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Effects of salinity and varying boron concentrations on boron uptake and growth of wheat

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Summary Two sandculture experiments were conducted with wheat (*Triticum aestivum*) to determine the effects of (1) osmotic potential (Ψ_π) and (2) fluctuating boron (B) concentrations on B availability (toxicity), shoot growth and leaf concentrations of B of wheat. The first experiment consisted of growing wheat to the spike emergence stage in sandcultures irrigated with a complete nutrient solution containing 1.0, 7.5, and 15.0 mg B l^{-1} and having Ψ_π values of -0.02, -0.07, -0.12, and -0.17 MPa produced by $CaCl_2$-NaCl additions. Statistically, shoot weight was independently influenced by the B and Ψ_π treatments but not by their interaction. Only the B treatment had a significant effect on leaf boron concentrations; the B × Ψ_π interaction was nonsignificant with respect to leaf B concentrations.

The second experiment was designed to determine if growth and B uptake of wheat responds to the time integrated mean (TIM) concentration of B. This experiment consisted of four fixed-B concentrations and four fluctuating-B concentrations designed to produce two TIM concentrations (3.9 and 7.4 mg B l^{-1}) approached low to high and vice versa. With respect to shoot weight, there was no statistical difference among treatments having the same TIM concentration during the 10 week experiment. However, shoot B concentrations differed greatly; they were higher when the B concentration was progressively increased over the 10 week period. Leaf B concentrations (Y leaf at flowering), while not as high as the shoot B concentrations, were also higher under the treatment of increasing B concentration, indicating B uptake rates are higher for mature plants than for seedlings.

Introduction

Because of its moderately high tolerance to salinity[8,9], wheat (*Triticum aestivum*) is frequently recommended as a crop to grow following the reclamation of salt-affected soils. Although wheat is moderately salt tolerant, it is sensitive to relatively low concentrations of boron (B); the B threshold concentration varies from 0.5 to 1.0 mg B l^{-1} in soil solution[5,8]. Because B is removed more slowly than salinity during leaching[10], it may still be excessive in some reclaimed soils and exist in various proportions with salinity. How crops respond to various combinations of salinity and B is relatively unknown. For example, it is not known whether salinity enhances or reduces the phytotoxicity of B. It is also unknown how crops respond to B concentrations in soil solution (B_{ss}) which vary throughout the growing season. Possibly crops respond to the TIM concentration as they do to salinity[2,6].

With these questions in mind, two experiments were conducted with wheat. The first consisted of testing the effect of salinity on the availability of excesssive concentrations of B to wheat. The second tested wheat's response to the manner in which the B concentrations were varied during its growth up to the flowering stage. This latter experiment was specifically designed to ascertain whether wheat responds to the TIM concentration of B. The results of these two experiments provide the basis of this paper.

Materials and methods

The two sandculture experiments were conducted in a temperature controlled glasshouse equipped with filters to remove smog from the incoming air. Each sandculture unit consisted of a 120 l reservoir tank, a cover supporting 2 sand-filled buckets containing approximately 10 kg of quartz sand, an air lift to pump nutrient solution from the reservoir onto the pots, and a manifold to distribute the solution to each pot. The air lift was activated by a timer which controlled time and length of irrigations. The solution percolated through the sand-filled pots back into the reservoir for 15 min 6-times daily[5]. The irrigation solutions contained the following salt additions per liter: 0.5 mmol KH_2PO_4, 2.1 mmol $Ca(NO_3)_2$, 1.2 mmol KNO_3, 0.17 mmol $Mg(NO_3)_2$, 0.5 mmol $MgSO_4$, 0.16 μmol $CuSO_4$, 4.6 μmol $MnSO_4$, 0.05 μmol H_3MoO_4, 0.38 μmol $ZnSO_4$, and 89 μmol Fe from Fe-EDDHA. Additional details concerning boron and chloride salt additions are given separately for each experiment.

