Is There A Biological Rationale For Foliar Fertilizers In Almond Production?

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Introduction

Foliar fertilization has been used by fruit growers since the early 19th century (Gris, 1884) and has become an important management practice in all well managed orchard systems. Though they are invariably more expensive than soil based fertilizers, foliar fertilizers nevertheless are widely and increasingly used in tree crop production. Two rationales are cited as justification for their use, 1) to overcome soil chemical or physical conditions that prevent nutrient uptake and 2) to provide targeted nutrients to prevent short term or 'transient' deficiencies such as those that may occur during reproductive growth, or periods of peak demand. Whereas the use of foliar fertilizers to overcome soil physical and chemical properties is well defined and many examples of its implementation are available, the fundamental nutritional physiology to support the use of foliar fertilizers to overcome 'transient' deficiencies is scant and generally inadequate to predict or explain the usefulness of these practices.

The focus of this paper will be a discussion of transient nutrient deficiencies as a justification for the use of foliar fertilizers. Considerable research into the physicochemical considerations for the use of foliars and the use of foliars to address soil chemical or physical conditions that prevent nutrient uptake is available from other reviews (Weinbaum, 1989; Schonherr, 2006) and numerous field experiments and will not be considered here.

It is widely hypothesized that transient nutritional deficiencies occur as a result of limitations in uptake or restrictions in nutrient delivery during periods of peak nutrient demand. To address this issue many horticultural producers utilize foliar fertilizers since this allows for highly localized and specifically tailored nutrient applications that are not as easily provided using solid or blended products. This approach is particularly relevant for micronutrients. Very little research is available, however, that demonstrates the effectiveness of foliar fertilizers and the role they play in ensuring continued nutrient supply during times of peak demand. In general the supply of fertilizers to roots through soil applications is far cheaper and in many (but not all) cases results in a more economical use of the applied nutrient (Weinbaum, 1989). Identification of the situations where foliar fertilization offers a specific advantage is critical to economic success and provides useful information on the relationship of demand to fertilization strategy.

Over the past 10 years we have conducted considerable research into the effectiveness of targeted B fertilization and have observed that foliar B applications frequently increase fruit set and yield if applied during reproductive growth. These responses are seen even in the absence of symptoms of B deficiency. Biochemical, isotopic and molecular experimentation demonstrate that a transient B deficiency is common during reproductive growth and that foliar B is frequently effective even when soil B is available. Additionally, research and field observations of localized spur and branch K deficiency in trees well supplied with soil K, provide evidence that within tree deficiencies can occur even in the presence of adequate soil nutrient.

In the following, experimental evidence for the occurrence of transient nutrient deficiencies and their efficient correction by foliar fertilization is presented. The broader implications of these results as a rationale for foliar fertilizers is discussed.

Materials and Methods

Response of Pistachio to foliar B.

In 1990-94 a large experimental site with potential B deficiency was established in mature Pistachio (*Pistacia vera* L.) cv. 'Kerman' trees growing in Yolo County, California, USA. In total over 1000 trees (tree spacing 5 x 6 m with 333 trees ha^{-1}) were utilized in this experiment. Treatments consisted of either 0, 12, 23, 35, and 47 g B per tree as Solubor ($Na_2B_8O_{13} \cdot 4H_2O$, containing 20.5% B) applied to the soil in November, or as foliar application of Solubor at four levels (0, 490, 1225, and 2450 mg•L^{-1} B) at a rate of 1000 L of water per hectare (equivalent of 0, 1.53, 3.82, and 7.64 g B per tree) by a tractor - mounted sprayer in January (late dormant spray) and again in July. A total of four fields were used (two foliar, two soils). In each field, the experiment was designed as a randomized complete block with 10 trees per replicate and five replicates per block. All treatments were bordered on all sides by two rows of untreated trees. In addition, a subset of trees (10 replicate trees per timing arranged in a completely randomized design) was utilized for the spray timing trial. In this site trees were sprayed with 490 ppm B at either of five dates, from late dormant through full leaf emergence. Total yield was determined on each tree and related to B application.

Response of Olive to foliar Boron. (from Perica et al, 2001)

In 1998 an orchard of bearing olive (*Olea europaea* L.) cv. 'Manzanilla' with July tissue B concentration of 17 ppm was selected in Butte County, California, USA. Experiments were conducted in both 1998 and 1999. The trees were planted at a density of 370 trees per hectare (Oroville). Boron as Solubor ($Na_2B_8O_{13} \cdot 4H_2O$), containing 20.5% B, was applied at four levels (0, 246, 491, and 737 mg.L^{-1} B), at a rate of 935 L of water per hectare by a tractor - mounted sprayer. Boron was applied 3 weeks before anthesis on April 21, 1998 and May 1, 1999. The treatments were imposed in a randomized block of five adjacent trees within a treatment, replicated six times, making a total of 120 experimental trees per site. Single border trees separated the treatments and minimized the effect of cross-treatment contamination. The design was identical in both experiments.

