DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Bromide and Atrazine Leaching in Furrow- and Sprinkler-Irrigated Corn

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ABSTRACT

Irrigation method is an important consideration in the management of nutrients and pesticides. A 2-yr study was undertaken to evaluate Br^- and atrazine [6-chloro-*N*-ethyl-*N*'-(1-methylethyl)-1,3,5-triazine-2,4-diamine] leaching following uniform spray application in a corn (*Zea mays* L.) field under three irrigation treatments: (i) furrow irrigation with water placement in every furrow (EF), (ii) furrow irrigation with water placement (at twice the rate) in alternate furrows (AF), and (iii) sprinkler irrigation (SP). The soil, a Fort Collins clay loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalf), was ridged and furrowed for all irrigation treatments. In both years of the study, Br^- movement under all three irrigation treatments was dominated by lateral flow into the ridge and/or dry furrow positions. The deepest Br^- leaching was found in the SP treatment, but with irrigation scheduled at 100% of evapotranspiration (ET) in no case in either year did Br^- mass below the root zone (1.2 m) exceed 3% of applied mass. Comparing the furrow irrigation treatments, applying water at twice the rate to alternative furrows neither increased nor decreased the plot averaged downward movement of Br^-. Atrazine movement was largely unaffected by the type and placement of irrigation, though in each treatment the downward leaching of atrazine was much greater than expected, suggesting nonequilibrium conditions and/or movement with a mobile reactive phase. A modified version of the unsaturated flow and transport code CHAIN-2D, which included two-dimensional root water and solute uptake with partitioning of the soil water into mobile and immobile regions, accurately simulated the Br^- concentration profiles. The model will be useful in evaluating management alternatives for the placement of water and chemicals that minimize losses below the root zone.

In irrigated agriculture, avoidance of deep leaching losses of fertilizers and pesticides is of interest to producers to minimize groundwater quality problems and to retain fertilizer and pesticides in the root zone where they can be effective. Sprinkler irrigation is generally thought to be more efficient than furrow irrigation because of better control of irrigation timing and uniformity. For example, deep percolation losses of water may occur with furrow irrigation because, to apply sufficient water to replenish the root zone of the soil farthest from the source, overirrigation occurs near the source. However, furrow irrigation is used in many areas because of lower capital requirements for the irrigation equipment.

Furrow irrigation involves two-dimensional water and solute movement in the soil because of surface shaping into ridges and furrows and application of water only in the furrows. It has been shown that in furrow irrigation, deep leaching losses of chemicals can be reduced if the chemicals are placed in the ridges (Kemper et al., 1975; Hamlett et al.,1986; Benjamin et al.,1996). It has also been shown that applying water in alternate furrows instead of every furrow may reduce irrigation requirements (Fischbach and Mulliner, 1974; Crabtree et al., 1985), which in turn may further decrease overall leaching of a chemical placed in the ridges or dry furrows (Benjamin et al., 1996).

In row crops, the root density is generally highest in the row zone and lowest in the interrow zone. This lateral distribution of root mass may cause two-dimensional water movement that will influence chemical leaching. Limited information is available on two-dimensional soil water and chemical movement as influenced by the lateral distribution of the row-crop root system. Arya et al. (1975) measured spatial patterns of soil water matric potential between two rows of a soybean [*Glycine max* (L.) Merr.] crop, and reported appreciable lateral gradients at certain stages of growth. Van Wesenbeeck and Kachanoski (1988) have reported similar gradients in soil water content under corn, with water content beneath the crop row almost always lower than water content between rows. In both corn and soybean, Timlin et al. (1992) measured lateral water gradients resulting from a gradient in root-density distribution. On a fine sandy loam soil, Timlin et al. (1992) found significantly less leaching of Br^- in the row zone of corn than in the interrow zone; on a clayey soil, factors other than root distribution influenced the results. One would expect from these results that there would be less deep percolation of water in the crop-row zone than in the interrow zone and that a chemical placed in the row zone would be less susceptible to downward leaching. Additionally, if the crop-row zone occurs on the ridges, as is common in furrow-ridge systems, leaching of a chemical placed in the row will be further reduced. A question to be answered is whether the overall leaching of a chemical that is not placed in the ridges or row

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Published in Soil Sci. Soc. Am. J. 64:1723–1732 (2000).

Abbreviations: AF, alternate-furrow irrigation treatment; EF, every-furro irrigation treatment; ET, evapotranspiration; LEPA, Low Energy, Precision Application; SP, sprinkler irrigation treatment.

zones, but is uniformly applied over the soil surface, is also reduced with furrow irrigation and a row crop.

The objective of this study was to investigate the two-dimensional movement of water and a uniformly applied solute in a row-crop system with alternate-furrow, every-furrow, and sprinkler irrigation. The focus of the analysis is twofold. First, to what extent does the irrigation pattern affect the two-dimensional movement of Br^- and atrazine? Specifically, does alternate-furrow irrigation reduce chemical leaching below the root zone relative to every-furrow placement or sprinkler irrigation at the same rate (100% ET)? Secondly, we seek to modify and test an existing two-dimensional unsaturated flow and transport model to simulate the water and solute movement under alternative irrigation strategies. The modifications of the numerical code include division of the soil water into mobile and immobile zones with solute transfer between these regions. Using solute data from the first year of a 2-yr study to calibrate portions of the model, we will compare observed and predicted solute distributions for the second year.

MATERIALS AND METHODS

Field

The field site selected for the 2-yr study, located near Fort Collins, CO, is a well-drained, nearly level Fort Collins clay loam. The combined thickness of the A and B horizons is ≈1.2 m and is composed of clay loam to clay with moderate to strong subangular blocky structure. The C horizon is a massive clay loam with a water table at a depth of ≈3.5 m. The near surface soil typically contains 2.3% organic matter and has a pH of 7.8 and a cation-exchange capacity of 25 cmol kg^{-1}. The field was prepared by disking, followed by ridging (0.76-m ridge spacing) and planting to corn. The field was divided into three treatment areas for EF, AF, and SP. Within each area, 4.5 by 4.5 m plots were delineated for application of KBr (at 8.0 g Br^- m^{-2}) and atrazine (at 0.4 g a.i. m^{-2}). The chemicals were dissolved in 3 L of solution and applied uniformly using multiple passes with a Weed Systems (Keystone Heights, FL) four-nozzle hand-held sprayer. On the date of solute application, replicate soil cores were taken to a depth of 1.8 m to measure the soil water content profile in each plot. The two furrow-irrigated plots were immediately adjacent, but separated from the sprinkler plot by ≈100 m.

