Temporal Dynamics of Preferential Flow to a Subsurface Drain

D. B. Jaynes,* S. I. Ahmed, K.-J. S. Kung, and R. S. Kanwar

ABSTRACT

We conducted a sequential tracer leaching study on a 24.4 by 42.7 m field plot to investigate the temporal behavior of chemical movement to a 1.2-m deep field drain during irrigation and subsequent rainfall events over a 14-d period. The herbicides atrazine [6-chloro-*N*-ethyl-*N′*-(1-methylethyl)-1,3,5-triazine-2,4-diamine], and alachlor [2-chloro-*N*-(2,6-diethylphenyl)-*N*-(methoxymethyl)acetamide] along with the conservative tracer Br were applied to a 1-m wide strip, offset 1.5 m laterally from a subsurface drain pipe, immediately before an 11.3-h long, 4.2-mm h^{-1} irrigation. Three additional conservative tracers, pentafluorobenzoate (PF), *o*-trifluoromethylbenzoate (TF), and difluorobenzoate (DF) were applied to the strip during the irrigation at 2-h intervals. Breakthrough of Br and the two herbicides occurred within the first 2-h of irrigation, indicating that a fraction of the solute transport was along preferential flow paths. Retardation and attenuation of the herbicides indicated that there was interaction between the chemicals and the soil lining the preferential pathways. The conservative tracers applied during the later stages of irrigation arrived at the subsurface drain much faster than tracers applied earlier. The final tracer, applied 6 h after the start of irrigation (DF), took only 15 min and 1 mm of irrigation water to travel to the subsurface drain. Model simulations using a two-dimensional, convective, and dispersive numerical model without an explicit preferential flow component failed to reproduce Br tracer concentrations in the drain effluent, confirming the importance of preferential flow. This study showed that preferential flow in this soil is not a uniform process during a leaching event.

Preferential flow of water and chemicals along soil macropores has been shown to contribute significantly to chemical losses to subsurface drain pipes (tiles) and ultimately to the degradation of surface water quality (Richard and Steenhuis, 1988; Jayachandran et al., 1994; Mohanty et al., 1998; Gächter et al., 1998; Gentry et al., 2000). For example, Kladivko et al. (1991) reported that small amounts of pesticides appeared in tile effluent within 3 wk of being applied to the soil surface and after only 2 cm of drainage. While overall mass losses in tile effluent were <1% of amount applied, pesticide concentrations in effluent often exceeded maximum contaminant levels set by the USEPA for drinking water. Southwick et al. (1992) found that >95% of the total atrazine lost in tile effluent occurred within the first 21 d after application. In a follow up study, Southwick et al. (1995) found that peak atrazine concentrations could occur in drainage from 1-m deep tiles on the first day after application. The rapid arrival to drains by a sorbing pesticide was attributed in both studies to preferential flow. Applying Cl to the soil surface, Laubel et al. (1999) also found Cl concentrations in tile water to peak within 1 h of the onset of irrigation, which they attributed to macropore flow through the soil.

Little is known about the stability of preferential flow pathways over time. Using large undisturbed soil blocks, Ogden et al. (1999) showed that spatial outflow patterns changed between irrigation events and were more variable in no-till soils where macropores are more likely to be preserved than in plow-till soils (Andreini and Steenhuis, 1990; Isensee et al., 1990). In a recent study, Lennartz et al. (1999) showed that preferential flow accounted for much of the Br mass loss to a tile at a field site over 3 yr. However, while the Br leaching pattern was consistent for the first 2 yr, a greater contribution from matrix flow was observed for the third year. They attributed this change in leaching pattern to differences in precipitation patterns shortly after Br application, with little rainfall occurring in the third year, rather than to changes in preferential pathways. The dependency of chemical transport via preferential flow on the time elapsed between chemical application and leaching has also been shown in laboratory columns (Kluitenberg and Horton, 1990; Edwards et al., 1992) and for chemigation of field soils (Jaynes et al., 1992).

Even less is known about temporal dynamics of preferential flow within a single leaching event. Are preferential flow pathways stable over time? Does macropore flow develop or change over time even if the boundary conditions remain constant? Knowing the answers to these questions would help in the development of more realistic conceptual constructs of preferential flow mechanisms and should lead to the development of more accurate simulation models of water and chemical movement where preferential flow is significant. Thus, the objectives of this study were to quantify the contribution of preferential flow to the overall chemical movement to a field drainage tile during the first few weeks after application and to investigate how the timing of chemical application relative to the start of irrigation affects the temporal behavior of preferential flow during an irrigation event.

