

Continued investigation into the interactions of saline drainage water on crop tolerance to boron?

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ABSTRACT

A potential limitation in implementing a drainage water reuse system in the drainage impacted areas on the westside of the San Joaquin valley (SJV) is determining the extent by which boron, a naturally occurring element in the drainage water, affects the selection, growth and yield of crops in the reuse system. Despite the common occurrence of high boron and high salinity in many parts of the world, very little research has been done to study the interaction of the two. For those that have been done, contradictory results have been obtained. We are currently conducting greenhouse studies to evaluate B tolerance particularly in relation to salinity.

A comprehensive greenhouse experiment was conducted in 2003 at the US Salinity Laboratory in Riverside to evaluate the interactions between B and salinity (Cl-based salinity and SJV salinity composition) on the performance of broccoli and to get a better indication how limiting B actually is to plants grown in drainage reuse systems. Particular interest in this study was directed towards the composition of the salinizing solution to determine what role various salts have on the salinity-boron interaction. Results from this study indicated that both Cl-based salts and those characteristic of shallow saline drainage water (i.e. a mixture of salts dominated by sodium sulfate) showed a significant salinity-boron interaction. At high salinity, increased B concentration was less detrimental, both visually and quantitatively (i.e. biomass), than it was at low salinity. That is, plants could tolerate a higher solution B-concentration at higher salinity. However there was no significant difference between salt types. The effects on head weights were more exaggerated than those on shoot biomass. Therefore these data indicate that salinity reduces boron's detrimental influence.

We conducted another study in 2004 on cucumber, a crop that has been documented as more sensitive to boron in the presence of salinity than broccoli. In this outdoor lysimeter study, pH was added as an additional variable because of the alkaline nature of Westside SJV soils and its known influence on B uptake by plants.

Analysis of variance indicated that increased salinity and pH significantly reduced total biomass, vine fresh weight, fruit yield, fruit number per plant and cumulative water use of cucumber. Increased boron, on the other hand, significantly reduced total biomass, fruit number and cumulative water use. It did not significantly affect fruit yield.

Significant interactions were found between boron and pH, but not between salinity and pH or between salinity and boron. These data indicate that under slightly acidic conditions, increased B caused a much more dramatic reduction in plant biomass and yield than did the same increase under slightly alkaline conditions. The alkaline conditions are characteristic of soils on the Westside of the SJV.

Cumulative water use of cucumber was evaluated in relation to the various treatments. Cumulative ET was, for the most part, directly related to cumulative biomass; the higher the cumulative biomass the higher the cumulative ET.

Remote sensing with hyperspectral leaf reflectance can characterize salinity, pH, and boron effects on cucumber. The differences in remote vegetative index values due to salinity, boron, and pH are primarily related to changes in leaf pigment concentrations influenced first by salinity and later by boron as the leaf ages before senescence.

Ion concentrations were determined on fruit, stem and leaf tissues from samples collected at the end of the season. Salinity, boron and pH treatments had profound and often interactive effects on ion relations within the plant.

It was not surprising to find that increased salinity increased tissue Na and Cl concentration. However it was interesting that B and pH treatments also influenced the accumulation of these monovalent ions. For example as solution boron increased fruit sodium increased. In the leaf, as pH increased, leaf Na increased at low salinity but decreased at high salinity. Increased pH reduced Cl concentration in all tissues. In the stem, increased B increased Cl concentration but there were some inconsistencies even though this relationship was significant.

Tissue B concentration increased with boron in the solution but as salinity increased, stem and fruit B concentrations were reduced in most cases. In addition, an increase in pH reduced B concentration in the fruit although this relationship was rather weak, yet significant. Boron isotope analyses in the soil water and the plant tissue indicate that cucumbers did not discriminate between boron isotopes (^{10}B or ^{11}B) in the soil solution.

In broccoli, like many other crops where experiments were conducted using SJV type drainage water, we found that salinity reduced boron's detrimental effect. This was not the case, however, with cucumber. In this study, we did not find any significant interactions between salinity and boron on plant biomass or yield but significant interactions were found between B and pH. An increase in pH had a profound influence on reducing yield and plant biomass. The increase in pH may have altered nutrient relations as significant reductions were found in Ca, P and key micronutrients. It is not clear as to the extent by which these reductions may have adversely affected plant growth or whether or not other more complex nutritional interactions were playing a role. Therefore another broccoli study is underway to investigate the role of pH on the salinity-boron interactions in more detail and allow comparisons with our findings in cucumber.

INTRODUCTION

Reuse of saline drainage water is a management option on the west side of the San Joaquin Valley (SJV) that is necessary for reducing the volume of drainage water (San Joaquin Valley Drainage Implementation Program, 2000). Several methods of utilizing saline water (i.e. sequential, cyclic and blending) have been tested experimentally or demonstrated under field conditions (Grattan and Oster, 2003). In addition to these methods of reuse, saline water table control has also been tested as a means of allowing certain agronomic crops (such as cotton and safflower) to extract water directly from this saturated zone. Regardless of how crops utilize this saline drainage water, crop roots are exposed to water containing both high concentrations of sulfate and chloride salts as well as high concentrations of boron.

Considerable controversy exists over the extent by which boron limits the reuse potential of SJV drainage water. This concern stems from several relationships. First, there is a small concentration window between the level of boron in the soil that is required for optimal crop growth and that considered toxic (Gupta et al., 1985). Second, the boron concentrations in drainage water exceed the published boron tolerance coefficients for most crops grown in the San Joaquin Valley, despite the fact that many are classified as moderately B-tolerant to B-tolerant (Maas and Grattan, 1999). Third, boron is adsorbed tightly to the soil and therefore is not as readily leached from the crop rootzone as the other salts are. This phenomenon provides the opportunity for boron to accumulate in the root zone more rapidly than salinity, eventually affecting crop selection and ultimately having a negative effect on crop growth and yield. Because of these concerns, it has long been thought that B is a much more limiting factor in drainage water reuse than is the salinity

of the drainage water.

On the other hand, some argue that the boron coefficients might be too conservative (e.g. Letey et al., 2001). Most of the coefficients are based on the concentration of B in the soil water that produces incipient injury and are not based on yield reduction criteria (i.e. yield reduction as a function of increased B in the soil solution). Moreover, these coefficients were developed in *non-saline* environments suggesting that they may not be appropriate for crops grown under saline conditions.

The question has recently been raised, are the effects of salinity and boron on crops additive, synergistic, or antagonistic? Despite the common occurrence of high boron and high salinity in many parts of the world, very little research has been done to study the interaction of the two (Grattan and Grieve, 1999). From a review of the limited number of studies that addressed the combined effects of salinity and boron on the plant, it appears that the results are contradictory.

