DIVISION S-2—SOIL CHEMISTRY

Plant Uptake of Boron as Affected by Boron Distribution Between Liquid and Solid Phases in Soil

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ABSTRACT

The effect of clay content and total boron content in soil on boron availability to plants (bell pepper) was studied, using a clay soil and a soil-sand mixture consisting of two parts of soil to one part of sand. Experimental results of boron in soil solution as a function of total boron content in soil were compared with values computed using a competitive adsorption model. The agreement between the calculated and the experimental results indicates that this model can be used to predict boron activity in soil solution at a water content lower than that of the saturated paste. Boron uptake by the plants was linearly correlated with the boron content in the soil for both soil systems. The boron content in the leaf tissue of the plants grown in the soil-sand mixture was significantly higher than that of the plants growing in the soil system at any level of boron added. However, when boron content in the leaf tissue was related to boron activity in soil solution, the experimental points for both soil systems lay on the same straight line, indicating that boron uptake by bell pepper and boron activity in soil solution were highly correlated. It is evident that the dry leaf weight is linearly correlated with the boron content in the leaf tissue, and, therefore, is linearly correlated with boron activity in soil solution. It is concluded that boron in soil solution, rather than adsorbed boron, influenced boron uptake by plants.

Additional Index Words: boron adsorption, boron availability for plants.


BORON is one of the essential micronutrients required for plant growth. However, there is a relatively small range between levels in the soil solution causing deficiency and toxicity symptoms in plants (Berger, 1949; Philipson, 1953).

According to Eaton (1935, 1944), the threshold boron concentration for irrigation water (the maximum permissible concentration for a given crop species that does not reduce yield or lead to injury symptoms) ranged from as low as 0.3 mg BL⁻¹ for sensitive crops to 2.0 mg BL⁻¹ for tolerant crops. These criteria which were obtained from sand culture experiments have provided the basis for boron toxicity criteria (U.S. Salinity Laboratory Staff, 1954).

In assessing the boron concentration in irrigation water, the physico-chemical characteristics of the soil must be taken into consideration, because of the in-
teraction between boron and soil. The existing criteria, however, make no reference to differences in soil type, since these criteria were obtained from sand culture experiments.

Boron can be specifically adsorbed by different clay minerals (Hingston, 1964; Keren and Mezuman, 1981; Sims and Bigham, 1967) by hydroxy-aluminum polymers (Keren and Gast, 1983; Sims and Bigham, 1968) and by soils (Elrashidi and O'Connor, 1982, Mezuman and Keren, 1981).

Important factors influencing the adsorption and removal of boron from the soil appear to be the boron concentration in soil solution, the pH of the system, the type of exchangeable ions, the ionic composition in soil solution (ionic strength), and wetting and drying cycles (Biggar and Fireman, 1960; Hingston, 1964; Keren and Gast, 1981; Keren and Mezuman, 1981; Keren and O'Connor, 1982; Mezuman and Keren, 1981; Parks and White, 1952; Sims and Bingham, 1987). Thus, the adsorption sites in soil may act as a source from where boron is supplied to solution or a sink for boron adsorption, depending on the solution composition and the affinity of the soil for boron. Ryan et al. (1977) determined the influence of boron adsorption capacity on the uptake of boron by oats at several boron concentrations in the irrigation water but their data is hard to interpret because equilibrium between adsorbed boron and boron in solution was not established nor did they attempt to relate boron uptake by plants at constant boron content.

Recently, it was shown that boron adsorption by clay minerals, hydroxy aluminum polymers and soils can be described by a competitive adsorption model (Keren et al., 1981; Keren and Mezuman, 1981; Keren and Gast, 1983; Mezuman and Keren, 1981). This model allows for the fact that two boron species, B(OH)4− and B(OH)3+, having different affinities to the adsorbent, are involved and that their proportions in the equilibrium solution vary with pH.

Using this adsorption model, it was predicted that the solution boron concentration increases very slightly during the drying process (at a given amount of boron in the soil). This occurs since soil adsorption sites act as a pool from where boron is supplied to the solution or to where boron is stored, depending on the change in solution boron concentration, soil pH, the affinity of the soil to boron, and the fraction of adsorption sites in the soil available for boron (Mezuman and Keren, 1981).

