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An Application of the Maas-Hoffman Salinity Response Model for Boron Toxicity[1]

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ABSTRACT

The Maas-Hoffman model for salinity tolerance was tested for boron toxicity (reduction in yields only) using wheat (*Triticum aestivum* L., var. *Inia 66R*), barley (*Hordeum vulgare* L., var. Briggs), and sorghum (*Sorghum bicolor* L., var. Dekalb C42A) as test crops. These crops were grown to maturity in sand cultures containing low to excessive concentrations of boron. The leaf immediately below the Y-leaf was collected at the early spike emergence stage and analyzed for boron. At harvest, the individual grain heads were collected, dried and weighed. Relative grain and shoot yields (Y, %) were related to the boron concentration of the nutrient solution (X, mg B L^{-1}) using the following equation $Y = 100 - m(X - A)$, where m is the decrease in yield per unit increase in soluble boron above the threshold concentration, and A, the maximum concentration not restricting yield (the threshold). The SALT computer program (van Genuchten, 1983) was used to derive the slope and threshold parameters. The respective threshold concentrations for the grain yields of wheat, barley, and sorghum were found to be 0.3, 3.4, and 7.4 mg B L^{-1}, respectively, which categorized these crops as being sensitive, moderately tolerant, and very tolerant to boron. The relationship between relative yield and leaf boron was linear for wheat whereas barley and sorghum followed the Maas-Hoffman model. The threshold leaf B values with reference to grain yield were found to be 55, 768, 171 mg B kg^{-1}, respectively, for wheat, barley, and sorghum. The study indicates that yield under the influence of soluble boron may be fitted to the Maas-Hoffman model for salt tolerance.

Additional Index Words: **boron tolerance, salt tolerance, small grains, leaf boron, *Triticum aestivum*, *Hordeum vulgare*, and *Sorghum bicolor*.**

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THE PREVALENT MANNER of expressing crop tolerance to salinity was modified when Maas and Hoffman (1977) concluded that response of agricultural crops to salinity could be expressed with the use of two parameters: (i) a maximum level of salinity which could be tolerated without loss of yield (threshold salinity) (ii) and a slope factor relating yield decreases linearly with further increases in salinity. With these concepts, they demonstrated that the yield of a large number of crops could be reasonably represented by the following equation if average salinity values were known:

$$Y = 100 - m\,(X - A) \qquad [1]$$

where X is the electrolytic conductivity of the saturation extract of soil, EC_e, expressed in dS m^{-1}, A, the threshold EC_e value, and m, the percent decrease in relative yield per unit increase in EC_e for values greater than A. Both the threshold and slope parameters are crop specific. More recently, van Genuchten (1983) published a computer program entitled SALT which facilitates the calculation of this yield-salinity response function plus alternative ones; for example, a sigmoidal expression which uses only one parameter.

Examination of boron-yield data (Eaton, 1944; El-Sheikh et al., 1971; Vlamis and Ulrich, 1973; Francois, 1984) as examples suggests that the Maas-Hoffman model could be used for calculating the effect of excessive concentrations of soluble B on yields. Therefore, the results of boron tolerance studies currently underway were subjected to the Maas-Hoffman model to assess its suitability for expressing boron toxicity (yield reductions). The tolerances of wheat (*Triticum aestivium*, var. Inia 66R), barley (*Hordeum vulgare*, var. Briggs), and sorghum (*Sorghum bicolor*, var. DeKalb C42A) were evaluated, since boron tolerance data for these crops are extremely limited and these crops are frequently planted in areas containing salt-affected soils because of their tolerance to salinity (Maas, 1984). Based upon limited observations of boron tolerance (Eaton, 1944; Maas, 1984), sorghum is more boron tolerant than barley or wheat.

MATERIALS AND METHODS

Automated sandculture units consisting of a 120-L reservoir, four sand-filled crocks, an air lift, and a manifold to irrigate each crock were used. These units were constructed such that the sand-filled crocks were irrigated for 15 min, four times daily. At the prescribed times, the irrigation solution was flooded on top of the sand to percolate through the pots back into the reservoir tanks (Torres and Bingham, 1973).