The field plots were irrigated approximately weekly at a rate equal to 100% of estimated ET using a Low Energy, Precision Application (LEPA) linear move irrigation system (Valmont Industries, Omaha, NE). Water application was typically 25 to 50 mm h^{-1}, and furrows were blocked near the perimeter of the plots to prevent run-on from adjacent areas. For the furrow-irrigated treatments, the drop nozzles on the LEPA system were fitted with socks to eliminate spray and place the irrigation water in the bottom of the furrows. The total volume of irrigation was distributed to every furrow or alternate furrows as appropriate.

Each treatment was sampled twice, mid season (late July) and postharvest (mid October), to measure the two-dimensional distributions of water, Br^-, and atrazine. Soil samples were retrieved using a platform-mounted Giddings (Giddings Machine Co., Ft. Collins, CO) hydraulic coring device with a 61 mm i.d. by 1.2 m long sampling tube with polyvinyl liner. Soil samples were taken at seven points along a line perpendicular to the ridge (at the midpoint of four consecutive furrows and three consecutive ridges). This perpendicular transect was

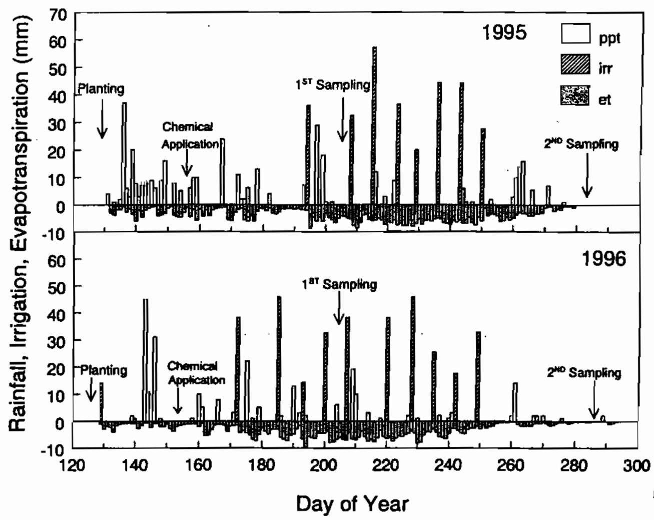

Fig. 1. Water balance and timing of experimental activities in the 1995 and 1996 growing seasons.

repeated at four locations in the plot (separated by ≈1 m) yielding a seven by four rectangular grid of samples. The soil was sampled to a depth of 0.95 to 1.2 m at the first sampling and to a depth of 1.9 to 2.3 m at the postharvest sampling. The soil cores were sectioned into 0.05-m increments in the upper 0.3 m and 0.1-m increments below the 0.3-m depth. At any depth, the four soil samples from the same ridge (or same furrow) were composited, yielding a final 7 by 16 or 7 by 26 (depending on sampling date) set of samples for extraction and analysis. All samples were stored at 4°C, split into zip-lock plastic bags for Br^- analysis and glass jars for atrazine analysis.

The experiment was repeated in consecutive years (1995 and 1996), though the designated treatment areas were staggered to avoid sampling chemicals from the previous season. The movement of atrazine was evaluated only in the first year of the study. Figure 1 summarizes the water balance and the timing of key events in each year of the study. The net applied water (cumulative application-cumulative ET) at each sampling time is indicated in Table 3. The major difference between the 2 yr of the study was the large quantity of rainfall in the spring of 1995. Consequently, only one irrigation was required prior to the first soil sampling event in 1995. Of the total applied water between chemical application and the first sampling, 81% occurred as rainfall in 1995 compared with 41% as rainfall for the same period in 1996. Thus, the irrigation treatment, for the most part, was not imposed by the first sampling of the 1995 season.

Analytical

Each soil sample was subdivided into three parts for determination of Br^-concentration, atrazine concentration, and gravimetric water content. A saturation paste was created using a known mass of soil (M_S) with known volume of deionized water (V_w) following the procedure of Rhoades (1986). After vacuum extraction, the Br^- concentration of the extracts (C_E) was determined using a Lachat ion-chromatography autoanalyzer (Zelleweger Analytics, Lachat Instruments, Mequon, WI) calibrated for a lower quantitation limit of 0.5 g Br m^{-3} (0.5 ppm). The soil water Br^- concentration (C_{SW}) was then calculated using the routine mass balance equation

$$C_{SW} = C_E\left[1 + \frac{V_w(1 + \theta_g)\rho_W}{M_S\theta_g}\right] \quad [1]$$

where θ_g is the gravimetric water content of the extracted soil and ρ_w is the density of water.

Table 1. Calibration parameters for soil water movement.†

Depth	ρ_b	θ_r	Field θ_s	α_v	n	K_s	β
m	Mg m^{-3}	m^3 m^{-3}		cm^{-1}		m d^{-1}	
0–0.3 (Ridge)	1.36	0.1	0.41	0.045	1.20	1.06	16
0–0.3 (Furrow)	1.42	0.1	0.41	0.085	1.23	0.41	13
0.3–0.45	1.47	0.1	0.38	0.025	1.20	0.17	15
0.45–0.6	1.50	0.1	0.37	0.028	1.24	0.23	12
0.6–0.75	1.40	0.1	0.39	0.030	1.25	0.24	10
0.6–0.75	1.45	0.1	0.42	0.060	1.25	0.24	7
0.75–1.05	1.35	0.1	0.41	0.015	1.40	0.24	7
1.05–1.5	1.36	0.1	0.39	0.030	1.25	0.24	8.5
1.5–2.10	1.38	0.1	0.39	0.030	1.23	0.24	11

† Parameters as defined for Eq. [2] and Eq. [3].
ρ_b is bulk density; θ_r is residual water content; θ_s is saturated water content; α_v, n, and β are fitting parameters; K_s is saturated hydraulic conductivity.

For atrazine analysis, soil samples were first fortified with $^2H_5$-atrazine (30 μL of 100 mg L^{-1} $^2H_5$-atrazine in iso-octane per 20 g of soil) to serve as an internal standard. Samples were then shaken for 2 h in 40 mL of 90% methanol followed by centrifuging. A 10-mL aliquot was then diluted (with distilled, deionized water) to 100 mL and extracted by flow through a 100-mg C-18 solid-phase cartridge. The extracts were analyzed using a Hewlett-Packard 5890 Gas Chromatograph with a mass spectrometer detector (HP 5972) (Hewlett-Packard, Palo Alto, CA). The lower quantitation limit of the method for atrazine was 0.2 mg m^{-3} (or 0.2 ppb).