In sand-culture experiments conducted in a greenhouse, researchers found that wheat responded to boron in the soil solution independently of salinity, made up of sodium chloride (NaCl) and calcium chloride (CaCl₂) salts (Bingham et al., 1987). That is, there was no salinity - B interaction with respect to leaf B concentration. Similarly, others have found that boron and salinity effects were independent of each other for corn, barley and alfalfa (Shani and Hanks, 1993 and Mikkelsen et al., 1988).

However in more recent studies, investigators found that Cl-based salinity enhanced B sensitivity in wheat (Grieve and Poss, 2000; Läuchli et al., 2001; Wimmer et al., 2003). Wheat is one of those crops that are tolerant to salinity but sensitive to B. Grieve and Poss (2000) found that Cl-salinity increased B accumulation in leaves and was associated with more injury. Wimmer et al., (2003) attribute its effect on B compartmentalization within the plant. They found that under saline conditions, total B concentration was reduced in the root, was unaffected in the basal portion of the leaf, and increased in the leaf tip. Therefore salinity enhanced B mobility within the plant.

In a greenhouse study using soil in pots, investigators found that NaCl salinity increased B sensitivity in tomato and cucumber (Alpaslan and Gunes, 2001). However they found that salinity reduced B concentration in tomato but increased it in cucumber. These results question the hypothesis that B is taken up passively by plants via the transpiration stream. Furthermore, these investigators found that NaCl increased membrane permeability but increasing B in the soil to toxic levels did not, except in the presence of salinity.

On the other hand, investigators who used a mixture of salts (i.e. Na⁺, Ca²⁺, Cl⁻ and SO₄²⁻) found the opposite effect. In one field study conducted in Northern Chile, a number of vegetable crop species and prickly pear cactus were irrigated with saline water (8.2 dS/m) containing a mixture of ions including 17 mg/L of boron (Ferreira et al., 1997). Plant growth and crop yields of artichoke, asparagus, broad bean, red and sugar beets, Swiss chard, carrot, celery, a local variety of sweet corn, potato, prickly pear cactus, onion, shallot, spinach, were all greater than expected based on published salt and boron tolerance coefficients. These investigators found that salinity reduced leaf boron levels. If separate effects of salinity and boron are additive, little or no growth would be expected for any of these crops. Interactions likely occur which increase the crop's tolerance for boron in the presence of saline conditions. The investigators suggested that a reduction in plant water uptake, due to higher salinity levels, would reduce the rate boron accumulation in the plant tissue thereby extending the time during which boron levels are not affecting plant growth.

Others also found that salinity, composed of a mixture of salts, reduced leaf B concentration of chickpea (Yadav et al., 1989), wheat (Holloway and Alston, 1992) as well as reduced B uptake and

accumulation in the stem of several *Prunus* rootstocks (El-Motaium et al., 1994), thereby decreasing B-toxicity symptoms. In the latter study, the investigators found a negative relationship between B and SO_4^{2-} concentrations in tissue suggesting that SO_4^{2-} could be responsible for the salinity-induced reduction in tissue B. Others have also found that a mixture of chloride and sulfate salinity reduces leaf injury in *Eucalyptus camaldulensis* (Grattan et al., 1996) and pistachio (Ferguson et al., 2002) by reducing tissue B concentrations and in pistachio (Ferguson et al. 2002) by some unknown mechanism. Studies that include a mixture of salts (i.e. Na^+ , Mg^{2+} , Ca^{2+} , Cl^- and SO_4^{2-}) are much more typical of the drainage waters of the San Joaquin Valley as well as a number of coastal California valleys than those using chloride salts alone.

In no study, however, were investigators able to suggest the actual mechanism that supports this phenomenon such as direct ion interactions, reduced transpiration in salt-stressed conditions or both. Consequently, many questions regarding the interactions between salinity and boron remain unresolved. Questions related to (1) the relationship between visual leaf symptoms and yield; (2) the dynamic relationships between boron concentration in irrigation water, adsorption of boron, boron uptake and distribution within the plant; (3) the influence of salinity, both concentration and composition, on boron tolerance of the crop; and (4) whether boron damage will ever exceed salinity damage when using saline drainage water.

A comprehensive greenhouse experiment was conducted in 2003 at the US Salinity Laboratory in Riverside to evaluate the interactions between B and saline drainage water on the performance of broccoli and to get a better indication how limiting B really is to plants grown in drainage reuse systems. Particular interest in this study was directed towards the composition of the salinizing solution to determine what role various salts have on the salinity-boron interaction. Results from this study indicate that both Cl-based salts and those characteristic of shallow saline drainage water (i.e. a mixture of salts dominated by sodium sulfate) showed a significant salinity-boron interaction. That is at high salinity, increased B concentration was less detrimental, both visually and quantitatively (i.e. biomass), than it was at low salinity. Plants could tolerate a higher solution B-concentration at higher salinity. However there was no significant difference between salt types. The effects on head weights were more exaggerated than those on shoot biomass. Therefore these data indicate that salinity and B are antagonistic.

Shoot B concentration was influenced by salinity, but interestingly the direction of influence was dependent upon the B concentration in the solution. Regardless of the composition of the salinizing solution, increased salinity increased shoot B concentration when B concentrations in the solution were relatively low (i.e. 0.5 mg/L). At the highest solution B concentration (28 mg/L), increased salinity reduced shoot B concentration. Solution B in itself had very little influence on shoot ion accumulation but both salinity (i.e. EC) and salinity composition had very strong influences on shoot tissue ion composition.

Cumulative water use of broccoli was evaluated in relation to the various treatments. Cumulative ET was, for the most part, directly related to cumulative biomass; the higher the cumulative biomass the higher the cumulative ET. Stable isotopic ratios of oxygen in the solution were used to separate evaporation and transpiration. With these estimates, we were able to provide insight into whether B uptake is truly passive with the transpiration stream as many have suggested in the literature or whether the plant is able to regulate the amount of B absorbs and transports to the shoot. In no treatment did shoot B accumulate to a level predicted based on transpiration volume times solution B-concentration. Plants treated with low B contained the largest percent of B uptake (10-60%), expressed relative to predicted passive uptake. Salinity treatments, regardless of composition, represented the higher percentage range. On the other hand, plants treated with high B (14 or 28 mg/L) only accumulated 1-2% of that predicted if uptake and accumulation were truly passive. Therefore based on our data, it appears that a mechanism is present in broccoli that

can reduce that amount of B absorbed and/or transported to the shoot at high solution B concentrations.

