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ScienceDirect

Soil & Tillage Research 90 (2006) 194–204

Soil & Tillage Research

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Effects of fertilizer placement on solute leaching under ridge tillage and no tillage

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Received 22 December 2004; received in revised form 14 September 2005; accepted 27 September 2005

Abstract

Elevated nitrate concentrations in ground water can be a problem in agricultural areas, especially where soils are sandy. Tillage operations, such as ridge tillage (RT) and no tillage (NT) can reduce runoff and erosion but leaching of soluble nutrients could adversely impact groundwater. In a 2-year study, Br was used to trace the effects of fertilizer placement on solute movement under corn (*Zea mays* L.) in RT and NT systems on a Monmouth fine sandy loam (Typic Hapludult) in Maryland. Treatments included 120 kg ha^{-1} of Br$^-$ or NO$_3$$^-$-N applied in a narrow band near the ridge top (RT-RA) or in the furrow (RT-FA) with ridge tillage, or in the inter-row with NT. Two-dimensional arrays of tensiometers and suction lysimeters were used to follow the movement of water and solutes during and after the corn-growing season. Tillage and fertilizer placement did not significantly affect N uptake when averaged across years. A pronounced argillic horizon beginning at 60 cm depth caused lateral movement of Br. It appears that Br leaching in RT-RA increased slightly due to the crop canopy funneling rain towards the ridge top. Therefore, when fertilizer is applied near the row, rain occurring after full corn canopy may cause greater solute leaching in RT-RA compared to other treatments. Rain during the beginning of the growing season or after harvest caused less leaching in RT-RA. Corn yield could be maximized and N leaching minimized by applying fertilizer to the upper portion of the ridge in RT.
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Keywords: Ridge tillage; No tillage; Fertilizer placement; Bromide tracer; Nitrate leaching

1. Introduction

Nitrogen fertilizers are applied to cropland to increase crop yield. Nitrogen fertilizer applied in excess of crop uptake may be susceptible to leaching below the root zone (Malhi et al., 2004). Losses of nitrate by leaching represent a cost to farmers and can cause environmental damage. Nitrate is especially important in contamination of shallow groundwater (Angle et al., 1993) and in the eutrophication of brackish waters, such as those of lower Chesapeake Bay.

A study in Maryland showed that ground water under intensively managed coastal plain soils had nitrate concentrations in excess of 25 mg N L^{-1} (Weil et al., 1990). Angle et al. (1993) in a 3-year study found soil solution and ground water nitrate concentrations under no-till corn (*Zea mays* L.) were double those from conventional tillage corn. Decontamination of ground water by natural processes may be very slow. For example, Owens and Edwards (1992) measured ground water contamination from a conservative tracer (Br) in a spring fed by subsurface flow 10 years after a one time surface application.

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0167-1987/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.still.2005.09.002

Wide adoption of no-tillage (NT) methods for corn production in the mid-Atlantic region during the past 25 years has reduced the potential for surface runoff of nutrients and sediment from crop land (Cogo et al., 1984; Glenn and Angle, 1987; Dillaha, 1990; Fuentes et al., 2003). The literature provides contradictory evidence concerning the relative downward mobility of agrochemicals through soils under NT and conventional tillage (CT) management. Following broadcast fertilization, Tyler and Thomas (1977) reported that leachate collected through pan lysimeters 1 m deep had up to three times as much nitrate under NT as under CT. In another study, however, Levanon et al. (1993) found that under similar conditions more nitrate was leached from CT plots. In the earlier study which utilized undisturbed soil cores, addition of fertilizer was followed by a spray of water that allowed penetration of nitrate into the soil matrix. Incorporating fertilizer into the soil matrix may reduce nitrate loss by preferential flow paths (Bathke and Cassel, 1991).

Banding fertilizer can reduce nutrient loss from the root zone by increasing plant uptake. For example, up to twice as much N was consumed by corn when urea-ammonium nitrate was applied in a band or point injected, as compared to when it was broadcast (Mengel et al., 1982; Maddex et al., 1991). Additionally, placement of fertilizer in a band where corn rooting density is greatest (i.e. non-trafficked inter-row or near the corn row) is known to increase fertilizer uptake efficiency (Fausey and Dylla, 1984; Maddex et al., 1991).

Conservation tillage systems that use permanent traffic lanes may increase yield and improve timeliness of operations (Taylor, 1983). Ridge tillage (RT) is a conservation tillage practice that utilizes controlled wheel traffic patterns. Liebig et al. (1993) identified three zones for RT with distinct soil properties: trafficked inter-rows, non-trafficked inter-rows, and crop rows. The ridge area is never compacted and is left undisturbed except during planting and tillage operations, producing a zone with soil conditions conducive to higher yields (Liebig et al., 1993; Kaspar et al., 1995).

It has been suggested (Kemper et al., 1975; Hamlett et al., 1990; Clay et al., 1992) that placement of the fertilizer N on or near the ridge top may reduce N leaching due to micro topography. During rainfall, a ridge-furrow system would be expected to concentrate water in the furrow (Willis et al., 1963) where it would not come in contact with fertilizer localized near the ridge top. Increased N uptake by young corn plants when N fertilizer is placed on the ridge rather than in the furrow (Blaylock and Cruse, 1992) would leave less N susceptible to leaching in RT.