The irrigation solution consisted of a complete nutrient solution with the following 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 $MgSO_4$, 0.01 mg Cu from $CuSO_4$, 0.25 mg Mn from $MnSO_4$, 0.005 mg Mo from H_3MoO_4, 0.025 mg Zn from $ZnSO_4$, and 5.0 mg Fe from Fe-EDDHA. Orthoboric acid was added at rates producing concentrations of 0.3 or 0.5, 1.0, 2.5, 5.0, 10.0, 15.0, 20.0, and 25.0 mg B L^{-1} for the wheat and barley, and 0.5, 1.5, 3.0, 5.0, 7.5, 10.0, 15.0, and 20.0 mg B L^{-1} for sorghum. All treatments were replicated four-fold. Following the addition of the above salts to the reservoirs containing deionized water, the tanks were adjusted to a volume of 120 L with deionized water. The sandcultures were subsequently irrigated for 48 h to mix the solutions. During this period, the pH values of the solutions were adjusted to 5.5 with either KOH or H_2SO_4.

Wheat ('Inia 66R') and barley ('Briggs') were grown to maturity during the December through May period whereas sorghum ('DeKalb C42A') was grown during July through October. The planting procedure consisted of sowing six to eight seeds approximately 2 cm deep in each sand-filled crock and then irrigating for 15 min four times daily until the plants reached a grain maturity stage. After emergence, the seedlings were thinned to two per crock.

Deionized water was added as needed to maintain the solution level at 120 ± 5 L throughout the experiment. In addition, pH values were maintained at 5.5 ± 0.5 using KOH or H_2SO_4. Boron concentrations were checked several times during the experiment to be certain that the desired

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Table 1. Plant yields in relation to B concentration of nutrient solution.

Boron treatment	Grain yield: Wheat 'Inia 66R'	Grain yield: Barley 'Briggs'	Grain yield: Sorghum 'DeKalb C42A'	Shoot yield: Wheat 'Inia 66R'	Shoot yield: Barley 'Briggs'	Shoot yield: Sorghum 'DeKalb C42A'
mg B L⁻¹	g plant⁻¹					
0.3	46.4			22.2		
0.5		17.0	23.2		64.1	20.0
1.0	41.2	25.2		20.9	60.3	
1.5			23.8			19.8
2.5	42.9	20.9		22.9	84.5	
3.0			24.5			20.8
5.0	37.2	22.1	26.1	18.5	56.4	20.0
7.5			21.7			21.8
10.0	32.0	13.1	22.9	15.9	47.8	20.9
15.0	23.0	7.3	18.9	14.0	38.6	22.3
20.0	18.9	7.4	7.7	10.2	34.4	14.5
25.0	13.3	1.8		6.9	32.5	

concentrations prevailed. No boron additions were required because the concentrations were found to vary less than 5% of the desired concentrations.

The plants were harvested at the mature-grain stage, separated into shoot and grain components, dried at 65°C and then weighed for yield data. Leaf samples were collected at the early spike emergence stage for boron analysis. The sample consisted of the leaf below the Y-leaf from each tiller. These leaves were rinsed in deionized water, blotted dry with diaper cloth, and dried in a forced draft oven set at 65°C. The dried leaf samples were then ground in a Wiley mill and stored in plastic vials. The leaf analysis procedure involved ashing 200 mg samples in a muffle furnace set at 500°C, dissolving the ash in dilute HCl, and then determining the concentration of boron in the HCl solution colorimetrically with azomethine-H (Bingham, 1982).

The relationship between boron level of the nutrient solution and shoot and grain yields were examined by the computer program SALT (van Genuchten, 1983) using option no. 5. This option employs least squares optimization techniques to determine the slope (m, % per mg B L^{-1}) and threshold concentration (A, mg B L^{-1}) in the equation $Y = 100 - m(X - A)$. This equation enables the calculation of relative yield (Y) for any given boron treatment level (X, mg L^{-1}). Similarly, relative yields were expressed as a function of leaf boron content to obtain threshold and slope parameters.

RESULTS AND DISCUSSION

Yield

Average shoot and grain yields are summarized in Table 1 according to B level. The relationship between grain yield and B concentration is described using the SALT tolerance model (option 5) in terms of the decrease in yield per unit increase in the B concentration above the threshold level (Fig. 1). Because of the exceedingly low apparent threshold salinity for wheat, its grain yield-B threshold concentration could not be determined using the SALT computer program. However, the Maas-Hoffman expression may be approximated by using 0.3 mg B L^{-1} as the threshold concentration and determining the slope parameter by linear regression analysis of relative grain yield vs. solution B concentration (Fig. 1).

