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ABSTRACT

This was a pilot study to investigate overall differences in solute leaching from soil beneath row vs. interrow zones of a row crop. Overall leaching could be minimized by exploiting such differences. Strontium bromide was uniformly applied to two, 7.2 by 6 m plots on Bosville fine sandy loam (fine, mixed, thermic Albaquic Paleudalf) planted in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. Within each plot, the surface soil texture varied from fine sandy loam to fine sandy clay loam. Soil water status was monitored with tensiometers. After the vegetative growth stage, soil samples were taken along five transects perpendicular to the crop rows at 0.2-m intervals, to a depth of 0.5 m. Sampling locations corresponded to row, quarter-row, and interrow positions. In the fine sandy loam half of the corn plot, there was significantly more leaching of Br below the 0.5-m depth in the interrow positions than in the row positions. This appears to be related to the soil water status, since soil conditions in the fine sandy loam half of the corn plot were, on the average, drier under row positions than under interrow positions. Overall leaching was less under soybean than under corn. Simplified two-dimensional simulations of solute transport in row–interrow zones further enhanced our understanding of the effects of net flux differences between those zones, overall net flux, and soil and crop type. The simulations indicated that overall leaching could be slowed by enhancing the differences in evapotranspiration between the row and interrow zones.

SOLUTE BEHAVIOR in soil planted in row crops is not fully understood. Knowledge of this behavior will help us better understand the implications of certain management practices, and utilize these to our advantage. For example, proper placement of fertilizer near the crop row, well known to increase availability to plant roots, may also reduce its downward movement. Similarly, the leaching risks of pesticides could be reduced by spatial placements, combined with some cultural practices if necessary. Here, we are seeking a reduction in leaching other than by plant uptake and recycling of solutes (Kung, 1990).

A major factor that may alter solute retention and transport in a row-cropped soil is differential, lateral root distribution. The differences in root density between the crop-row and interrow zones will result in differences in water uptake between these zones, and hence differences in downward movement of water and solutes. Depending on the spacing between rows and the type of crop, the lateral differences in root density may occur only during early stages of growth (Bland and Dugas, 1989), or may persist throughout the growth period. These differences are expected to be greater in the topsoil than in the subsoil (Arya et al., 1975).

Arya et al. (1975) measured strong lateral soil water-potential gradients in soybean. The potentials were lowest in the rows, and the differences were greatest near the surface early in the season. Zhai et al. (1990) and van Wesenbeeck and Kachanoski (1988) using TDR to measure soil water content, reported lower water contents, for most times, below the row zone of a corn crop than below the interrow zone, within the surface 0.2 m. The average seasonal differences in the soil water content between the row and interrow zones measured in these studies were in the range of 0.01 to 0.02 m^3 m^{-3}. The average seasonal water contents were lower in the row zone, even though the soil water contents were often higher in this zone immediately after a rainfall (van Wesenbeeck and Kachanoski, 1988). These differences, which persisted until crop maturity, were obviously due to differences in root uptake between the two zones.

Greater root water uptake and lower soil water contents in the crop-row zone will result in smaller downward soil water and solute fluxes below this zone than below the interrow zone. Greater downward fluxes in the interrow zone would be due to higher antecedent water contents and greater wetting-front advance during a recharge event, as well as greater water movement during the subsequent redistribution. Due to lateral gradients, however, some of the solute from the interrow zone may also move with water to the row zone.

Some soil conditions may enhance the above effects of lateral root distribution in reducing leaching of solutes below the row zone. For example, ridging or hilling in the soil near the plant stems will shed rainwater away from the plant-row zone, causing greater infiltration of water and leaching in the interrow zone (Saffigna et al., 1976). Some other factors, such as crop geometry, may have an opposite effect. The crop canopy has been shown to funnel a significant proportion of the rainfall to the soil via stemflow (Quin and Laflen, 1983) causing relatively greater infiltration in the row zone (van Wesenbeeck and Kachanoski, 1988).

As a result of protection from raindrop impact by the crop canopy, the surface soil in the row zone may also have a higher infiltration rate than that of the unprotected interrow zone. The infiltration of rainwater in the row zone may thus be greater than in the interrow zone even without stemflow. Both these effects of crop canopy, of course, depend very much on the rainfall intensity and amount, hydraulic properties of soil, and the soil's susceptibility to crusting.

Under natural field conditions, in corn on a silty clay loam soil, van Wesenbeeck and Kachanoski (1988) measured a preferential recharge of the root zone as a result of the above canopy effects. The differences in plant water uptake between the row and interrow zones, however, still dominated overall, as indicated by the lower soil water contents in the row zone. No

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Abbreviations: TDR, time domain reflectometry; R, row; IR, interrow; QR, quarter row; ANOVA, analysis of variance; ET, evapotranspiration; AET, actual evapotranspiration; PET, potential evapotranspiration.

work has yet been reported on the differences in solute leaching between the row and interrow zones in any crop.

The primary objective of this initial study was to investigate overall differential solute movement, if any, between the row and interrow zones of corn and soybean crops, grown under natural rainfall and field conditions. Bromide was used as a tracer chemical. The soil was not ridged or hilled, and the leaching from the surface 0.5 m was determined. Variability of soil texture within the field plot enabled us to evaluate the effects of differing soil water properties as well. The secondary objective was to carry out simplified theoretical analysis of the two-dimensional solute movement in a row crop using a finite-element computer model. The purpose of the theoretical analysis was to further enhance our understanding of the process, in relation to effects of different degrees of lateral root water-uptake variation, soil type, infiltration, and overall crop evapotranspiration, and to help explain our experimental results.

MATERIALS AND METHODS

The field plots for corn and soybean were located on the Bosville fine sandy loam soil series. Within each plot, the topsoil texture actually varied from fine sandy loam on one side of the plot to fine sandy clay loam on the other side. Particle-size data are given in Table 1. The B horizon texture was fine sandy clay loam to clay loam. Mean depth to the B horizon was 0.5 m. The increase in clay content near the surface in the fine sandy clay loam area was probably due to soil disturbance during construction activities 10 to 15 yr ago.