The primary focus of experiments conducted by Hamlett et al. (1990) and Clay et al. (1992) was to evaluate the effects of fertilizer placement on nitrate leaching occurring early in the corn-growing season. Both studies simulated rainfall less than one day after fertilizer application, thus, maximizing the potential for ridge to furrow runoff. Hamlett et al. (1990) placed nitrate as a line source on top of newly created ridges and compared the N leaching to that in CT, in which N was placed in the inter-row. With 72 mm of simulated rain, recovery of N in the upper 1.2 m of soil averaged 89% of that applied for RT and 53% for CT. However, most of the N remained above 0.6 m after drainage had ceased. Clay et al. (1992) used 150 mm of simulated rain in RT with fertilizer placed in a band 23 cm wide either on the ridge top or in the furrow. Pan lysimeters that spanned a corn row at a 60 cm depth collected most water directly under the furrow position compared to the ridge position in the 24-h period following the rain. Solute concentrations in leachate collected from the furrow-applied treatment were significantly greater under the furrow than under the ridge position, indicating a unidirectional flow. With fertilizer applied to the ridge, soil retained 70% of the total applied N in the upper 30 cm.

The studies cited above lacked established ridges and growing crops, two factors that limit their applicability to normal field conditions. The physical condition and pore structure typical of established RT and NT soils take several seasons to form; therefore, research conducted on new plots will not be representative of the systems in use. Also, evapotranspiration of water, stem flow in crop canopy (Waddell and Weil, 1996), and uptake of anions by corn may influence distribution of solutes with time.

We used a Br tracer to determine the effect of fertilizer placement (either near the ridge top or in the furrow in RT or in the inter-row position in NT) on the movement of anionic solutes within and beyond the root zone.

2. Materials and methods

A field experiment was conducted near Upper Marlboro, Maryland in a 2 ha field containing 5-year-old RT and NT demonstration plots in a corn-soybean (*Glycine max* L. Merr.) rotation. The moderately well drained soil was a Monmouth fine sandy loam (fine loamy, mixed, mesic Typic Hapludult). For each replication, one non-trafficked inter-row was selected for instrumentation after visual inspection for uniformity of crop growth, soil type and soil surface conditions. The experiment was conducted on a sideslope with less than 2% grade. Pre-plant fertilizer was broadcast at rates (kg ha^{-1}) of 83 N, 36 P and 69 K. Pioneer brand 3142 corn was seeded to achieve a stand of 65,000 plants ha^{-1} using a Buffalo® RT corn planter. The established NT plots were treated with glyphosate (*N*-(phosphonylmethyl) glycine) at a rate of 5 L active ingredients ha^{-1}. The RT plots received no herbicides but were cultivated on 28 May and 10 June in 1991 and on 24 May, and 8 and 16 June in 1992. Soil physical properties were reported in Waddell and Weil (1996).

Tensiometers and suction lysimeters were installed immediately after the second cultivation in June 1991, and after the third cultivation in June 1992. Four arrays of suction lysimeters and two arrays of tensiometers were installed in the RT plots and two arrays of lysimeters and one array of tensiometers were installed in the NT plot. Lysimeters and tensiometers were constructed of a five cm long and 2.5 cm diameter high-flow ceramic cup (bubbling pressure of −100 kPa) glued to rigid poly vinyl chloride tubes of various lengths. A drop-hammer insertion devise was used to create a hole with minimal disturbance and slurry made from 200 mesh silica dust and water (1:1, v/v) was poured into the hole to insure good soil contact. After insertion of each tensiometer or suction lysimeter, the upper 5 cm was filled with bentonite to prevent water flow along the instrument. Each 100 cm × 76 cm array was composed of 30 suction lysimeters or tensiometers installed 15 to 90 cm deep in 15 cm intervals (Fig. 1). Five suction lysimeters or tensiometers at each depth were installed 19 cm apart along a transect perpendicular to the corn rows bordering one non-wheel trafficked inter-row. Suction was applied to suction lysimeters and extracted water for up to 24 h and samples were frozen until analysis.

Following plot instrumentation (after RT cultivation in mid-June each year), 1.2 M nitrate and 0.2 M Br solutions, as potassium salts, were surface applied at a rate of 120 kg ha^{-1} of NO_3^--N and Br, either in the furrow (RT-FA) or near the ridge top (RT-RA). The ridge application was split and added 5 cm on either side of the corn row on the ridge top. The NO_3^--N and Br solution was also added to the inter-rows in the NT plots at the same rate as the RT plots. Leachate sampling was attempted immediately after fertilizer application, but the soil profile in 1991 was not sufficiently wet until after corn harvest for the suction lysimeters to extract soil water.

After corn harvest, soil samples were collected. For each replication, an undisturbed zone for soil coring was established encompassing the same two corn rows and their inter-row as the instrumented areas (Fig. 1). Five evenly spaced soil samples were taken along a transect perpendicular to the corn row. Samples were separated into 15 cm segments to a depth of 90 cm in 1991/1992 and to 150 cm in 1992/1993. Samples were chilled immediately for transport to the lab and rapidly forced-air dried at 25 °C.