The problem encountered with wheat did not occur for barley and sorghum. The Maas-Hoffman equations for relative grain and shoot yields (Y, %) vs. B concentration in nutrient solution (X, mg B L^{-1}) are:

Table 2. Maas-Hoffman B parameters.

Crop	Threshold, mg B L⁻¹	Slope, %	Source
Wheat head	0.3	3.3	Present investigation
Wheat shoot	2.4	3.0	Present investigation
Barley head	3.4	4.4	Present investigation
Barley shoot	2.5	2.7	Present investigation
Sorghum head	7.4	4.7	Present investigation
Sorghum shoot	15.8	7.2	Present investigation
Tomato fruit	5.7	3.4	Francois (1984)
Tomato shoot	3.3	3.0	Francois (1984)
Squash shoot† (*Cucurbita pepo*)	3.7	5.4	El-Sheikh et al. (1971)
Melon shoot† (*Cucumis melo*)	3.5	4.8	El-Sheikh et al. (1971)
Cucumber shoot† (*Cucumis sativus*)	0.2	6.2	El-Sheikh et al. (1971)
Corn shoot† (*Zea mays*)	0.2	3.5	El-Sheikh et al. (1971)
Sugarbeet shoot† (*Beta vulgaris*)	8.5	4.2	Vlamis and Ulrich (1973)
Sugarbeet root†	4.9	4.1	Vlamis and Ulrich (1973)

† Up to a treatment level of 16 mg B L⁻¹.

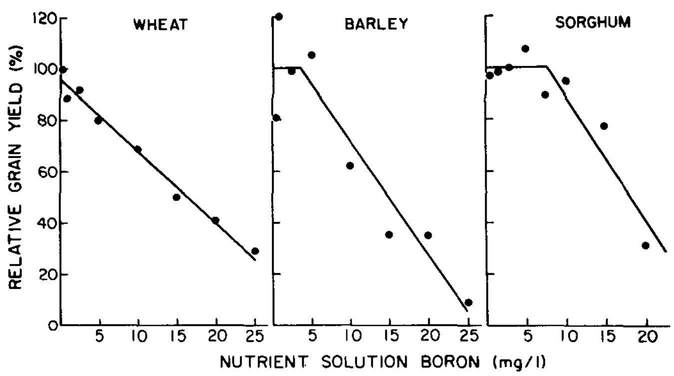

Fig. 1. Relative grain yield in relation to B concentration in nutrient solution.

Wheat

grain head $Y = 100 - 3.3\ (X - 0.3)$

shoot $Y = 100 - 3.0\ (X - 2.4)$

Barley

grain head $Y = 100 - 4.4\ (X - 3.4)$

shoot $Y = 100 - 2.7\ (X - 2.5)$

Sorghum

grain head $Y = 100 - 4.7\ (X - 7.4)$

shoot $Y = 100 - 7.2\ (X - 15.8)$

Maas (1984) recently categorized B tolerance of crops according to the maximum permissible concentration of B in soil water which does not restrict yield (threshold concentration) as follows: *very sensitive*, <0.5 mg B L^{-1}; *sensitive*, 0.5 to 1.0 mg B L^{-1}; *moderately sensitive*, 1.0 to 2.0 mg B L^{-1}; *moderately tolerant*, 2.0 to 4.0 mg B L^{-1}; *tolerant*, 4.0 to 6.0 mg B L^{-1}; and *very tolerant*, >6.0 mg B L^{-1}. Accordingly wheat, barley, and sorghum fall into the very sensitive, moderately tolerant, and very tolerant categories, respectively, when referring to grain yields. Based upon shoot yield data, these crops would be classified as moderately tolerant, moderately tolerant, and very tolerant, using Maas' soluble boron levels.

