Bromide movement and uptake under bare and cropped soil conditions at Dire Dawa, Ethiopia

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The worst-case scenario of NO3--N leaching is often determined using conservative tracers since it undergoes complex and interdependent transformations in the soil. However, few tracer studies have hitherto been done under cropped soil conditions. In this study, a field experiment was conducted to compare Br− transport under bare and maize planted soil conditions at the experimental site of the Alemaya University, Dire Dawa (East Ethiopia). At the beginning of the experiment, KBr was applied in a solution form. Soil and plant samples were taken several times during the growing season and the concentration of Br− determined. At the end of the experimental period, Br− peak was transported to depths of 900 mm and 1300 mm on bare and maize plots respectively. The percentage of Br− recovery from bare and maize plots was 99.8% and 86.8% respectively. Bromide velocity was slightly higher than the pore-water velocity. The maize plants took up about 8.1% of the applied bromide. The concentration of Br− in the plant tissue decreased as the crop grew while the total uptake was increasing.

Keywords: bromide, Ethiopia, leaching, maize

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Introduction

Knowledge about the rate at which NO3--N is leached through the soil is very important when implementing different fertilizer management practices and also to determine the extent of groundwater contamination. However, NO3--N transport is a very complex process in which chemical, physical and biological components interact. Owing to its anionic character, tracer studies of conservative chemicals, such as chloride and bromide, are consequently often used to study the movement of NO3--N towards the groundwater (Kelly & Pomes, 1998; Silvertooth et al., 1992; Bowman, 1984; Onken et al., 1977).

Bromide is a commonly used tracer under field conditions because its background concentration is very low, it is easily detected and is unlikely to contaminate the environment (Nachabe, Ahuja & Butters 1999; Jaynes, Bowman & Rice, 1988; Onken et al., 1977). However, since most of the reported studies were conducted on bare soils, information is limited on water movement and solute leaching in the presence of crops (Iragavarapu, Posner & Bubenzer, 1998). Plant uptake of solutes can significantly reduce mass transport through the soil profile. Therefore, it is important to improve our understanding of movement of tracers and agrochemicals in the presence of crops. According to the few studies conducted under cropped conditions, Br− is readily absorbed by plants although it is not an essential nutrient. Jemison and Fox (1991) reported Br− uptake of maize (Zea mays L.) as high as 38% of the applied Br−. Owens, Van Keuren & Edwards (1985) indicated that about 30% of the applied (168 kg ha−1) Br− was taken up by a mixture of orchardgrass (Dactylis glomerata L.) and Kentucky blue grass (Poa pratensis L.).

The objective of this study was to conduct a field experiment to investigate Br− movement under bare and maize planted plots. For this purpose, soil and plant samples were taken at different times during the growing season and analysed for bromide concentration.

Material and methods

Field experiment

The experiment was conducted at the Dire Dawa field experimental farm of the Alemaya University, East Ethiopia, located at 9°15′ N latitude, 41°48′ E longitude, and 1210 m altitude. The monthly mean minimum and maximum temperatures of the area were 16°C and 32°C, respectively. The mean annual rainfall was 650 mm with two rainy seasons: July–August and March–May. The soil of the area is alluvial with sandy loam texture in the 0-600 mm layer. The experiment was conducted from March to May 2001.

Six (5 m x 5 m) plots were prepared on land which was not cultivated before. The inner (3 m x 3 m) of the plots was isolated from the surrounding using galvanized metal sheets inserted 200 mm into the soil and the remaining 200 mm protruding above ground. The sheets help to prevent runoff and seepage at least at shallow depth. There were two treatments: bare plots and plots planted with a maize crop. Each treatment was replicated three times. The bare plots were sprayed with herbicides to prevent weed growth. Soil particle size distribution was determined using the Hydrometer method (Table 1). Bulk density was obtained by taking six core samples per 200 mm depth interval from the sides of a soil profile opened near the plots.

Before tracer application, initial composite soil sampling took place to determine the background concentration of bromide, which was found to be about 2.3 mg/l. Potassium bromide was applied at a rate of 200 kg KBr ha−1 (134.2 kg Br ha−1). The chemical was dissolved in water and sprayed onto the plots just before sowing the crop. On 1 March 2001, an early maturing maize (Zea mays L.) variety was planted in rows at a density of 5 plants m−2. Since irrigation water was applied in reduced amounts of a high frequency, there was no
through a determination and subsequent chemical analysis. The dry matter was determined from the plant samples taken for bromide analysis. The mass of bromide taken up was calculated using the plant dry matter mass and the concentration of the elements.