Salinity-boron interaction experiment

Wheat (*Inia* 66R — a short statured spring wheat with an early maturing semi-hard red grain[4]) was seeded directly into each sandculture and thinned to two plants per pot when approximately 10 cm in height. Boron was added as orthoboric acid two days later to the respective sandculture solutions producing concentrations of 1.0, 7.5 and 15.0 mg B l^{-1}. During the next three days, the B-treated sandcultures were salinized with $CaCl_2$-NaCl salts (1:1 molar solution) to lower the osmotic potentials (Ψ_π) of the nutrient solutions -0.02, -0.07, -0.12 and -0.17 MPa. These Ψ_π values correspond to electrical conductivities (EC) of approximately 0.6, 2.0, 3.4 and 4.8 dS m^{-1}. The Ψ_π values were calculated from the EC values with the relation $\Psi_\pi = 0.036\,EC$ expressed in dS m^{-1}. These twelve combinations of B and Ψ_π were replicated six-fold in a randomized complete block design. The sandculture solutions were maintained at a volume of 120 l with deionized water during the growth period. In addition, the pH values of the solutions were kept within the range of 5.5 to 6.0 by addition of KOH or H_2SO_4.

Leaf samples consisting of the Y-leaf and the first leaf below the Y-leaf were collected at the spike emergence stage for boron analysis by the azomethine-H procedure[3]. The shoots (above sand portion of the plant) were harvested immediately after collecting the leaf samples, dried in a forced draft oven maintained at 65°C and weighed. Analysis of variance (ANOVA) was conducted on the data pertaining to the dry shoot weights, and concentrations of B (mg kg^{-1}) in the leaf samples. This experiment was conducted during the winter season 1983.

Time integrated boron experiment

The following winter the second experiment was conducted in the following manner. Wheat (*Inia* 66R) was planted and germinated directly in the sandcultures as described above except that the initial irrigation solution contained no $CaCl_2$-NaCl; however, the B concentration was 1.0 mg B l^{-1}. Two weeks after emergence, the seedlings were thinned to two per pot and three sets of differential B treatments were imposed. One set consisted of B concentrations of 1.0, 5.0, 10.0 and 15.0 mg B l^{-1} held constant for the 8 week duration of the experiment (treatments 1, 2, 3, and 4). A second set was designed to expose the wheat to a TIM concentration of 3.9 mg B l^{-1} with the B increasing with time in one case and decreasing with time in another. This was achieved by irrigating for 2 week periods with solutions having 1.0, 2.5, 5.0 and 10.0 mg B l^{-1} in the first case and with 10.0, 5.0, 2.5, and 1.0 mg B l^{-1} in the second case (treatments 5 and 6). The third set of treatments was analogous to the 3.9 mg l^{-1} TIM concentration experiment except that a TIM concentration of 7.4 mg B l^{-1} was achieved by successive two week exposures to 1.0, 5.0, 10.0, and 20.0 mg B l^{-1} and the reverse sequence (treatments 7 and 8). The above eight treatments were replicated four-fold in a randomized complete block design (see Table 1 for a summary of treatments).

The nutrient solutions were renewed after each two week exposure period by draining the reservoir tanks, leaching the sand-filled pots with deionized water, and then adding a freshly prepared nutrient solution containing the desired concentration of B. Samples of the nutrient solutions were checked for B concentration to verify that the objective concentrations existed. The B concentrations were found to be within 5% of the desired concentrations, thus no adjustments of the B concentrations were made.

Leaf samples were collected at the spike initiation stage for B analysis as described above. Ten weeks after seeding, the shoots were harvested, dried at 65°C in a forced draft oven, weighed, ground, and analyzed for B.

The above experimental design of varying the concentration of B is comparable to that used by Bernstein and Pearson[2] to demonstrate that plants respond to the TIM concentration of soluble salts.

Results

Salinity-boron interaction experiment

Table 2 contains a summary of dry shoot weights in relation to Ψ_π and B treatments. Significant treatment effects of Ψ_π and B were manifested by the shoot weight data; however, the $\Psi_\pi \times$ B interaction was not significant. The Ψ_π treatments of -0.02, -0.07, -0.12, and -0.17 MPa resulted in mean shoot weights averaged across B treatments of 26.3, 26.5, 23.7, and 20.0 g per plant. Only the 20.0 g weight differed significantly from the other weights. The B treatments of 1.0, 7.5,

Table 1. Schedule of treatments for wheat grown in sandcultures

Treatment* No.	Boron concentration (mg B l^{-1})					
	0–2 wks	2–4 wks	4–6 wks	6–8 wks	8–10 wks	Mean**
1	1.0	1.0	1.0	1.0	1.0	1.0
2	1.0	5.0	5.0	5.0	5.0	4.2
3	1.0	1.0	2.5	5.0	10.0	3.9
4	1.0	10.0	5.0	2.5	1.0	3.9
5	1.0	10.0	10.0	10.0	10.0	8.2
6	1.0	1.0	5.0	10.0	20.0	7.4
7	1.0	20.0	10.0	5.0	1.0	7.4
8	1.0	15.0	15.0	15.0	15.0	12.2

* Replicated 4-fold.