Table 2 presents threshold boron concentrations and slope parameters according to the Maas-Hoffman model as calculated using the SALT computer program and published data. The slope values of the various crops range from 2.7 to 7.2%. The threshold val-

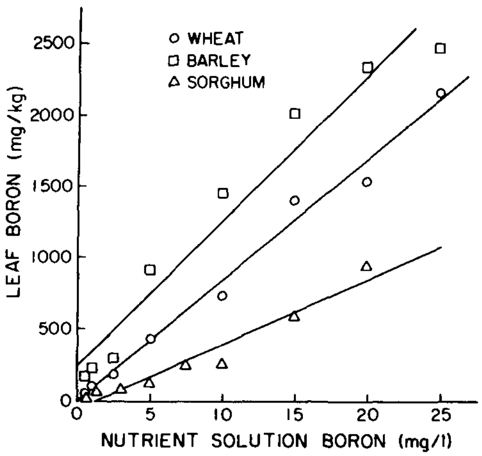

Fig. 2. Leaf boron content in relation to B concentration in nutrient solution.

ues are much more variable (0.2 to 15.8 mg B L^{-1}), and there is greater uncertainty in establishing the threshold concentration. These parameters may vary according to climate, soil properties, and crop varieties (Maas, 1984) and should not be used as absolute values (Maas, 1984, van Genuchten, 1983).

There does not appear to be a general association between boron tolerance and salinity tolerance. As examples, wheat and tomato, (*Lycopersicon esculentum* L.), respectively, are categorized as being very sensitive and tolerant of boron whereas they are categorized as being moderately tolerant and moderately sensitive to salinity (Maas, 1984). Furthermore, barley and sorghum respectively fall into the moderately tolerant and very tolerant categories of boron tolerance, yet both are moderately salt tolerant crops (Maas, 1984).

Leaf Boron

The B uptake and accumulation data are of interest to agronomists and plant scientists concerned with use of leaf analysis to assess toxicities. The approximately linear character of B uptake for wheat and sorghum and the curvilinear relationship for barley as judged by leaf B values of the plants is shown in Fig. 2 and Table 3. These data also show marked differences in

Table 3. Leaf boron content in relation to B concentration of nutrient solution.

Boron treatment	Leaf boron Wheat	Barley	Sorghum
mg B L^{-1}	mg kg^{-1}		
0.3	55		
0.5		177	20
1.0	97	270	
1.5			59
2.5	186	565	
3.0			72
5.0	422	1006	111
7.5			245
10.0	732	1454	251
15.0	1401	1516	577
20.0	1521	2227	943
25.0	2155	2115	

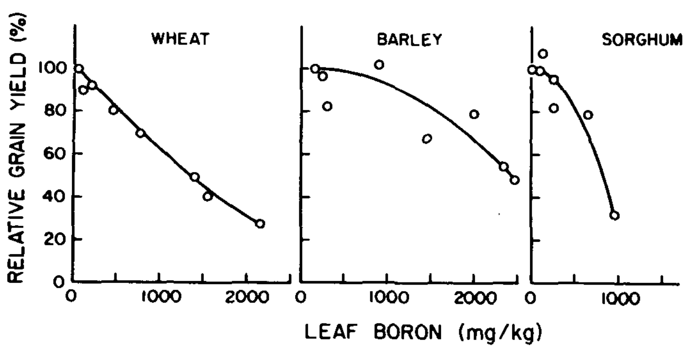

Fig. 3. Relative grain yield in relation to leaf B concentration.

leaf B values among the three crop species studied. The greatest overall uptake and accumulation in foliage was manifested by barley, followed by wheat and then sorghum.

The relationship between relative grain yield (%) and leaf B concentration (mg B kg^{-1}) is shown in Fig. 3. SALT generated Maas-Hoffman parameters were obtained as before for barley and sorghum. The threshold value for wheat was set at the lowest leaf B concentration (55 mg B kg^{-1}) and the slope again determined by linear regression analysis. The equations for relative grain yield (Y, %) vs. leaf B concentration (X, mg B kg^{-1}) are as follows:

Wheat	$Y = 100 - 0.041\ (X - 55)$
Barley	$Y = 100 - 0.068\ (X - 768)$
Sorghum	$Y = 100 - 0.083\ (X - 171)$

The threshold leaf boron with reference to grain yield is accordingly associated with the following values: barley, 768 mg B kg^{-1}; wheat, 55 mg B kg^{-1}; and sorghum, 171 mg B kg^{-1}. These values may vary with changes in environmental factors and management.

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