An interdisciplinary research project involving scientists from the University of California and the USDA-ARS with expertise in soils and irrigation management, plant physiology, salinity and plant nutrition are continuing our investigation into salinity-boron interactions using sand cultures at the US Salinity laboratory to better understand the relationship between SJV salinity and boron interactions in crops. This report describes research conducted in 2004 where the interactive effects of SJV salinity on B tolerance were investigated under both slightly acid and slightly basic conditions. The later is more representative of the soil conditions in the SJV and it is known that pH affects B speciation in the soil solution and uptake by the plant.

MATERIALS AND METHODS

An experiment in large, outdoor sand tanks was conducted at the USDA-ARS, George E. Brown, Jr. Salinity Laboratory located at the UC Riverside campus. The experiment was designed to determine the interactive effects of SJV salinity, boron and pH on cucumber performance including growth, yield, injury, and ion relations. Cucumber (*Cucumis sativus* L.), cv 'Turbo' (hybrid) was selected because it is a crop grown the Westside of the SJV and is known to be moderately sensitive to salinity and moderately sensitive to B in both saline and non-saline systems.

Outdoor sand tank system

The experiment was conducted using an elaborate sand-tank system arranged in a completely randomized complete block design. The system consists of 24 large tanks (82 cm x 203 cm x 85 cm deep) filled with washed sand with a high, saturated soil hydraulic conductivity (400 cm day⁻¹). Each tank was plumbed with 5.1 cm PVC pipes, one for irrigation to the sand tank, and the other for return flow to separate 1740-L reservoirs in the basement below. The sand tank system was equipped with automated data acquisition system that characterized the fluid dynamics, temperature, and electrical conductivity within the system (Poss et al., 2004).

Salinity-B-pH treatments were complemented with modified half-strength Hoagland's nutrient solution. Solutions were pumped from the reservoirs below the sand tank facility to the tanks and then returned to the reservoirs several times per day. This irrigation frequency and volumes used each irrigation were sufficient to allow the sand-water concentration to approach that in the irrigation water, thereby creating a uniform distribution of salt in the crop rootzone. Calculations indicate that the salinity of the irrigation water was more or less equivalent to that of the sand water and previous studies (Wang, 2002) have indicated that the EC of the sand water is approximately 2.2 times the EC of the saturated soil extract (EC_e), the salinity parameter used to characterize salt-tolerance. Total evapotranspiration from each tank was measured by solution-volume changes in the storage reservoirs as well as by pressure transducers wired to a computer that plotted real-time water level dynamics in the reservoirs. Water lost was replenished to maintain constant osmotic potentials in the treatment irrigation waters.

The irrigation treatments consisted of two salinity levels, 3 and 8 dS/m; three boron concentrations, 0.7, 5 and 8 mg/L and two pH levels where solutions were frequently adjusted to 6.5 and 8. The salt solutions were prepared from predictions based on appropriate simulations using compositions typical to those found in the SJV (Suarez and Simunek, 1997).

Cucumber sampling and harvest

Cucumber was planted on 21 July, 2004 and salinization began 11 days later when plants had approximately two leaves. Plants were routinely observed for foliar injury and fruit development. Several plants were periodically harvested from each tank for biomass (fresh and dry weights of fruit, leaves, stems and roots) and fruit number. Ion concentrations (i.e. N, P, K, B, Na, Ca, Mg, Cl, S, Zn, Mn, Cu and Fe) were determined on dry ground tissue to assess their distribution within the plant and possible ion interactions within the plant. Shoot tissue samples were also analyzed for isotopic compositions of boron (i.e. $^{10}\text{B}/^{11}\text{B}$) to determine if there was preferential uptake of one isotope over the other.

Remote Sensing

Remote sensing using hyperspectral leaf reflectance is a useful tool for characterizing and possibly distinguishing crop response to salinity and boron stresses. In our study we used a hyperspectral characterization of leaf reflectance where the foreoptic was close to the leaf surface. Reflectance of the second leaf developed from the cotyledon was measured at 350 to 2500 nm with a peak-to-peak bandwidth of about 1.5 nm with an ASD FieldSpec Pro spectroradiometer (Analytical Spectral Devices, Inc., Boulder, CO)¹. During each measurement day, three scans were obtained for three plants from each plot. The spectroradiometer was equipped with a fiberoptic cable configured with an 8° foreoptic accessory and was positioned about 5 cm from and perpendicular to the leaf surface for a spot size of less than 1 cm diameter. Measurements were made as quickly as possible under full sun on DOY 223, 229 and 236. Special attention was made to avoid shadows and minimize the effect of glare by positioning the foreoptic between the sun and the plot. Immediately following leaf reflectance measurements, leaf discs were taken to the laboratory for pigment extractions and determinations including chlorophylls a and b, total carotenoids and anthocyanins.

RESULTS AND DISCUSSION

Biomass, fruit yield, fruit number and water use

Analysis of variance indicated that increased salinity and pH significantly reduced total biomass, vine fresh weight, fruit yield, fruit number per plant and cumulative water use of cucumber (Table 1). Increased boron, on the other hand, significantly reduced total biomass, fruit number and cumulative water use. The concentration of B in the irrigation water did not significantly affect fruit yield.

Significant interactions were found between boron and pH, but not between salinity and pH or between salinity and boron. These data indicate that under slightly acidic conditions, increased B had a much more dramatic reduction in plant biomass and yield than did the same increase under slightly alkaline conditions. This significant interaction between boron and pH is not surprising since pH has a profound influence on boron speciation and availability to the plant (Marschner, 1995).

Cumulative water use of cucumber was evaluated in relation to the various treatments. Cumulative ET was, for the most part, directly related to cumulative biomass; the higher the cumulative biomass the higher the cumulative ET.

Remote sensing

¹ Use of a company or product name is for the convenience of the reader and does not imply endorsement of the product by the USDA to the exclusion of others that may also be suitable.

Remote sensing indices were strongly correlated with pigment concentrations. Pigment concentrations were significantly influenced by boron, salinity, and pH treatments (Table 2) and depended upon the time of sampling. Salinity influenced all pigment concentrations when the second leaf was young but as the plant developed and the leaf aged, the influence of boron became more significant. At the time of the final sampling, when leaves were beginning to senesce, salinity effects were no longer apparent but boron continued to influence the chlorophyll b and anthocyanin concentrations. The effect of pH was significant only for chlorophyll a, chlorophyll a+b, and anthocyanin with an indication of a pH x boron interaction for chlorophyll b and anthocyanin on DOY 229 only.