On each replicate tree, five shoots in 1998 and twenty shoots in 1999, uniform in length and exposure with full floral differentiation (>95%), were selected before anthesis and tagged a few nodes above the shoot base. In 1998 all flowers and fruit set on each tagged shoot were counted, in 1999 the total number of inflorescences was determined on each tagged shoot. At anthesis (May 10, 1998 and May 18-22, 1999) five uniform shoots per tree were detached and taken to the lab where the number of complete and incomplete inflorescences per shoot was counted and the number of perfect and imperfect flowers was recorded. 'Complete inflorescence' in this report is defined as an inflorescence with at least one single complete flower; 'incomplete inflorescence' means no single flower in an inflorescence is completely developed. The number of perfect vs. imperfect flowers was also counted on a single inflorescence arbitrarily chosen from the fourth node from the base of the detached shoot.

Transgenic manipulation of B transport in Tobacco (from Brown et al., 1999).

Three tobacco (*Nicotiana tabacum* L.) lines were used; SR1, wild-type tobacco; A4, tobacco transformed with the anti-sense gene construct for S6PDH; and S11, tobacco line transformed with the sorbitol synthesizing sense construct (Tao et al., 1995). A4 and SR1 served as controls. A4 and S11 are identical in all regards with the exception of the orientation of the S6PDH coding region with respect to the CaMV 35S promoter.

Homozygous seed of each tobacco line were germinated, then grown in vermiculite for four weeks with adequate supply of all nutrients including 0.05 ppm B. At four weeks, plants were transferred to hydroponic solutions with aeration (1/2 strength Hoagland solution (Hoagland and Arnon, 1950), minus B) and the following treatments imposed. 1), 0.05 ppm B, consisted of a continual supply of 0.05 ppm B in the rooting medium; 2), 0 ppm B, received no B in the rooting medium; 3) 'foliar' treated plants, received bi-weekly foliar applications of B to three mature leaves (described below) with no B supplied in the root nutrient medium.

Potassium Deficiency in Almond. (from Reidel et al, 2004)

Potassium fertilizer was applied to drip irrigated 'Nonpareil' almond trees in a Modesto, California orchard at the rates of 0, 240, 600, and 960 lbs K_2O/A/year as K_2SO_4, beginning in 1998. The fertilizer was applied directly beneath six drip emitters per tree, split 3 times (May 23, June 17, and July 3) in 1998 and 2 times (Feb. 26 and April 29) in 1999. Forty individual branch units from trees in the control (0 K) and 960 lbs K_2O/A rates ("low-K" and "high-K", respectively) were selected to monitor yield determinants and individual spur longevity over several years. Yield and leaf K concentrations were also measured.

Results:

Response of Pistachio to Foliar and Soil B:

Table 1 compares the effectiveness of soil B applications with respect to foliar B applications. It can be seen that soil applied B was most effective at raising tissue B levels. Plants supplied 170 to 227 g•tree^{-1} Solubor (35 to 47 g•tree^{-1} B) in 1990 had tissue B concentrations (in 1992) higher than trees that received foliar applications alone. Nevertheless, trees that received foliar B showed a positive yield response while those receiving soil B did not. This indicates that adequate leaf B status does not ensure optimal tree productivity. Apparently, foliar applications of B serve a unique role in enhancing pistachio fruit set.

Table 2 demonstrates that the most effective time for application of foliar B was the late dormant spray (immediately pre-anthesis) in which a yield increase of as much as 20% over unsprayed control trees were recorded. Later sprays effectively increased tissue B levels but did not increase fruit yield, though all B sprayed trees yielded more than trees not receiving supplementation. The effectiveness of early but not late B sprays, is evidence that B is critical for pollination or fertilization of pistachio flowers.

Response of Olive to Foliar :

Foliar B application immediately pre-anthesis significantly altered the ratio of perfect to imperfect flowers, increased fruit set (results not shown) and increased final yield (Table 3). Soil B status did not influence the response of plants to foliar B (results not shown).

Transgenic manipulation of phloem B transport and its effect on susceptibility to B deficiency in tobacco:

Following removal of B from the growth medium, significant flower abortion and subsequently reduced seed production occurred in both wild-type and antisense tobacco plants (in which B is immobile), demonstrating that a brief deficiency of B can have a profound effect on flowering (Fig. 1). The application of foliar B had no beneficial effect on these plants. Tobacco plants with the capacity to transport B in the phloem to the flowers (transgenic) did not exhibit rapid flower abortion and in all cases produced significantly more seed than plants with limited phloem B mobility (Fig 1). With the application of foliar B, the transgenic tobacco performed equally to the control plants receiving root B indicating that the capacity to effectively use foliar fertilizers can entirely replace the need for soil B supply. The reduced seed set in the transgenic tobacco grown for an extended period in 0 ppm B is a consequence of the depletion of all remobilizable B and the ultimate occurrence of B deficiency throughout the plant.