In addition to the soil sample analysis, plant samples taken at harvest were analyzed for Br^-. Following the procedure of Abdalla and Lear (1975), 1 g of dried, ground plant material (composite of corn stalks and leaves) was extracted using 25 mL of 0.1 *M* $NaNO_3$. Following shaking (1 h) and centrifuging, the extracts were analyzed for Br^- using a Dionex ion-chromatograph (Dionex, Sunnyvale, CA).

Modeling Approach

We used the model developed by Benjamin et al. (1996), which couples a two-dimensional model of unsaturated water flow and solute transport (CHAIN-2D; Simunek and van Genuchten, 1994) with a two-dimensional root growth model. The code uses Galerkin-type linear finite element schemes to numerically evaluate Richards' equation for saturated–unsaturated water flow and the convection–dispersion equation for solute transport.

Soil hydraulic properties are described using the van Genuchten (1980) soil water retention function and a simple power function for the unsaturated hydraulic conductivity

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + |\alpha_v h|^n)^m} \quad [2]$$

$$K(h) = K_S S_e^{\beta} \quad [3]$$

where α_v (m^{-1}), n, and β are fitting parameters; $m = 1 - 1/n$; θ (m^3 m^{-3}) is the volumetric water content; θ_r (m^3 m^{-3}) is the residual water content, θ_S (m^3 m^{-3}) is the saturated water content; K_S (m d^{-1}) is the saturated hydraulic conductivity; and h (m) is the soil water pressure head. The values of the parameters in Eq. [2] and [3] used in the model simulations are given in Table 1. The soil water retention parameters were determined in the laboratory from pressure-plate water desorption measurements on 100 mm diam. by 75 mm tall soil cores. Hydraulic conductivity parameters were derived from field infiltration measurements. The parameters in Eq. [2] and [3] were further refined by matching model-predicted water contents within row position and depth with neutron moisture measurements collected in 1994. A full description of field water content measurement with row position, depth, and time can be found in Benjamin et al. (1998).

The root-growth model delineates a soil region to the left, right, and below the center line of the plant row in which root growth may occur. The size of the region is defined by the extension rate of the root system (γ) and the growth angle (ϕ) from the horizontal. The horizontal extension of the root region is assumed to progress by

$$X = X_p + \gamma \cos(\phi)\Delta t \quad [4]$$

where X is the new horizontal limit of the root zone (m), X_p is the previous horizontal limit of the root zone (m), and Δt is the time increment (d). The zones of potential root growth are assumed to be symmetric to the left and right of the plant. The vertical extension of the root system is assumed to progress by

$$Z = Z_p + \gamma \sin(\phi)\Delta t \quad [5]$$

where Z is the new vertical limit of the root zone (m) and Z_p is the previous vertical limit of the root zone (m). Values for the coefficients γ (m d^{-1}) and ϕ (°) depend on the corn hybrid and the age of the plant. Equations [4] and [5] define an expanding zone under the row in which root growth can occur and roots can extract water and nutrients. Plant and root growth coefficients used in the model simulations are given in Table 2.

For this work, the model proposed by Benjamin et al. (1996) was further modified by dividing the soil water into mobile and immobile regions with solute transfer between zones as suggested by van Genuchten and Wierenga (1976). In the

Table 2. Plant growth calibration parameters (Benjamin et al., 1996). Root pattern determined by Eq. [4] and Eq. [5] with range of γ and ϕ used from planting to crop maturity.

Plant growth parameters (1994 calibration)†							
Growing degree days to maturity	HYB_L	HYB_B	Plant population	ε	σ	γ	ϕ
d °C			1000 plant ha^{-1}			mm d^{-1}	°
1300	0.60	2.0	71.6	0.25	0.05	20→0	20→90

† LAI (leaf area index) = LA_{max}(POP/10)/{1 + [LA_{max}/0.01] exp[−HYB_b NC]}, where LA_{max} is the maximum leaf area per plant for the hybrid, POP is the plant population (thousands of plants ha^{-1}), HYB_B is an empirical growth coefficient, and NC is the time from a normalized crop calender. LA_{max} is calculated from the plant population and a hybrid-dependant growth factor, HYB_L, by: LA_{max} = −0.0019POP + HYB_L. Root growth is determined by $dR_d/dt = \varepsilon R_d - \sigma R_d^2$, where R_d is the root density at time t and ε and σ are growth coefficients.

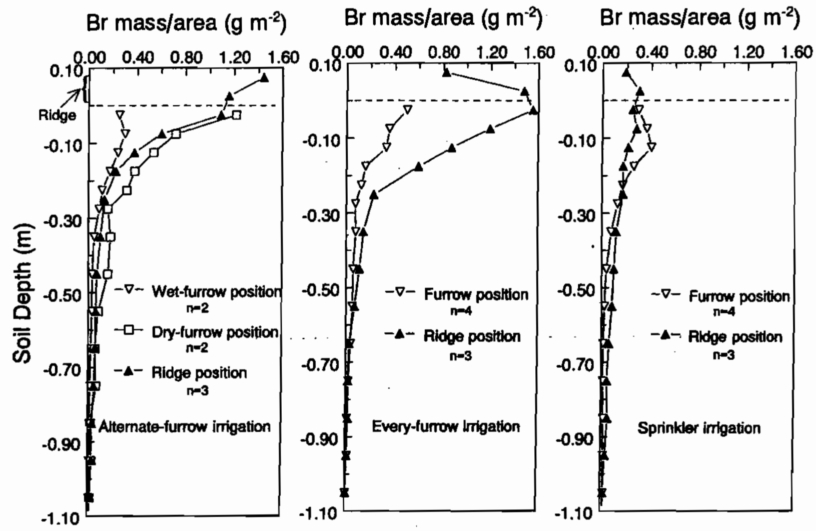

Fig. 2a. Bromide mass/area as a function of sampling position for each irrigation treatment from the July 1995 sampling (see Table 3). The profiles are the average of *n* like positions within the treatment.

absence of independent measurements and to simplify the numerical solution, we set the immobile content at $\theta_{im} = 0.2$ m^3 m^{-3}. The effect of this assignment is that soil regions typically drier than 0.2 m^3 m^{-3} (e.g., ridge or dry furrow positions) are diffusional sinks with transfer between θ_{im} and θ_m governed by a mass transfer coefficient (α). The ratio θ_{im}/θ in the wetted soil regions ranged from ≈0.5 to 0.8, which is consistent with measurements for a field clay loam reported by Jaynes et al. (1995). The remaining solute transport parameters required in the model were estimated by least-squares curve fitting the model to Br^- concentration profiles observed in the first year of the study (see below).