Data from the early leaf-measurement indicate a strong relationship between the concentration of pigments (expressed on an area basis) with increasing salinity stress (Table 3). This may be partially due to a thickening of leaves with salinity stress resulting in more leaf volume. Although similar results were found upon a fresh weight and dry weight basis, they were most significant on a leaf area basis.

Several remote sensing indices were sensitive to salinity primarily by an association between salinity and pigment concentration (Figure 1). Salinity increased the concentration of chlorophyll a+b and its linear correlation with the Leaf Chlorophyll Index as defined by Datt et al. (2003) was quite good ($r^2 = 0.82$).

Boron concentration in leaves was significantly correlated with nine indices with the best index only accounting for about 35% of the variation in leaf boron ($r^2 = 0.21$, $B_{mm} = 9.438 * T1445_{vapos} + 12619$). A linear model of indices including T1445vapos and NDVIshi, a normalized difference vegetation index, increased this relationship r^2 to 0.35.

Remote sensing with hyperspectral leaf reflectance can characterize salinity, pH, and boron effects on cucumber. The differences in remote vegetative index values due to salinity, boron, and pH are primarily related to changes in leaf pigment concentrations influenced by the salinity at first and then by boron later as the leaf ages before senescence. All three factors were significantly related to various leaf reflectance indices and the explanations for these differences are under study.

Ion Relations

Ion concentrations were determined on fruit, stem and leaf tissue from samples collected at the end of the season. Salinity, boron and pH treatments had a profound and often interactive effect on ion relations within the plant (Tables 4-6). These results and relationships among ions will require a more thorough evaluation than are presented here but some of the highlights are discussed below.

Many studies have found that increased salinity reduces plant N concentration (Grattan and Grieve, 1999). This was the case in this study as well. As salinity increased, N concentrations (both nitrate and total N) in the leaf, stem and fruit were significantly decreased (data not presented).

The influence of treatments on tissue P concentration was different from that of N. In the leaf, as salinity increased, P decreased. Effects from solution changes in boron concentration or pH did not significantly affect leaf P. The opposite was found in the stem and fruit tissue. Increased salinity did not affect P concentrations in stems or fruits but increased pH reduced tissue P concentrations.

The effect of salinity on tissue K concentration was characteristic of those treatments where Na concentrations increase in the soil water environment. As salinity increased, tissue K decreased

presumably due to competitive effects between these two monovalent cations. Surprisingly this effect was only significant in the stem and fruit tissue, not the leaves despite a similar trend of reduction of K with increasing salinity. In the leaves, on the other hand, increased boron increased leaf K.

Increases in sodium-sulfate salinity increased the sulfur concentration in stems and leaves, but not significantly in the fruit. In addition, increased boron in solution reduced the S concentration in the stems and fruits in most cases.

In most cases, increased salinity increased the Ca concentration in the leaves but not stems or fruit. Increased pH generally resulted in lower tissue Ca concentrations. In the fruit, increased boron in the solution decreased tissue Ca concentration. However in the stem, increased boron increased Ca, but not at low pH or low salinity.

Increased salinity and pH increased Mg concentrations in stems and leaves. This influence was not significant in the fruit.

It was not surprising to find that increased salinity increased tissue Na concentration. However it was interesting that B and pH treatments had influence as well. For example as boron increased fruit sodium increased. In the leaf, as pH increased, leaf Na increased at low salinity but decreased at high salinity.

Tissue Cl also increased with increased salinity but it too has some interesting relations with B and pH. Increased pH reduced Cl concentration in all tissues. In the stem, increased B increased Cl concentration but there were some inconsistencies even though this relationship was significant.

Tissue B concentration increased with boron in the solution but as salinity increased, stem and fruit B concentrations were reduced in most cases. In addition, an increase in pH reduced B concentration in the fruit although this relationship was rather weak, yet significant. Boron isotope analyses in the soil water and the plant tissue indicate that cucumbers did not discriminate in boron uptake regarding in the isotopic composition of boron (^{10}B or ^{11}B) in the soil solution (data not presented).

There were also significant relationships among treatments and micronutrient concentrations. The relationships that were most notable were Mn and Zn concentrations being reduced under alkaline and to some extent saline conditions.

CONCLUDING REMARKS

Many plant experiments that have been conducted over the years using water compositions typical of the Westside SJV drainage water have found that the plants appear more tolerant of boron in the presence of salinity than in its absence. From our salinity-boron experiments over the past few years, data indicate that interactions can occur between salinity, boron and pH. In broccoli, we found that salinity, regardless of its composition, reduced boron's detrimental effect. This was not the case, however, with cucumber. In this study, we did not find any significant interactions between salinity and boron on plant biomass or yield but significant interactions were found between B and pH. An increase in pH had a profound influence on reducing yield and plant biomass. The increase in pH may have altered nutrient relations as significant reductions were found in Ca, P and key micronutrients. It is not clear as to the extent by which these reductions may have adversely affected plant growth or whether or not other more complex nutritional interactions were playing a role. We therefore found it important to conduct an additional experiment with broccoli get a better understanding of its increased tolerance to boron

in the presence of salinity and to what extent the pH of the media plays in the salinity-boron interactions.

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Table 1. Influence of salinity, boron and pH on cucumber biomass, fruit yield, fruit number and cumulative water use.

Dependent Variable	Significant ANOVA (p<0.05)	Significant Interaction (p<0.05)	Mean Separation ECw (alpha = 0.05)	Mean Separation Boron (alpha = 0.05)	Mean Separation pH (alpha = 0.05)
Vine Fresh Wt (kg/ 3 plants)	ECw	B-pH	ECw= 3 A 2.7 kg		pH = 6 A 2.7 kg
	pH		ECw =8 B 1.3 kg		pH = 8 B 1.4 kg
Fresh Cucumber (kg/ 3 plants)	ECw	B-pH	ECw= 3 A 4.9 kg		pH = 6 A 4.9 kg
	pH		ECw =8 B 3.0 kg		pH = 8 B 3.1 kg
Fruit number per 3 plants	ECw	None	ECw= 3 A 24.1	B = 5 A 21.8	pH = 6 A 24.1
	B		ECw =8 B 15.9	B = 0.9 A 21.7	pH = 8 B 15.9
	pH			B = 8 A 16.6	
Total Biomass (kg/ 3 plants)	ECw	B-pH	ECw= 3 A 7.7 kg	B = 0.9 A 6.6 kg	pH = 6 A 7.7 kg
	B		ECw =8 B 4.4 kg	B = 5 A 6.5 kg	pH = 8 B 4.4 kg
	pH			B = 8 A 4.9 kg	
Water Use (L/tank)	ECw	B-pH	ECw= 3 A 770 l	B = 0.9 A 701 l	pH = 6 A 742 l
	B		ECw =8 B 568 l	B = 5 AB 686 l	pH = 8 B 596 l
	pH			B = 8 B 621 l	

Table 2. Factorial analysis of variance for pigments in cucumber as influenced by boron, salinity, and pH and the boron*pH interaction.