Potassium Deficiency in Almond:

The application of differential K rates in 1998 and 1999 increased average leaf K in 1998, 1999 and 2000 but had no significant effect on tree yield in 1998 or 1999 and a small (18%) increase in yield in 2000 (control<240=600=960 Kg/ha). The majority of the effect of K on yield was a consequence of prior year fruiting status, and K application rate expressed at an individual spur level. Table 4 illustrates that addition of K increased the number of vegetative$_{1999}$ spurs that became reproductive in 2000 by 14%, and the number of reproductive$_{1999}$ spurs that remained reproductive in 2000 by 20%. Spurs represent only a small percentage of whole plant biomass and were the only site at which clear K deficient leaves were observed (Fig 2a). The highly localized occurrence of K deficiency on otherwise symptom free trees is also frequently seen in leaves immediately adjacent to fruit in almond and pistachio even in trees well provided with soil K (Fig. 2a,b).

Discussion:

The results of experimentation in both Pistachio and in Olive as well as many other reports in the literature (Nyomora et al., 1997; 1999 and references therein) demonstrates that foliar B application can result in correction of an apparent deficiency that is not responsive to soil B application nor easily indicated by leaf B concentrations. This is most apparent in pistachio where foliar B fertilization applied pre-anthesis increases pollen germination, reduces blanking and non-splits (results not shown) and consequently increases yield. This stimulation occurs even in trees with summer leaf B concentrations in excess of 150 ppm, indicating that there is a specific requirement for B in the developing flower. Foliar applications are the most effective method to ensure adequate B for the flowers. Soil applications of B are effective at raising leaf B levels but are not as effective as foliar sprays at increasing yield since B availability from soil is apparently not coincident with reproductive demand.

The apparent superiority of foliar B can best be explained as a consequence of a transient inadequacy in B supply to the reproductive tissues from the soil. This may occur as a consequence of low root activity in cool soils, high B requirement in developing flowers, or low transport of B to the reproductive tissues. All of these explanations suggest that transient deficiencies of B can occur and they may not be efficiently corrected by soil fertilization. To our knowledge this is the clearest example of a transient nutrient deficiency and a justification for application of foliar fertilizers.

The suggestion that the phloem immobility of B greatly enhances susceptibility to transient limitations in supply of B from the soil was verified using a novel transgenic approach. In tobacco plants in which phloem B mobility was enhanced through introduction of the gene for sorbitol synthesis, the susceptibility of these cultivars to B withdrawal from the soil solution was greatly reduced. These transgenic tobaccos were also capable of obtaining their B requirements solely through foliar fertilization. Phloem immobility clearly contributes to plant susceptibility to transient nutrient deficiencies.

In Almond, and other nut crops, nutrient demand is highly localized both within the tree and within the year coinciding with periods and sites of rapid fruit development. Local and temporal deficiencies can therefore occur at an individual branch or spur level even for an element of high within plant mobility such as K. Since whole tree aggregate above ground nutrient demand drives root nutrient uptake (Gessler et al 2004), it may be predicted that highly localized deficiencies in individual spurs may not per se, trigger enhanced root uptake. The relationship between nutrient demand and uptake is further complicated since high levels of CHO demand to meet the demand of the rapid crop growth also inhibits soil nutrient uptake. Thus there is a propensity for a uniquely high incidence of local nutrient deficiencies in high yield years that may not be efficiently corrected by supplemental soil applications. Under these circumstances it is generally believed by growers that foliar applications are uniquely effective. Though this presumption has a logical basis in science, and is supported by anectodal field evidence, there have been no studies demonstrating that foliar fertilization can effectively or uniquely enhance yield under these circumstances.

Summary:

The results provided here, clearly demonstrate that transient B deficiencies occur and can be important determinants of yield. The evidence also suggests that foliar B fertilizers can on occasions, be uniquely effective at correcting these deficiencies. Based upon these results, we conclude that transient deficiencies of B may occur as a consequence of a combination of spatial and temporal variations in plant nutrient demand and supply, and will be influenced by the relative mobility of the nutrient in the plant. Though these results demonstrate the occurrence of transient nutrient deficiencies of B and provide a biological justification for the use of foliar B, they do not predict plant response to other foliar fertilizers. Nevertheless, we have provided evidence of a strong temporal and spatial demand for K in Almond and a high demand for macronutrients also likely exists in many nut crops and has been shown to have a significant negative effect on return yield.

