The role of organic matter in B distribution between the liquid and solid phases of soils is not yet fully understood. The amount of B adsorbed by soils can affect B uptake by plants because of changing B concentration in the soil solution. This regulation depends on the changes in solution B concentration and on the affinity of the soil constituents for B (Mezuman and Keren, 1985). Boron adsorption and desorption from soil adsorption sites regulate the B concentration in the soil solution. This correlation coefficient is 0.88 with the B concentration adjusted in the soil solution. This correlation coefficient was further improved when B concentration in the soil solution was calculated using a B adsorption model. The results presented herein indicate that organic matter plays an important role in controlling B concentration in the soil solution, and that it has a prominent effect on reducing B uptake by plants.

Boron is one of the seven essential micronutrients required for the normal growth of most plants. However, the range of B concentrations in the soil solution causing neither deficiency nor toxicity symptoms in plants is narrow. The amount of B adsorbed by soils varies greatly with the contents of various soil constituents, mostly clay minerals, sesquioxides, and organic matter (Keren and Bingham, 1985). The factors influencing B adsorption and desorption from soil constituents are: (i) B concentration in the soil solution, (ii) pH, (iii) type of exchangeable ions, (iv) ionic composition of the soil solution, and (v) wetting and drying cycles (Keren and Bingham, 1985). Boron adsorption and desorption from soil adsorption sites regulate the B concentration in the soil solution. This regulation depends on the changes in solution B concentration and on the affinity of the soil constituents for B (Mezuman and Keren, 1981). Thus, adsorbed B may buffer fluctuations in solution B concentration, and B concentration in soil solutions may vary only slightly with changes in soil water content.

The role of organic matter in B distribution between the liquid and solid phases of soils is not yet fully understood. Boron deficiency has been observed in soils with high organic matter contents (Hue et al., 1988; Mascarenhas et al., 1988; Liu et al., 1989; Valk et al., 1989). This deficiency has been shown to be related to the high affinity of organic matter to B (Berger and Pratt, 1963; Yermiyahu et al., 1988, 1995; Liu et al., 1989). The positive correlations between soil organic matter content and B adsorption (Elrashidi and O’Connor, 1982; Hue et al., 1988) support this hypothesis. Boron adsorption by soils has been observed to be minor in acidic to near neutral pH, but may be of greater significance in high pH soils.
pH soils in the presence of organic matter (Gu and Lowe, 1990). Garate and Meyer (1983) concluded that the main factors affecting B retention by organic matter were pH, Ca, and fulvic acid contents, and the humic:fulvic acid ratio. In contrast, Marzadori et al. (1991) reported that the amount of B adsorbed by soil is considerably greater after the organic matter has been removed and that hysteresis is observed. Adding organic matter to soil has also been reported to increase B content and its availability to plants (Blagojevic and Zarkovic, 1990; Pakrashi and Haldar, 1992). These observations are in contradiction with the well-known findings that boron adsorption by organic matter is substantially higher than that adsorbed by clays (Yermiyahu et al., 1988).

Boron adsorption by organic matter and soils has been described by a competitive adsorption model (Mezuman and Keren, 1981; Yermiyahu et al., 1988). This model allows for the fact that two aqueous B species, B(OH)\(^n\)\(^+\) and B(OH)\(_n\), having different affinities to the adsorbent, are involved and that their proportions in the equilibrium solution vary with pH. With this adsorption model, the B adsorption capacity of the soil-COM mixture was seen to increase with COM content (Yermiyahu et al., 1995).

The role of soil organic matter content on B soil solution concentration and B uptake by plants is not fully understood. Boron uptake by plants is, generally, controlled by the B level in the soil solution rather than total B content in the soil (Keren et al., 1985a,b). Because the affinity of organic matter for B is higher than that of clay minerals, at a given total B content, B uptake by plants is expected to decrease as the organic matter content in the soil increases. This hypothesis is tested in the current study, the objective of which to determine the effects of organic matter in soil on B availability to the test plant bell pepper.

**MATERIALS AND METHODS**

**Soil and Composted Organic Matter**

Soil (Loess, calcic Haploxeralf) was collected from an uncultivated field in the southern coastal plain of Israel. This soil developed from loessial windblown material originating from the Sinai Desert. Soil characteristics obtained by routine procedures were: contents of clay, silt, and sand: 16, 43, and 41%, respectively; CaCO\(_3\), 45 g kg\(^{-1}\) (Nelson, 1982); organic matter, 11 g kg\(^{-1}\) (Nelson and Sommers, 1982); cation exchange capacity, 168 mmol kg\(^{-1}\) (Rhoades, 1982); pH of saturated paste, 7.8 (McLean, 1982); and B concentration in saturated soil extract, 0.028 mmol L\(^{-1}\) (Gupta and Stewart, 1975).