**Table 1 Particle size distribution, textural class and bulk density of the soil profile**

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Soil texture</th>
<th>Bulk density (g cm⁻³)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-200</td>
<td>70</td>
<td>18</td>
<td>12</td>
<td>Sandy loam</td>
<td>1.37±0.06</td>
</tr>
<tr>
<td>200-400</td>
<td>75</td>
<td>13</td>
<td>12</td>
<td>Sandy loam</td>
<td>1.42±0.05</td>
</tr>
<tr>
<td>400-600</td>
<td>83</td>
<td>10</td>
<td>7</td>
<td>Loamy sand</td>
<td>1.31±0.03</td>
</tr>
<tr>
<td>600-800</td>
<td>74</td>
<td>16</td>
<td>10</td>
<td>Sandy loam</td>
<td>1.32±0.04</td>
</tr>
<tr>
<td>800-1000</td>
<td>56</td>
<td>23</td>
<td>21</td>
<td>Sandy clay loam</td>
<td>1.34±0.07</td>
</tr>
<tr>
<td>1000-1200</td>
<td>52</td>
<td>27</td>
<td>21</td>
<td>Sandy clay loam</td>
<td>1.17±0.04</td>
</tr>
<tr>
<td>1200-1400</td>
<td>54</td>
<td>26</td>
<td>20</td>
<td>Sandy clay loam</td>
<td>1.35±0.19</td>
</tr>
<tr>
<td>1400-1600</td>
<td>53</td>
<td>27</td>
<td>20</td>
<td>Sandy clay loam</td>
<td>1.14±0.09</td>
</tr>
</tbody>
</table>

* Mean of six values ± standard deviation

ponding and runoff.

**Soil and plant sampling and laboratory analysis**

The inner 3 m x 3 m area of each plot was used for soil sampling. Soil samples were taken at 200 mm depth intervals to a maximum depth of 1600 mm using an auger type coring tube of 200 mm length and 42 mm diameter. There were eleven samplings taken at about weekly intervals. At one sampling time soil samples were taken randomly from two positions and the samples taken from the same depths were mixed to get a composite sample for each treatment. The core sampler was cleaned with water before re-insertion for the next depth of sampling. Following retrieval of the cores, the resultant holes were backfilled with soil from outside the plot and the position marked with a thick wire peg. About 100 g of soil from each composite sample was taken and put in paper bags for gravimetric water content determination by drying it for 24 h at 105°C. The remaining soil sample was put in polyethylene bags for bromide analysis. The soil samples were oven-dried and ground to pass a 2 mm sieve in the preparation for laboratory analysis.

In the preparation of the filtrate for the ion chromatograph, 50 g of the soil was mixed with 50 ml distilled water. The mixture was shaken using a laboratory shaker and the solution was subjected to filtration. The concentration of Br⁻ in the filtrate was determined using an ion chromatograph (Dionex Corp., Sunnyvale, CA) and the concentration per soil volume calculated taking into account the mass of soil from which it was extracted, the volume of water used for extraction and the gravimetric water content of the soil sample.

Above-ground plant samples were taken to determine the amount of Br⁻ taken up by the maize crop. In order to keep the number of plants in the inner area the same throughout the growing season, the plant samples were taken from the outside area of each plot. The whole sampled plant was shredded, weighed, and oven-dried at 70°C for dry matter determination and subsequent chemical analysis. The dry mass was multiplied by the number of plants in each plot to get total dry matter per plot, which was converted to a hectare basis. Oven-dried plant samples were ground and passed through a 0.25 mm sieve. One gram of the prepared plant was mixed with 50 ml distilled water and shaken on a laboratory shaker. The suspension was filtered and analysed for Br⁻ concentration using an ion chromatograph. Dry matter was determined from the plant samples taken for bromide analysis. The mass of bromide taken up was calculated using the plant dry matter mass and the concentration of the elements.

**Equations and data calculations**

The components of the water balance were irrigation and rainfall (water inputs), evaporation (EV)/evapotranspiration (ET) and deep percolation (water loss) and change in stored soil water. Deep percolation below the rooting zone was determined from the soil profile water balance equations given by Equations 1a and 1b for bare and planted soils respectively. Since the plots were enclosed with sheet metal protruding above ground, there was no runoff from the plots.

\[
D_p = R + I - EV - DS
\]  
\[
D_p = R + I - ET - DS
\]

where \( D_p \) = deep percolation, \( R \) = rainfall, \( I \) = irrigation, \( DS \) = change in water content, \( EV \) = evaporation, \( ET \) = evapotranspiration.