MATERIALS AND METHODS

Field Experiment

The chemical leaching study was conducted at the Iowa State University Agronomy and Agricultural Engineering Research Center near Ames, IA. The soil at this site is predominantly Nicollet loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) in the Clarion-Nicollet-Webster soil association (Andrews and Dideriksen, 1981). Nicollet soils are somewhat poorly drained and have weak structure and moderate permeability. These soils were formed on uplands from glacial

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Abbreviations: DOY, day of year; PF, pentafluorobenzoate; TF, *o*-trifluoromethylbenzoate; DF, difluorobenzoate.

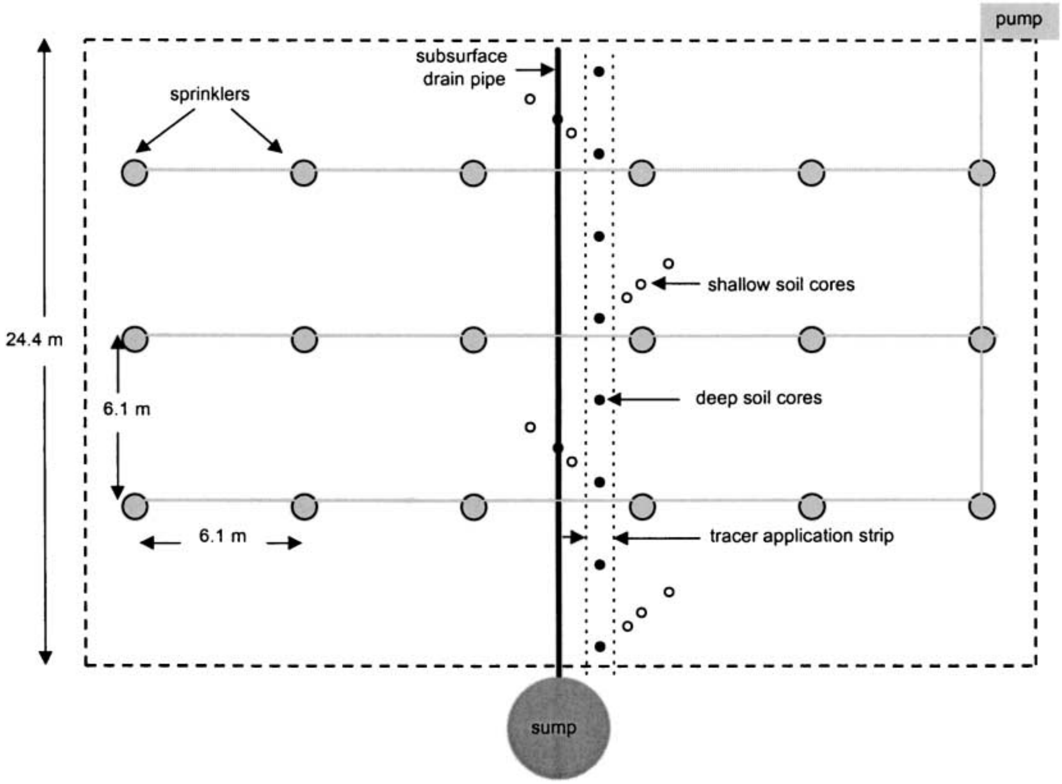

Fig. 1. Schematic diagram of irrigation plot showing location of subsurface drain pipe, tracer strip, irrigation grid, sump, and deep soil cores.

till and have a slope of 1 to 3%. Over the years, this site has been intensively investigated (Kanwar et al., 1988; Kanwar et al., 1989; Everts and Kanwar, 1990; Jayachandran et al., 1994; Mohanty et al., 1994) and water and chemical flow to the underlying tiles have been shown to be strongly influenced by preferential flow.

