Boron Management and Remediation in Almond

Project No.: WATER12.BROWN

Project Leader: Patrick Brown, Professor, Department of Plant Sciences, One Shields Ave., University of California, Davis, CA, 95616; Phone: (530) 304-1390; e-mail: phbrown@ucdavis.edu.

Project Cooperators and Personnel:

Kirk Pumphrey, Boron Solutions and Westwind Farms. Katherine Jarvis-Shean, Farm Adviser Sacramento-Solano-Yolo County. Christine M. Armstrong (Stockert), Staff Research Associate, UC Davis Plant Sciences. Pedro Lima, Postdoc Scientist, UC Davis Plant Sciences.

A. Summary

2019 served as a baseline for this project. The novel system developed to remove B from irrigation water had to be re-engineered and therefore the planned treatments were not delivered over the 2019 growing season. Nevertheless, the soil column leaching studies and the baseline field data was collected and soil column experiments carried out. The orchard was 5 years old and has mainly seen 2 ppm B in irrigation water except for the 2018 season. In 2018, hull B at harvest for Carmel averaged 459 ppm and for Nonpareil 373 ppm. In 2019, hull B in Nonpareil dropped to 276 ppm. This may be due to the decreased B levels at irrigation water delivered in 2018 when the system was working partially. Preliminary results from the soil leaching columns showed that water at a pH of 6 leached a higher quantity of B than control and pH 9 solutions.

B. Objectives

1. To determine how irrigation water boron (B) concentration, time of exposure and life-stage of the orchard interact to cause B toxicity, productivity loss and orchard decline.

2. Measure soil B leaching by different soil types and remediation strategies, so new B leaching guidelines are established.

C. Annual Results and Discussion

Boron field experiment

Leaf tissue from Nonpareil trees was collected in April and Mid-July and mineral elements (Boron, Sodium, Magnesium, Phosporous, Potassium and Calcium) measured. Data from early season sampling is presented at table 1, as late in the season samples are being processes. Early sampling is important but the tree during this period is transferring large amounts of nutrients from source to sink, and may be devoting more nutrients to new growth instead of developing foliage. Nevertheless, P, K, Ca, Mg and Na nutrient levels were adequate according to established limits for almond leaves (Brown & Uriu, 1996).

Table 1. Early season Nonpareil leaf tissue analysis from almond trees at different rates of B applied through irrigation water (Rate trail); and at different times of exposure to high B concentration (2 ppm) irrigation water (Season Trial).

Treatment	B [ppm]	Na [ppm]	Mg [%]	P [%]	K [%]	Ca [%]
0.5 ppm	76.42 ± 4.04	39.19 ± 12.73	0.68 ± 0.08	0.28 ± 0.01	1.83 ± 0.66	2.46 ± 0.10
1.0 ppm	74.62 ± 3.59	36.59 ± 13.34	0.67 ± 0.06	0.27 ± 0.01	2.00 ± 0.62	2.48 ± 0.06
3.0 ppm	74.43 ± 2.06	33.66 ± 5.27	0.64 ± 0.08	0.28 ± 0.03	1.94 ± 0.66	2.29 ± 0.24
Early Season	71.65 ± 4.03	65.97 ± 13.83	0.64 ± 0.06	0.28 ± 0.01	1.98 ± 0.27	2.38 ± 0.11
Mid-Season	73.37 ± 2.04	44.12 ± 10.51	0.66 ± 0.08	0.28 ± 0.01	2.07 ± 0.40	2.35 ± 0.17
Late Season	71.45 ± 3.17	69.45 ± 27.25	0.63 ± 0.05	0.28 ± 0.02	1.92 ± 0.46	2.30 ± 0.09
Average ± SD (n=30)	73.66 ± 3.70	48.16 ± 20.91	0.65 ± 0.07	0.28 ± 0.02	1.96 ± 0.54	2.38 ± 0.16

Soil samples using were collected to evaluate existing available nutrients (Boron, Sodium, Magnesium, Phosporous, Potassium and Calcium) as well as soil pH and electrical conductivity (Table 2) using saturated paste. No statistical difference was estated once the planned tratments were not delivered. In 2020 difference between treatments is expected, especially at higher B concentrations (3 ppm).