Change in the storage of water in the root zone over a given time interval was determined as the difference in soil water content at the beginning and end of the interval. The soil water content was determined using the gravimetric method. The rainfall data during the experimental period was obtained from a nearby (about a kilometre) weather station at Dire Dawa Airport. Reference evapotranspiration (ETₒ) was estimated from weather data (temperature, relative humidity, wind speed, and sunshine hours) recorded at the weather station using the well-known Modified Penman-Monteith Equation according to the procedure given by Allen et al. (1998). Crop factors (\( K_c \)) were used to calculate maize evapotranspiration from the reference evapotranspiration.

Potential evaporation or the energy-limiting evaporation rate was calculated using Priestley and Taylor's (1972) equation and the soil-limiting or actual evaporation rate from the bare plots was determined using Ritchie's (1972) equation.

The mass balance of applied solute was checked from the amount of recovered mass by core sampling. The mass of Br⁻ (g) recovered from a core, \( m \), was calculated as

\[
m = c(z, t_1)\theta_m(z, t_1)A\Delta z
\]

where \( c \) (mg/l) = Br⁻ concentration at depth \( z \) and sampling time \( t_1 \), \( \theta_m(z, t_1) \) = gravimetric soil water content, \( A \) = cross sectional area of the core sampler, and \( \Delta z = \) depth interval.

Then the total recovered Br⁻, \( m \), from a soil depth \( D \) is the sum of these masses as given by

\[
m = \sum_{z=D}^{z=0} \theta(z, t_1)c(z, t_1)A\Delta z
\]

The mass of Br⁻ recovered as a percentage of total applied mass was calculated as \( r(\%) = 100 \times m/M \), where \( M \) = the total mass of applied solute at the soil surface.
The average downward movement of solute front can be estimated by the pore water velocity as

\[ v_w = \frac{q}{\theta} \]  

(4)

where \( q \) is the Darcian flux and \( \theta \) is the average volumetric soil water content. Darcian flux was estimated as the ratio of deep percolation to the duration of the experiment.

To evaluate the nature of the solute transport, the average pore water velocity \( V_w \) was compared with the solute velocity \( v_s' \).

The mean velocity of the area-averaged pulse of Br\(^-\) was estimated by monitoring the downward movement of the applied chemical. The velocity of the concentration peak was calculated as the ratio of the depth traversed by the concentration peak for two consecutive sampling events to the time interval between the two sampling events as

\[ v = \frac{\Delta z_p}{\Delta t} \]  

(5)

where \( \Delta z_p \) is the change in depth of concentration peak of solute pulse and \( \Delta t \) is the change in time between the two peaks.

The depth to the centre of mass of the solute profiles was calculated as

\[ X_i = \frac{1}{m} \sum_{z=0}^{z=D} z \theta(z, t_i) c(z, t_i) 4 \Delta z \]  

(6)

where \( X_i \) is the depth to the centre of mass at the sampling time \( t_i \).

The velocity of the centre of mass of the solute between two sampling dates was calculated as

\[ v = \frac{X_{i+1} - X_i}{\Delta t} \]  

(7)

where \( X_i \) and \( X_{i+1} \) are the depths to centre of mass of the solutes at sampling times \( t_i \) and \( t_{i+1} \).

Results and discussion

Soil water balance

The total rainfall during the experimental period (March to May 2001) was 203 mm, which is lower than the 22-year (1979-2000) average of 269 mm for this period in the Dire Dawa area. As the rainfall was not sufficient to grow a maize crop, much of the crop water requirements were met by irrigation. Figure 1 shows the components of the water balance for bare and maize plots. It can be observed that water input (irrigation and rain) and water output (evaporation/deep percolation) for the maize plots was higher than for the bare plots.

The depth to the centre of mass of the solute profiles for the

bare and maize plots are presented in Figure 2. Soil water content in the top 1000 mm was lower for maize plots than for bare plots owing to water absorption by maize. The rooting depth of the maize variety used in this study is about 1.5 m with most of the roots concentrated in the top 1 m. At greater depths, the water content of the maize plots was higher than that of the bare plots because the larger amount of water applied to the maize plots resulted in increased deep percolation below the root zone.