Precipitation was recorded every half hour by a weather station located within 100 m of the plots. In addition to natural rainfall, a rainfall simulator was used to apply one application, 28 mm h^{-1} of water for a period of 1.6 h, to each plot during the period 28 September through 1 October 1991. The rainfall simulation device

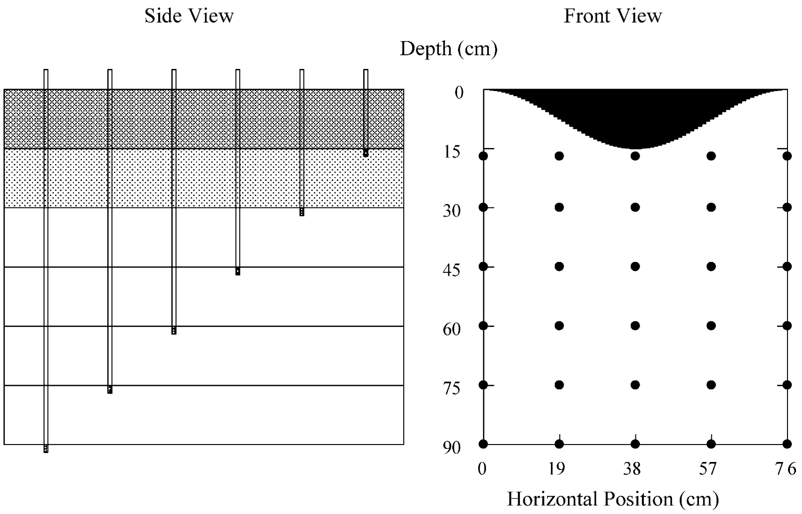

Fig. 1. Schematic of the tensiometer and suction lysimeter array.

was capable of raining on an individual plot with drop size and intensities similar to natural conditions (Meyer and Harmon, 1979). Rainfall simulation results were used to compare infiltration rates for NT and RT surfaces. No-till had significantly higher infiltration rates than RT (Waddell and Weil, 1996).

Soil water samples collected from suction lysimeters were diluted with distilled deionized water (4 ml water: 1 ml sample) and analyzed for nitrate and Br using a Dionex model 450 ion chromatograph with a Dionex AS-4 separator column and eluant containing 1.8 mM carbonate and 1.7 mM bicarbonate. Soil samples were extracted with 0.1 M K_2SO_4 and analyzed for nitrate (Abdalla and Lear, 1975) and Br (Vendrell and Zupancic, 1990) with ion specific electrodes. The highly concentrated solute used to extract soil nitrate prohibited the use of ion chromatographic techniques used for soil water samples. A mass-to-mass relationship was desired to compare leachate and soil concentrations. Soil water retention data (Waddell and Weil, 1996) enabled calculation of volumetric water contents from tensiometer readings taken simultaneously with suction lysimeters and soil core samples. Calculated concentrations from the suction lysimeters accounted for varying soil wetness.

Corn was harvested on 14 September 1991 and 20 October 1992. Yields of grain and stover from each 0.76 m^2 area with instrumentation were recorded and samples were forced-air dried at 70 °C for one week. Dried corn grain and stover were ground and passed through a 2 mm sieve. Total Kjeldahl N was measured with the use of an ammonia sensitive electrode (Eastin, 1976) after digestion. Bromide uptake was measured with extraction in 1 M K_2SO_4 using a Br sensitive electrode (Kung and Kung, 1990).

The data analysis for this paper were generated using SAS/STAT software, Version [8] of the SAS System for Windows. Corn yield and anion uptake were analyzed, with fertilizer applied to the ridge and furrow in the RT plots and fertilization in the inter-row of NT plots being the three treatments. Soil data were analyzed with an analysis of variance for each sampling date. There were two replications of each treatment in each year. Two-dimensional contour plots showing the horizontal and vertical distribution of anions in the soil were generated using the spline function.

3. Results and discussion

Rainfall distribution for each year, including the simulated rainfall events on 28 September through 1 October 1991, was reported in Waddell and Weil (1996). Drier than normal conditions early in the 1991 growing season prohibited extraction of water from the soil by most of the suction lysimeters. Complete sets of soil water samples from the sampling arrays were first obtained in 1991 after the rainfall simulation wetted the profile. Even with the simulated rain events, precipitation during the 1991 growing season (305 mm) was below normal, while precipitation in 1992 (481 mm) was closer to the 31-year mean (578 mm).

Corn plants generally took up greater N than was applied, while Br^- taken up by corn was lower than that applied (Table 1). Br was lower in corn tissue in 1991 (average of 12% of total applied Br) than in the 1992 growing season (average of 16% of total applied Br), similar to the range measured by Kohler et al. (2005). This difference was attributed to higher precipitation in 1992 than in 1991. The RT-RA corn recovered significantly greater Br over both years than RT-FA, suggesting higher uptake of solutes when applied to ridges. In 1992, percent recovery of Br by corn in the three treatments did not differ. Corn stover yield (7.5 ± 0.9 Mg ha^{-1}) and grain yield (9.0 ± 0.5 Mg ha^{-1}) did not differ significantly among

Table 1
Bromide and total N in the combination of corn stover and grain as a percent of that applied in the 1991 and 1992 growing seasons and the mean of both years for three tillage and fertilizer placement combinations

	Percent of applied					
	Br			Total N		
	1991	1992	Mean	1991	1992	Mean
RT-RA	17.0 a	14.2 a	15.6 a	114.0 b	124.4 a	119.2 a
RT-FA	5.9 c	14.6 a	10.3 b	111.7 b	107.7 b	109.7 a
NT	11.8 b	18.5 a	15.1 a	130.4 a	92.2 c	111.3 a

Means within a column followed by different letters are significantly different ($p < 0.05$). RT-RA is ridge tillage with Br or fertilizer applied near the ridge top. RT-FA is ridge tillage with Br or fertilizer applied in the furrow. NT is no tillage with Br or fertilizer applied between the corn rows.

various treatments or years (data not shown). In 1991, NT corn took up 130% of the total applied N, significantly greater than plants in the RT plots. During the 1992 growing season, NT corn took up significantly lower N (92%) than RT-FA (108%) and RT-RA (124%).