** Time integrated mean concentration.

Table 2. Dry shoot weights of wheat in relation to boron concentration and osmotic potential of nutrient solutions

Boron $mg\,l^{-1}$	Shoot weight (g $plant^{-1}$)				
	Osmotic Potential (MPa)				
	−0.02	−0.07	−0.12	−0.17	$\bar{x}$
1.0	33.5	31.8	29.0	24.1	29.6 x
7.5	26.6	26.8	24.0	21.8	24.8 x
15.0	18.8	20.9	18.2	14.0	18.0 z
$\bar{x}$	26.3 y	26.5 y	23.7 y	20.0 z	

ANOVA

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F ratio	Statistical significance
Salinity	3	499.9	166.6	7.9	***
Boron	2	1643.4	821.7	39.1	***
Salinity x boron	6	54.5	9.1	0.4	N.S.
Error	60	1261.4	21.0		
Total	71	3459.2			
Coefficient of variation = 19.0%					

*** and N.S. respectively indicate significance at the 0.001 level of probability and nonsignificance at the 0.05 level of probability. The small letters by the $\bar{x}$ values denote Multiple Range groupings at the 5% level.

and 15.0 $mg\,l^{-1}$ resulted in mean shoot weights averaged across Ψ_π treatments of 29.6, 24.8, and 18.0 g per plant. Statistically, the 18.0 g weight was different.

The leaf boron data are reported in Table 3. Analysis of variance shows only the B additions producing a significant effect of leaf boron concentrations. Average leaf boron values increased from 73 to 1009 mg B kg^{-1} as B concentration increased from 1.0 to 15.0 $mg\,l^{-1}$ over the range of Ψ_π treatments. Lowering to −0.17 MPa caused leaf boron to decrease from 576 to 437 mg B kg^{-1} but this change was not statistically significant.

Linear regression analysis of leaf boron as a function of Ψ_π yields three distinct curves:

B addition	*Equation*
1.0	leaf B = 100 + 286Ψ_π
7.5	leaf B = 517 + 688Ψ_π
15.0	leaf B = 1187 + 1846Ψ_π

As evidenced by the slope parameters there is a tendency for decreasing Ψ_π to decrease the leaf concentration. However, analysis of covariance

Table 3. Leaf boron concentration in relation to boron concentration and osmotic potential of nutrient solutions

Boron concentration $mg\,l^{-1}$	Leaf boron ($mg\,B\,kg^{-1}$)				
	Osmotic potential (MPa)				
	−0.02	−0.07	−0.12	−0.17	$\bar{X}$
1.0	95	84	58	56	73 x
7.5	516	441	446	400	450 y
15.0	1116	1105	960	857	1009 z
$\bar{X}$	576	544	488	437	

ANOVA

Source of variation	Degrees of freedom	Sum of squares	Mean square	F ratio	Statistical significance
Salinity	3	2.0×10^5	6.7×10^4	2.6	N.S.
Boron	2	106.5×10^5	532.6×10^4	208.9	***
Salinity × boron	6	1.3×10^5	2.1×10^4	0.8	N.S.
Error	60	15.3×10^5	2.5×10^4		
Total	71	125.1×10^5			
Coefficient of variation = 31.2%					

*** and N.S. respectively indicate significance at the 0.001 level of probability, and nonsignificance at the 0.05 level of probability by the F-test. The small letters by the $\bar{X}$ values indicate Duncan Multiple Range groupings at the 5% level.

shows that there were no significant differences between the individual slopes which indicates that no Boron x Ψ_π interaction occurs.