Mature compost produced from the solid fraction of separated straw-containing cattle manure was used in this study. The COM was leached in a column with deionized water and then dried through a 2-mm sieve and mixed thoroughly with washed COM, and pure sand was added as an inert substance with respect to B adsorption. The total amount of added COM in the mixture (soil-sand-COM on a dry-weight basis) was 0, 10, 30, 60, or 100 g kg\(^{-1}\) of mixture and the added sand content was 100, 90, 70, 40, or 0 g kg\(^{-1}\) of mixture, respectively. The loess soil content was constant in all mixtures. Each soil-sand-COM mixture was tested at four levels of added B (0, 0.1, 0.5, or 1.0 mmol kg\(^{-1}\)) of mixture, respectively. Boron was added as boric acid (B(OH)\(_{3}\)) in solution. Each treatment consisted of five pots, filled with 2 kg of soil-sand-COM mixture, and arranged in the randomized complete block experiment design. Two days after B addition, 2-wk-old pepper seedlings were planted in each pot. The water contents of the soil mixtures in the pots were maintained between 25 to 30% (w/w) by adding distilled water at least daily. A mulch of polystyrene spheres was used to reduce evaporation during the growing season. Boron-free half-Hoagland solution of 100 mL per pot was added weekly (Hoagland and Arnon, 1950). The plants were harvested 45 d after planting by removal of the entire plant from the pot. Leaves were separated from stems, rinsed three times with deionized water, and dried at 65°C. The dried leaves were weighed, ground, and stored in a desiccator. Leaf samples were analyzed by ashing 0.25-g samples in a furnace at 550°C for 4 h. Five milliliters of 1 M HCl were added to the cooled ash, and the solution was filtered after 15 min. A 3-mL aliquot was taken for B analysis using the azomethine-H procedure (Gupta and Stewart, 1975). After plant harvest, the moist soil from each pot was well-mixed and a saturated paste was prepared and allowed to reach an equilibrium. Boron in the saturated paste solution was determined by the azomethine-H procedure. The electrical conductance of all saturated paste extracts was below 1.5 dS m\(^{-1}\), considered the value above which pepper growth is impaired by salinity (Maas, 1977).

**Computations**

Boron distribution between the solid and liquid phases at a water content of 30% (w/w) for different soil-sand-COM mixtures was calculated using the adsorption equations (Eq. [1] and [2]) proposed by Keren et al. (1981):

\[
Q_{ar} = \frac{T[K_{H[B]}(HB) + K_B(B)]}{1 + K_{H[B]}(HB) + K_B(B) + K_{OH}(OH)}
\]

where \(Q_{ar}\) is the total amount of sorbed B; \(T\) is the maximum possible B adsorption capacity (mol kg\(^{-1}\)); \(K_{H[B]}\), \(K_B\), and \(K_{OH}\) are adsorption coefficients; \((HB), (B),\) and \((OH)\) are solution.
Table 1. Maximum boron adsorption and adsorption coefficients $K_{HB}$, $K_B$, and $K_{OH}$ for the various soil–sand–composted organic matter (COM) mixtures.

<table>
<thead>
<tr>
<th>System</th>
<th>Adsorbent</th>
<th>COM content</th>
<th>Maximum B adsorption</th>
<th>Adsorption coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>soil + sand†</td>
<td>0</td>
<td>$7.0 \times 10^{-3}$</td>
<td>$K_{HB}$ $K_B$ $K_{OH}$</td>
</tr>
<tr>
<td>2</td>
<td>soil + sand + COM†</td>
<td>1</td>
<td>$1.0 \times 10^{-2}$</td>
<td>5.4 $\times 10^1$ 1.0 $\times 10^0$ 6.0 $\times 10^1$</td>
</tr>
<tr>
<td>3</td>
<td>soil + sand + COM†</td>
<td>3</td>
<td>$1.2 \times 10^{-2}$</td>
<td>4.3 $\times 10^1$ 1.9 $\times 10^0$ 2.6 $\times 10^1$</td>
</tr>
<tr>
<td>4</td>
<td>soil + sand + COM†</td>
<td>6</td>
<td>$1.4 \times 10^{-2}$</td>
<td>8.8 $\times 10^0$ 1.5 $\times 10^0$ 4.4 $\times 10^0$</td>
</tr>
<tr>
<td>5</td>
<td>soil + sand + COM†</td>
<td>10</td>
<td>$2.5 \times 10^{-2}$</td>
<td>9.4 $\times 10^0$ 1.6 $\times 10^0$ 2.6 $\times 10^0$</td>
</tr>
<tr>
<td>6</td>
<td>COM alone‡</td>
<td>100</td>
<td>$5.4 \times 10^{-2}$</td>
<td>3.7 $\times 10^0$ 4.2 $\times 10^0$ 1.5 $\times 10^0$</td>
</tr>
</tbody>
</table>