Table 2. Soil saturated paste mineral nutrient, pH and electrical conductivity (EC) analysis at an almond orchard under different rates of B applied through irrigation water (Rate trail); and different times of exposure to high B concentration (2 ppm) irrigation water (Season Trial). Treatments with the same letters within the same column are not statistically different by Tukey-Kramer's HSD test ($p < 0.05$).

Treatment	B [ppm]	Na [ppm]	Mg [ppm]	P [ppm]
0.5 ppm	1.02 ± 0.14 a	154 ± 31.1 a	36.2 ± 8.0 a	0.89 ± 0.65 a
1.0 ppm	0.80 ± 0.09 a	128 ± 35.6 a	39.4 ± 12.9 a	0.87 ± 0.89 a
3.0 ppm	0.93 ± 0.17 a	142 ± 38.8 a	37.0 ± 14.6 a	0.97 ± 0.76 a
Early Season	0.89 ± 0.19 a	126 ± 34.1 a	35.6 ± 6.3 a	0.65 ± 0.56 a
Mid-Season	0.98 ± 0.15 a	153 ± 28.9 a	39.9 ± 18.0 a	0.54 ± 0.29 a
Late Season	0.81 ± 0.14 a	117 ± 27.8 a	31.9 ± 3.0 a	0.61 ± 0.55 a
Average ± SD (n=30)	0.91 ± 0.16	136 ± 33.2	36.7 ± 10.9	0.76 ± 0.61
Treatment	**K [ppm]**	**Ca [ppm]**	**pH**	**EC [mS cm^{-1}]**
0.5 ppm	12.9 ± 16.8 a	120 ± 48.4 a	6.94 ± 0.21 a	1.45 ± 0.31 a
1.0 ppm	11.9 ± 12.6 a	139 ± 34.9 a	7.01 ± 0.11 a	1.38 ± 0.25 a
3.0 ppm	13.7 ± 12.4 a	130 ± 46.0 a	7.08 ± 0.07 a	1.42 ± 0.37 a
Early Season	13.7 ± 8.5 a	105 ± 23.5 a	7.09 ± 0.15 a	1.24 ± 0.10 a
Mid-Season	12.4 ± 9.3 a	121 ± 70.6 a	7.14 ± 0.03 a	1.39 ± 0.41 a
Late Season	10.0 ± 10.3 a	102 ± 36.3 a	7.19 ± 0.11 a	1.16 ± 0.11 a
Average ± SD (n=30)	12.4 ± 10.9	119 ± 43.6	7.07 ± 0.14	1.34 ± 0.28

Nonpareil Fruit was collected on 6/3/2019, 7/22/2019 and 8/29/2019 and hull B measured (table 3). Boron concentration in hulls were below toxicity limits established (200 ppm) at early June, where kernels are still in the late stages of maturing and growing to its full size. However, such hull concentration were above limits indicated from late July until harvest.

In 2018, hull B at harvest for Carmel averaged 459 ppm and for Nonpareil 373 ppm. In 2019, hull B in Non-Pareil dropped to 276 ppm. This may be do to the 50% B reduction at the irrigation water delivered in 2018 (all treatments equally) when the system was working. Greater reductions on hull B levels are expected in 2020 and moreso in 2021 after B reduction treatment effectively works.

Table 3. Boron concentration, in ppm, in Nonpareil almond hulls submitted at different rates of B applied through irrigation water (Rate trail); and at different times of exposure to high B concentration (2 ppm) irrigation water (Season Trial). Treatments with the same letters within the same column are not statistically different by Tukey-Kramer's HSD test ($p < 0.05$).