Time integrated boron experiment

Plant weights and shoot and leaf boron contents are summarized according to B treatment in Table 4. Shoot weights decreased from 55 to 27 g per plant as the B concentration was increased from 1.0 to 12.2 $mg\,l^{-1}$ (treatments 1, 2, 5, and 8). The shoot weights for the three treatments having a TIM concentration of 4.2, 3.9, and 3.9 $mg\,B\,l^{-1}$ (treatments 2, 3, and 4) were 41, 51, and 45 g per plant, respectively; these values were not statistically different from one another. The higher B concentrations of 8.2, 7.4, and 7.4 $mg\,B\,l^{-1}$ (treatments 5, 6, and 7) resulted in shoot weights of 40, 38, and 30 g per plant, respectively, which likewise were not significantly different.

Leaf B concentrations were strongly influenced by the boron treatments. For example, leaf boron ranged from 231 $mg\,B\,kg^{-1}$ for the 1.0 $mg\,B\,l^{-1}$ treatment to 3593 $mg\,B\,kg^{-1}$ for the 7.4 $mg\,B\,l^{-1}$ treatment in which B increased from 1 to 20 $mg\,B\,l^{-1}$. The manner of varying the B concentration in nutrient solution over time exerted a strong effect on leaf B concentrations. Higher leaf B concentrations were produced when

Table 4. Dry plant weight and shoot and leaf boron concentration of wheat in relation to time integrated mean concentration of boron in nutrient solution

Treatment*			Plant weight† ($g\ plant^{-1}$)	Leaf boron† ($mg\ kg^{-1}$)	Shoot boron† ($mg\ kg^{-1}$)
Number	Boron ($mg\ l^{-1}$)				
1	Constant 1.0	(1.0)	55 a	231 a	47 a
2	Constant 5.0	(4.2)	41 ab	1142 b	140 a
3	Fluctuating 1 to 10	(3.9)	51 a	1845 c	300 b
4	Fluctuating 10 to 1	(3.9)	45 ab	500 a	71 a
5	Constant 10	(8.2)	40 ab	1833 c	346 b
6	Fluctuating 1 to 20	(7.4)	38 ab	3593 e	552 c
7	Fluctuating 20 to 1	(7.4)	30 b	895 b	116 a
8	Constant 15	(12.2)	27 b	2693 d	346 b

*The concentration value enclosed within parenthesis is the calculated time integrated B concentration for the 10 week period.
†The small letters indicate Duncan Multiple Range grouping at the 5% level.

the nutrient solution level of B was increased from low to high (compare treatments 3 to 4 and 6 to 7). Similar results prevailed for shoot B data although the B concentrations of the shoot were lower than that found in Y-leaf samples.

Discussion

The B concentration in soil solution (B_{ss}) is influenced by a large number of factors such as B content of irrigation water (B_{iw}), irrigation management, drainage regime, and certain soil properties[7]. B_{ss} concentrations tend to increase as the irrigation season progresses and then to decrease during the winter season depending upon rainfall. According to the results of the Ψ_π-B experiments, changes in soil salinity would not likely alter the response of the crop to a given B_{ss} concentration. This is consistent with the implicit assumption in the current irrigation water criteria for B[7,8,12] that salinity does not influence the availability of B_{iw}.

Changes in B_{ss} concentration, such as those taking place during the irrigation season or due to use of more than one water supply[11], are likely to influence the crop's response in a way proportional to the TIM concentrations of B_{ss}. In the past, B_{ss} concentrations have been equated with B_{iw} concentrations[1,8,12]. However, as pointed out by Rhoades[10], the B_{ss} concentrations eventually exceed that of B_{iw} once the boron adsorption capacity of the soil is reached. If the irrigation season is short and the soil is leached over the winter or pre-irrigated heavily between crops, annual crops are probably exposed to B_{ss} concentrations that approximate that of B_{iw}. The use of more than one water source for the irrigation of a particular crop leads to changes in B_{ss} paralleling the B_{iw} concentrations of the respective waters. In this case, the effective B_{iw} concentration could be estimated as the TIM concentration. Likewise, soil analysis for B_{ss}, if performed throughout the growing season, could be time weighted to obtain the effective B_{ss} concentration. Results of the TIM concentration experiment (Table 4) tend to support this view since wheat, at least its shoot growth, responded to the TIM B concentration.

The results of the two experiments with wheat (Inia 66R) indicate plants respond to B_{ss} independently of soil salinity levels. The TIM experiment indicated that wheat and possibly other crop species repond to the TIM concentration comparable to the responses of plants to soil salinity concentrations varying with time. However, general conclusions await additional studies of the above two concepts with a number of crop species.

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