The field, which had been left fallow for 2 yr, was sprayed with the herbicide glyphosate [isopropylamine salt of N-(phosphono-methyl) glycine], and clean tilled with a rotary tiller to a depth of 0.15 m. Phosphorus was applied as 18% P_2O_5 superphosphate at the rate of 0.45 g P m^{-2} before tillage. Two plots measuring 6.0 by 7.2 m each and separated by a 1.0-m border were then laid out (Fig. 1). One of the plots was planted by hand with sweet corn cv. Kandy Korn and the other with soybean cv. Centennial in late May 1989. The distance between rows for both crops was 0.80 m. The plants were thinned to maintain a uniform spatial distribution and hand weeded twice, 2 and 3 wk after planting. Sixteen water-filled tensiometers were installed in the center of each of the two plots at 0.15- and 0.35-m depths. Eight were placed in the plant rows and the other eight midway between rows (Fig. 1). The tensiometers were monitored with a hand-held pressure transducer. The plots were then gently raked, to break a light crust that had developed after a rainfall and remove any compaction that may have been caused by trampling, before chemical application. Following this, 11 transects were laid out perpendicular to the rows at 0.6-m intervals forming grid cells with corners at crop-row and transect intersections (Fig. 1).

Strontium bromide was applied 4 wk after planting, 20 June 1989, at the rate of 30.0 g Br m^{-2} (300 kg ha^{-1}). Nitrogen, as urea, was mixed with the tracer at the rate of 9.2 g N m^{-2} for corn and 4.6 g N m^{-2} for soybean (92 and 46 kg ha^{-1}, respectively). The Br tracer was mixed with tap water in a large container at the rate of 2888 g $SrBr_2$ to 108 L of water for each crop. A 1.22-L portion of the solution was applied to each grid cell (0.6 by 0.8 m) using a hand sprayer, and going over the grid cell two to three times to achieve uniformity.

The plots were sampled for Br during the period from 26 July to 1 Aug. 1989. Each sample was collected at 0.2-m intervals along a transect to 0.5 m in depth using a coring device 27 mm in diam. The spacing corresponded to R, IR, and QR positions (Fig. 1). For each crop, 32 samples were collected on five out of the original 11 transects (Fig. 1) (total 160 samples per crop). Each sample was mixed well and one 20-g subsample was taken for analysis.

Bromide was extracted from soil samples by mixing 20 g of soil with 100 mL of distilled water, shaking for 30 min, decanting 50 mL of the solution, and centrifuging. Bromide concentrations were determined using a Br-specific-ion electrode. Calibration of the Br ion electrode was determined using a standard solution of $SrBr_2$. From these data, Br content in the top 0.5-m depth per unit area of soil was determined at each sampling point.

All aboveground plant material in both plots was collected to determine yield and average uptake of Br. Each row of plants was harvested separately. A subsample of this plant material was finely ground and extracted with distilled water (1 g to 20 mL) for Br analysis.

For one proposed interpretation of the data, we estimated the Br content per unit area of soil down to the 0.5-m depth, had there been no plant uptake, from the measured data in the presence of uptake. To do this, a part of the Br recovered in plant material was added to the Br measured in the soil. The area of uptake was considered to be a rectangle extending 0.2 m on either side of the row, to the QR positions, and along the length of the row. We assumed that, during the growing season, if plant uptake of Br had not occurred, some of the plant Br would have leached from beyond the 0.5-m zone sampled. The fraction of plant Br that would have remained within the surface 0.5 m was calculated approximately from the ratio of the measured amount remaining in this depth interval to the total amount available for leaching per unit area:

$$\text{Fraction} = \frac{\text{Br measured in sample to 0.5–m depth in row}_i}{\text{Br applied} - \text{measured uptake in row}_i} \quad [1]$$

The denominator is the amount available for leaching, and the index i corresponds to the crop row the sample was taken from. A fraction was calculated for each sample (total 160). The amount of plant uptake per unit area in the sample that would have remained in the 0- to 0.5-m depth was calculated as

$$(\text{Fraction}) \times (\text{measured uptake per unit area in row}_i) \quad [2]$$

The full amount calculated by Eq. [2] was assigned to R positions and one-half of this amount assigned to QR positions, given R to be the center and QR to be the boundary of each assumed rectangle of uptake. These proportions were assigned for an extreme case, i.e., no uptake of Br

Table 1. Particle-size analysis for the soils in two areas of the corn and soybean plots.

Area	Depth	Sand	Silt	Clay
	m		%	
		Corn plot		
Sandy	0–0.25	68.5†	15.0	16.5
	0.25–0.50	67.9	15.0	17.1
Clayey	0–0.25	61.0	15.0	24.0
	0.25–0.50	59.8	15.0	25.3
		Soybean plot		
Sandy	0–0.25	68.5	15.0	16.5
	0.25–0.50	71.0	12.5	16.5
Clayey	0–0.25	62.3	15.0	22.8
	0.25–0.50	66.6	13.8	19.6

† Each value is the mean of two measurements.

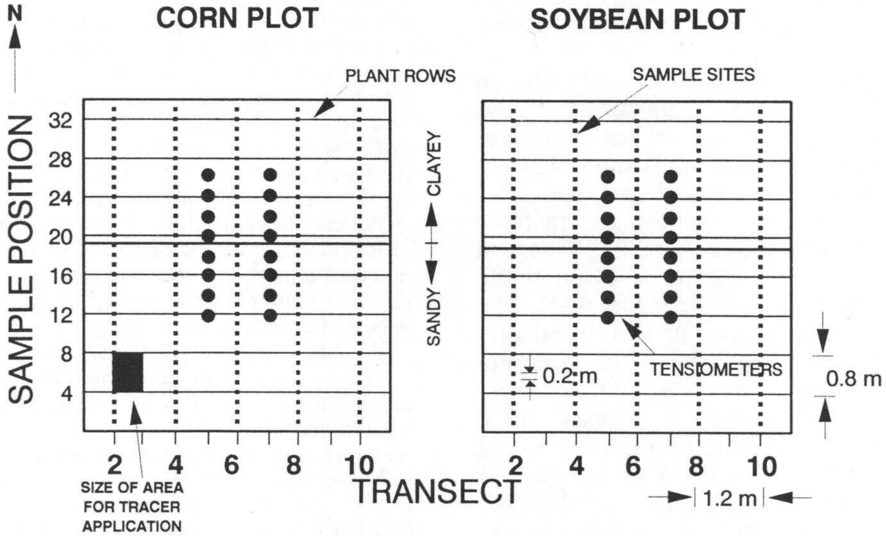

Fig. 1. Field plot layout showing locations of transects and rows and locations of tensiometers.

from the interrow zone and 100% uptake from the row zone. This was done for comparative purposes only.