The experiment was conducted during the growing season of 1998 within a field plot that was under no-till continuous corn (*Zea mays* L.) management since 1984. In late June, a solid set sprinkler irrigation system (SM20H 17° nozzles, Rain Bird, Glendora, CA[1]) was installed in a regular grid pattern with a 6-m spacing covering an area 24.4-m long by 42.7-m wide, centered over a 1.2-m deep tile (Fig. 1). Corn rows and all field traffic were perpendicular to the direction of the tile. Preliminary tests had shown that this arrangement of sprinklers provided the most uniform water application pattern with the nozzles used. To prevent surface ponding, water was pumped to the sprinklers at a controlled pressure to provide a target irrigation rate of 4 mm h^{-1}. The volume of water pumped was periodically measured with a mechanical flow meter and recorded versus time, and total irrigation depth was confirmed by measuring depth of irrigation intercepted by catch cans placed in each quadrant of the plot. Rain fell on several days after irrigation and before the cessation of tile flow. Rainfall was measured onsite with a tipping bucket rain gauge.

On 1 July, a sequential tracer leaching experiment was initiated on the site. Thirty minutes before starting a continuous 10-h long irrigation, we uniformly sprayed 3.5 L of water containing 2.610 kg of NaBr, 10 L of water containing 49.45 g of atrazine, and 10 L of water containing 51.86 g of alachlor on a 1-m wide strip of ground spanning the 24.4-m length of the plot (Fig. 1). The tracer strip had previously been cleared of corn by hand to allow uniform application of tracers and irrigation. Chemical application was with a backpack sprayer and required 6 passes along the length of the strip. The center of the tracer strip was offset from the tile by 1.5 m to minimize chemical leaching through the disturbed soil above the tile, even though tile installation had occurred >10 yr before the experiment. During the irrigation three additional conservative tracers were applied to the tracer strip. Two hours after irrigation started, 9 L of water containing 995 g of PF, was sprayed onto the tracer strip in the same manner as the Br solution. A third tracer (995 g of TF in 9 L of water) and a fourth tracer (994 g of DF in 9 L of water) were sprayed onto the tracer strip 4 and 6 h after the start of irrigation, respectively. The benzoate tracers used in this experiment were the same used by Jaynes (1994), who showed them to be conservative and to have transport properties nearly identical to Br in this soil.

The center of the plot was drained by a tile located 1.2-m below surface that empties into a sump at the lower end of the plot. Flow rate from the tile was measured by pumping from the sump through a FP-5300 paddle wheel flow meter (Omega, Stamford, CT) and recording pumped volume every minute with a datalogger. Tile water samples were collected for chemical analysis by pumping a 300 mL sample from the tile outlet using a peristaltic pump autosampler (model 3700 ISCO, Lincoln, NE). A 5 min interval between water samples was used for the first 10 h after irrigation started. Thereafter, composite samples were collected consisting of either two or three subsamples collected every 10 min—increasing to every 60 min, 9 d after the start of the experiment—until 14 d after the start of irrigation. All water samples were stored in the dark at 4°C until chemical analysis.

Twenty-one days after irrigation, a 1.2-m deep soil core was taken every 3 m along the tracer strip for a total of 8 cores.

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[1] Trade and company names are used for the benefit of readers and do not imply endorsement by the USDA over similar products.

Two additional cores were taken outside the plot to test for background levels of the chemicals used. Soil cores to a depth of 0.15 m were also taken adjacent to the strip at distances of 0.5, 1, and 2 m to check for movement of tracers in surface runoff from the strip. Soil cores were collected by pushing a 38.1-mm diam. steel soil probe fitted with a removable acetate liner into the soil with a hydraulic ram. The soil core and liner were removed from the steel probe, capped on each end, and stored at −10°C until tracer extraction. The frozen soil cores were cut into 150-mm long sections, removed from the liners, thawed, and mixed by hand. The soil was weighed and added to an Erlenmeyer flask with an approximately equal mass of 0.001 *M* CaSO4 solution and shaken on a wrist shaker for 15 min. Twenty mL of solution were filtered through 0.45 μm filter paper for chemical analysis and the remainder of the sample was dried at 104°C for 48 h and weighed to determine initial water content.