These predicted data indicate that waters which contain high boron levels (above the toxicity threshold of particular crops) can be used for irrigation of soils that show a high affinity and high capacity for boron. This hypothesis was tested in the present study, the objectives of which were to determine the influence of clay content in soil on boron availability to plants, and the influence of soluble and adsorbed boron on its uptake by plants.

**MATERIALS AND METHODS**

The experiments were conducted with a montmorillonitic soil (Vertisol) developed on basaltic alluvium. Soil from the surface horizon (0-20 cm) was collected, air-dried, passed through a 2-mm screen and mixed thoroughly.

The characteristics of the soil obtained by routine procedures (Black, 1965) are as follows: The clay, silt and sand contents are 62.0, 23.4 and 14.6%, respectively; the calcium carbonate content is 22.3%; and the soil pH is 7.6.

**Boron Adsorption Experiments**

Boron adsorption by the soil was studied by shaking 5 g of soil in 50 ml polypropylene centrifuge tubes containing 20 ml of solution with boron in 5 × 10−4 mol L−1 CaCl2 solution at 24 ± 2°C. The pH of the soil suspension was adjusted prior to boron additions by successive washings with boron free 5 × 10−3 mol L−1 CaCl2 solution at the appropriate pH. The washings were repeated until there was no pH change after 24 h of shaking. After pH adjustment the suspensions were centrifuged and the solution was replaced with boron solution having the appropriate CaCl2 concentration and pH. The boron concentration of the initial solution (before adsorption took place) ranged from 9.25 × 10−4 to 1.39 × 10−3 mol L−1. The suspensions were then brought to the final volume by adding an appropriate amount of 5 × 10−3 mol L−1 CaCl2 solution with the desired pH, taking into account the volume of solution remaining in the soil after centrifugation.

Preliminary experiments indicated that adsorption equilibrium was established less than 2 h after boron was added to the soil suspension. However, samples were shaken for 24 h. After equilibrium time, the suspensions were centrifuged and aliquots of the supernatant were analyzed colorimetrically for boron, using the Azomethine-H method (Gupta and Stewart, 1975).

**Greenhouse Experiment**

The soil was sieved through a 2-mm sieve, mixed thoroughly and divided into two parts, one of which was mixed thoroughly with pure sand (0.6-0.8 mm in diameter) at a ratio of two parts of soil to one part of sand; the second part of the soil remained untreated. The sand was added in order to obtain a soil with a lower clay content but with the same boron adsorption affinity coefficients.

The total amount of soil or soil-sand mixture in a pot was about 3 kg. Four boron levels (1.0 × 10−4, 5.0 × 10−4, 1.0 × 10−3 and 1.9 × 10−3 mol kg−1 soil) were studied and there were six replications of each treatment. In order to minimize the variability in boron distribution in soil, the soil of each pot was divided into ten equal parts, each of which was wetted to the appropriate water capacity using 5 × 10−3 mol L−1 CaCl2 solution containing boron (as boric acid) at the appropriate concentration to obtain the desired boron level in the soil. Then the soil was covered to prevent evaporation.

After 7 days of equilibration, the soils in the pots were leached with 5 × 10−3 mol L−1 CaCl2 solution containing boron at the desired concentration which is in equilibrium with the desired amount of adsorbed boron. After reaching steady state in respect to boron, the soils were allowed to drain to "field capacity".

The soils were sown with bell pepper seeds (Capsicum frutescens) and covered with small polystyrene balls in order to minimize evaporation during the growing season. Bell pepper was chosen because it is a semitolerant crop in respect to boron (Wilcox and Durun, 1967).

During the first few weeks of the experiment, the seedlings were thinned to one plant per pot. The plants were irrigated with nutrient solution and the water content in the soils was allowed to change in a range corresponding to the water potential range of 0.01 to 0.03 Pa. During the growing season Hoagland's nutrient solution (boron-free) was used, with the concentration increased according to the development of the plants. However, during the first few weeks only deionized water was used. Twice, during the growth period, the soils were leached to reduce the salinity level.
At the first stage of flowering, the plants were cut off approximately a few millimeters above the soil surface, rinsed three times with deionized water, and dried at 65°C. The dried samples were weighed, ground (leaves and stems separately) in a stainless steel Wiley mill to pass through a 40-mesh screen, and stored in a desiccator over P_2O_5 until analyzed. Subsamples of 0.2 g were then placed in a crucible and heated at 550°C for 21 h in a muffle. After cooling, 10 cm^3 of 1 mol L^{-1} HCl solution was added to the ash in the crucible and allowed to stand for 15 minutes. An aliquot of this solution was analyzed colorimetrically for boron using the Azomethine-H method (Gupta and Stewart, 1975).