Sample DOY	Type of leaf pigment mg dm ²	Full model r ²	Boron	EC P > F	pH	b*pH
223	Chl a	0.84	NS	<0.0001	NS	NS
	Chl b	0.94	NS	<0.0001	0.005	0.0296
	Chl a&b	0.9	NS	<0.0001	NS	NS
	Carotenoids	0.55	NS	0.0051	NS	NS
	Anthocyanins	0.91	NS	<0.0001	0.0036	0.0165
229	Chl a	0.83	0.03	<0.0001	NS	NS
	Chl b	0.8	NS	<0.0001	0.0042	NS
	Chl a&b	0.85	0.04	<0.0001	0.0275	NS
	Carotenoids	0.6	NS	0.0083	NS	NS
	Anthocyanins	0.72	NS	<0.0016	NS	NS
236	Chl a	0.53	0.04	NS	NS	NS
	Chl b	0.65	NS	NS	0.031	NS
	Chl a&b	0.54	0.04	NS	NS	NS
	Carotenoids	0.41	NS	NS	NS	NS
	Anthocyanins	0.51	0.05	NS	NS	NS

Table 3. Leaf pigment concentration means ± standard error in cucumber sampled on DOY 222.

Treatment			Pigment Mean ± Standard Error				
EC	Boron	pH	Chlorophyll a	Chlorophyll b	Chlorophyll a + b	Total Carotenoids	Total Anthocyanins
			mg dm ²				
3	0.9	6	2.99± 0.34	0.931± 0.084	3.92± 0.43	0.755± 0.087	0.307± 0.025
3	5	6	2.77± 0.41	0.745± 0.051	3.51± 0.46	0.738± 0.107	0.288± 0.029
3	8	6	2.41± 0.20	0.789± 0.043	3.20± 0.16	0.556± 0.130	0.261± 0.002
3	0.9	8	2.48± 0.00	0.706± 0.023	3.19± 0.02	0.700± 0.011	0.252± 0.006
3	5	8	2.78± 0.21	0.876± 0.010	3.64± 0.20	0.742± 0.143	0.303± 0.032
3	8	8	2.00± 0.46	0.651± 0.045	2.65± 0.50	0.531± 0.171	0.236± 0.030
8	0.9	6	3.63± 0.15	1.19± 0.221	4.83± 0.37	0.840± 0.059	0.364± 0.039
8	5	6	3.67± 0.18	1.00± 0.087	4.67± 0.20	0.954± 0.030	0.341± 0.031
8	8	6	3.71± 0.03	1.23± 0.110	4.94± 0.14	0.887± 0.094	0.347± 0.018
8	0.9	8	3.34± 0.06	0.970± 0.050	4.31± 0.11	0.820± 0.052	0.318± 0.006
8	5	8	3.26± 0.19	1.02± 0.010	4.27± 0.20	0.821± 0.010	0.308± 0.008
8	8	8	3.09± 0.07	0.915± 0.072	4.01± 0.08	0.752± 0.024	0.293± 0.000

Table 4. Concentrations \pm standard error of macronutrient elements in fruit, stems, and leaves of cucumber when grown under varying salinity, boron, and pH in the irrigation water.