Statistical Analysis

Because of soil textural differences noted earlier within the plots, each crop plot was divided into equal subplots for analysis (Fig. 1). Analysis was performed using ANOVA. The treatments were R, IR, and QR positions.

Frequency analysis of the Br data indicated that the data were log-normally distributed (data not shown). This type of distribution is common in measured soil properties that are related to flow processes in the soil (Biggar and Nielson, 1976). Therefore, all statistical analyses were done on the log-transformed data. Means given in the tables were calculated as geometric means, i.e., the antilog of the mean logarithm.

Statistical analysis of the matric-potential data was accomplished by treating the row and interrow measurements for each time as pairs and testing (by *t*-test) whether the mean difference was significantly different from zero for the period of measurement.

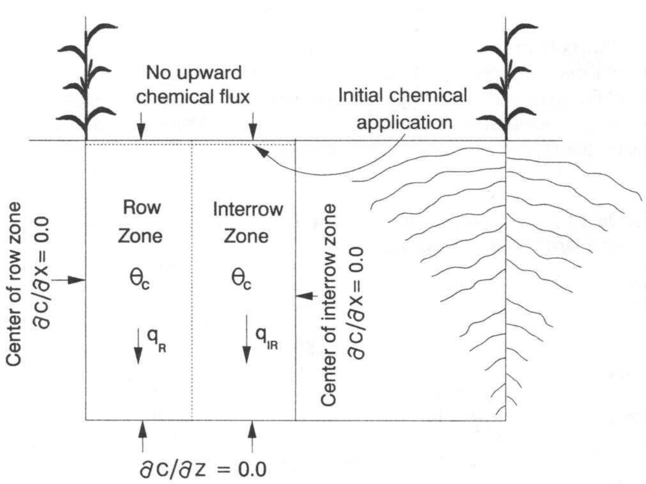

Fig. 2. Conceptualization of the steady-state water flow and unsteady transport in row and interrow zones. The q_R and q_{IR} are the steady water fluxes, θ_c the steady soil water content, and $\partial C/\partial x$ and $\partial C/\partial z$ the lateral and vertical concentration gradients, respectively.

Two-Dimensional Simulations

As noted in the objectives, the purpose of these computer simulations was to further enhance our understanding of the row vs. interrow leaching process as some of the important factors were varied beyond the levels observed in the field study. These include differences in lateral root water uptake, soil type, infiltration, and overall crop evapotranspiration. The purpose was not to make specific predictions of the experimental observations, which would have required a detailed knowledge of the spatial and temporal changes in soil hydraulic properties, rainfall intensities, and root growth with time (this experiment was not planned for this purpose, but we are planning future studies to address this problem). Rather, we were specifically interested in how differences in assumed partitioning of ET between R and IR zones affect the calculated relative solute leaching in these zones when average rates of ET, infiltration amounts, and average soil water contents are varied. These factors were varied around the best estimates of the actual field values. The analysis, therefore, helped interpret the experimental results.

For the above comparative analysis, we simplified the conceptualization of the flow and transport problem within the crop rows. The space between the crop rows was divided equally into R and IR zones (Fig. 2). In each zone, the highly transient water movement normally expected during the growing season was replaced with an effective average, unsaturated soil water content. The solute transport was, however, still unsteady and two-dimensional. The two-dimensionality of solute transport was due to dispersion only. Such a steady-state approximation of the flow problem has been used successfully in describing one-dimensional transient flow and solute transport in laboratory columns and in the field (Wierenga, 1977; De Smedt and Wierenga, 1978a,b; Rose et al., 1982; Smith et al., 1984). Because of greater root water uptake from the R zone, the seasonal average steady downward water flux in the R zone, q_R, was smaller than that in the IR zone, q_{IR}. The constant average soil water content at which the flow occurred, θ_c, was, however, assumed to be the same in both zones. The average seasonal differences in θ_c on the order of 0.01 to

Table 2. Values of net water flux in row (q_R)† and interrow (q_{IR})‡ zones used in the simulations for three rates of infiltration and two rates of actual average evapotranspiration (AET).

Average infiltration rate (I)	Flux difference ($q_{IR} - q_R$)	Flux AET = 0.225 q_{IR}	AET = 0.225 q_R	AET = 0.350 q_{IR}	AET = 0.350 q_R
	mm d^{-1}				
5.5	0.5	3.50	3.00	2.25	1.75
	1.0	3.75	2.75	2.50	1.50
	1.5	4.00	2.50	2.75	1.25
	2.0	4.25	2.25	3.00	1.00
	2.5	4.50	2.00	3.25	0.75
5.8	0.5	3.80	3.30	2.55	2.05
	1.0	4.05	3.05	2.80	1.80
	1.5	4.30	2.80	3.05	1.55
	2.0	4.55	2.55	3.30	1.30
	2.5	4.80	2.30	3.55	1.05
6.1	0.5	4.10	3.60	2.85	2.35
	1.0	4.35	3.35	3.10	2.10
	1.5	4.60	3.10	3.35	1.85
	2.0	4.85	2.85	3.60	1.60
	2.5	5.10	2.60	3.85	1.35

† $q_R = I - \text{AET} - (q_{IR} - q_R)/2$
‡ $q_{IR} = I - \text{AET} + (q_{IR} - q_R)/2$

Table 3. Values of the parameters used in the simulation of two-dimensional transport of Br in the row and interrow zones.