† Yermiyahu et al. (1995).
‡ Yermiyahu et al. (1988).

activities of the aqueous species B(OH)$^2_-$, B(OH)$^-_2$, and OH$^-$, respectively.

Equation [1] can be rearranged to relate the total amount of sorbed B, $Q_{BT}$, to total B in the soil, $Q_T$ (sorbed B + B in solution), and to the solution-to-sorbent ratio, R:

$$Q_{BT} = T \left[1 + \frac{PR}{F(Q_T - Q_{BT})} [1 + K_{OH}(OH)]^{-1} \right] \quad [2]$$

where $P = 1 + 10^{14}K_0(OH)$; $K_0$ is the hydrolysis constant of the reaction ($pK_0 = 9.23$) of the reaction:

$$\text{B(OH)}_3 \text{(aq)} + 2\text{H}_2\text{O} \leftrightarrow \text{B(OH)}^-_2 \text{(aq)} + \text{H}_2\text{O}^+ \quad [3]$$

and $F = K_{HB} + K_{OH}(P-1)$.

The concentrations of the other B species can be ignored because their $pK_a$ values are 12.3 and 13.3 (Ingrri et al., 1957). The adsorption parameters [maximum B adsorption ($T$) and the adsorption coefficients $K_{HB}$, $K_B$, and $K_{OH}$] for the various soil–sand–COM mixtures were taken from Yermiyahu et al. (1988, 1995) and are given in Table 1.

Boron concentration in the soil–sand–COM mixture solutions was predicted using the B adsorption model (Eq. [1]–[3]). Adsorption parameters used in our calculations (Table 1) were obtained from adsorption experiments (solution to soil–sand–COM mixture ratio of 4) conducted for the same components as those used in the present study (Yermiyahu et al., 1995). The estimation of the adsorption parameters for each soil–sand–COM mixture was based on B adsorption isotherms at various pH values (Yermiyahu et al., 1995). Boron concentrations in solution were calculated for the following conditions: pH 7.7, a solution to soil–sand–COM mixture ratio of 0.3 and the appropriate added B, using the adsorption parameters suitable for each mixture.

RESULTS AND DISCUSSION

The B concentration values measured in the saturated paste extracts were adjusted to water content of 30% (w/w) using Eq. [2]. The adjusted B concentrations in the soil solution, as a function of COM content for four levels of added B after 2 d of equilibration, are presented in Fig. 1A. Boron concentration in the soil–sand–COM mixture solution was affected by the total amount of B added and the COM content. The higher the amount of B added, the higher was its concentration in the solution. However, at this level, 66% of the total added B was adsorbed by the soil (Yermiyahu et al., 1995). Using this value, the calculated B concentration in the soil solution was 0.33 mmol L$^{-1}$ assuming no adsorption. However, at this level, 66% of the total added B is adsorbed by the soil (Yermiyahu et al., 1995). Using this value, the calculated B concentration in the soil solution is 0.11 mmol L$^{-1}$, which is close to the value of 0.08 mmol L$^{-1}$ found for the adjusted value at 30% water content (Fig. 1A). Although the calculated B concentration in the soil–sand–COM mixture solution at a COM content of 10% is 0.04 mmol L$^{-1}$ (Yermiyahu et al., 1995), the observed concentration was 0.09 mmol.