Organ	EC	Boron	Ph	P \pm SE	K \pm SE	S \pm SE	Ca \pm SE	Mg \pm SE	Na \pm SE	Cl \pm SE
				mmoles kg ⁻¹	mmoles kg ⁻¹	mmoles kg ⁻¹	mmoles kg ⁻¹	mmoles kg ⁻¹	mmoles	mmoles
Fruit	3.0	0.9	6.0	397.2 \pm 32.3	2146.2 \pm 205.1	139.7 \pm 15.3	174.7 \pm 17.5	189.3 \pm 4.1	101.8 \pm 15.7	430.2 \pm 49.4
Fruit	3.0	5.0	6.0	337.5 \pm 9.4	2175.6 \pm 88.5	143.5 \pm 1.3	160.9 \pm 11.2	185.2 \pm 4.1	112.4 \pm 3.7	468.2 \pm 2.8
Fruit	3.0	8.0	6.0	335.8 \pm 32.3	1988.5 \pm 60.3	131.9 \pm 1.3	132.2 \pm 7.5	172.8 \pm 0.0	122.7 \pm 11.3	427.3 \pm 12.7
Fruit	3.0	0.9	8.0	243.8 \pm 1.6	1446.2 \pm 153.9	138.7 \pm 9.5	107.3 \pm 5.0	174.9 \pm 2.1	120.3 \pm 3.7	231.3 \pm 0.0
Fruit	3.0	5.0	8.0	243.8 \pm 4.8	1588.5 \pm 44.9	128.4 \pm 7.6	112.3 \pm 5.0	168.7 \pm 0.0	91.1 \pm 5.9	227.1 \pm 4.2
Fruit	3.0	8.0	8.0	237.3 \pm 1.6	1826.9 \pm 152.6	147.7 \pm 14.2	106.0 \pm 16.2	162.5 \pm 2.1	136.2 \pm 4.4	265.1 \pm 42.3
Fruit	8.0	0.9	6.0	332.6 \pm 0.0	1661.5 \pm 105.1	165.8 \pm 14.8	146.0 \pm 1.3	176.9 \pm 16.5	295.6 \pm 55.0	538.7 \pm 50.8
Fruit	8.0	5.0	6.0	301.9 \pm 59.7	1515.4 \pm 169.2	145.7 \pm 7.5	132.2 \pm 7.5	166.6 \pm 10.3	298.0 \pm 3.9	534.5 \pm 29.6
Fruit	8.0	8.0	6.0	303.5 \pm 12.9	1538.5 \pm 92.3	152.7 \pm 9.8	124.8 \pm 7.5	164.6 \pm 8.2	401.9 \pm 52.6	600.8 \pm 2.8
Fruit	8.0	0.9	8.0	192.1 \pm 40.4	1371.8 \pm 82.1	148.5 \pm 1.3	131.0 \pm 1.3	183.1 \pm 6.2	247.9 \pm 4.4	380.8 \pm 0.0
Fruit	8.0	5.0	8.0	213.1 \pm 25.8	1415.4 \pm 107.7	136.2 \pm 1.1	114.8 \pm 17.5	166.6 \pm 6.2	244.0 \pm 67.0	393.5 \pm 21.2
Fruit	8.0	8.0	8.0	214.7 \pm 21.0	1442.3 \pm 9.0	138.0 \pm 2.7	97.3 \pm 10.0	172.8 \pm 8.2	382.6 \pm 2.4	427.3 \pm 4.2
Stem	3.0	0.9	6.0	272.8 \pm 4.8	2347.4 \pm 29.5	108.9 \pm 1.6	467.8 \pm 6.2	226.3 \pm 8.3	187.0 \pm 23.1	853.2 \pm 15.5
Stem	3.0	5.0	6.0	221.2 \pm 56.5	2355.1 \pm 109.0	95.8 \pm 1.3	386.7 \pm 7.5	218.1 \pm 4.1	249.9 \pm 18.5	894.1 \pm 0.0
Stem	3.0	8.0	6.0	250.2 \pm 53.3	2234.6 \pm 55.1	92.3 \pm 0.6	336.8 \pm 37.4	230.4 \pm 8.2	281.7 \pm 17.2	936.5 \pm 50.8
Stem	3.0	0.9	8.0	127.5 \pm 1.6	2116.7 \pm 6.4	106.1 \pm 10.0	290.7 \pm 3.7	265.4 \pm 6.2	251.9 \pm 21.8	368.1 \pm 4.2
Stem	3.0	5.0	8.0	151.8 \pm 6.5	2180.8 \pm 119.2	88.0 \pm 5.6	273.2 \pm 21.2	261.3 \pm 10.3	270.3 \pm 29.4	307.5 \pm 16.9
Stem	3.0	8.0	8.0	125.9 \pm 32.3	2135.9 \pm 64.1	117.0 \pm 10.9	338.1 \pm 81.1	290.1 \pm 10.3	293.8 \pm 73.3	359.6 \pm 4.2
Stem	8.0	0.9	6.0	256.7 \pm 17.8	1587.2 \pm 64.1	158.9 \pm 2.3	415.4 \pm 83.6	351.8 \pm 10.3	707.1 \pm 138.5	1188.9 \pm 29.6
Stem	8.0	5.0	6.0	240.6 \pm 53.3	1561.5 \pm 23.1	131.0 \pm 8.4	410.4 \pm 48.7	364.1 \pm 18.5	584.6 \pm 1.3	1167.7 \pm 0.0
Stem	8.0	8.0	6.0	218.0 \pm 50.1	1464.1 \pm 133.3	143.2 \pm 1.9	502.7 \pm 53.6	390.9 \pm 20.6	746.4 \pm 53.9	1276.3 \pm 15.5
Stem	8.0	0.9	8.0	127.5 \pm 33.9	1450.0 \pm 126.9	127.6 \pm 1.9	331.8 \pm 27.5	417.6 \pm 26.7	563.7 \pm 57.0	904.0 \pm 57.8
Stem	8.0	5.0	8.0	138.8 \pm 16.1	1646.2 \pm 25.6	130.1 \pm 0.6	344.3 \pm 15.0	395.0 \pm 28.8	483.3 \pm 40.9	898.4 \pm 12.7
Stem	8.0	8.0	8.0	135.6 \pm 16.1	1656.4 \pm 25.6	123.2 \pm 5.9	364.3 \pm 17.5	411.4 \pm 20.6	580.3 \pm 18.3	940.7 \pm 4.2
Leaf	3.0	0.9	6.0	240.6 \pm 1.6	1207.7 \pm 71.8	234.9 \pm 5.3	1242.5 \pm 54.9	364.1 \pm 22.6	90.7 \pm 12.4	310.3 \pm 62.1
Leaf	3.0	5.0	6.0	229.3 \pm 32.3	1238.5 \pm 84.6	231.3 \pm 7.6	1202.6 \pm 89.8	411.4 \pm 4.1	106.1 \pm 13.9	335.7 \pm 36.7
Leaf	3.0	8.0	6.0	258.3 \pm 3.2	1301.3 \pm 96.2	217.4 \pm 17.5	1175.2 \pm 122.3	479.3 \pm 63.8	105.1 \pm 8.5	397.7 \pm 16.9
Leaf	3.0	0.9	8.0	182.4 \pm 30.7	1134.6 \pm 50.0	244.5 \pm 6.9	1180.1 \pm 20.0	652.1 \pm 14.4	108.3 \pm 11.3	124.1 \pm 16.9
Leaf	3.0	5.0	8.0	326.1 \pm 42.0	1191.0 \pm 19.2	210.4 \pm 4.2	1109.0 \pm 43.7	711.8 \pm 28.8	113.5 \pm 8.7	107.2 \pm 8.5
Leaf	3.0	8.0	8.0	192.1 \pm 53.3	1197.4 \pm 123.1	265.6 \pm 6.7	1167.7 \pm 77.4	722.1 \pm 121.4	111.4 \pm 27.4	124.1 \pm 0.0
Leaf	8.0	0.9	6.0	185.7 \pm 11.3	701.3 \pm 29.5	427.3 \pm 5.6	1508.2 \pm 143.5	722.1 \pm 51.4	340.8 \pm 69.4	588.1 \pm 24.0
Leaf	8.0	5.0	6.0	201.8 \pm 43.6	880.8 \pm 91.0	374.5 \pm 1.1	1492.0 \pm 104.8	736.5 \pm 24.7	262.7 \pm 12.2	662.9 \pm 59.2
Leaf	8.0	8.0	6.0	198.6 \pm 40.4	782.1 \pm 48.7	345.0 \pm 9.7	1341.1 \pm 131.0	685.0 \pm 14.4	312.1 \pm 66.3	658.6 \pm 12.7
Leaf	8.0	0.9	8.0	156.6 \pm 50.1	800.0 \pm 28.2	399.7 \pm 25.7	1294.9 \pm 25.0	892.8 \pm 28.8	197.3 \pm 6.3	356.8 \pm 40.9
Leaf	8.0	5.0	8.0	166.3 \pm 50.1	823.1 \pm 41.0	380.2 \pm 24.0	1407.2 \pm 187.1	884.6 \pm 8.2	184.4 \pm 11.3	372.3 \pm 25.4
Leaf	8.0	8.0	8.0	179.2 \pm 1.6	847.4 \pm 11.5	347.2 \pm 5.3	1235.0 \pm 39.9	845.5 \pm 10.3	213.8 \pm 15.0	372.3 \pm 33.9

Table 5. Concentrations \pm standard error of micronutrient elements in fruit, stems, and leaves of cucumber when grown under varying salinity, boron, and pH of irrigation water.