Treatment	B [ppm]	B [ppm]	B [ppm]
	06/03/2019	07/22/2019	08/29/2019
0.5 ppm	132 ± 16 a	232 ± 65 a	260 ± 38 a
1.0 ppm	120 ± 15 a	216 ± 63 a	270 ± 34 a
3.0 ppm	119 ± 15 a	221 ± 39 a	244 ± 16 a
Early Season B	112 ± 20 a	256 ± 69 a	284 ± 06 a
Mid-Season B	125 ± 19 a	320 ± 63 a	313 ± 78 a
Late Season B	125 ± 18 a	278 ± 46 a	284 ± 35 a
Average ± SD (n=30)	122 ± 17	254 ± 65	276 ± 43

The quality of the Nonpareil almond nuts was accessed through physical parameters: dry weight at sample bags, number of nuts at 4 lbs sample bags (Table 4); almonds hulls, in-shell and kernel weights (in grams) of 50 nuts (Table 5); and almond defects in 75 nuts (Table 6). Average kernel weight of 1.346 grams is below the 2018 California nonpareil average (1.70 grams) and Sacramento Valley average (1.61 grams) (USDA, 2018). Most common defect stated were twin-kernels, followed by double kernels.

Table 4. Almond nuts dry weitgh (DW) and number of nuts (Nut Count) for 4 lbs sample bags at: different rates of B applied through irrigation water (Rate trail); and at different times of exposure to high B concentration (2 ppm) irrigation water (Season Trial). Treatments with the same letters within the same column are not statistically different by Tukey-Kramer's HSD test ($p < 0.05$).

Treatment	DW (kg)	Nut Count
0.5 ppm	3.98 ± 0.02 a	306 ± 41.8 a
1.0 ppm	4.02 ± 0.04 a	318 ± 24.2 a
3.0 ppm	4.02 ± 0.02 a	282 ± 34.1 a
Early Season	3.97 ± 0.03 a	309 ± 26.2 a
Mid-Season	3.97 ± 0.01 a	307 ± 27.0 a
Late Season	3.97 ± 0.03 a	314 ± 40.1 a
Average ± SD (n=30)	3.99 ± 0.03	306 ± 31.6

Table 5. Nonpareil almond hulls, inshell and kernel weight of 50 nuts, in grams, for almonds submitted at different rates of B applied through irrigation water (Rate trail); and at different times of exposure to high B concentration (2 ppm) irrigation water (Season Trial). Treatments with the same letters within the same column are not statistically different by Tukey-Kramer's HSD test ($p < 0.05$).