Fig. 1. Adjusted B concentration in soil solution at a water content of 30% (w/w) after 2 d of equilibration (A) and after harvest of the plants (B) vs. the COM content of the soil–sand–COM mixture at four levels of B application (B concentration was measured in the saturated paste extract and adjusted to a water content of 30% using Eq. [2]).
Table 2. Boron uptake, leaf dry matter and boron distribution between the liquid and the solid phases of the soil–sand–COM mixture at the end of the experiment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Amount of B in pot</th>
<th>In soil solution</th>
<th>Leaf dry matter</th>
<th>Fraction of added B</th>
</tr>
</thead>
<tbody>
<tr>
<td>COM</td>
<td>B level</td>
<td>Added</td>
<td>F†</td>
<td>I-F†</td>
</tr>
<tr>
<td>% mmol kg⁻¹</td>
<td></td>
<td></td>
<td>μmol</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0 15.6</td>
<td>-5.4</td>
<td>3.2</td>
</tr>
<tr>
<td>0</td>
<td>0.1</td>
<td>200 36.0</td>
<td>9.6</td>
<td>4.8</td>
</tr>
<tr>
<td>0</td>
<td>0.5</td>
<td>1000 205.2</td>
<td>22.8</td>
<td>10.6</td>
</tr>
<tr>
<td>0</td>
<td>1.0</td>
<td>2000 517.8</td>
<td>61.8</td>
<td>14.9</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0 20.4</td>
<td>-5.4</td>
<td>18.8</td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>200 43.2</td>
<td>-7.2</td>
<td>22.2</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>1000 180.0</td>
<td>22.8</td>
<td>49.8</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
<td>2000 400.2</td>
<td>31.8</td>
<td>105.6</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0 25.8</td>
<td>-7.8</td>
<td>29.7</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>200 48.6</td>
<td>-12.8</td>
<td>37.3</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>1000 153.6</td>
<td>26.4</td>
<td>63.4</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>2000 328.2</td>
<td>58.2</td>
<td>121.7</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0 36.0</td>
<td>0</td>
<td>31.9</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>200 54.0</td>
<td>-10.8</td>
<td>33.2</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>1000 143.4</td>
<td>12.6</td>
<td>51.7</td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
<td>2000 271.8</td>
<td>54.2</td>
<td>95.3</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0 36.0</td>
<td>0</td>
<td>31.5</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>200 54.0</td>
<td>0</td>
<td>30.8</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>1000 138.6</td>
<td>47.4</td>
<td>43.6</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>2000 276.6</td>
<td>53.4</td>
<td>76.9</td>
</tr>
</tbody>
</table>

† I and F are the amount of B in the soil solution at the beginning and the end of the experiment, respectively.
§ Uptake by pepper leaves.
¶ Adsorbed by the soil components (the difference between the total amount of added B and the sum of the B amounts in soil solution and leaves).

The adjusted B concentration in the soil–sand–COM mixture solution decreased with increasing COM content at higher levels of applied B. This reduction was due to B adsorption by COM, which has a higher adsorption capacity than soil (Yermiyahu et al., 1995). At these B levels, the amount of B contributed by the COM compared with the amount of added B is negligible. The decrease of the adjusted B concentration in soil solution was more pronounced at higher B levels and at low levels of COM (Fig. 1A).

Adjusted B concentrations in the soil solution after harvesting the plants, as a function of COM content at various total added B levels, are shown in Fig. 1B. At the zero and lowest added B levels, B concentration in the soil solution was equal or somewhat higher than that observed at the beginning of the experiment (Table 2). This small increase was probably due to release of native B existing in sparingly soluble minerals in the soil and COM during the growing season. At the highest B levels, B concentration in the soil solution after harvesting was substantially lower than that observed at the beginning of the experiment. This decrease was due to B uptake by plants (Table 2) because no leaching or drying-and-wetting processes (which have a significant effect on B adsorption and desorption by soil) took place (Keren and Bingham, 1985). The amount of B uptake was higher than the decreases amount in the soil solution at most levels of added COM (Table 2), due to the buffer capacity of the soil solid phase (this will be discussed later).

A high correlation ($r^2 = 0.92$) was observed between adjusted B concentrations in the current experiment and the predicted B concentrations best on B adsorption parameters given in Table 1 (Fig. 2). This high correlation indicates that the B adsorption model may provide good estimates of B concentration under field conditions. Since water content does not significantly affect the B-soil interaction (Mezuman and Keren, 1981), B concentration in the soil solution can be evaluated across a wide range of solution-to-soil ratios. The good agreement between the adjusted and predicted B concentrations suggests that the adsorption sites of the soil–sand–COM mixture act as a pool from which B is supplied to the solution or stored. The COM used in this study had a much higher adsorption capacity than the mineral component of the soil (=7.7 times higher on a L⁻¹ (Fig. 1A). This value was similar to that obtained for soil alone.