3.1. Bromide distribution in 1991 and 1992

Fig. 2 shows the distribution of Br in the upper 100 cm of soil sampled on 6 October 1991, 21 November 1991, and 14 March 1992. Up to 98 kg ha^{-1} (82% of total

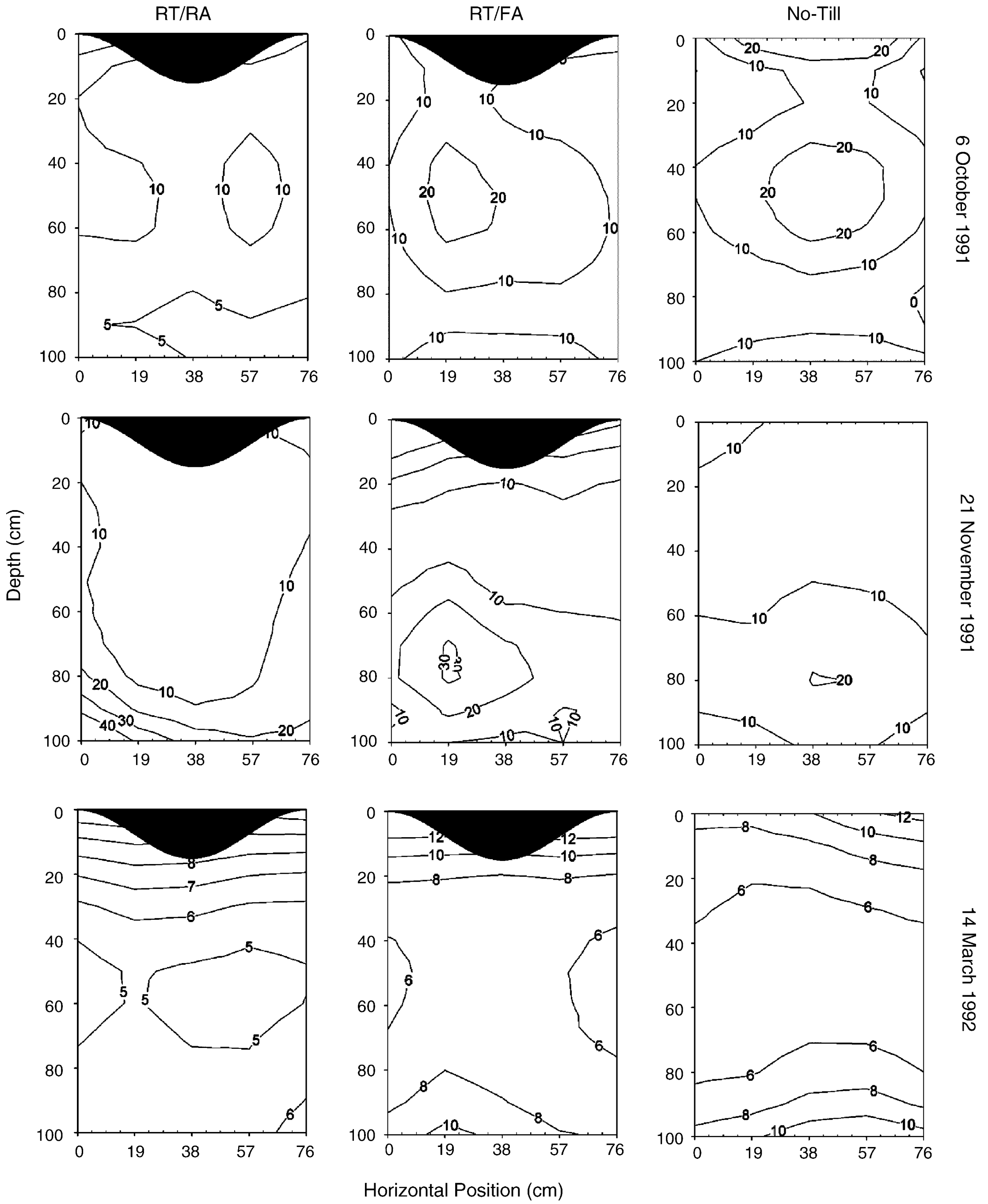

Fig. 2. Concentrations of Br measured from soil samples during 1991 and 1992. Contours were plotted with a spline function. RT-RA is ridge tillage with Br or fertilizer applied near the ridge tops; RT-FA is ridge tillage with Br or fertilizer applied in the furrow; and NT is no tillage with Br or fertilizer applied midway between corn rows.