After harvesting, the moist soil of each pot was mixed well and then 500 g of soil was used to obtain a saturation extract (U.S. Salinity Laboratory Staff, 1954). The soil samples were never dried during the analysis process. The solution extracts were immediately analyzed for pH, electrical conductivity and boron.

**Computations**

Adsorbed boron was calculated as the difference between the amount added and that found in solution at equilibrium. The negative adsorption of borate ions, B(OH)_4^-, in the soil-water system was neglected. The adsorption coefficients of the soil were obtained using the adsorption equation derived by Keren et al. (1981).

The ionic strength, I, was calculated using the equation derived by Griffin and Jurinak (1973): I = 0.013 EC, where EC is the electrical conductivity, in dS m^{-1}. The ionic strength corrections for boron in solution were made using single-ion and single-molecule activity coefficients (Keren and O'Connor, 1982). The boron distribution between the solid and the liquid phases at "field capacity" was calculated from these data using the adsorption model proposed by Keren et al. (1981).

**RESULTS AND DISCUSSION**

Boron adsorption isotherms at different pH's are shown in Fig. 1. The dots in this figure represent experimental results, whereas the solid lines were calculated using the adsorption equation proposed by Keren et al. (1981) and described by Mezuman and Keren (1981). The estimated values of the maximum boron adsorption, and the coefficients related to the binding energy for B(OH)_3, B(OH)_2 and OH^-, were 8.8 × 10^{-3} mol kg^{-1}, and 141, 3495 and 25111 L mol^{-1}, respectively. These values are similar to those obtained on another sample of the same soil by Mezuman and Keren (1981) except for the affinity coefficient for OH^- which was one order of magnitude lower. These results show that, in accordance with Mezuman and Keren (1981), the adsorption model can be used to predict boron adsorption by soils.

The boron activities in the equilibrium solution as a function of the total boron content for the two soil systems at water content of "field capacity" are presented in Fig. 2. The solid lines were calculated using the adsorption equation which relates the total amounts of adsorbed boron to total boron in the soil,
The adsorption equations which were derived by Keren
and the solution-to-soil ratio (Keren et al., 1981), and
and the solution-to-soil ratio (Keren et al., 1981), and
and the adsorption coefficients mentioned above. The
and the adsorption coefficients mentioned above. The
symbols in Fig. 2 represent the values at total boron
symbols in Fig. 2 represent the values at total boron
contents of 5 × 10⁻⁴ and 1 × 10⁻³ mol kg⁻¹ calculated
contents of 5 × 10⁻⁴ and 1 × 10⁻³ mol kg⁻¹ calculated
from the saturation extract solution analysis and using
from the saturation extract solution analysis and using
the adsorption equations which were derived by Keren
the adsorption equations which were derived by Keren
et al. (1981) for boron adsorption as a function of pH
et al. (1981) for boron adsorption as a function of pH
and boron activity in solution, and for the case where
and boron activity in solution, and for the case where
the adsorbed boron is related to the total boron in the
the adsorbed boron is related to the total boron in the
soil (adsorbed boron + boron solution), and to the
soil (adsorbed boron + boron solution), and to the
solution-to-soil ratio. The saturated pastes were pre-
solution-to-soil ratio. The saturated pastes were pre-
pared after boron equilibration with the soils was ob-
pared after boron equilibration with the soils was ob-
tained. A good agreement between the values in soil
obtained. A good agreement between the values in soil
solution of both systems was obtained, indicating that
solution of both systems was obtained, indicating that
within the tested range of soil clay and water ratios,
within the tested range of soil clay and water ratios,
the water content does not affect the boron-surface
the water content does not affect the boron-surface
interaction as expressed by the adsorption coefficients.
interaction as expressed by the adsorption coefficients.
The data show that the boron activity in soil solution
The data show that the boron activity in soil solution
is higher for the soil-sand mixture than for the
is higher for the soil-sand mixture than for the
soil alone at any total boron content. The response of
soil alone at any total boron content. The response of
the soil systems to boron activity in soil solution can
the soil systems to boron activity in soil solution can
be explained as follows: Boron can be specifically ad-
be explained as follows: Boron can be specifically ad-
sorbed on broken edge surfaces of the clay minerals
adsorbed on broken edge surfaces of the clay minerals
(Keren and O'Conner, 1982; Keren and Talpaz, 1984),
(Keren and O'Conner, 1982; Keren and Talpaz, 1984),
and on hydroxy-aluminum and iron polymers (Keren
and hydroxy-aluminum and iron polymers (Keren
and Gast, 1983; Sims and Bingham, 1968). Such spe-
and Gast, 1983; Sims and Bingham, 1968). Such spe-
cific adsorption occurs irrespective of the sign of the
specific adsorption occurs irrespective of the sign of the
net surface charge (Hingston et al., 1972; Keren
net surface charge (Hingston et al., 1972; Keren
and O'Conner, 1982). Since the difference between the
certain that boron activity in soil solution is higher for
the two soil systems is in the clay content, the number of
the two soil systems is in the clay content, the number of
adsorption sites in a unit weight of soil is smaller in the
adsorption sites in a unit weight of soil is smaller in the
soil-sand mixture than in the soil alone. It was shown
soil-sand mixture than in the soil alone. It was shown
that increasing the number of adsorption sites per unit
that increasing the number of adsorption sites per unit
weight of adsorbent, increased the amount of ad-
weight of adsorbent, increased the amount of ad-
sorbed boron for a given boron content and a adsorp-
sorbed boron for a given boron content and a adsorp-
tion-to-soil ratio (Keren et al., 1981). Therefore, the
orption-to-soil ratio (Keren et al., 1981). Therefore, the
boron activity in solution at the soil alone is lower
boron activity in solution at the soil alone is lower
than that of the soil-sand mixture at any boron con-
than that of the soil-sand mixture at any boron con-
tent level (up to saturation). This difference is related
tent level (up to saturation). This difference is related
only to the adsorption capacity, since the affinity of
only to the adsorption capacity, since the affinity of
the adsorbents to boron in both systems is the same.
the adsorbents to boron in both systems is the same.