Organ	EC	Boron	Ph	B \pm SE ppm	Zn \pm SE ppm	Mn \pm SE Ppm	Fe \pm SE ppm	Cu \pm SE ppm
Fruit	3.0	0.9	6.0	33.5 \pm 2.5	68.0 \pm 7.0	30.5 \pm 0.5	133.0 \pm 13.0	7.1 \pm 0.7
Fruit	3.0	5.0	6.0	132.0 \pm 6.0	58.5 \pm 1.5	29.5 \pm 0.5	244.5 \pm 26.5	12.5 \pm 2.4
Fruit	3.0	8.0	6.0	180.0 \pm 4.0	53.5 \pm 0.5	24.5 \pm 0.5	171.0 \pm 8.0	7.4 \pm 0.0
Fruit	3.0	0.9	8.0	31.0 \pm 1.0	40.5 \pm 1.5	23.5 \pm 3.5	161.0 \pm 42.0	3.9 \pm 1.1
Fruit	3.0	5.0	8.0	88.0 \pm 17.0	24.0 \pm 3.0	18.0 \pm 0.0	172.0 \pm 59.0	4.0 \pm 1.3
Fruit	3.0	8.0	8.0	180.0 \pm 16.0	38.5 \pm 13.5	16.0 \pm 0.0	149.0 \pm 26.0	5.3 \pm 2.3
Fruit	8.0	0.9	6.0	32.0 \pm 3.0	57.0 \pm 1.0	23.0 \pm 3.0	169.0 \pm 18.0	9.2 \pm 2.4
Fruit	8.0	5.0	6.0	98.0 \pm 9.0	51.0 \pm 6.0	19.5 \pm 0.5	125.5 \pm 19.5	6.1 \pm 1.3
Fruit	8.0	8.0	6.0	172.0 \pm 6.0	49.5 \pm 5.5	19.5 \pm 1.5	98.0 \pm 12.0	6.9 \pm 1.0
Fruit	8.0	0.9	8.0	34.5 \pm 1.5	30.5 \pm 1.5	18.0 \pm 2.0	150.5 \pm 49.5	3.7 \pm 1.3
Fruit	8.0	5.0	8.0	90.5 \pm 1.5	30.0 \pm 0.0	16.0 \pm 1.0	116.5 \pm 23.5	3.0 \pm 0.4
Fruit	8.0	8.0	8.0	153.0 \pm 11.0	31.5 \pm 1.5	14.5 \pm 2.5	103.0 \pm 17.0	3.3 \pm 1.2
Stem	3.0	0.9	6.0	36.5 \pm 0.5	50.5 \pm 2.5	31.0 \pm 1.0	371.0 \pm 165.0	11.2 \pm 3.1
Stem	3.0	5.0	6.0	104.0 \pm 2.0	35.5 \pm 1.5	28.5 \pm 0.5	258.0 \pm 5.0	8.9 \pm 1.2
Stem	3.0	8.0	6.0	136.5 \pm 5.5	38.5 \pm 0.5	26.0 \pm 3.0	683.0 \pm 487.0	15.4 \pm 7.6
Stem	3.0	0.9	8.0	31.5 \pm 3.5	44.5 \pm 22.5	41.0 \pm 14	5262.5 \pm 5017	65.2 \pm 58.7
Stem	3.0	5.0	8.0	90.5 \pm 1.5	16.5 \pm 0.5	17.0 \pm 0.0	435.0 \pm 51.0	11.1 \pm 1.7
Stem	3.0	8.0	8.0	166.0 \pm 16.0	22.5 \pm 4.5	17.5 \pm 0.5	215.0 \pm 14.0	6.9 \pm 1.1
Stem	8.0	0.9	6.0	32.0 \pm 1.0	38.0 \pm 2.0	21.5 \pm 0.5	580.0 \pm 354.0	14.2 \pm 5.4
Stem	8.0	5.0	6.0	84.0 \pm 5.0	36.5 \pm 7.5	21.0 \pm 2.0	465.0 \pm 262.0	11.4 \pm 5.2
Stem	8.0	8.0	6.0	166.5 \pm 27.5	32.0 \pm 0.0	23.0 \pm 2.0	373.5 \pm 88.5	11.1 \pm 1.7
Stem	8.0	0.9	8.0	29.5 \pm 0.5	26.0 \pm 7.0	18.0 \pm 3.0	1486.0 \pm 1124	24.2 \pm 16.0
Stem	8.0	5.0	8.0	69.5 \pm 0.5	17.5 \pm 1.5	13.5 \pm 1.5	350.5 \pm 20.5	10.9 \pm 3.0
Stem	8.0	8.0	8.0	97.5 \pm 11.5	17.0 \pm 1.0	11.5 \pm 1.5	447.0 \pm 114.0	9.8 \pm 0.6
Leaf	3.0	0.9	6.0	108.0 \pm 6.0	62.0 \pm 3.0	84.0 \pm 3.0	268.5 \pm 7.5	8.3 \pm 0.7
Leaf	3.0	5.0	6.0	639.0 \pm 30.0	53.5 \pm 0.5	85.5 \pm 1.5	282.5 \pm 13.5	8.5 \pm 0.9
Leaf	3.0	8.0	6.0	1069.0 \pm 125.0	58.0 \pm 3.0	72.5 \pm 9.5	285.0 \pm 66.0	6.8 \pm 0.8
Leaf	3.0	0.9	8.0	121.0 \pm 2.0	34.0 \pm 2.0	76.0 \pm 16	260.0 \pm 22.0	5.7 \pm 0.7
Leaf	3.0	5.0	8.0	604.0 \pm 0.0	26.0 \pm 1.0	57.5 \pm 0.5	227.0 \pm 15.0	6.6 \pm 0.5
Leaf	3.0	8.0	8.0	1140.0 \pm 5.0	36.0 \pm 10.0	49.5 \pm 2.5	196.5 \pm 14.5	4.8 \pm 0.2
Leaf	8.0	0.9	6.0	127.5 \pm 0.5	50.5 \pm 3.5	59.0 \pm 7.0	272.0 \pm 28.0	9.7 \pm 3.0
Leaf	8.0	5.0	6.0	696.0 \pm 25.0	49.5 \pm 7.5	52.5 \pm 0.5	279.5 \pm 50.5	7.1 \pm 1.5
Leaf	8.0	8.0	6.0	1072.5 \pm 34.5	48.5 \pm 1.5	54.0 \pm 4.0	249.0 \pm 7.0	7.4 \pm 0.9
Leaf	8.0	0.9	8.0	118.5 \pm 2.5	30.0 \pm 2.0	34.0 \pm 4.0	232.0 \pm 13.0	6.3 \pm 0.3
Leaf	8.0	5.0	8.0	612.5 \pm 67.5	26.5 \pm 3.5	35.0 \pm 2.0	195.5 \pm 1.5	5.9 \pm 0.2
Leaf	8.0	8.0	8.0	928.0 \pm 13.0	31.0 \pm 0.0	32.0 \pm 6.0	694.0 \pm 483.0	10.5 \pm 3.5