Bromide concentration profile

The change in Br\(^-\) concentration of the soil profile at some selected times of the growing season is presented in Figures 3 and 4. During this experiment, the total amount of water applied (rain plus irrigation) was 682.6 mm and 797.6 mm for bare and maize plots, respectively. Although the amount of water applied in this short period (3 months) was higher than the mean annual rainfall (650 mm), almost all the bromide was not leached beyond the sampling depth of 1600 mm. This can be observed from Figures 3 and 4 in which the relative concentration curve tended to return to the background con-
concentration before it reached the 1600 mm depth.

The average recovered mass of bromide in the soil at different sampling times is given in Table 2, expressed as a percentage of the mass of the chemical applied at the beginning of the experiment. The average recovery of bromide was 99.8% and 86.8% for the bare and maize plot, respectively, which shows that about 13% of bromide in the maize plots leached beyond the sampling depth and/or was taken up by the crop. It can also be observed that at the end of the experiment, bromide concentration peaks have moved to 900 mm and 1300 mm depths on bare and maize plots respectively (Figures 3 and 4).

Crop uptake and recovery of bromide
The maize plants were harvested on 7 June 2001 from the centre (3 m x 3 m) area of each plot. A summary of the dry matter, plant tissue concentration and uptake of bromide by the maize crop is presented in Table 3. It can be observed that the concentration decreased as the plants grew owing to the dilution effect caused by dry matter accumulation. The mass of bromide taken up by the crop increased during the growing season. A similar trend has also been observed, for example, by Jemison and Fox (1991). Maize plant bromide concentrations during the growing season ranged from 1.28 to 5.02 g kg$^{-1}$, with an average of 1.95 g kg$^{-1}$. Concentrations of Br$^{-}$ higher than 4.6 g kg$^{-1}$ have been shown to be toxic to livestock and should not be used for feeding (Knight & Reina-Guerra, 1976). Iragavarapu et al. (1998) found a Br concentration of 1.9 g kg$^{-1}$ in maize plants harvested from a soil to which 197 kg Br ha$^{-1}$ had been applied. At harvesting, the leaf, stem and grain parts of the plant samples were analysed separately.

The total uptake of Br$^{-}$ by maize at maturity was 10.9 kg ha$^{-1}$ (Table 3) which is 8.1% of the applied tracer. Different, and sometimes contradictory, results have been obtained by other researchers as to the uptake of Br$^{-}$ by a maize crop. Iragavarapu et al. (1998) found uptake of Br$^{-}$ by maize in the range of 8 to 10% of the applied Br$^{-}$. Their result was low when compared to results from previous studies (Jemison & Fox, 1991; Owens et al., 1985). For example, Jemison and Fox (1991) reported maize uptake of 38 kg ha$^{-1}$ of bromide which was about 40% of what was applied. Gish and Coffman (1987), after applying 112 kg KBr ha$^{-1}$ on a no-till maize plot, found that bromide uptake by the plants was negligible.

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Table 2 Percentage recovery of Br$^{-}$ at different sampling times during the season

<table>
<thead>
<tr>
<th>Sampling time after chemical application (days)</th>
<th>Average recovery (%)</th>
<th>Bare plots</th>
<th>Maize plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>128.3</td>
<td>109.9</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>109.8</td>
<td>124.5</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>89.8</td>
<td>69.0</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>63.8</td>
<td>113.3</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>111.5</td>
<td>122.0</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>112.4</td>
<td>74.0</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>112.6</td>
<td>67.0</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>81.9</td>
<td>69.4</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>79.3</td>
<td>111.9</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>62.8</td>
<td>64.5</td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>91.2</td>
<td>29.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Average dry matter, bromide content and uptake by the maize crop at different times during the growing season

<table>
<thead>
<tr>
<th>Sampling date/ Plant part</th>
<th>Dry matter (kg ha$^{-1}$)</th>
<th>Br$^{-}$ concentration (g kg$^{-1}$)</th>
<th>Br$^{-}$ uptake (kg Br$^{-}$ ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 April</td>
<td>1629</td>
<td>5.0</td>
<td>8.2</td>
</tr>
<tr>
<td>03 May</td>
<td>3208</td>
<td>1.6</td>
<td>5.0</td>
</tr>
<tr>
<td>10 May</td>
<td>4174</td>
<td>1.9</td>
<td>7.8</td>
</tr>
<tr>
<td>24 May</td>
<td>7038</td>
<td>1.3</td>
<td>9.0</td>
</tr>
<tr>
<td>07 June (at harvest)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaf</td>
<td>2356</td>
<td>1.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Stem</td>
<td>1285</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Grain</td>
<td>5432</td>
<td>1.0</td>
<td>5.2</td>
</tr>
<tr>
<td>Total</td>
<td>9073</td>
<td>1.5</td>
<td>10.9</td>
</tr>
</tbody>
</table>
Gish and Jury (1982) also found bromide uptake to be only 2 to 3% of the applied bromide. The average percentage of bromide recovered by soil sampling in this study was 86.8% (Table 2). The total mass of bromide recovered from the soil plus uptake by the maize is therefore 94.9%. Since the percentage recovery from the bare plots was almost 100%, it can be assumed that the unrecovered bromide mass in the maize plots might have been stored in the roots, which were not measured in this study.