Parameter	Value
Steady-state soil water content	0.18 m^3 m^{-3} (sandy)
	0.25 m^3 m^{-3} (clayey)
Bromide applied	30 g m^{-2}
Longitudinal dispersivity	40 mm
Transverse dispersivity	8 mm
Apparent molecular diffusion (D_{xx})†	90 mm^2 d^{-1}
Apparent molecular diffusion (D_{yy})†	90 mm^2 d^{-1}
Decay coefficient	0.0
Bulk density of soil	1.3 Mg m^{-3}

† D_{xx} and D_{yy}, diffusion rate of Br in soil that includes the effects of tortuosity, moisture content, and any anion repulsion.

0.02 m^3 m^{-3} between the two zones reported in the literature were neglected in our simulations, since it is the water-flux differences that would have a major effect on chemical transport. The chemical or solute was taken as present initially within a small thickness of the surface soil. The amount of this chemical was chosen as 30 g m^{-2} of soil area, the same as in our experimental studies.

The boundary conditions for the transport problem are shown in Fig. 2. It should be noted that some net lateral movement of water and chemical, expected to occur from the IR zone to the R zone, is not explicitly included in the above formulation. This formulation is conservative in the sense that the lateral chemical flux will further enhance the role of the R zone in reducing overall leaching, and increase relative leaching differences between the two zones.

A two-dimensional saturated–unsaturated water-flow and chemical-transport model (Huyakorn et al., 1984, 1985) was used for the simulations. This is a finite-element numerical model based on Richards' and the convective–dispersive equations, which has been verified for accuracy for a variety of problems (Huyakorn et al., 1984). As indicated above, the water flow in our simulations was assumed to be effectively steady. Only the transport component of the model was used.

The input data used in the model are given in Tables 2 and 3. The three average infiltration rates for water were based on the measured total rainfall during the experimental period (tracer application to soil sampling times) and an estimated surface runoff of 10, 12.5, or 15% of the rainfall. These runoff fractions are based on previous experimental measurements on this soil type, and the values of 10 and 15% were assumed to apply to the sandy and clayey halves of the plots, respectively. The AET from the crop plots, including both R and IR zones, was estimated from measured pan evaporation during the experimental period. Since this period encompassed crop growth stages from early vegetative to full canopy cover, it was assumed that the AET was from 50 to 70% of the PET. The PET was approximated as the pan values times a crop coefficient of 0.75. The AET values thus obtained were 2.25 and 3.50 mm d^{-1}. The smaller value will be appropriate for corn, and the larger for soybean, based on their canopy covers. For each combination of infiltration rate and AET, we chose differences in ET between R and IR zones of 0.5, 0.10, 1.5, 2.0, and 2.5 mm d^{-1}, representing different degrees of hypothetical root distribution between these two zones. These difference values were then used to compute the effective steady water fluxes, q_R and q_{IR}, for the R and IR zones, respectively (Table 2).

Table 3 gives other input used in the simulations. Two values of θ_c were used in separate simulations — 0.18 m^3 m^{-3} to represent sandy halves of the plots and 0.25 m^3 m^{-3} to represent clayey halves. These θ_c values corresponded to measured average soil water suctions of −150 kPa in the two halves. The values of longitudinal and transverse dispersivities were taken from the literature for field conditions (Biggar and Nielson, 1976; Huyakorn et al., 1984).

Table 4. Paired t-test results for mean differences between row (R) and interrow (IR) matric potentials in the two textural areas of corn and soybean plots.

Textural area	Depth	Mean differences (R − IR)	Standard error	$P > t$
	m	kPa		
		Corn plot		
Sandy	0.15	57.7	13.62	0.0002
	0.35	4.3	0.90	0.0001
Clayey	0.15	28.6	10.4	0.0089
	0.35	3.4	2.1	0.1110
		Soybean plot		
Sandy	0.15	38.2	14.0	0.0096
	0.35	36.7	18.8	0.0589
Clayey	0.15	37.0	19.8	0.0670
	0.35	−3.9	6.0	0.5141

RESULTS AND DISCUSSION

Soil Water-Potential Data

Average matric potentials measured in R and IR zones of corn at different times during the experimental period are presented in Fig. 3a. Results of the statistical analysis (paired t-test) are shown in Table 4. At the 0.15-m depth, the matric potentials were significantly lower (suctions higher) in the R zone than in the IR zone for both the sandy and clayey areas throughout the experimental period. The differences were, however, smaller at all times in the clayey area and immediately following rainfall events in both areas. At the 0.35-m depth, the differences were small, if any. It appears that lateral root-density differences may have been small in corn at the 0.35-m depth.

For soybean (Fig. 3b), the matric potentials were, overall, lower than for corn. The potentials at the 0.15-m depth in the R zone of both the sandy and clayey areas were lower than in the IR zone, but only during the early part of the experiment. At later times, the potentials were about the same in both zones in the sandy area, but in the clayey area the potentials were actually higher in the R zone (the gradient was reversed). The mean seasonal differences at the 0.15-m depth were significantly different from zero for the sandy area, but not for the clayey area (Table 4). At the 0.35-m depth, in the sandy area, the R-zone potentials were much lower than the IR potentials for a short period midway through the experiment, whereas in the clayey area the differences were small. For both areas, the differences at the 0.35-m depth were not significant (Table 4). It can be inferred from the data that, in both areas, the soybean roots attained greater lateral uniformity after about Day 50 at the 0.15-m depth, and in the sandy area may have grown deeper at a faster rate in the R zone to create some differences in root density between R and IR zones at 0.35 m. The reversal of potentials in the clayey area in soybean occurred after the last rain (Day 55), and could have been due to lower infiltration in the IR zone than in the R zone, caused by a crusting–sealing of the IR zone that was observed. The effect of crusting–sealing on infiltration may not have been detected during the two previous rainfall events because of wetting-front advance past the 0.35-m depth. The root growth and water uptake in soybean were greater than in corn, as indicated by overall smaller matric potentials (larger suctions) recorded in soybean at both depths.