Table 2
Bromide recovered from soil samples taken on various dates after Br was applied in June of 1991 and 1992 corn-growing seasons

Soil sampling dates	kg ha^{-1} recovered			
	RT-RA	RT-FA	NT	Mean
1991 Br application				
6 October 1991	63.9	82.3	91.2	80.5 a
21 November 1991	68.2	101.5	82.2	83.9 a
14 March 1992	46.7 y	57.5 x	50.6 xy	51.9 b
1992 Br application				
21 November 1992	52.8	60.7	56.3	56.6 a
31 December 1992	41.3	44.6	51.8	45.9 b

Within application years, means followed by different letters within a column (a, b) or row (x, y are significantly different at $p < 0.05$. RT-RA is ridge tillage with Br or fertilizer applied near the ridge tops. RT-FA is ridge tillage with Br or fertilizer applied in the furrow. NT is no tillage with Br or fertilizer applied midway between corn rows.

applied) of the residual Br was found (Table 2) in soil samples to 100 cm. The mean percent recovery of Br was similar on 6 October and 21 November 1991 (Table 2). There were no significant differences in Br concentrations in the soil on these two dates. It is apparent a pulse of Br moved to deeper depths in the soil, although not below our deepest sampling depth (Fig. 2) so that total recovery percentages were similar among treatments. By 14 March 1992, much of the Br had leached beyond the sampling depths and recoveries were lower than on the previous two dates (Table 2). The recovery for the RT-RA treatment was least, although not significantly different from the NT treatment. The RT-FA treatment had the greatest recovery, but not significantly different from the NT treatment.

The Br concentration profiles and isolines measured with suction lysimeters for the 1991–1992 season are shown in Fig. 3. On 1 November, midway between the two soil sampling dates, water movement in the RT plots was very different from that in the NT plots (Waddell and Weil, 1996). During this time under the RT treatments, a negative hydraulic gradient existed that tended to move water and solutes toward the ridge tops. Water movement in the NT plot on 1 November was only in the downward direction.

From Br data obtained using suction lysimeters (Fig. 3), Br movement was generally in the vertical direction. The greatest Br concentration for the RT-RA treatment was directly below the ridges while the highest concentration of Br for the RT-FA and NT treatments was under the furrow or inter-row positions. However, distribution of Br after the rainfall simulation indicated some movement of solutes other than in the downward direction. For example, it appears there was some movement of Br toward the ridge top on 20 November 1991 in the RT-FA treatment. One explanation of upward movement was that the ridge tops being drier caused a hydraulic gradient that moved water toward the ridge top (Benjamin et al., 1990). Lateral movement can be explained by the nature of the soil at the site. A clay enriched Bt horizon with a lower hydraulic conductivity (Waddell and Weil, 1996) exists from a depth of 63–92 cm, where clay content varies from 23 to 27%. Above this, clay content ranges from 8 to 12% and the soil has higher hydraulic conductivity. During larger rain events (like the rainfall simulation), water could have perched on the Bt horizon resulting in lateral flow.

3.2. Bromide distribution in 1992 and 1993

Soil samples were taken on 21 November and 31 December 1992 to a depth of 150 cm. The higher rainfall amounts in 1992 resulted in lower concentrations of Br throughout the profile (Fig. 4) compared to those in the previous year. Although concentrations were lower, the amount of Br recovered in 1992 was similar to that in 1991 because we sampled 50 cm deeper in 1992. No differences in the amount of Br recovery were seen between various treatments on 21 November and 31 December 1992. However there was a significant decrease in recovery from soil with time (Table 2), indicating that Br leached beyond the sampling depth.

Soil water samples were taken earlier in 1992 (Fig. 5) because the soil contained more moisture available for extraction by suction lysimeters compared to 1991 (Waddell and Weil, 1996). Rainfall through October was close to the long-term average (approximately 400 mm) followed by below-normal rainfall following harvest. Therefore, the leaching that occurred through October is probably representative of a typical year. On 19 August, the deepest movement of Br was in the RT-