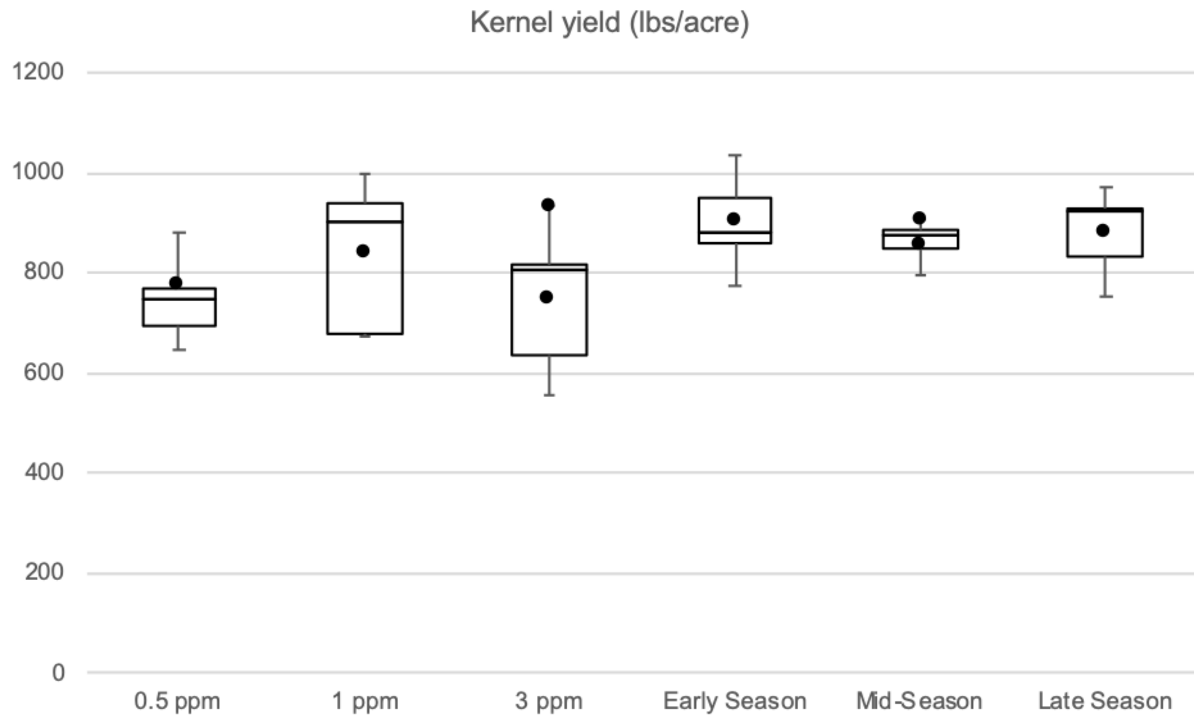
Treatment	Hulls wt (g)	Inshell wt (g)	Kernel wt (g)
0.5 ppm	158 ± 12.2 a	91.9 ± 5.15 a	64.2 ± 3.14 a
1.0 ppm	156 ± 10.5 a	92.2 ± 3.34 a	64.1 ± 2.57 a
3.0 ppm	166 ± 10.4 a	89.4 ± 5.34 a	66.6 ± 4.13 a
Early Season	159 ± 4.42 a	98.6 ± 5.88 a	70.6 ± 4.56 a
Mid-Season	153 ± 12.1 a	94.1 ± 7.79 a	68.2 ± 6.41 a
Late Season	129 ± 61.3 a	93.3 ± 6.28 a	69.8 ± 5.72 a
Average ± SD (n=30)	154 ± 26.7	93.2 ± 5.89	67.3 ± 4.85

Table 6. Nonpareil almond count defects in 75 nuts submitted at different rates of B applied through irrigation water (Rate trail); and at different times of exposure to high B concentration (2 ppm) irrigation water (Season Trial). Treatments with the same letters within the same column are not statistically different by Tukey-Kramer's HSD test ($p < 0.05$).

Treatment	Deffects Count Number out of 75 nuts
0.5 ppm	19.4 ± 4.56 a
1.0 ppm	20.0 ± 2.74 a
3.0 ppm	22.8 ± 4.55 a
Early Season	16.8 ± 3.03 a
Mid-Season	20.8 ± 4.02 a
Late Season	20.0 ± 5.15 a
Average ± SD (n=30)	20.0 ± 4.08

Yield average (833 lbs $acre^{-1}$), presented at figure 1, is below California average for the 2019/2020 season forecast, which is 2,200 lbs per acre (Almond Board of California, 2019). After treatment application becomes more consistent we expect to be able to determine how irrigation water boron (B) concentration, time of exposure and life-stage of the orchard interact to cause B toxicity, productivity loss and orchard decline.