Table 6. Factorial analysis of variance for mineral elements in fruit, stems and leaves of cucumber as influenced by main effects of boron, salinity, and pH and interactions.

Ion	Organ	full model r ²	Boron	EC P > F	EC*Boron	pH	b*pH	EC*pH	EC*B*pH
N	Fruit	0.64	NS	<0.0025	NS	NS	NS	NS	NS
P	Fruit	0.77	NS	NS	NS	<0.0001	NS	NS	NS
K	Fruit	0.84	NS	0.0002	NS	0.0005	NS	0.0373	NS
S	Fruit	0.53	NS	NS	NS	NS	NS	NS	NS
B	Fruit	0.98	<0.0001	0.0477	NS	0.0329	NS	NS	NS
Ca	Fruit	0.82	0.0191	NS	NS	0.0001	NS	0.0427	NS
Mg	Fruit	0.56	NS	NS	NS	NS	NS	0.0471	NS
Na	Fruit	0.93	0.007	<0.0001	NS	NS	NS	NS	NS
Cl	Fruit	0.95	NS	<0.0001	NS	<0.0001	NS	NS	NS
Zn	Fruit	0.87	NS	NS	NS	<0.0001	NS	NS	NS
Mn	Fruit	0.89	0.0043	0.0002	NS	<0.0001	NS	0.0434	NS
Fe	Fruit	0.61	NS	0.0252	NS	NS	NS	NS	NS
Cu	Fruit	0.77	NS	NS	NS	0.0002	NS	NS	NS
NO3	Fruit	0.65	NS	0.0035	NS	NS	NS	NS	NS
N	Stem	0.85	0.0017	0.0306	NS	0.0002	NS	0.0265	NS
P	Stem	0.72	NS	NS	NS	0.0002	NS	NS	NS
K	Stem	0.95	NS	<0.0001	NS	NS	NS	0.0357	NS
S	Stem	0.93	0.0125	<0.0001	NS	NS	NS	0.005	0.0195
B	Stem	0.96	<0.0001	0.0299	NS	0.0529	NS	0.0167	0.006
Ca	Stem	0.7	0.0191	NS	NS	0.0021	NS	NS	NS
Mg	Stem	0.95	NS	<0.0001	NS	0.0007	NS	NS	NS
Na	Stem	0.93	NS	<0.0001	NS	NS	NS	0.019	NS
Cl	Stem	0.99	0.0119	<0.0001	NS	<0.0001	NS	<0.0001	NS
Zn	Stem	0.68	0.0458	NS	NS	<0.0051	NS	NS	NS
Mn	Stem	0.76	0.0321	0.0046	NS	<0.0525	NS	0.0434	NS
Fe	Stem	0.45	NS	0.0252	NS	NS	NS	NS	NS
Cu	Stem	0.42	NS	NS	NS	NS	NS	NS	NS
NO3	Stem	0.9	NS	<0.0001	0.0436	0.0222	NS	NS	NS
N	Leaf	0.52	NS	0.0336	NS	NS	NS	NS	NS
P	Leaf	0.61	NS	0.0174	NS	NS	NS	NS	NS
K	Leaf	0.91	<0.0001	NS	NS	NS	NS	NS	NS
S	Leaf	0.97	0.0066	<0.0001	0.0056	NS	NS	NS	NS
B	Leaf	0.98	<0.0001	NS	NS	NS	NS	NS	NS
Ca	Leaf	0.61	NS	0.0047	NS	NS	NS	NS	NS
Mg	Leaf	0.93	NS	<0.0001	NS	<0.0001	NS	0.0454	NS
Na	Leaf	0.88	NS	<0.0001	NS	0.018	NS	0.006	NS
Cl	Leaf	0.976	NS	<0.0001	NS	<0.0001	NS	NS	NS
Zn	Leaf	0.9	NS	0.0395	NS	<0.0001	NS	NS	NS
Mn	Leaf	0.89	NS	<0.0001	NS	<0.0001	NS	NS	NS
Fe	Leaf	0.44	NS	NS	NS	NS	NS	NS	NS
Cu	Leaf	0.54	NS	NS	NS	NS	NS	NS	NS
NO3	Leaf	0.66	NS	0.0008	NS	NS	NS	NS	NS

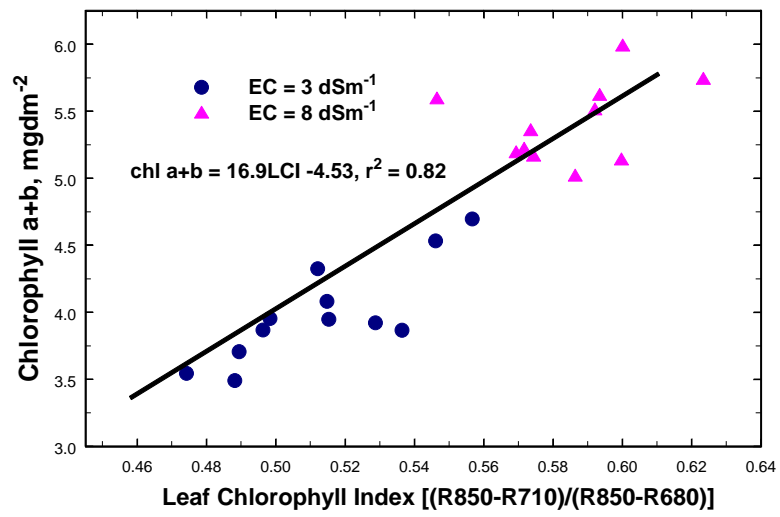


Figure 1. Leaf chlorophyll index in cucumber is linearly related to leaf chlorophyll a+b concentrations. Leaf tissue from salinized plots had higher chlorophyll concentrations.