RESULTS AND DISCUSSION

Bromide

Figure 2 presents the spatial distribution of Br^- mass in each of the irrigation treatments at the two sampling dates in both years of the study. The mass profiles, as referenced by position, are the average of *n* like positions. For clarity, confidence limits are omitted, but statistical comparisons between treatments are discussed below. It is immediately evident in Fig. 2 that, regardless of irrigation treatment, the majority of soil Br^- was recovered in the upper portion of the root zone, predominantly in the ridge or dry furrow position. In the furrow-irrigated treatments for example, 90% of the soil Br^- remained in the upper 0.6 m by the end of season, with about four times more Br^- mass below the average ridge position than below the average wet furrow position. The end of season Br^- recovery (soil + plant tissue) ranged from 79 to 118% of applied mass, with the low observed in the sprinkler-irrigated corn (Table 3). Note that, of the applied Br^-, ≈45% (or 34 kg Br^- ha^{-1} in the first year and 37 kg Br^- ha^{-1} in the second year) was found in the aboveground crop biomass. This uptake rate is nearly identical to the 38 kg ha^{-1} uptake reported for corn by Jemison and Fox (1991)].

Importantly, in comparing the EF and AF irrigation treatments, deeper Br^- leaching in the wet furrow position of AF was not found despite the 2× water applica-

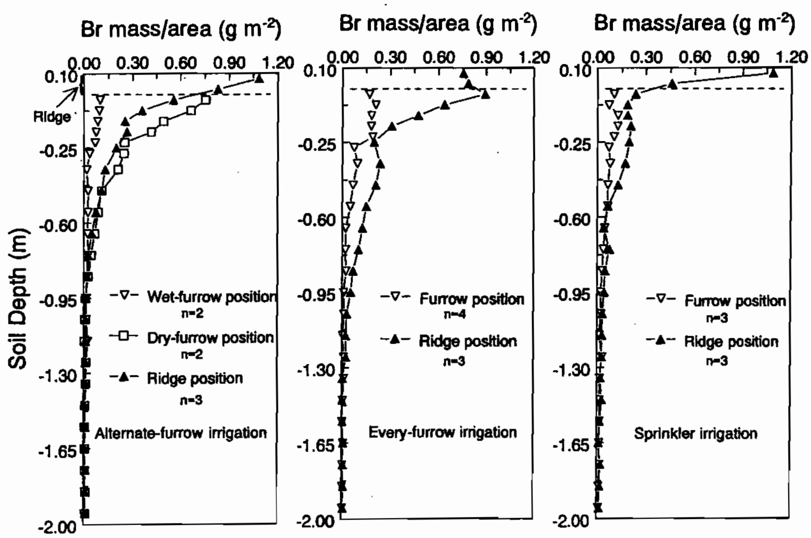

Fig. 2b. Bromide mass/area as a function of sampling position for each irrigation treatment from the October 1995 sampling (see Table 3). The profiles are the average of *n* like positions within the treatment.

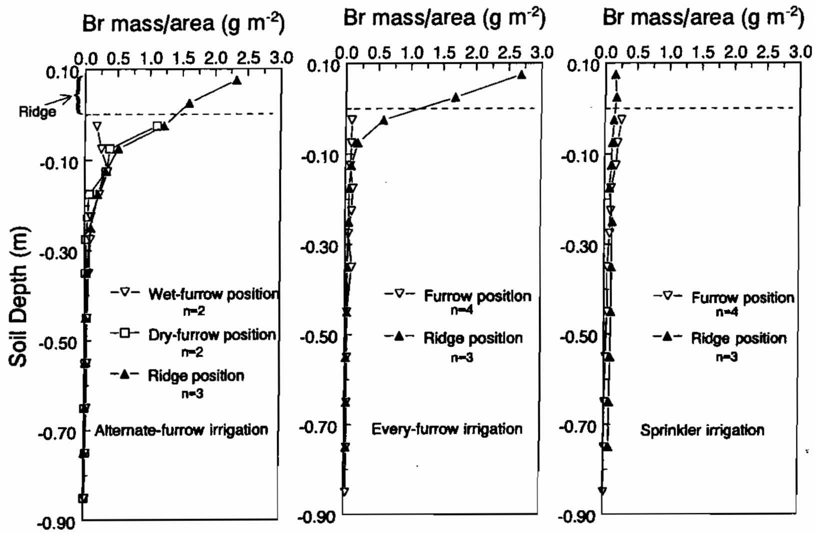

Fig. 2c. Bromide mass/area as a function of sampling position for each irrigation treatment from the July 1996 sampling (see Table 3). The profiles are the average of *n* like positions within the treatment.

tion rate to this position. Examining the center of mass of the Br^- by position and treatment (Table 3), no consistent difference is found for the wet furrow position when comparing EF and AF; the somewhat deeper movement in the AF wet furrow in 1995 was not observed in1996 when the downward Br^- leaching in the EF furrow was greater. In statistical comparison of the EF and AF treatments, Br^- mass at any specific depth in the wet furrow of AF was not statistically different ($P = 0.05$) from the Br^- mass at the same depth in the furrow position of EF (with the exception of a few spurius cases). Statistical difference ($P = 0.05$) was found between Br^- mass in the dry furrow of AF and Br^- mass in the irrigated furrows of the EF treatment. The Br^- mass in the ridge soil was typically greater in the EF treatment than in AF; the difference is statistically significant ($P = 0.05$) at the end of the second field season. On a plot average basis, the Br^- center of mass at each sampling time is remarkably similar for the AF and EF treatments (Table 3). Thus, while the dry furrow position did serve to retain Br^-, it did so largely at the expense of ridge accumulation, and consequently, there was no net increase or decrease in downward Br^- movement with the AF treatment relative to EF.

A two-dimensional visualization of the soil Br^- concentration (Plates 1a and 1b) further aids comparison of AF and EF results. The seven vertical grid lines indicate the soil sampling locations, with Br^- concentration measurements taken at 0.05-m resolution in the upper 0.3 m and with 0.1-m resolution below 0.3 m soil depth. The cross-hatching in the furrow indicates an irrigated position. The contouring in Plates 1a and 1b was generated by a 10 by 50 mesh grid and hence the detail is idealized, especially in the lateral direction between vertical grid lines, but the figure conveys the essence of the data and reveals the spatial variation in the soil Br^- concentration. The Br^- accumulation in the ridge and dry furrow positions is clear, as is the absences of deep Br^- leaching below the irrigated furrow positions.