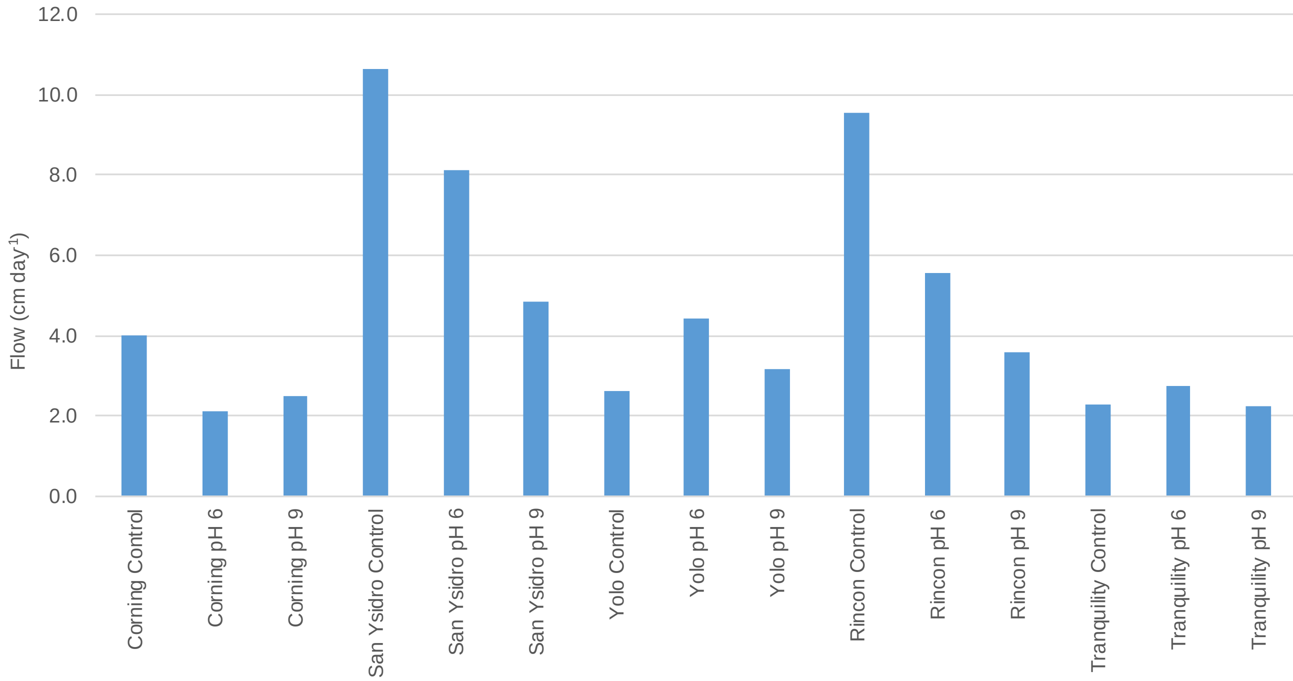
Figure 1. Kernel yield (lbs $acre^{-1}$) of an almond orchard submitted at different rates of B applied through irrigation water (Rate trail); and at different times of exposure to high B concentration irrigation water (Season Trial).



Boron leaching experiment

Different soil properties directly influence water movement through saturated soil columns, such as bulk density. The bulk densities expressed in Mg m^{-3} were 1.66 for Corning, 1.51 for Rincon, 1.63 for San Ysidro, 1.42 for Tranquility and 1.44 for Yolo. Measured flow (Figure 2) indicates different permeabilities at soil columns as expected. Tranquility, Yolo and Corning samples have lower flow rates, less than 4 cm per day. Consequently, leaching process at those soils takes longer than at San Ysidro and Rincon soils samples.