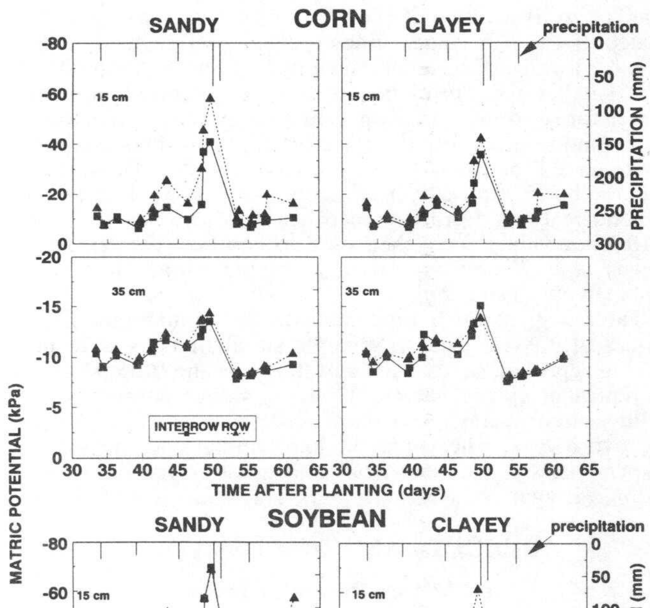

Fig. 3. Moisture potentials in row and interrow zones of (a) corn and (b) soybean for sandy and clayey areas vs. time. Each data point is an average of two measurements. Vertical lines on the top indicate precipitation.

Tracer Data

Plots of geometric mean Br remaining in the top 0.5 m of soil vs. sampling position along transects (Fig. 4) indicate that, for corn, there were large, consistent differences in Br content between R and IR positions in the sandy-textured area. In the clayey area there were no consistent differences. In the sandy area, the amount of Br remaining under the plant rows was significantly greater than that remaining under the IR or QR positions (Table 5). In other words, there was significantly less leaching under the rows. Overall, the leaching was less in the clayey area than in the sandy area.

In the soybean plot, there were no significant differences among the sampling positions for Br remaining in the sandy area (Table 5, Fig. 5); however, Br contents tended to be slightly and consistently higher beneath the rows than in the interrows. In the area with the higher clay content, there was a significant difference between the R and IR values, but the Br remaining under the IR positions was greater than under the R positions (Table 5). This reversal of trend

Table 5. Bromide remaining in the surface 0.5-m depth in the row (R), quarter row (QR), and interrow (IR) positions in corn and soybean plots.

Textural area	Row position	*n*	Geometric mean of Br remaining: Without uptake	With uptake†
			$g\ m^{-2}$	
		Corn		
Sandy	IR	20	1.45a‡	1.45a
	QR	40	1.51a	1.79a
	R	20	4.10a	5.88b
Clayey	IR	20	7.40a	7.40a
	QR	40	6.27a	7.22a
	R	20	5.52a	7.54a
Overall	IR	40	3.27b	3.27a
	QR	80	3.08ab	3.59a
	R	40	4.76a	6.66b
		Soybean		
Sandy	IR	20	3.21a	3.21a
	QR	40	4.53a	4.98b
	R	20	4.61a	5.65b
Clayey	IR	20	9.88a	9.88a
	QR	40	8.14ab	8.62a
	R	20	6.15b	6.95a
Overall	IR	40	5.63a	5.63a
	QR	80	6.07a	6.55a
	R	40	5.33a	6.26a
Overall corn	All	160	3.48a	4.10a
Overall soybean	All	160	5.76b	6.24b

† 100% of the fraction of uptake, calculated by Eq.[1] and [2], was added to R positions, 50% to QR and 0% to IR.
‡ numbers followed by the same letter within each category are not significantly different at 0.05 level of probability.

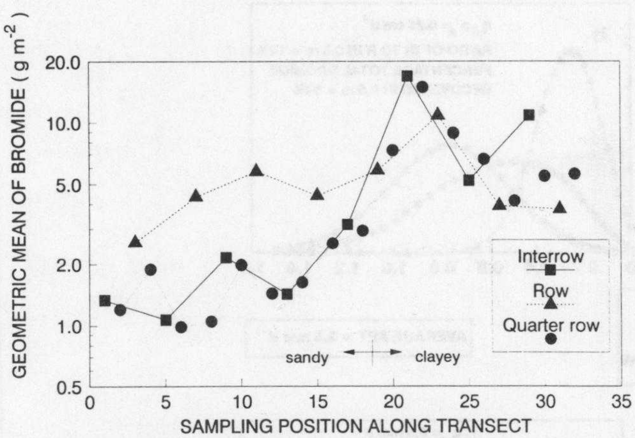

Fig. 4. Bromide content in the surface 0.5 m of soil in corn as a function of sampling position. Each value represents the geometric mean of five transects.

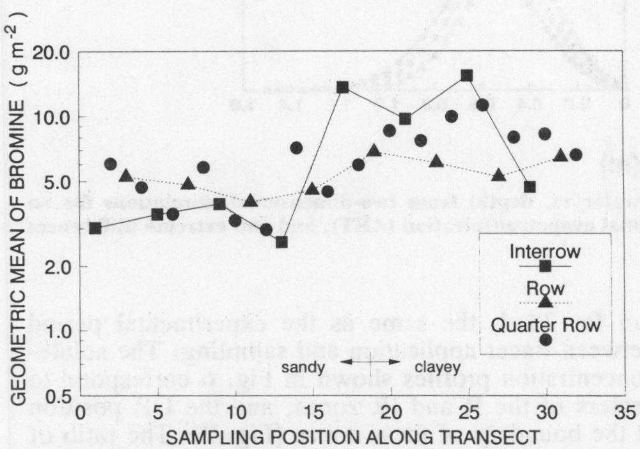

Fig. 5. Bromide content in the surface 0.5 m of soil in soybean as a function of sampling position. Each value represents the geometric mean of five transects.

in the clayey area is discussed below. Overall, more Br was recovered from the high-clay area than from the sandy-textured area, as was the case in corn, though the difference was less for soybean. An interesting and useful finding was that the overall leaching of Br was significantly lower under soybean than under corn (Table 5).

Overall, less leaching of Br from clayey areas of both corn and soybean plots was obviously due to less net downward water movement. The crop-growth and canopy-cover conditions on the clayey areas were about the same as on sandy areas for the respective crops. Therefore, we did not expect much difference in plant water uptake between the two areas. Thus, it appears that the net infiltration of rainwater was less on the clayey areas than on the sandy areas. Now, with less overall leaching past the 0.5-m depth, especially when the center of mass of solute is still within 0.5 m, the differences between the R and IR zones would be small and difficult to detect. The influence of other factors, such as spatial variability, stemflow, crusting–sealing, and differences in surface evaporation between the zones, could then dominate over the root-density effects.

