	2
23	0	21	23	24		46	53		75	14	16	31	5
24	0.3	128	91	108		.	.		33	11	33	4	15

Key:

TREE= tree #; TRT= 0, 0.1, 0.2, 0.3 %B (0, 5, 10, 15 g Solubor tree^{-1});

LF1= leaf B conc. @ 2 d after trt.; LF2= leaf B conc. @ 7 d after trt; LF3= 35 d after trt;

FL1= flower B conc @ 2 d " " ; FL2= flower B " @ 7 d " " ;

CT1= fruit set count 1 m after trt, on 5 shoots per tree (a - e);

CT2= fruit count 2 m after trt, " " " " " " ;

	B, %		Fruit set per shoot, April.				
TREE	**TRT**	*	**CT2a**	**CT2b**	**CT2c**	**CT2d**	**CT2e**
1	0.2		14	29	1	14	80
2	0.1		31	22	31	7	24
3	0.2		14	10	5	30	42
4	0.3		10	8	7	27	15
5	0.3		40	9	1	48	8
6	0.1		1	9	5	8	0
7	0.1		28	36	20	12	21
8	0.2		19	3	17	14	5
9	0.3		65	38	17	4	10
10	0		8	2	10	8	8
11	0		25	0	6	4	1
12	0.1		3	5	12	11	0
13	0.3		12	20	11	63	22
14	0.3		19	1	4	16	3
15	0		22	29	4	8	21
16	0.2		49	12	5	1	2
17	0.2		17	34	14	25	4
18	0		3	9	0	2	12
19	0		0	4	1	0	1
20	0.2		16	3	25	6	4
21	0.1		23	46	29	7	0
22	0.1		0	0	2	0	0
23	0		53	12	13	19	5
24	0.3		0	6	3	0	3

Fruit set, slight deformity, severe deformity per shoot, June

	B, %	Shoot a			Shoot b			Shoot c			Shoot d			Shoot e		
Tre	Trt	CT3	LD3	SD3	CT3	LD3	SD3	CT3	LD3	SD3	CT3	LD3d	SD3	CT3	LD3e	SD3
1	0.2	10	4	0	5	1	0	4	2	0	8	2	0	16	2	0
2	0.1	20	6	5	12	2	5	26	7	3	7	4	0	23	7	3
3	0.2	8	0	0	8	1	3	10	1	0	16	2	1	25	4	6
4	0.3	13	3	2	9	1	0	7	2	0	16	9	0	11	9	0
5	0.3	12	2	0	10	2	3	1	0	0	12	0	2	7	1	1
6	0.1	1	0	1	9	2	1	1	0	1	5	1	0	0	0	0
7	0.1	6	1	1	8	3	2	6	2	2	8	3	1	8	2	1
8	0.2	4	2	0	2	0	0	10	5	0	4	2	0	4	2	0
9	0.3	14	0	0	11	0	0	14	1	0	3	0	1	9	1	0
10	0	6	1	1	0	0	0	.	.	.	7	2	1	7	3	2
11	0	20	9	8	0	0	0	5	1	1	.	.	.	1	0	1
12	0.1	2	0	0	7	3	0	7	2	0	13	0	3	0	0	0
13	0.3	8	3	0	16	4	4	6	2	2	23	1	4	16	3	3
14	0.3	11	7	0	0	0	0	5	2	0	17	10	0	3	1	0
15	0	5	1	1	11	2	2	3	1	2	5	2	0	4	0	1
16	0.2	21	1	0	5	0	1	2	0	0	0	0	0	3	0	0
17	0.2	5	1	0	15	2	6	8	3	0	8	1	5	0	0	0
18	0	3	2	1	7	2	3	0	0	0	1	0	1	13	4	5
19	0	0	0	0	6	3	2	1	0	1	0	0	0	1	1	0
20	0.2	6	1	0	3	0	0	9	0	3	4	0	0	3	0	0
21	0.1	17	4	4	30	3	4	14	1	4	8	2	4	0	0	0
22	0.1	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
23	0	14	3	4	3	0	3	12	2	3	14	3	4	2	0	2
24	0.3	1	0	0	5	1	0	3	0	1	0	0	0	3	0	1

Key:

CT3= fruit count 4 m after trt, on 5 shoots per tree (a-e); CT4= frt count @ 8 m after trt;
LD3= number of slightly deformed fruits per shoot; LD4= # of slightly deformed fruit;
SD3= number of severely deformed fruits " " ; SD4= # of severely " " ;

Fruit set, slight deformity, severe deformity per shoot, - October

	B, %	Shoot a			Shoot b			Shoot c			Shoot d			Shoot e		
Tre	Trt	CT4	LD4	SD4	CT4	LD4b	SD4	CT4	LD4	SD4	CT4	LD4d	SD4	CT4	LD4	SD4
1	0.2	3	1	0	4	0	0	3	1	0	3	0	0	3	0	0
2	0.1	12	3	5	4	1	3	17	4	5	5	3	0	16	3	4
3	0.2	6	0	0	5	0	0	3	1	0	7	0	1	17	2	4
4	0.3	12	2	5	6	1	0	5	0	0	12	3	3	7	2	4
5	0.3	11	1	1	9	0	2	1	0	0	3	0	0	4	1	0
6	0.1	1	0	1	2	2	0	0	0	0	2	1	0	0	0	0
7	0.1	1	0	0	3	1	1	4	0	3	0	0	0	1	0	0
8	0.2	3	0	1	1	1	0	4	1	0	1	0	0	4	0	2
9	0.3	10	1	0	4	1	0	7	2	0	3	1	0	3	0	0
10	0	7	1	1	1	0	0	.	.	.	4	0	0	4	1	0
11	0	6	1	4	2	0	0	2	0	1	.	.	.	1	1	0
12	0.1	1	0	0	4	0	1	3	1	0	7	1	1	0	0	0
13	0.3	8	2	1	8	2	3	5	2	0	14	3	4	10	2	6
14	0.3	4	2	1	0	0	0	5	0	1	12	2	6	2	0	0
15	0	5	1	2	6	3	1	3	2	1	4	0	0	1	1	0
16	0.2	12	1	0	3	0	0	2	0	0	0	0	0	2	0	0
17	0.2	2	1	0	8	3	2	2	0	0	4	1	2	0	0	0
18	0	4	1	2	6	1	4	3	0	0	1	0	1	13	1	7
19	0	0	0	0	6	1	4	1	0	1	0	0	0	1	1	0
20	0.2	9	2	1	3	0	0	10	1	3	1	0	0	1	0	0
21	0.1	12	1	4	16	2	6	12	0	4	4	0	4	0	0	0
22	0.1	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
23	0	12	4	4	6	1	4	9	0	5	13	6	3	3	3	0
24	0.3	1	0	0	5	0	1	3	0	0	0	0	0	3	1	2

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