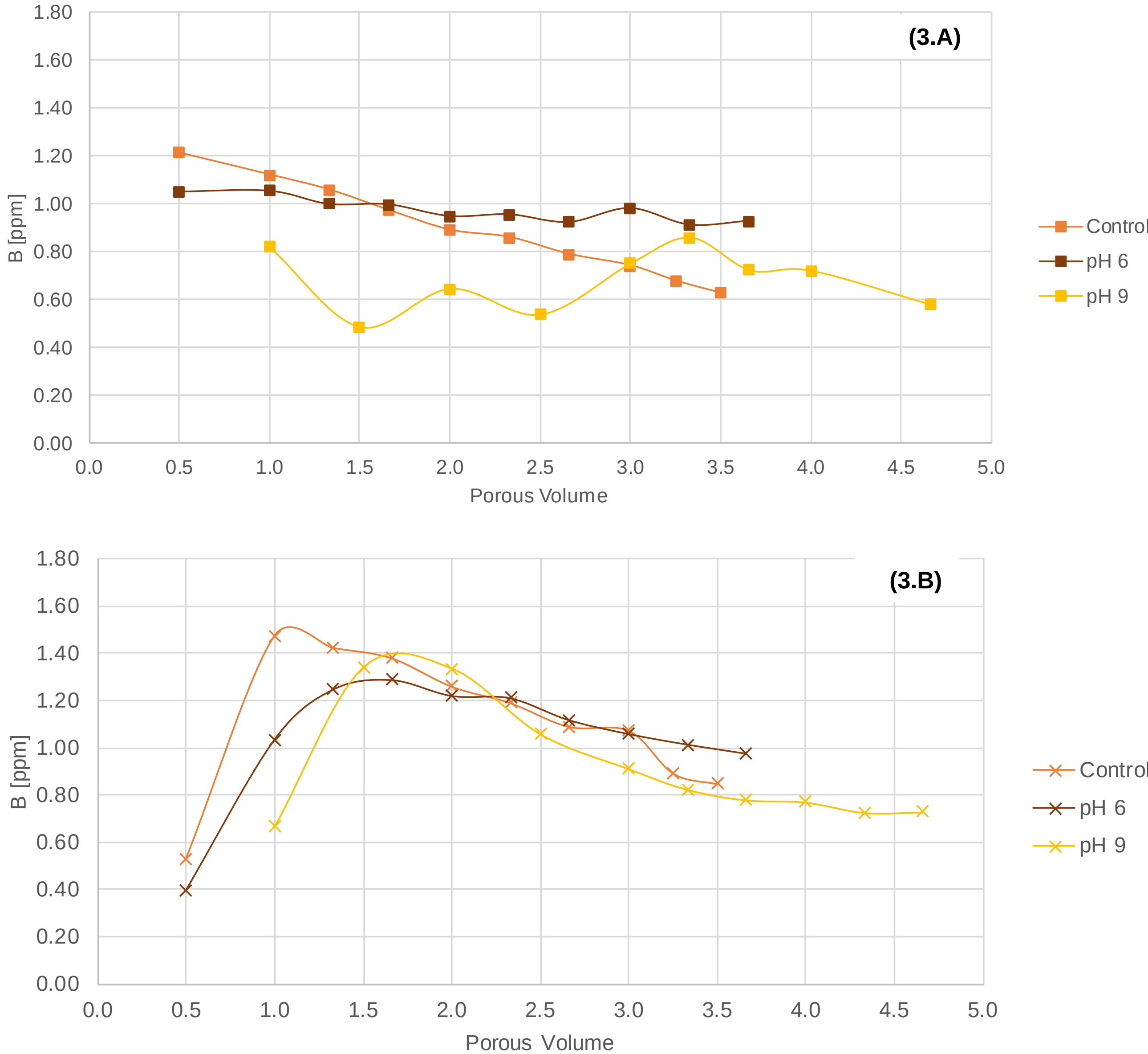
Figure 2. Flow (cm day^{-1}) for different soils (Corning, San Ysidro, Yolo, Rincon, Tranquility) irrigated with different pH solutions (Control, pH 6 and pH 9).