In view of Fig. 2 and Plates 1a and 1b, and considering

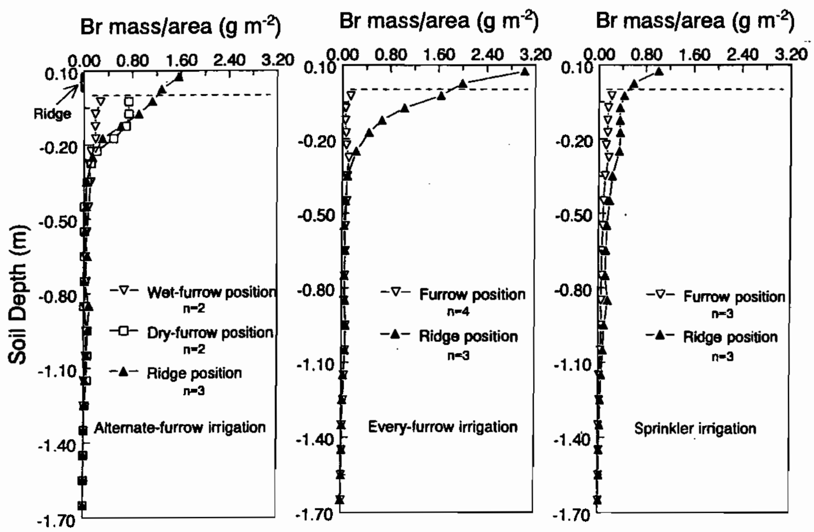

Fig. 2d. Bromide mass/area as a function of sampling position for each irrigation treatment from the October 1996 sampling (see Table 3). The profiles are the average of *n* like positions within the treatment.

Table 3. Bromide mass recovery and center of mass as function of sampling position for each irrigation treatment at each sampling date. Note that in the center of mass data, $z = 0$ is the soil surface of the furrow.

			Mass recovered		Center of mass by position			
Treatment†	Sampling date	NAW‡	Plant	Soil	Plot avg.	Ridge	Wet furrow	Dry furrow
		mm	%		m			
AF	7/25/95	22	NS§	42	−0.10	−0.10	−0.27	−0.23
	10/10/95	26	42	48	−0.20	−0.20	−0.65	−0.32
	7/23/96	16	NS	54	−0.02	−0.01	−0.25	−0.13
	10/10/96	26	48	61	−0.12	−0.12	−0.37	−0.25
EF	7/25/95	22	NS	60	−0.09	−0.10	−0.22	NA¶
	10/5/95	27	46	50	−0.24	−0.26	−0.43	NA
	7/24/96	16	NS	44	−0.01	−0.00	−0.33	NA
	10/15/96	25	44	74	−0.11	−0.10	−0.62	NA
SP	7/25/95	22	NS	31	−0.24	−0.28	−0.25	NA
	10/17/95	25	40	39	−0.33	−0.34	−0.67	NA
	7/24/96	16	NS	20	−0.23	−0.30	−0.23	NA
	10/18/96	25	47	52	−0.30	−0.34	−0.49	NA

† AF = alternate-furrow irrigation; EF = every-furrow irrigation; SP = sprinkler irrigation.
‡ NAW = [Cumulative(irrigation + precipitation) − Cumulative ET] from time of chemical application.
§ NS = not sampled.
¶ NA = not applicable.

the complete Br^- recovery, the results indicate that the low Br^- concentrations in the irrigated furrow positions are a result of lateral movement to the ridge and dry furrow positions rather than loss to deep leaching. During irrigation, two-dimensional infiltration carries Br^- into the ridge and presumably down the profile beneath the wetted furrow position. Between irrigations, greater evapotranspiration in the ridge than in the furrow induces additional lateral (and perhaps upward) flow and accumulation of Br^- in the ridge position and dry furrow positions. On the mid and end of season sampling dates, the gravimetric soil water content (θ_g) in the furrow irrigated plots (not shown) reflected the spatial pattern of the water placement and plant uptake with minimums (θ_g = 0.1–0.15) in the upper soil of the ridge and dry furrow positions. These minimums occur in what was otherwise a nearly spatially uniform soil water content (θ_g = 0.20 ± 0.003, mean and 95% confidence limit) indicative of a fairly homogeneous, well-drained soil profile.

Figure 2 and Table 3 also reveal greater downward leaching of Br^- under sprinkler irrigation than with either of the furrow-irrigation treatments. Under sprinkler irrigation, the Br^- accumulation in the ridge soil was again observed (Fig. 2b and 2d), though the pattern was slower to develop (i.e., it was not evident by mid season, Fig. 2a and 2c) presumably due to the more uniform placement of water. With the exception of the October 1995 sampling, Br^- mass in the ridge position of SP was significantly less ($P = 0.05$) than in the ridge position of either the AF or EF treatments. Additionally, Br^- mass below the root zone at the end of the growing season in SP was typically greater than in AF and EF, the differences often significant ($P = 0.05$). Consequently, at both sampling times in each year of the study, the Br^- center of mass (plot average) was deepest for the SP (Table 3). Sprinkler irrigation on the ridge position with possible enhancement from stem flow leaches the ridge soil, elevates ridge soil water content, and reduces lateral soil water potential gradients driving water flow into the ridge. The result was less Br^- accumulation in the ridges and greater downward leaching of Br^- in the sprinkler-irrigated corn than with either of the furrow-irrigated treatments.

Atrazine

The atrazine mass distributions as a function of position for each irrigation treatment are illustrated in Fig. 3. Unlike Br^-, similar atrazine mass was observed in the furrow and ridge positions in all irrigation treatments. In no case was atrazine detected below 1.2 m (sampling to 2.3-m depth) and, by the end of the growing season, ≈90% of the soil atrazine in each irrigation treatment was found in the upper 0.30 m. Because of its adsorptive properties, atrazine is less susceptible to lateral relocation than is the Br^- tracer and consequently the atrazine two-dimensional distribution appears largely unaffected by differences in the irrigation patterns employed in this study. It follows that a one-dimensional solute transport model could be used to simulate the atrazine movement. However, a surprising result is the deep movement of atrazine, particularly evident at the mid-season sampling (Fig. 3a) in the sprinkler-irrigated plot. The leading edge of movement (>1 m) is similar to the Br^- tracer (Fig. 2a), suggesting nonequilibrium transport of atrazine (preferential flow and/or kinetically limited sorption) or enhanced movement through sorption to mobile colloids. Note that the linear, equilibrium sorption coefficient for atrazine has a reported range of K_{OC} = 38 to 288 $m^3\ Mg^{-1}$, with K_{OC} = 147 $m^3\ Mg^{-1}$ considered a typical value (Wauchope et al., 1992). Assuming the average K_{OC} and the measured organic matter in this soil, we estimate a $K_D = 2\ m^3\ Mg^{-1}$ and, for the observed range of soil water contents, a retardation factor of 8 to 15. Johnson et al. (1995) reported rapid movement of atrazine to subsurface drains (interpreted as preferential flow) in a clay soil with a very high atrazine K_{OC} of 347 $m^3\ Mg^{-1}$. In this study, the center of atrazine mass at the mid-season sampling was −0.25 m in AF, −0.15 m in EF, and −0.28 m in SP, each of which was deeper than Br^- center of mass (Table 3). Interpreting the ratio of mean vertical travel distances of Br^- to atrazine as