The adjusted B concentration in the soil–sand–COM mixture solution decreased with increasing COM content at higher levels of applied B. This reduction was due to B adsorption by COM, which has a higher adsorption capacity than soil (Yermiyahu et al., 1995). At these B levels, the amount of B contributed by the COM compared with the amount of added B is negligible. The decrease of the adjusted B concentration in soil solution was more pronounced at higher B levels and at low levels of COM (Fig. 1A).

Fig. 2. A comparison between adjusted B concentration in the soil solution (adjusted to a water content of 30%) after 2 d of equilibration and B concentration calculated using Eq. [1], [2], and [3] and the adsorption coefficients given in Table 1. The calculation was performed for the same pH, solution-to-soil ratio, and total added B as in the plant growth experiment.
weight basis) (Table 1). Thus, adding a small amount of COM significantly increased the number of adsorption sites and hence the pool controlling the soluble B concentration.

Leaf tissue B concentration as a function of COM level in the mixture for the different amounts of added B is given in Fig. 3. Boron concentration was only measured in the leaves since the B amount in the stem has been found to be relatively low (Keren et al., 1985b). According to Chapman (1966), the normal level of B in pepper leaves is in the range of 3.1 to 10.9 mmol kg$^{-1}$ dry matter. At levels above 30.5 mmol kg$^{-1}$ dry matter, toxicity symptoms may appear (Keren et al., 1985b).

Boron uptake by the plant was affected by the amount of B applied and COM content (Fig. 3): the higher the level of added B, the higher the B concentration in the leaves. Boron concentration at the leaves exceeded the potentially toxic level of 30.5 mmol kg$^{-1}$ dry matter only at the highest B application rate for the system without COM. The COM only had a significant effect on B uptake by the plant at the two highest added B levels. These results support the hypothesis that soil organic matter plays an important role in B availability to plants, particularly at high total B concentrations (Parks and White, 1952; Berger and Pratt, 1963).

Boron uptake by the plants and B content in the soil after plant harvesting is shown in Table 2. Boron uptake increased with increasing B application rate for the same level of COM. This increase in B uptake was due to the increasing B concentration in the leaves since the growth and dry matter yield were similar for each level of COM (Table 2). The increasing uptake of B with increasing COM at the same level of added B, up to 3%, was a result of higher dry matter yield despite a lower B concentration in the leaves (Fig. 3). When COM content exceeded 3%, B uptake decreased, due mainly to reduced B concentration in the leaves because dry matter yield was similar in these COM treatments. The amount of B in the plants was relatively small in comparison with the total B content in the system, and even in relation to B content in the soil solution (Table 2). The fraction of B uptake by plants from total B added was highest at the lower added B levels and decreased sharply (below 6%) as the total B content increased. Since most of the B in the system was sorbed to the solid phases, only a small fraction of adsorbed B had to be desorbed in order to maintain the equilibrium between the B concentration in solution and the B content in the adsorbed phase.

Boron concentration in the leaf tissue plotted against B concentration in the soil solution for the various soil–sand–COM mixtures is shown in Fig. 4. The linearity of the relationship ($r^2 = 0.88$) suggests that plant uptake of B was controlled by soil solution B concentration. Keren et al. (1985a, 1985b) showed that B uptake by bell pepper and wheat plants is better related to the concentration of B in the soil solution rather than to the total B concentration in the soil. Boron uptake by barley (Murtadha et al., 1988), peanut (Lombin, 1985) and alfalfa (Gestring and Soltanpour, 1987) also was linearly correlated with soil solution B concentration. A correlation coefficient ($r^2$) of 0.98 was obtained when B concentration in the leaf tissue was regressed against the predicted B concentration in the soil–sand–COM mixture solution (Eq. [1]–[3]) and the adsorption coefficients (Table 2). Boron concentration in the leaves was $=3.0$ mmol kg$^{-1}$ dry matter when no B was added, which is the minimum B concentration associated with growth of bell pepper plants (Chapman, 1966).

The experimental results indicate that organic matter is important in B distribution between the solid and liquid phases in soils, and that it can have a prominent effect on B uptake by plants. Adsorption of B by organic matter is much greater than that by clay mineral components (Yermiyahu et al., 1995). Addition of organic matter to soils can decrease or increase B uptake by plants dependent on total B levels in the soil. In a soil high in total B, a reduction in soluble B can be achieved by adding organic matter, thereby reducing B availability and toxicity to plants. In sandy soils where B leaching results in low total B, additions of organic matter may reduce leaching and increase B nutrition of plants.
REFERENCES