Boron concentration (ppm) of Corning soil leachate under different irrigation water qualities are presented in Figures 3A (soil solution extracted with Rhizotron (Rhizosphere, The Netherlands)) and 3B (soil solution collected at bottom). Preliminary results for this soil show that it is not necessary to leach B with pH 9 solution, being pH 6 enough to leach a higher quantity of B than control solution. This finding suggests that B is best leached at normal soil pH levels at which all nutrients are better absorbed by plants (pH levels ranging from 6.0 to 7.0). It is necessary to measure B at saturated paste for soils to plot effluent curves as relative concentration (C/C_o) where C_o is the B concentration at saturated paste. Such plots will allow running data at deterministic models such as Unsatchem.

It is important to point out that the data shown in this report is a preliminary data for the first year of a three year project, thus nonconclusive yet. Our goal is to establish new B guidelines to different soil types (Corning, Rincon, San Ysidro, Tranquility and Yolo series) and remediation strategies (e.g. pH levels, soil organic matter, compost, cover cropping).

Figure 3. Boron concentration, in ppm, of soil columns leachate collected at 15 cm (**3.A**) and at 30 cm (**3.B**) in Corning soil at pH 6.0, pH 9.0 and artificial rain (control), all as a function of pore volumes of applied water.



D. Outreach Activities

December 2018. Almond Board Conference. Sacramento, CA. "Boron remediation in almonds".

May 2019. Annual Statewide Farm Advisor and Extension Tour. Woodland, CA. "Boron remediation in almonds". Aprox number of participants: 60. Audience: Farm Advisor and Extension professionals.

December 2019. Almond Board Conference. Sacramento, CA. "Boron remediation in almonds".