Chemical Analysis

Analysis of the tracers was performed on a Dionex Series 4500i ion chromatograph (Dionex, Sunnyvale, CA) using the method described by Bowman and Gibbens (1992). For the fluorobenzoates, a SAX column (Regis Chemical Co., Morton Grove, IL) was used with a mobile phase consisting of 30 m*M* KH_2PO_4 buffer, adjusted to a pH of 2.85 with H_3PO_4, and 200 mL L^{-1} acetonitrile as an organic modifier. Flow rate was 1 mL min^{-1} and the detection wavelength was 205 nm. Bromide could not be quantified with the above procedure because of interferences caused by high NO_3 levels. Instead, Br^- was determined using a Dionex AG9 guard column (Dionex, Sunnyvale, CA) followed by an AS9 separator column (Dionex, Sunnyvale, CA). The eluting solution was 1 m*M* Na_2CO_3 and 0.75 m*M* $NaHCO_3$ at a pH of 10.4 with 12.5 m*M* H_2SO_4 used for suppression. Flow rate was 1 mL min^{-1} and electrical conductance was measured with a conductivity detector. The quantitation limit for both Br^- and benzoates was 0.1 mg L^{-1} in the extract solutions. Concentrations below the quantitation limit were assigned values of zero in all analyses. Tracer concentrations in soil samples were calculated by multiplying measured concentrations by the sum of the mass of soil water plus added $CaSO_4$ solution and dividing by the mass of soil water.

The extraction procedures for herbicides from water and soil samples are described in Hatfield et al. (1999). Water samples were passed through an SPE cartridge (Bond Elute LRC, 500 mg C-18, Varian, Harbor City, CA) and eluted with 2 mL of ethyl acetate using a Zymark robotic arm (Zymark Corporation, Hopkinton, MA) and system V controller coupled to a system consisting of a custom-built sample rack. Soil samples were extracted with methanol and water followed by cleanup on a solid phase extraction cartridge with elution using ethyl acetate (Koskinen et al., 1991). A Zymark robotic system was also used for this procedure. Herbicide samples were analyzed by gas chromatography (GC)/mass spectroscopy (MS) using a SIM Hewlet Packard 5970 (Hewlett Packard, Palo Alto, CA). Quantitation limits for both atrazine and alachlor for the conditions used were 0.2 μg L^{-1} and values below this were assigned zero.

Model Simulation

The two-dimensional model HYDRUS–2D (Šimůnek et al., 1999) was used to simulate the leaching experiment. HYDRUS–2D numerically solves Richard's equation for variably saturated soil and the convective–dispersive equation for solute transport. The modeled system was 17.4-m wide and 3.0-m deep. The 1.2-m deep tile in the middle of the plot was simulated with a boundary node surrounded by four regular square elements with hydraulic conductivities adjusted according to the electric analog approach of Vimoke et al. (1963) and Fips et al. (1986) and implemented by HYDRUS–2D. The soil was divided into four layers, 0- to 0.15-, 0.15- to 0.3-, 0.3- to 0.6-, and 0.6- to 3-m deep, and assigned hydraulic properties as described by Mohanty et al. (1994) and Mohanty et al. (1998) who measured soil hydraulic properties at this site. A longitudinal dispersivity of 15 cm from Rice et al. (1986) was used for the global dispersion process represented by the averaged soil core results. All other model parameters were estimated internally by HYDRUS–2D. Initial moisture conditions were defined by simulating the draining of the profile from an initially wet state until simulated tile discharge was within 0.1 mm h^{-1} of the measured tile discharge before irrigation started. Initial solute conditions consisted of a concentrated layer of solute within the top 1 cm of the soil profile within a 1-m wide zone whose center was offset laterally from the tile by 1.5-m. Input solute concentrations were adjusted to give a mass of solute equal to that applied in the field. Boundary conditions included no flow boundaries on the sides, specified irrigation or rainfall rates at the surface, and a bottom boundary with a variable seepage rate as permitted by the model. A total of 1551 nodes and 2944 quadrilateral elements were used with a finer discretization near the soil surface, in the zone of chemical placement, and surrounding the tile to improve descriptions of abrupt changes in pressure gradients and solute concentration.

RESULTS AND DISCUSSION

Tile Effluent

Irrigation started at day of year (DOY) 181.53 and lasted until DOY 182.00 for a duration of 11.4 h (Fig. 2). A total of 47.6 mm of water was applied at an average rate of 4.2 mm h^{-1}. Despite the low application rate, ponding of water on the soil surface was observed in the wheel-tracked interrows after 6 h of irrigation. However, little lateral movement of ponded water was observed. During the next 20 d, an additional 69.3 mm of rain fell on the site (Fig. 2).