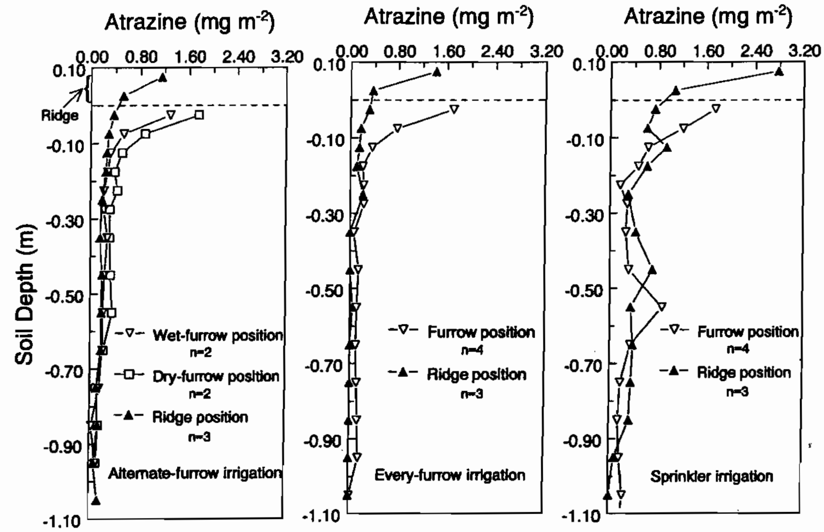

Fig. 3a. Atrazine mass/area as a function of sampling position for each irrigation treatment from the July 1995 sampling (see Table 3). The profiles are the average of *n* like positions within the treatment.

the retardation factor, we estimate $R < 1$ for atrazine. Apparently, the transport mechanisms enhancing the early downward movement of atrazine did not facilitate lateral and upward relocation of the atrazine between irrigation events. For example, this might result from adsorption–desorption hysteresis (i.e., adsorption rates much faster than desorption rates) or the obvious lack of upward, preferential flow under unsaturated conditions. Swanson and Dutt (1973) and Johnson et al. (1995) demonstrated adsorption–desorption hysteresis for atrazine in a variety of soils. Because of the early deep penetration of atrazine and because resident atrazine resists lateral and upward movement into the ridge more so than Br^-, the net downward movement of atrazine was much greater than would be expected based on the mean downward movement of Br^- and an assumption of equilibrium sorption–desorption for atrazine. By the final sampling (Fig. 3b), the atrazine mass has decreased throughout the profile, with proportionally less reduction in the upper 0.3 m. Consequently, unlike the Br^-, the atrazine center of mass (−0.07 m for AF, −0.08m for EF, and −0.09 m for SP) was closer to the soil surface at the second sampling than at the first sampling. This result, given the increase in net applied water between the two sampling dates (Table 3), was not expected and is difficult to explain. The result is consistent with a larger atrazine degradation rate in the subsoil than near the soil surface, which could be a consequence of drier soil conditions near the surface in the ridge and dry furrow positions.

Modeling Results

As discussed above, the hydraulic and root-growth parameters required for the numerical simulations were estimated through a combination of field and laboratory measurements and model fitting to previous studies at the field site (see Tables 1 and 2). The solute transport

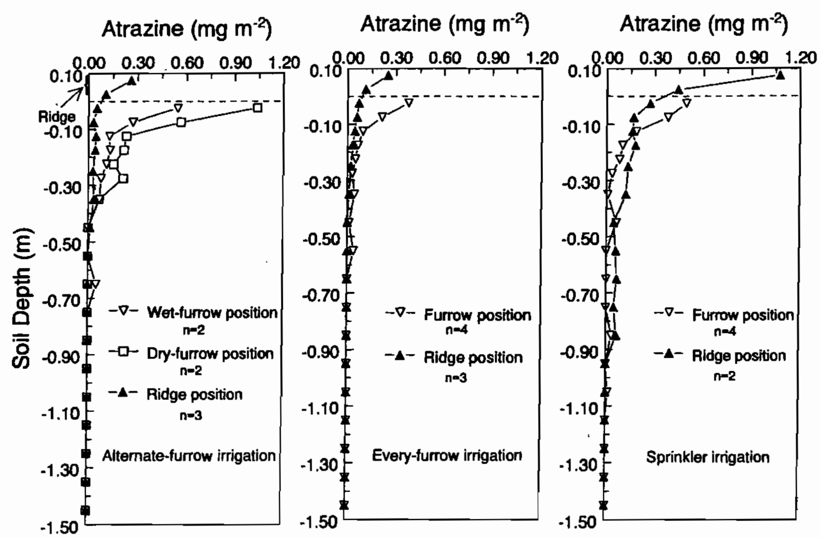

Fig. 3b. Atrazine mass /area as a function of sampling position for each irrigation treatment from the October 1995 sampling (see Table 3). The profiles are the average of *n* like positions within the treatment.

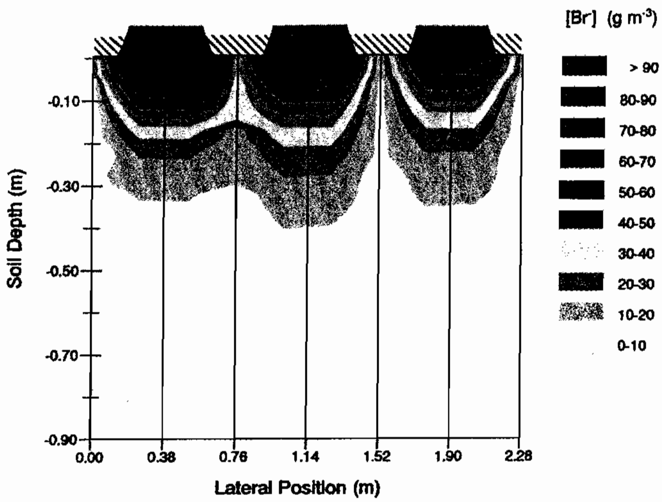

Plate 1a. Spatial distribution of Br^- at the end of the second growing season (15 Oct. 1996) with every-furrow placement of water. The maximum observed Br^- concentration was 391 g m^{-3} (ridge position, +0.05 to +0.10 m). The contouring is idealized (based on 7 by 26 array of measured points interpolated to a 10 by 50 grid).