Table 6. Recovery of Br in plant material and the fraction that would have remained in the 0- to 0.5-m depth of soil had there been no uptake.

Row number†	Total Br recovered		Geometric mean fraction‡ for row	
	Corn	Soybean	Corn	Soybean
	g m^{-2}			
1	8.69	5.35	0.044	0.100
2	8.60	7.56	0.046	0.221
3	10.05	6.27	0.120	0.213
4	9.62	2.55	0.073	0.171
5	6.96	2.82	0.036	0.116
6	6.38	3.43	0.038	0.133
7	9.43	4.26	0.176	0.214
8	9.10	3.23	0.040	0.221
Mean	8.60	4.43		

† Length of row = 6 m, width of row = 0.4 m.
‡ Calculated using Eq. [1].

In fact, we did observe that the IR zones on the clayey areas developed a hard surface crust on the soil surface, whereas the R zones were much less crusted. The hard crust in the IR zones must have reduced infiltration, relative to the R zones, thus counteracting the effect of root-density differences between the two zones. The reduction in infiltration could have been especially significant during heavy rains received after Day 50 (Fig. 3). The available tensiometer data, however, do not generally support this except for a brief period after the final rain. Before the last rain, the soil water suctions were higher in the IR zone; they remained higher than those of the R zone after the rain, suggesting that less infiltration occurred in the IR zone. It is possible that, during the previous two rain storms, the wetting front advanced beyond the depths of the tensiometers. Another evidence of a possible crust effect is that Br measured under the R position in both crops varied less between the clayey and sandy areas than did Br measured under the QR or IR zones (Table 5, Fig. 4 and 5). This crust effect may explain the fact that leaching was actually less (the amount remaining was greater) in the IR zones than in the R zones (Table 5) for both crops in the clayey area.

Overall, less leaching from the soybean plot than from the corn plot was apparently due to greater ET in soybean. The observed crop growth in soybean was very good and the canopy cover greater than in corn. Lower matric potentials in soybean (Fig. 3b) substantiated this observation. The limited matric-potential data in Fig. 3 also indicated that lateral root distribution at the 0.15-m depth may have become more uniform with time in soybean than in corn. This is especially true in the sandy area, but is also apparent after 50 d in the clayey area. Both of these factors may explain the result that, even in the sandy area of the soybean plot, the differences in Br leaching between the R and IR zones, although present, were small and statistically not significant.

Appreciable amounts of Br were recovered from the aboveground plant material, with corn having the largest (Table 6). The fractions, calculated using Eq. [1], of recovered Br that would have remained in the 0- to 0.5-m depth, with no uptake, were small (Table 6). Our calculations suggest that, had the Br not been

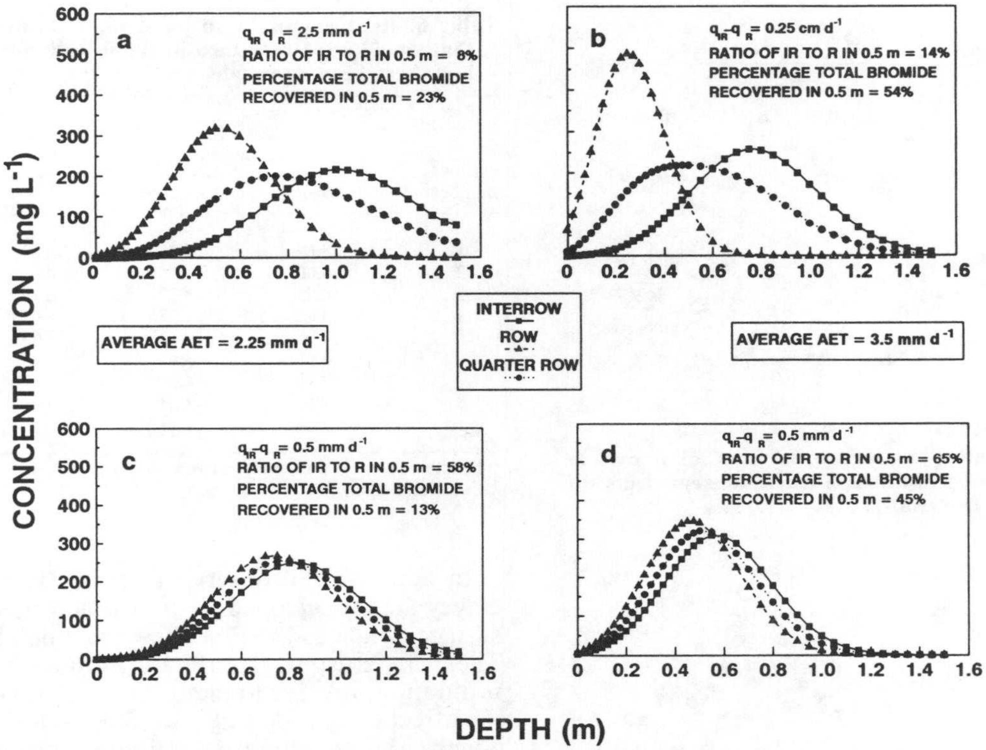

Fig. 6. Calculated solute-distribution curves (concentration in soil water vs. depth) from two-dimensional simulations for an average infiltration rate (q) of 6.1 mm d^{-1}, two rates of average actual evapotranspiration (AET), and two extreme differences in water flux between interrow and row zones ($q_{IR} - q_R$).

taken up by the plants, more than 85% of it would have leached past the 0.50-m depth sampled. Hence the differences between measured and estimated (uptake added by Eq. [2]) Br are relatively small (Table 5). When plant uptake is included, however, row–interrow differences are more pronounced (Table 5). Note that, by adding plant uptake to the R positions and none to IR positions (Table 5), we are assuming there was no water uptake by the plant from the IR zone, an extreme case.