While these results support a role for targeted foliar fertilizers we are unaware of any studies that specifically address the role of foliar fertilizers to correct these spatially variable or temporally transient deficiencies. Further research must be conducted to determine if transient deficiencies are relevant to the management of nutrients in perennial crops and if targeted foliar fertilizers can play a unique role in their correction.

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Table 1. Influence of B application on yield, bud and July leaf B of pistachio

FOLIAR ($mg \cdot L^{-1}$ B)	YIELD (kg in-shell splits/tree)	$mg \cdot kg^{-1}$ B Buds	$mg \cdot kg^{-1}$ B Leaves (July)
0	8.6	35	170
490	10.0*^{z}	37	185
1225	11.8**	39	171
2450	9.5	41	210
SOIL ($g \cdot tree^{-1}$ B)			
12	8.6	35	172
23	8.6	38	189
35	9.1	44	201
47	9.5	50	219

[z]*, ** significantly greater than control at 0.05, and 0.01%, respectively.

Table 2. Effect of application date of foliar B (1225 mg•L^{-1} B) on yield and leaf B in Pistachio

APPLICATION DATE	GROWTH STAGE	YIELD[1] (kg)	LEAF B (JULY) mg•kg^{-1}
28-Feb	Late Dormant	32**	188
19-Mar	Early Bud Break	24	188
3-Apr	Flowering	25	187
17-Apr	Leafing Out	23	256**
8-May	Fully Leafed Out	22	468**

** significantly greater than control at 0.01%
[1]All yields are fresh weight of fruit per tree.

Table 3. Influence of pre-anthesis foliar B on olive reproduction[z].

	1998	1999	
B spray rate (mg.L^{-1})	Imperfect flowers	Imperfect flowers	Yield (kg/tree)
0	55 a[y]	49 a	12.6 b
246	35 b	38 b	14.9 a
491	33 b	40 b	17.8 a
737	48 a	47 a	13.5 b

[z]Applications were only effective pre-anthesis
[y]Within a column values followed by different letters differ significantly at $p < 0.05$ by Fisher's LSD.

Table 4. Effect of K treatment and spur bearing status in 1999 on status of spurs in 2000.

		Spur bearing status in 2000				
Spur bearing		Vegetative		Flowering		
Status In 1999	K-availability	N	(%)	n	(%)	Total
vegetative	high-K	18	(14)	114	(86)	132
vegetative	Low-K	29	(25)	89	(75)	118
fruiting	high-K	60	(52)	55	(48)	115
fruiting	low-K	53	(60)	36	(40)	89
Totals		160		294		454

Figure. 1. Seed yield of tobacco lines (transgenic, wild type, antisense) grown for 28 days with adequate B then transferred to either 0 ppm B, 0.05 ppm B supplied to the roots, or 100 ppm B supplied to three mature leaves. Seed yield was determined 56 days after transfer to treatment solutions. Values represent mean +/- standard error of six replicates.

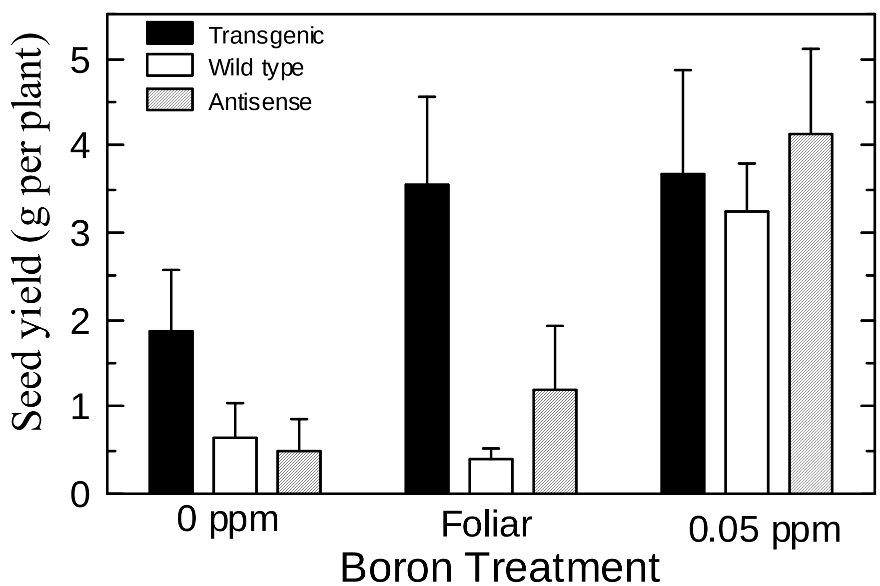

Figure 2a and 2b: Potassium deficiency in leaves immediately adjacent to almond (2a) and Pistachio (2b) fruits. Leaves on these trees not directly associated with fruit were not deficient according to current UC standards.