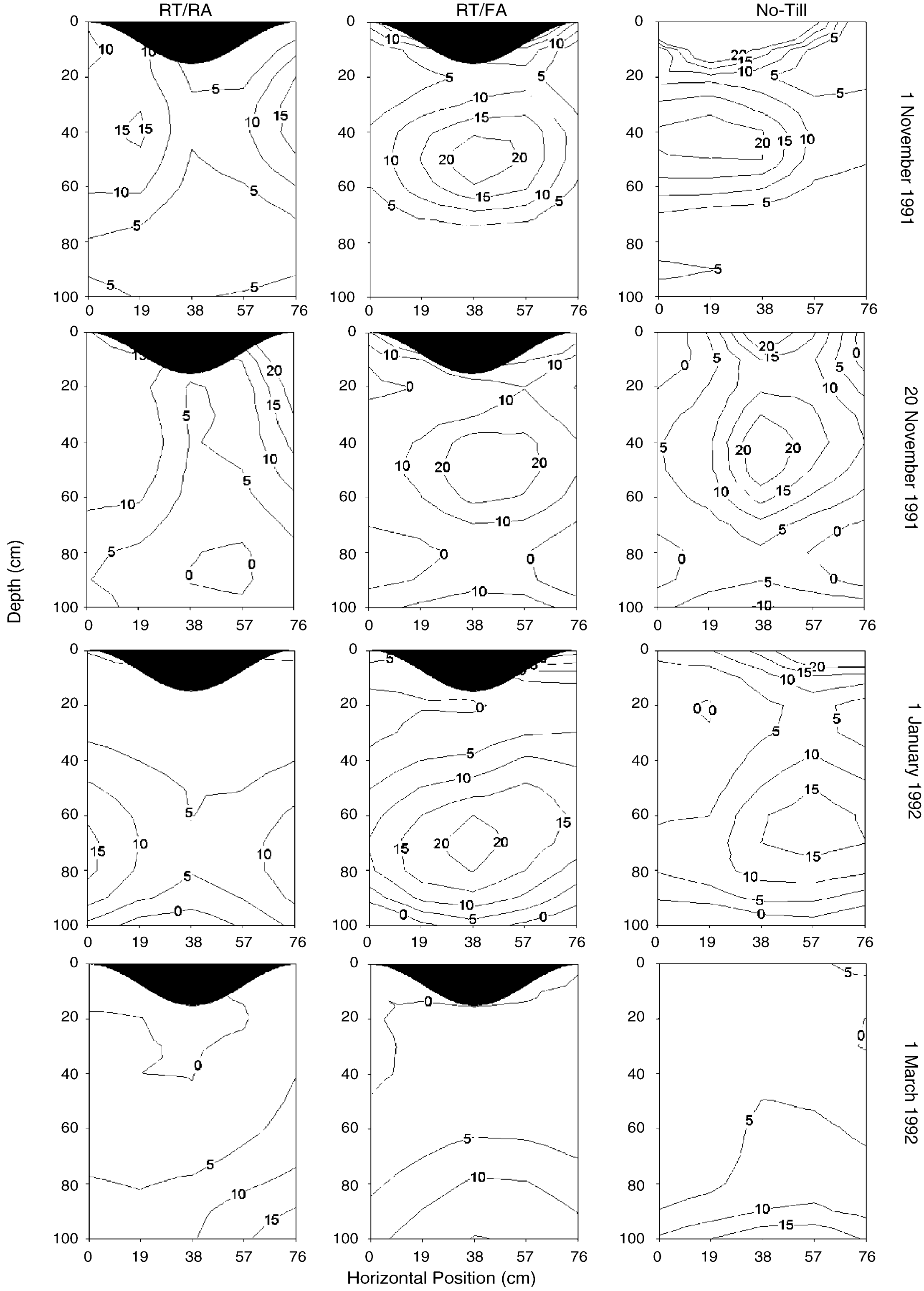

Fig. 3. Concentrations of Br in soil water extracted from suction lysimeters during 1991 and 1992. Contours were plotted with a spline function. RT-RA is ridge tillage with Br or fertilizer applied near the ridge tops; RT-FA is ridge tillage with Br or fertilizer applied in the furrow; and NT is no tillage with Br or fertilizer applied midway between corn rows.