Uptake of Br by plants may also contribute to some increase in Br content in the soil under the R position. Bromide in the plant may leach from the plant canopy onto the soil during rainfall. Bromide flushes in areas planted in grasses have been observed after rainfall events in several unpublished studies done at this laboratory. However, our results on Br content of R vs. IR zones in clayey areas of corn and both areas of soybean suggest that this contribution was at least not a dominant factor.

Two-Dimensional Simulations

The simulation results for average seasonal infiltration rate (q) of 6.1 mm d^{-1}, average AET of 2.25 and 3.50 mm d^{-1}, and two extreme differences in net water flux between IR and R zones ($q_{IR} - q_R$) (see Table 2) are presented in Fig. 6. The flux (q) value of 6.1 and AET value of 2.25 would correspond approximately to the estimated values for the sandy area of the corn plot, whereas $q = 6.1$ and AET = 3.5 would represent the sandy area of the soybean plot. The average θ_c used in these simulations was 0.18 m^3 m^{-3}, corresponding to the sandy areas. The simulation was run for 38 d, the same as the experimental period between tracer application and sampling. The solute-concentration profiles shown in Fig. 6 correspond to centers of the R and IR zones, and the QR position at the boundary of these zones (Fig. 2). The ratio of IR to R noted in Fig. 6 are the amounts of solute remaining in the 0- to 0.5-m depth of soil at the IR position (center of IR zone) expressed as a percentage of the amounts remaining at the R position.

When the difference in the net water flux between the IR and R zones (assumed to be a result of root-density differences) was 2.5 mm d^{-1} (Fig. 6a, b)., the centers of mass of the solute were distinctly separated in depth. The solute moved deeper in the IR zone and was more dispersed than in the R zone. At the lower rate of average AET (Fig. 6a), overall leaching of the solute was greater than with the higher rate of AET (Fig. 6b); IR/R values in the top 0.5 m were 8 and 14%, respectively.

When the difference in net water flux between the IR and R zones was as small as 0.5 mm d^{-1}, there were still distinct differences in the calculated solute movement between the two zones (Fig. 6c and 6d), though much less than with the larger difference ($q_{IR} - q_R$) of 2.5 mm d^{-1}. For this smaller net flux difference, however, the concentrations at the QR position were approximately equal to the mean of concentrations at R and IR positions at each depth. Furthermore, transport at the centers of the R and IR zones was also little affected by the transverse dispersivity. Thus, transport at the centers could be approximated by a one-dimensional transport model, and the concentrations at the QR positions estimated as

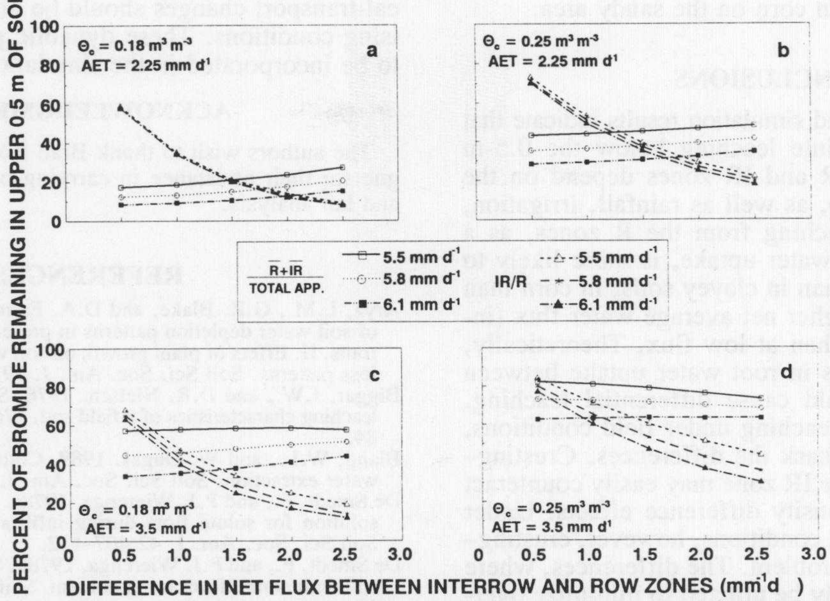

Fig. 7. Summary of results of two-dimensional simulation using three rates of average infiltration (q), two rates of actual evapotranspiration (AET) and two values of steady water content (θ_c).

mean values of the concentrations at the two centers. For small to intermediate net flux differences, this finding simplifies the calculation of leaching from R and IR zones.

Summary results of our simulations, in terms of the percentage of solute remaining in the top 0.5 m of soil (as in our experiments) vs. the net flux differences, $q_{IR} - q_R$, for the two soil and crop conditions and three infiltrating rates, are presented in Fig. 7. The parameter $(\overline{R} + \overline{IR})$/(total applied) is the overall average solute remaining in the top 0.5 m of soil (integrated across depth and zonal width of both zones).

The results in Fig. 7 show that, for sandy areas ($\theta_c = 0.18$), the total solute remaining in the top 0.5 m generally increased with an increase in $q_{IR} - q_R$ and with a decrease in q. This trend was also present in the clayey area, except at the lowest infiltration rate (5.5 mm d^{-1}) and higher value of AET (3.5 mm d^{-1}), where the trend was reversed. This is an interesting finding in that the overall, simulated leaching of solute (from both R and IR zones) generally decreases with an increase in root-density differences (i.e., the net flux differences) between the R and IR zones. In the exception, the center of solute mass was close to the surface, so the leading edge of the pulse passed through the 0.5-m depth as the flux difference increased rather than the trailing edge as in the other cases. Future research should investigate crop-variety selection and appropriate management (e.g., fertilizer placement) to obtain differential rooting as a possible way of decreasing overall leaching.

On the other hand, the IR/R solute percentage decreased (differential leaching increased) with an increase in $q_{IR} - q_R$ and with an increase in q in both textural areas and at both AET values. The IR/R percentages were higher for clayey areas than for sandy areas, and higher at a larger value of AET than at lower AET. The effect of infiltration rate was also greater in clayey areas and at a larger value of AET. It should be noted that the decrease in IR/R with increase in net flux difference was not linear; the decrease was rapid at first and slow later. This nonlinearity in IR/R percentages was actually the cause of the decrease in overall leaching with increasing root-density differences between the zones, as discussed above.