parameters required in the modeling were estimated empirically using the Br^- distributions from the first year of the study. The key adjustable parameters are the dispersivity, both longitudinal (D_L) and transverse (D_T); the immobile-water fraction (θ_{im}); and the mass transfer coefficient (α) for solute movement between the mobile and immobile liquid phases. After setting θ_{im} = 0.2 m^3 m^{-3}, the remaining parameters were adjusted by trial and error to produce the best overall representation (by minimizing the sum of the squared deviations between the data and the simulation) of the plot average Br^- concentration profiles from 1995. Figure 4 shows an example result of this partial fitting of the numerical model using D_L = 0.2 m, D_T = 0.02 m, and α = 0.05 d^{-1}. This set of effective parameter estimates results in good representation of both the mid-

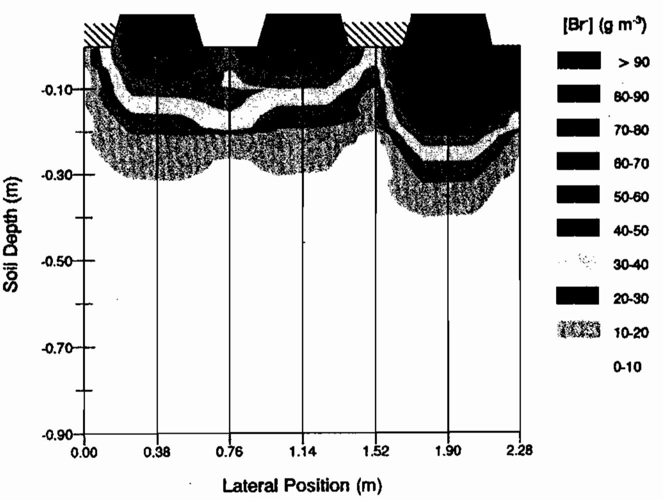

Plate 1b. Spatial distribution of Br^- at the end of the second growing season (10 Oct. 1996) with alternate-furrow placement of water. Irrigated furrows are indicated by cross-hatching in the furrow. The maximum observed Br^- concentration was 186 g m^{-3} (ridge position, +0.05 to +0.10 m). The contouring is idealized (based on 7 by 26 array of measured points interpolated to a 10 by 50 grid).

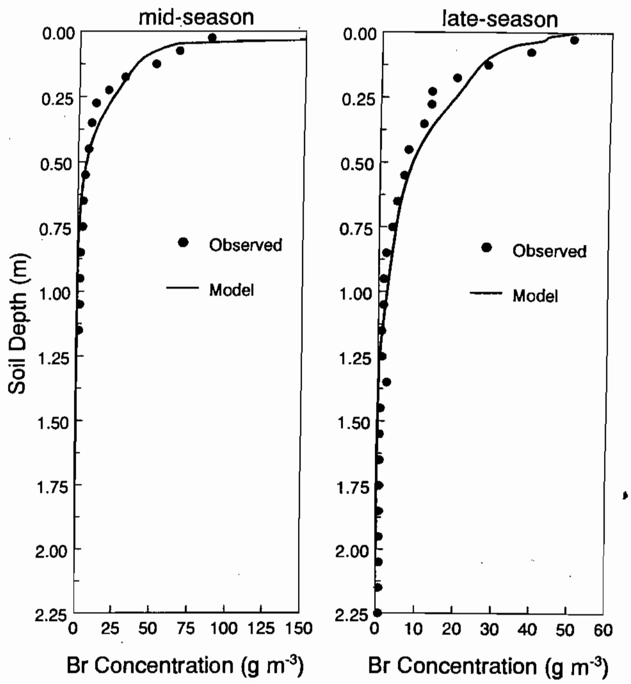

Fig. 4. Model adjusted representation of the plot average Br^- concentration profile at mid (25 July 1995) and late (10 Oct. 1995) first growing season with alternate-furrow irrigation placement.

and late-season Br^- profile in all three (not shown) irrigation treatments and will be used without further adjustment to for the second season model predictions.

As an aside, assignment of θ_{im} was an important factor in the accuracy of the model simulations. If a one-dimensional convection–dispersion type model was used to simulate the Br^- movement, it would require an assumption of a convective transport volume (i.e., θ_m) less than θ to accurately predict the center of mass of the Br^- plume in any of the irrigation treatments. That is, despite the lateral movement of Br^- into the ridge and dry furrow positions, the mean vertical travel distance of Br^- was greater than expected based on the net

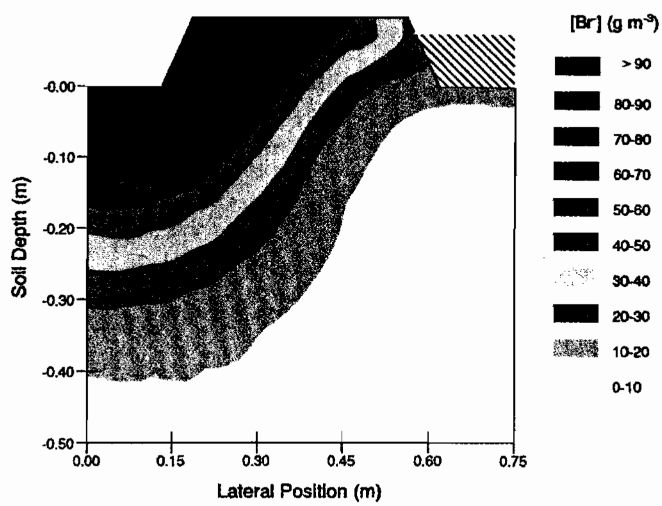

Plate 2. Model prediction of two-dimensional Br^- distribution at the end of the second growing season (10 Oct. 1996) with alternate-furrow irrigation. Contouring is based on predicted concentration at 51 by 51 points.

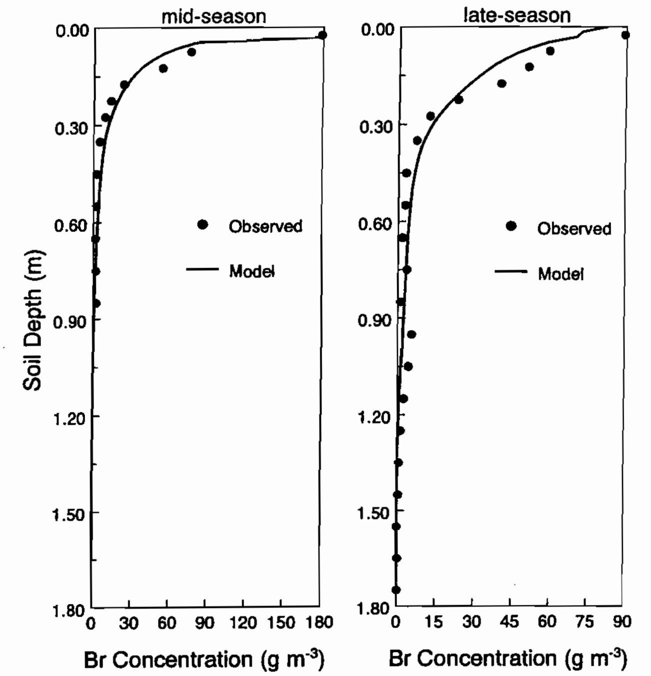

Fig. 5a. Model prediction of the plot average Br^- concentration profile at mid (23 July 1996) and late (10 Oct. 1996) second growing season with alternate-furrow irrigation.