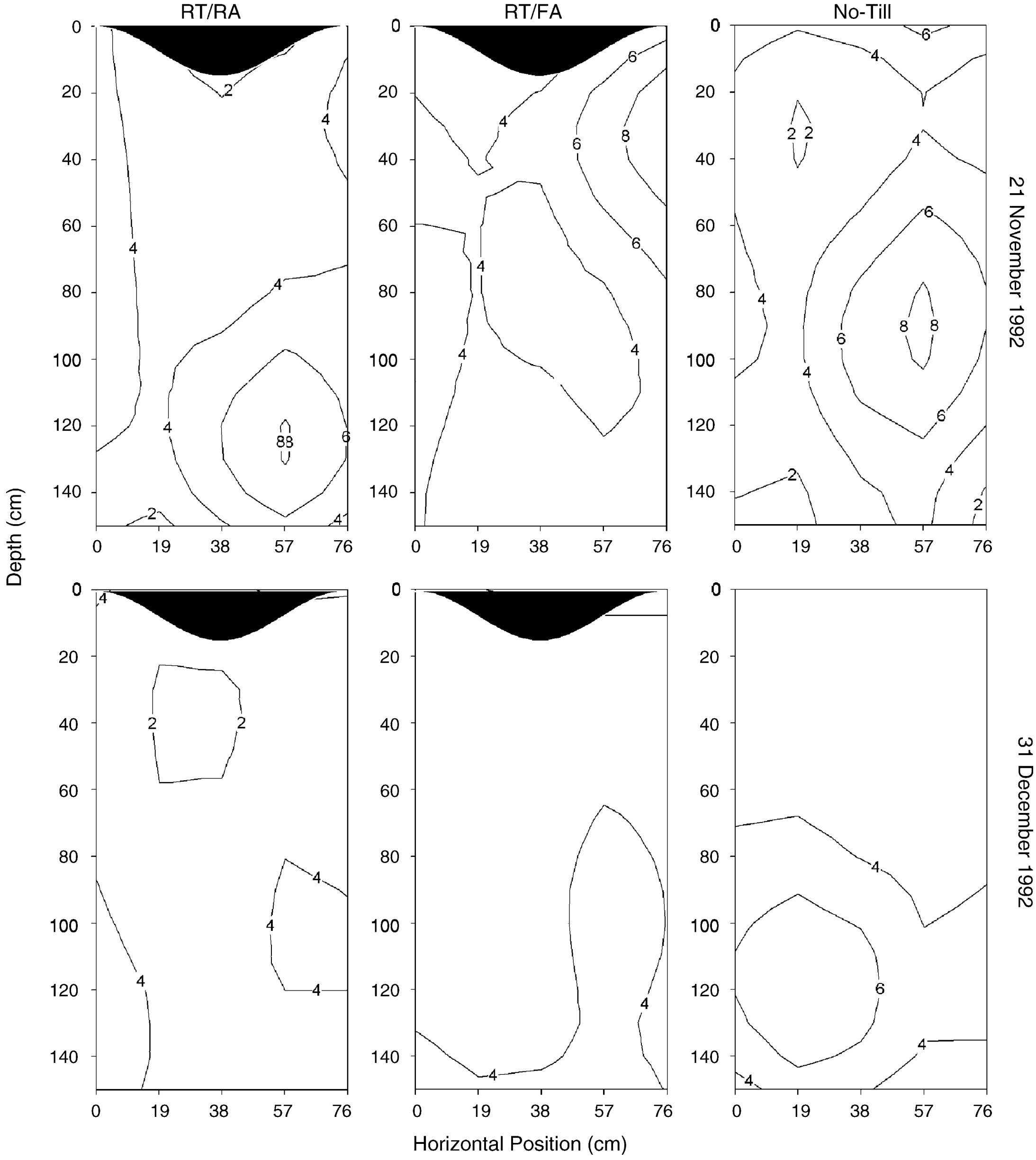

Fig. 4. Concentrations of Br measured from soil samples during fall and winter 1992. Contours were plotted with a spline function. RT-RA is ridge tillage with Br or fertilizer applied near the ridge tops; RT-FA is ridge tillage with Br or fertilizer applied in the furrow; and NT is no tillage with Br or fertilizer applied midway between corn rows.

FA treatment (Fig. 5). Visual observations of plant cover prior to August indicated that the leaf canopy had not fully closed, thus, more rain fell in the inter-row position. For the same reason, there was less movement of Br in the RT-RA treatment. However, there seems to have been some lateral movement of Br at about the 40 cm depth caused by the argillic horizon that limited downward water flow. In the NT treatment on 19 August Br was concentrated just below the point of application, but seemed to be moving laterally. The downward movement of Br appears to have continued based on the data obtained on 11 September and 11 October. In the RT-RA treatment on 11 October, it is difficult to discern the influence of fertilizer placement since the concentrations of Br seemed to be equally distributed between the 50 and 75 cm depths.

Suction lysimeter data from 30 November and soil core data from 21 November 1992 (Figs. 4 and 5) were

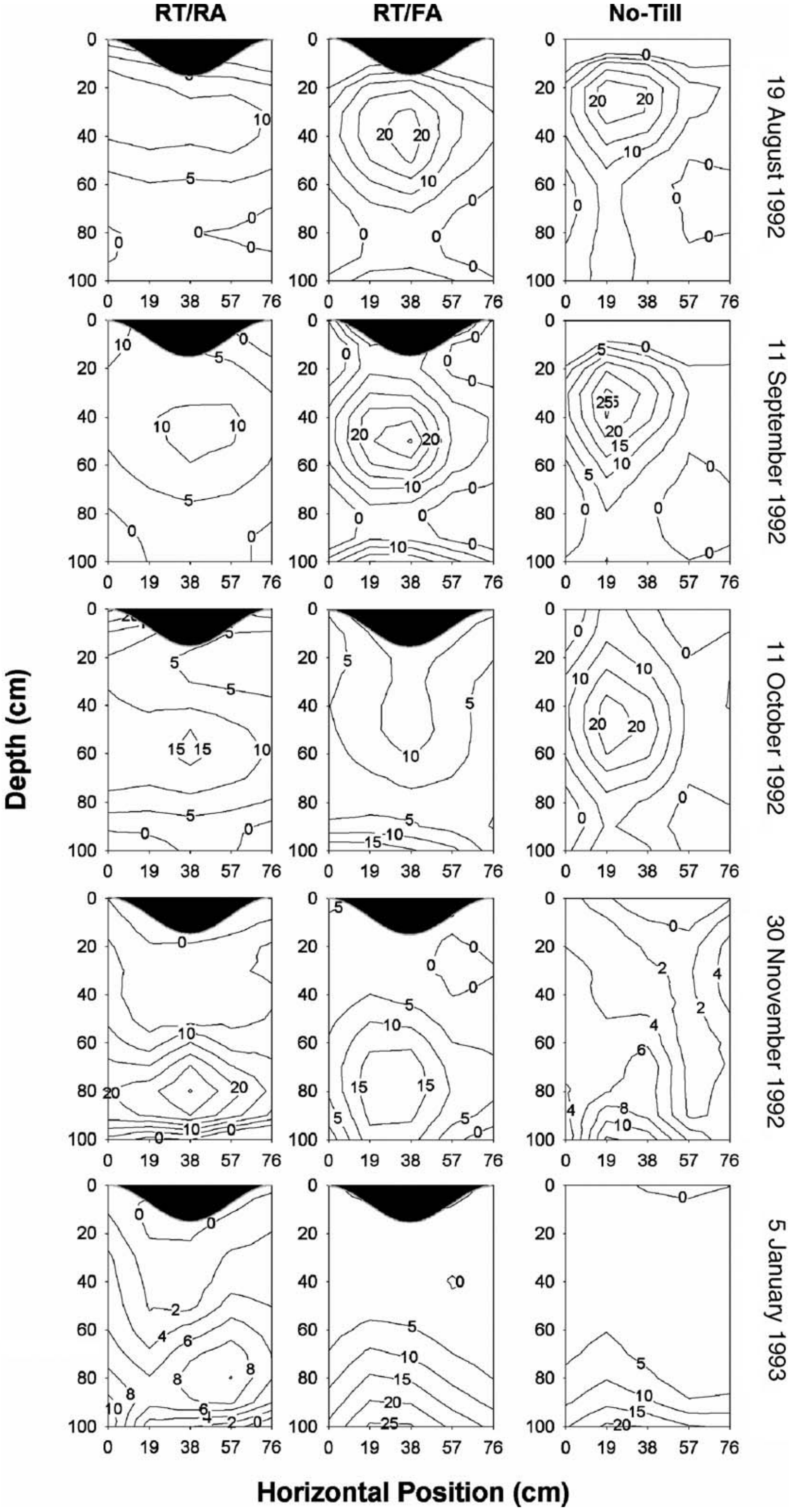

Fig. 5. Concentrations of Br in soil water extracted from suction lysimeters during 1992 and 1993. Contours were plotted with a spline function. RT-RA is ridge tillage with Br or fertilizer applied near the ridge tops; RT-FA is ridge tillage with Br or fertilizer applied in the furrow; and NT is no tillage with Br or fertilizer applied midway between corn rows.