The simulations suggest reasons why the expected differences in row vs. interrow leaching were not found in either area of soybean and in clay areas of corn. The AET rates were higher under soybean, and hence the overall leaching rates were lower. In the clayey areas, leaching rates were also lower because of lower infiltration and higher water retention than in the sandy areas. The results in Fig. 7 show that, when the amount of total solute remaining is higher (i.e., less overall leaching), the IR/R percentage is also higher (less differential leaching) (i.e., Fig. 7a vs. 7c). Thus, in soybean and in clayey areas where net leaching is less, the differences in leaching between R and IR zones would be small, and it would be more difficult to detect these differences under field conditions. The spatial variability in leaching and some other factors may, in fact, dominate the leaching process under these conditions.

Comparison of measured amounts of total Br concentrations within 0.5 m with Br concentrations calculated by the model indicated that an AET difference of 0.75 mm d^{-1} with an average AET rate of 2.25 mm d^{-1} and a precipitation rate of 5.8 mm d^{-1} most closely matched our measured data in the sandy-textured area in corn. This suggests that, based on our assumptions, there may have been, on the average, a relatively small difference in AET rates between the R and IR areas. Our analysis of the row–interrow soil-water-content data of Zhia et al. (1990) measured under experimental conditions similar to ours also showed AET differences on the order of 0.5 to 1.0 mm d^{-1} between R and IR zones during a drying period. Results here show that, even at these small AET differences, significant measurable and useful differences in leaching occurred in corn on the sandy area.

CONCLUSIONS

Our experimental and simulation results indicate that the differences in solute leaching below the 0.5-m depth between crop R and IR zones depend on the types of soil and crop, as well as rainfall, irrigation, and ET. Reduced leaching from the R zones, as a result of greater root water uptake, is more likely to occur in sandy soils than in clayey soils, in corn than in soybean, and at higher net average water flux (infiltration minus ET) than at low flux. Theoretically, even small differences in root water uptake between R and IR zones would cause differential leaching. Spatial variability in leaching under field conditions, however, can easily mask the differences. Crusting–sealing problems in the IR zone may easily counteract or surpass the root-density difference effects. Under minimum-till or no-till conditions, however, crusting–sealing will not be a problem. The differences, where they exist, can certainly be utilized to minimize overall leaching. Furthermore, biodegradable chemicals and plant nutrients that remain in the biologically active area of the soil will be more likely to degrade or be taken up by the plant.

The simulation studies have also provided some further interesting results. Overall leaching from R and IR zones generally decreased with increasing net flux difference between the two zones, under fixed levels of other factors. The ratio of solute leaching from the IR to that from the R zone generally decreased logarithmically (differential leaching increased) with the increase in net flux difference. This ratio also decreased with increasing overall net infiltration flux. Factors that reduce this ratio will also reduce overall leaching under a given net infiltration flux. It follows that further research on management practices that increase root density in the R zones relative to the IR zones may yield methodologies to reduce net overall leaching.

This was an initial pilot study to investigate overall leaching differences between R and IR zones. Results of this study justify more detailed research into the processes involved, and management practices that may hold promise. Dynamic measurements of root growth with time and accompanying water-flow and chemical-transport changes should be undertaken for promising conditions. These dynamic processes also need to be incorporated in the simulation model.

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REFERENCES

Arya, L.M., G.R. Blake, and D.A. Farrell. 1975. A field study of soil water depletion patterns in presence of growing soybean roots. II. Effect of plant growth on soil water pressure and water loss patterns. Soil Sci. Soc. Am. J. 39:430–436.

Biggar, J.W., and D.R. Nielsen. 1976. Spatial variability of the leaching characteristics of a field soil. Water Resour. Res. 12:78–84.

Bland, W.L., and W. Dugas. 1989. Cotton root growth and soil water extraction. Soil Sci. Soc. Am. J. 53:1850–1855.

De Smedt, F., and P.J. Wierenga. 1978a. Approximate analytical solution for solute flow during infiltration and redistribution. Soil Sci. Soc. Am. J. 42:407–412.

De Smedt, F., and P.J. Wierenga. 1978b. Solute transport through soil with nonuniform water content. Soil Sci. Soc. Am. J. 42:7–10.

Huyakorn, P.S., J.W. Mercer, and D.S. Ward. 1985. Finite element matrix and mass balance computational schemes for transport in variably saturated porous media. Water Resour. Res. 21:346–358.

Huyakorn, P.S., S.D. Thomas, and B.M. Thompson. 1984. Techniques for making finite elements competitive in modeling flow in variably saturated porous media. Water Resour. Res. 20:1099–1115.

Kung, K.-J.S. 1990. Influence of plant uptake on the performance of bromide tracer. Soil Sci. Soc. Am. J. 54:975–979.

Quin, N.W., and J.M. Laflen. 1983. Characteristics of raindrop throughfall under corn canopy. Trans. ASAE 26:1445–1450.

Rose, C.W., F.W. Chichester, J.R. Williams, and J.T. Ritchie. 1982. Application of an approximate analytical method of computing solute profiles with dispersion in soil. J. Environ. Qual. 11:151–155.

Saffigna, P.G., C.B. Tanner, and D.R. Keeney. 1976. Non-uniform infiltration under potato canopies caused by interception, stemflows, and hilling. Agron. J. 68:337–342.

Smith, S.J., L.R. Ahuja, and J.D. Ross. 1984. Leaching of a soluble chemical under field crop condition. Soil Sci. Soc. Am. J. 48:252–258.

van Wesenbeeck, I.J., and R.G. Kachanoski. 1988. Spatial and temporal distribution of soil water in the tilled layer under a corn crop. Soil Sci. Soc. Am. J. 52:363–368.

Wierenga, P.J. 1977. Solute distribution profiles computed with steady-state and transient water movement models. Soil Sci. Soc. Am. J. 41:1050–1055.

Zhai, R., R.G. Kachanoski, and R.P. Voroney. 1990. Tillage effects on the spatial and temporal variations of soil water. Soil Sci. Soc. Am. J. 54:186–192.