**Bromide movement in the soil**

At the end of the experiment, bromide concentration peaks had moved to 900 mm and 1300 mm depths on bare and maize plots respectively (Figures 3 and 4). In the soil solute transport, convection, rather than dispersion, determines the position of the concentration peak. Parker and van Genuchten (1984) demonstrated that for variable velocities, the contribution of the dispersion coefficient is minimal and can be neglected. In such cases, the velocity of a tracer can be estimated by the pore-water velocity, assuming that the applied water containing the tracer displaces the water already present in the soil pores.

Pore-water velocity is determined as the ratio of Darcian flux to the volumetric soil water content. The cumulative deep percolation from bare and maize plots was 140.9 mm and 202.3 mm respectively (Figure 1). For the 98-day duration of the experiment, Darcian fluxes (q) of 1.44 mm d⁻¹ and 2.06 mm d⁻¹ were calculated for the bare and maize plots respectively. The average soil profile volumetric water content during the season was 0.149 and 0.137 for these plots. The pore-water velocity, vₚ, calculated using Eq. (6), was 9.6 mm d⁻¹ and 15.0 mm d⁻¹ for the bare and maize plots respectively. The higher pore-water velocity in the maize plots than in the bare plots resulted in higher deep percolation. However, the actual solute velocity, vₛ, is determined from the displacement of the concentration peak and solute centre of mass. The velocity of concentration peak was determined using the time it took for the concentration peak to shift to a given depth, Eq. (7). The centre of mass velocity was determined using Eq. (9). Table 4 presents the average bromide velocity determined for the three bare and the three maize plots.

It can be observed that the velocity of bromide in the bare plots was lower than the corresponding velocity in the maize plots. The amount of water applied and the deep percolation of the maize plots were higher than that of the bare plots (Figure 1). Solute leaching rate increases with the net water flux and this may be the reason for the higher velocity of Br⁻ on the maize plots. The average ratio (vₛ/vₚ) was 1.18 for the bare plots and 1.08 for the maize plots, which implies that the solutes have slightly bypassed the maize plots, which is expected. Since major cracks are not expected in this sandy loam soil, it is difficult to attribute this phenomenon to cracking.

**Conclusions**

Results of this study indicated that Br⁻ is a suitable tracer to infer solute movement patterns and can be used to determine the worst case scenario of fertilizer NO₃⁻N leaching loss in the absence of sources and sinks of nitrogen in the soil. However, specific issues regarding the fate of fertilizer N in a soil-plant system cannot be determined by using a conservative tracer such as Br⁻.

The solute velocities were slightly higher than the velocities predicted using pore-water velocity, indicating preferential flow. The maize crop attenuated the peak of Br⁻ concentration in the soil profile. As bromide is not an essential plant nutrient, its crop recovery was only 8.1%. The solute concentration profiles in this analysis are the results of the interaction of numerous factors influencing processes such as preferential flow, evaporation, hydrodynamic dispersion, diffusion, and exclusion of anionic solute from negatively charged minerals.

**References**


**Table 4 The concentration peak and centre of mass velocity of Br⁻ on bare and maize plots**

<table>
<thead>
<tr>
<th>Plot number</th>
<th>Concentration peak</th>
<th>Centre of mass</th>
<th>Plot number</th>
<th>Concentration peak</th>
<th>Centre of mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Plots</td>
<td>Maize Plots</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>12.6</td>
<td>10.6</td>
<td>1</td>
<td>16.2</td>
<td>15.4</td>
</tr>
<tr>
<td>2</td>
<td>10.8</td>
<td>9.7</td>
<td>2</td>
<td>18.4</td>
<td>13.8</td>
</tr>
<tr>
<td>3</td>
<td>10.8</td>
<td>10.8</td>
<td>3</td>
<td>15.7</td>
<td>16.8</td>
</tr>
<tr>
<td>Average</td>
<td>11.4</td>
<td>10.4</td>
<td>Average</td>
<td>16.8</td>
<td>15.3</td>
</tr>
</tbody>
</table>