<table>
<thead>
<tr>
<th>Soil system</th>
<th>Boron content in stem tissue (mol kg⁻¹) x 10⁻⁴</th>
<th>Boron content in soil (mmol kg⁻¹) x 10⁻⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil alone</td>
<td>1.1 ± 0.1</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>Soil-sand mixture</td>
<td>0.9 ± 0.1</td>
<td>1.7 ± 0.1</td>
</tr>
</tbody>
</table>

† Standard deviation.

The data indicate also that the slope of the line for
The data indicate also that the slope of the line for
the soil-sand mixture increases more sharply than that
the soil-sand mixture increases more sharply than that
of the soil alone. This difference in the slope steepness
of the soil alone. This difference in the slope steepness
can be explained by considering the differences in the
can be explained by considering the differences in the
total number of adsorption sites (clay content) in the
total number of adsorption sites (clay content) in the
two systems. Because the maximum boron adsorption
two systems. Because the maximum boron adsorption
capacity of the soil-sand mixture system is much lower
capacity of the soil-sand mixture system is much lower
than that of the soil alone, the saturation level of bo-
than that of the soil alone, the saturation level of bo-
rorn in this mixture is obtained at a lower boron
rorn in this mixture is obtained at a lower boron
concentration in solution than for the soil alone.
concentration in solution than for the soil alone.
The boron content in the leaf tissue as a function of
The boron content in the leaf tissue as a function of
the total amount of boron added to soil for both
the total amount of boron added to soil for both
soil systems is given in Fig. 3. Only the boron content
soil systems is given in Fig. 3. Only the boron content
in the leaves is presented, since that in the stems was
in the leaves is presented, since that in the stems was
relatively low (Table 1: 8-20% of the total boron in
relatively low (Table 1: 8-20% of the total boron in
the plants). It is evident that the boron uptake by the
the plants). It is evident that the boron uptake by the
plants is linearly correlated with the boron content in
plants is linearly correlated with the boron content in
the soil for both soil systems at the studied boron con-
the soil for both soil systems at the studied boron con-
centration range. The results indicate also that the bo-
centration range. The results indicate also that the bo-
rorn content in the leaf tissue of the plants growing in
rorn content in the leaf tissue of the plants growing in
the soil-sand mixture was significantly higher than that
the soil-sand mixture was significantly higher than that
of the plants growing in the soil system, at any level
of the plants growing in the soil system, at any level
of boron added. This latter finding is in accordance
of boron added. This latter finding is in accordance
with Wear and Patterson (1962), who found that alf-
with Wear and Patterson (1962), who found that alf-
falfa grown in a coarse-textured soil had a greater up-
falfa grown in a coarse-textured soil had a greater up-
take of boron than plants growing in fine-textured soil.
take of boron than plants growing in fine-textured soil.
The higher boron content in the leaf tissue of the plants
The higher boron content in the leaf tissue of the plants
growing in the soil-sand mixture is due to the higher
growing in the soil-sand mixture is due to the higher
activity of boron in soil solution in this system than
activity of boron in soil solution in this system than
was found in the soil alone for any boron level in soil.
was found in the soil alone for any boron level in soil.
As shown in Fig. 3, the boron content in the leaf
tissue was always higher in the plants growing in the
the leaf tissue was always higher in the plants growing in the
soil-sand mixture than in the soil alone, for a given