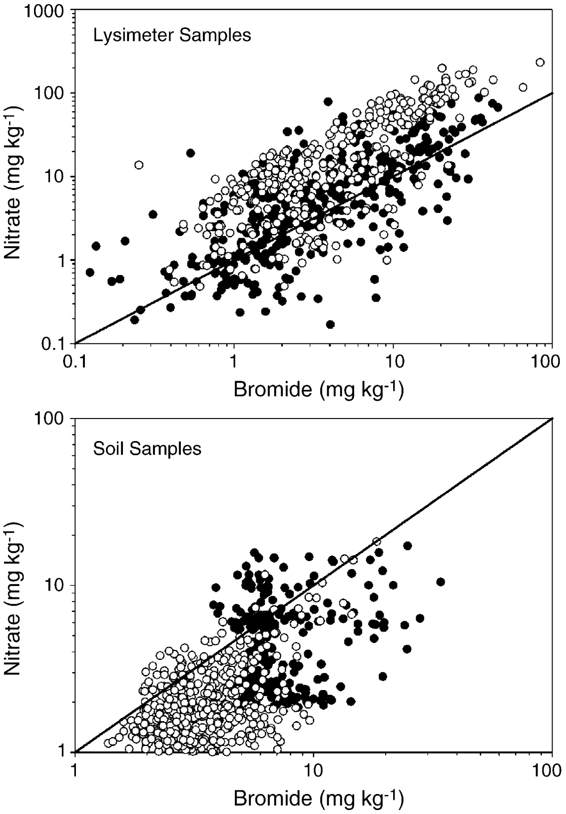

Fig. 6. Comparison of measurements of Br and nitrate in water extracted with suction lysimeters and soil samples in 1991–1992 (filled circles) and 1992–1993 (open circles).

selected to evaluate the differences in Br recovered from the different techniques. Bromide concentrations from 20 to 50 mg kg^{-1} soil were measured from suction lysimeters in the RT treatments compared to Br values $\leq$10 mg kg^{-1} soil from soil samples. A similar comparison can be made between suction lysimeter data for 5 January 1993 and soil core data for 31 December 1992. Concentration of Br from water extracted with suction lysimeters was again greater than that in soil. The relative downward movement of Br was evident in both types of sample. Almost all of the Br had leached past the 100 cm depth by this time.

3.3. Bromide versus nitrate

In order to validate the premise of using Br as a tracer for nitrate, the concentrations of each were plotted in Fig. 6. In 1991, the data for suction lysimeter samples showed approximately a 1:1 ratio of Br to nitrate. In 1992, the nitrate concentrations were generally greater than the Br concentrations. For soil samples, concentrations of Br were less closely related to NO_3^--N in both years, but generally the Br concentrations were significantly higher (distributed to the right of the 1:1 line) than those for NO_3^--N. This follows the work of Clay et al. (2004) whose results indicated that if Br were used as a NO_3^--N tracer, leaching losses may be overestimated because of increased sorption of nitrate compared to Br. Concentrations of Br and N measured in 1991 were significantly higher than those in 1992. These overall differences in concentrations between years may be due to the difference in depth of sampling along with higher rainfall in 1992 that caused more N and Br to leach.

4. Conclusions

Nutrient management is becoming more important with the use of site specific farming in the United States. Simple methods to reduce the impact of nitrate leaching into the ground water are complicated by surface soil properties and plant structure. Water can be funneled down the corn stalk, thus, increasing the potential for leaching when full canopy cover is established. However, uptake of nutrients applied on the ridge top is increased over application in the furrow. An order of magnitude difference was observed between N uptake compared to Br uptake by corn plants in all three treatments in the present study. Data on uptake of N for drier years (like 1991) indicated that NT provided a greater potential for uptake compared to either RT-RA or RT-FA. In 1992, a year with average rainfall, the trend was reversed, with greater uptake under RT-RA, followed by RT-FA and finally no-till. With respect to Br, the uptake over both years followed the trend: RT-RA = NT > RT-FA, indicating that RT-RA may be a more efficient method of fertilizer placement under ridge tillage.

Bromide and nitrate leaching are highly dependent on rainfall. In our soil, an argillic horizon limited the downward flow of water and nutrients and may have caused some lateral flow of solutes. However, by the following winter any residual N or Br in the soil was leached beyond the depth from which it could be taken up by corn.

The data presented shows the complexity of soil surface micro-topography and mode of application of N fertilizer. Besides indicating the best management practice for application of N in RT systems, data also provide clues for further explanations with computer simulations designed to address the impact of soil and plant systems on economic and environmental quality of agricultural systems.

Acknowledgments

This study was based on work supported by the USDA Cooperative State Research Service under Agreement no. 91-34214-6054. We thank the Chesapeake Bay Foundation for additional financial and material support for this project. In particular, Michael Heller provided field support on the plots and contributed to the implementation of this study.

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