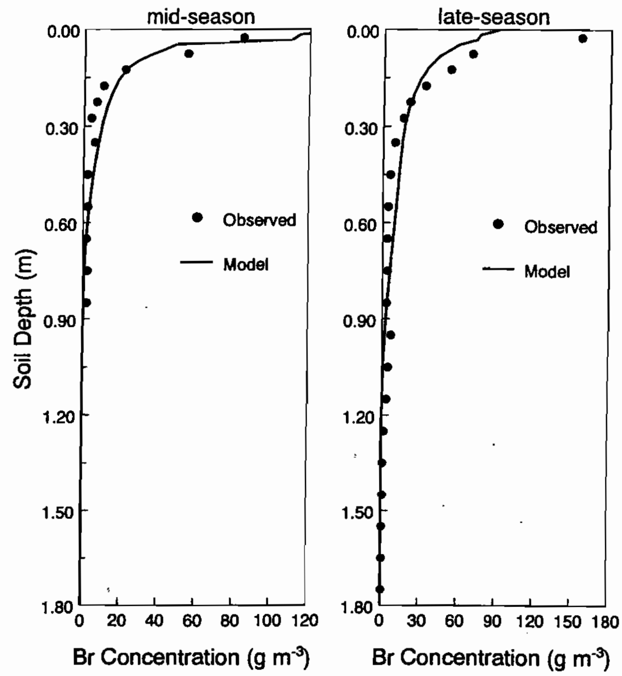

Fig. 5b. Model prediction of the plot average Br^- concentration profile at mid (24 July 1996) and late (15 Oct. 1996) second growing season with every-furrow irrigation.

applied water at sampling time (Table 3) and the time-averaged soil water content.

Plate 2 shows the model prediction of the two-dimensional Br^- distribution at the end of the second season in the alternate furrow irrigation treatment. Similar to the observed distribution (Plate 1b), the model predicts Br^- accumulation in the dry furrow and ridge position with very little Br^- (<8% of the applied mass) below the 0.4-m depth. The model predicts lower Br^- concentrations in the wetted furrow position than observed though, consistent with observation, there is no deep Br^- movement predicted below the wetted furrow. The model predictions of the plot average Br^- concentration with depth (Fig. 5) represent the second year data very well, except in the sprinkler irrigated treatment where the model tends to underestimate the small Br^- concentrations below ≈0.9 m. In modeling attempts to simulate the atrazine data (using D_L, D_T, α, and θ_{im} found from the Br^- data) we found very poor results (not shown). Reasonable simulation of the atrazine center of mass position was only achieved by reducing the adsorption coefficient, K_D, to ≈0.02 m^3 Mg^{-1}, which is two orders of magnitude smaller than expected for this soil (see discussion of atrazine results above). Clearly, the model does not include mechanisms responsible for the deep atrazine movement.

SUMMARY AND CONCLUSIONS

Comparing Br^- leaching under furrow-irrigated corn as a function of water placement, irrigation of alternate furrows neither increased nor decreased downward Br^- movement relative to every-furrow placement of water. Despite a 2× application of water to the alternately irrigated furrows, lateral relocation of Br^- into the ridge and dry furrow positions sufficiently reduced downward leaching such that virtually no Br^- was found below the root zone at the end of the growing season. Lateral gradients inducing accumulation of Br^- in the ridge position developed more slowly under sprinkler irrigation, and thus somewhat greater downward leaching of Br^- was observed than with furrow irrigation. The irrigation type and placement had only a small affect

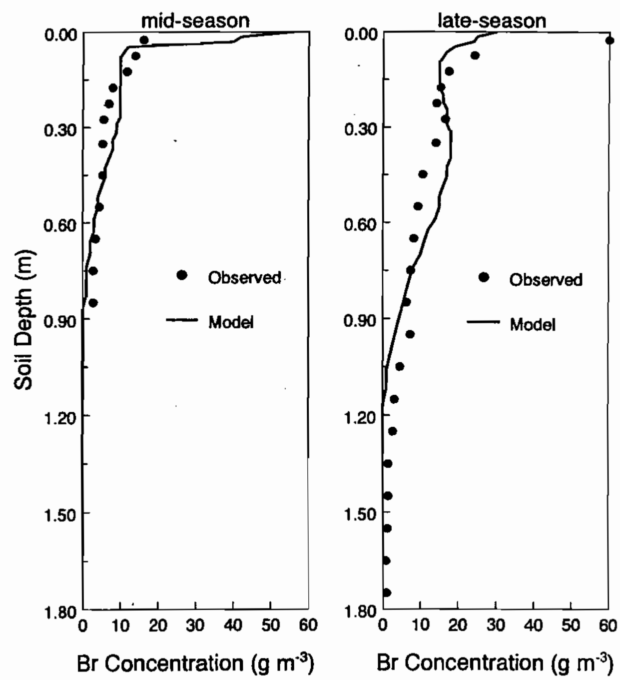

Fig. 5c. Model prediction of the plot average Br^- concentration profile at mid (24 July 1996) and late (18 Oct. 1996) second growing season with sprinkler irrigation.

on atrazine mass distribution in the soil, though relatively deep movement suggestive of preferential flow, chemical nonequilibrium, and or transfer with a mobile reactive phase was observed. A two-dimensional flow and transport model, calibrated with on-site measurements, successfully predicted Br^- movement in the second year of the study in both EF and AF treatments. In addition to the benefit of on-site calibration, the success of the model may be attributed to its realistic spatial description of water placement and uptake combined with partitioning of the soil water into mobile and immobile regions. The net effect was simulations consistent with the observed spatial patterns of the surface-applied Br^-: accumulation of Br^- in the ridge and upper soil of the dry furrow positions (as these positions are water flow and diffusional sinks), and deeper interrow movement than one would expect assuming a single water content domain. The model will be used in further study to examine the effects of varying irrigation rates and chemical placement.

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