soil-sand mixture than in the soil alone, for a given
addition of boron. However, when the boron content
addition of boron. However, when the boron content
in the leaf tissue was plotted against boron activity in
in the leaf tissue was plotted against boron activity in
the soil solution at “field capacity” water content (Fig.
the soil solution at “field capacity” water content (Fig.
4), the experimental points for both soil systems lie
4), the experimental points for both soil systems lie
on the same line. The regression coefficient was 0.982,
on the same line. The regression coefficient was 0.982,
indicating that boron uptake by bell pepper and boron
indicating that boron uptake by bell pepper and boron
activity in soil solution were highly correlated. These
activity in soil solution were highly correlated. These
results indicate that the plants obtain their boron from
results indicate that the plants obtain their boron from
the solution only.
the solution only.
The effect of boron content in dry leaf tissue on dry
The effect of boron content in dry leaf tissue on dry
leaf weight of bell pepper is presented in Fig. 5. It is
deaf weight of bell pepper is presented in Fig. 5. It is
evident that the dry leaf weight is linearly correlated
evident that the dry leaf weight is linearly correlated
(at least for the studied range) with the boron content
(at least for the studied range) with the boron content
in the leaf tissue, and therefore is linearly correlated
in the leaf tissue, and therefore is linearly correlated
with the boron activity in soil solution.
with the boron activity in soil solution.
Since the soil adsorbed boron and the plant obtains
Since the soil adsorbed boron and the plant obtains
its boron from the soil solution, the greater the ability
its boron from the soil solution, the greater the ability
of the soil to adsorb boron - the lower the boron con-
of the soil to adsorb boron - the lower the boron con-
tent in the plant (below the saturation adsorption con-
tent in the plant (below the saturation adsorption con-
tent). The solution-to-soil ratio is an important deter-
tent). The solution-to-soil ratio is an important deter-
minant of the boron partition (at a given amount)
dinant of the boron partition (at a given amount)
between the soil solution and the solid phase. Since
boron adsorption takes place in soil, the solution boron concentration increases very slightly during the drying process (Mezuman and Keren, 1981). Thus, the soil adsorption sites may act as a pool from where boron is supplied to the solution, or in which boron is stored, depending on the change in solution boron concentration in the soil. The drying of clays (Keren and Gast, 1981) and soils (Biggar and Fireman, 1960) after boron addition not only increased the amount of boron adsorbed, but also significantly reduced the reversibility of the adsorption process as well. Since the soil surface is subjected to considerable drying under field conditions, the reversibility of the boron adsorption process probably only exists in the lower soil layers where the soil remains wet.

CONCLUSIONS

The suitability of irrigation water has been evaluated on the basis of criteria which determine the potential of the water to cause plant injury and yield reduction. In assessing the boron in irrigation water, however, the physico-chemical characteristics of the soil must be taken into consideration because of the interaction between boron and soil and since the boron uptake by plants is dependent only on boron activity in soil solution. This reassessment may improve the efficiency of waters of different qualities, whereby water with a high boron level could be used to irrigate boron-sensitive crops in soils that show a high affinity and high adsorption capacity for boron.

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REFERENCES