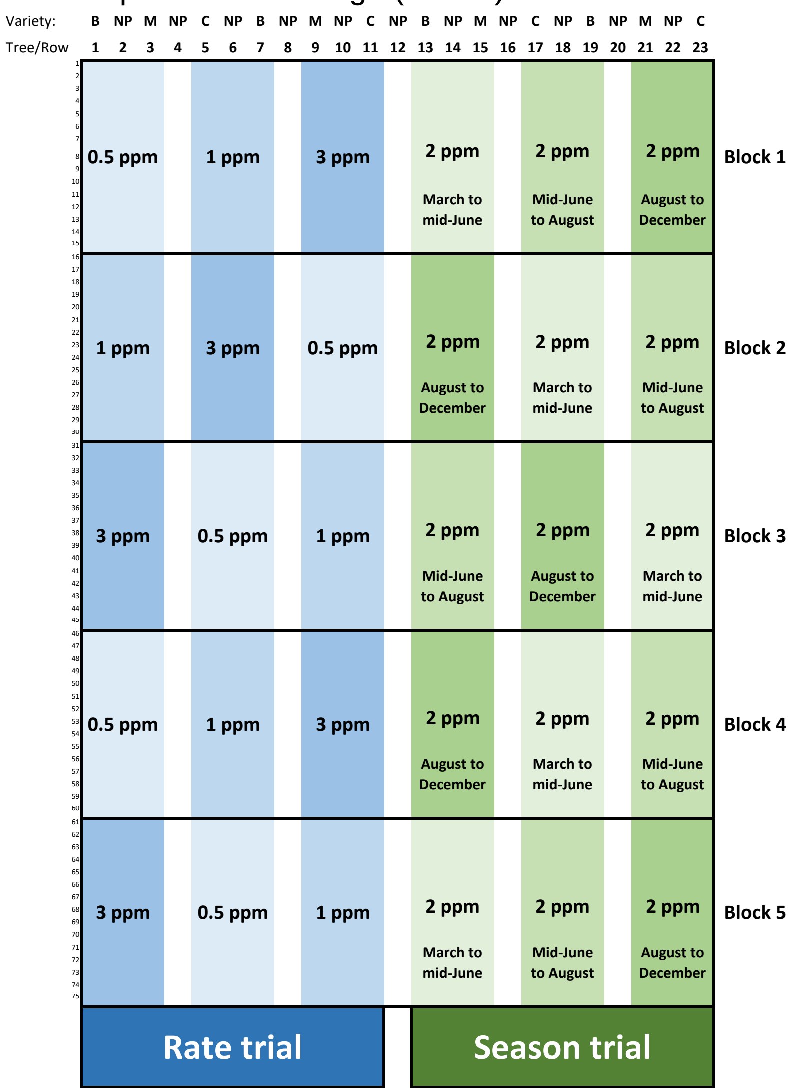
E. Materials and Methods

Boron field experiment

Nonpareil leaf tissue was collected in April and in Mid-July and mineral elements (Boron, Sodium, Magnesium, Phosporous, Potassium and Calcium) measured. Fruit from Nonpareil trees was collected on 6/3/2019, 7/22/2019 and 8/29/2019 and hull B measured through Inductively coupled plasma mass spectrometry.

The novel system developed to remove B from irrigation water had to be re-engineered and therefore the planned treatments were not delivered over the growing season. However, the experimental design for a B rate and season trial was established (Figure 4) in an area of the orchard with predominately San Ysidro Loam.

Figure 4. Randomized Complete Block Design (RCDB) at Westwind Farms.



Boron leaching experiment

In order to evaluate soil B leaching by different soil types and remediation strategies, soil columns (n=45) were established in the lab (Figure 5). To ensure representativeness and to be able to interpolate to different environmental conditions, soil columns were built with samples from different soil composition (wide soil textural range) and properties (pH levels). The five soil series selected were Corning, Rincon, San Ysidro, Tranquility and Yolo series under irrigation water at control, pH 6.0 and 9.0 conditions. Prior to the columns set up, incubation were carried out at the field capacity of each soil in order to standardize different soil B concentrations. B levels at the soil were increased to toxic levels (3 ppm).

Figure 5. Soil columns (n=45) of different soil series (Corning, Rincon, San Ysidro, Tranquility and Yolo series) from high B almond orchard sites, submitted to different irrigation treatments (Control, irrigation water solution with pH of 6.0 and 9.0).

The soils were air dried, sieved to 2 mm, and packed into 3-cm-diameter polystyrene columns to a soil depth of 30.0 cm. Rhizotron (Rhizosphere, Netherlands) where installed to extract pore water at 15 cm height (Figure 6). Solutions at pH 6.0 were prepared from ultrapure water with 2 $mmol_c$ L^{-1} of Mg^{2+}, 2 $mmol_c$ L^{-1} of Na^+, 4 $mmol_c$ L^{-1} of Cl^-, and 0.082 mmol L^{-1} of B (as HBO_3). Minor pH adjustment was made with HCl. Solutions at pH 9.0 were prepared with 2 $mmol_c$ L^{-1} of Na+, HCO_3^-, Mg^{2+}, and Cl^-, and 0.082 mmol L^{-1} of B (as NaH_3BO_3) (Suarez et al., 2012). Control solutions were obtained as suggested by OECD/OCDE guidelines for the testing of chemicals (2004) with 0.01 M $CaCl_2$ solution in ultra pure water. Hydraulic conductivity was not adversely impacted by these solution concentrations as the sodium adsorption ratio (SAR) is 2.0 ($mmolc^{0.5}$).

Figure 6. Rhizotron pore water sampling detailed.

Soil columns were first saturated and equilibrated from the bottom by capillarity with artifical rain solutions (Control) free of B. Then the surface of each soil column was treated with the respective treatment. After the adsorption phase with addition of almost 10 pore volumes (PV), B concentration was measured at the effluent solution to get **B concentration vs porous volume curve**. The data was converted to PV based on the calculated volumetric porosity. Porosity was calculated from soil mass and soil volume when packed, assuming a soil mineral density of 2.65 Mg m^{-3}.

F. Publications that emerged/will emerge from this work

Manuscript in preparation: “Boron management and leaching on irrigated agriculture”. Target Audience: California growers, researchers and other agricultural professionals.

G. References

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