Tile discharge responded to the irrigation ~6 h after the start of irrigation (Fig. 3 and 4) Discharge rates increased from 0.13 mm h^{-1} at the start of irrigation to

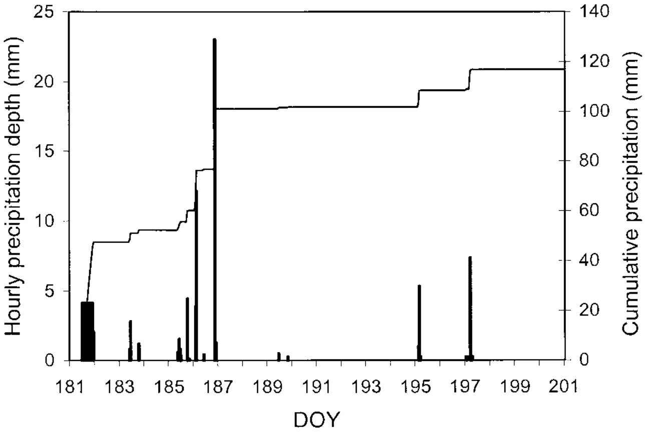

Fig. 2. Hourly and cumulative irrigation [day of year, (DOY 182)] and precipitation (DOY > 182) from the start of irrigation on DOY 181.5.

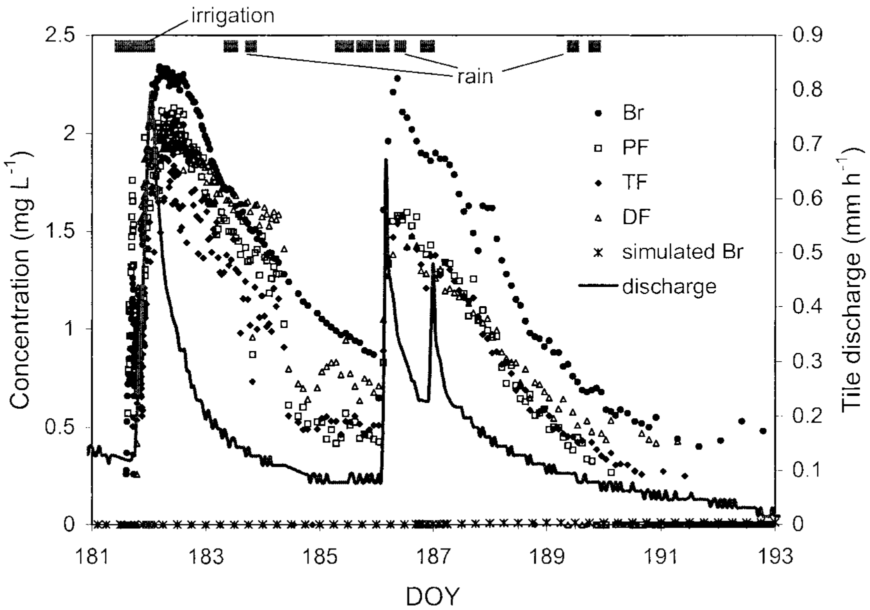

Fig. 3. Timing of irrigation and rain, tile flow rate, and conservative tracer concentrations in tile effluent versus day of year (DOY) for entire monitoring period. Also shown are simulated Br concentrations.

over 0.8 mm h^{-1} immediately after the end of irrigation. Discharge rates then decreased sharply within the first hour after irrigation ceased. Increases in discharge rate around DOY 186 and 187 were in response to several large rainfall events on those days. Tile discharge ceased by DOY 195 due to lack of additional water inputs and cumulative evaporation and drainage. Total water discharged through the tile drain equaled 44.1 mm or about 40% of the total irrigation and rain. Much of the difference between applied and drained water volumes was probably because of canopy interception and evapotranspiration during the 21-d period (135 mm of pan evaporation were measured during the 21 d at a location 0.5-km distant, R. Carlson, personal communication). However, some of the difference between water applied and discharged by the tile may be attributed to seepage below or laterally away from the tile.

The conservative tracers in the tile water all exhibited two marked peaks in concentration during the 21-d observation period (Fig. 3). Concentrations of all of the conservative tracers increased from below the detection limit of 0.1 mg L^{-1} to over 1.8 mg L^{-1}. The concentrations peaked about 1.5 d after the start of irrigation and about 12 h after tile discharge had reached its maximum rate and was in recession. This is in contrast to the behavior found by Laubel et al. (1999) for a similar irrigation experiment on a till-derived Typic Hapludalf using a Cl tracer. They found the Cl concentration reaching a maximum several hours before the maximum tile flow rather than after as found here. Later time to peak concentration than peak tile discharge was also in contrast to a leaching experiment conducted by Kung et al., 2000b on a loess derived Typic Ochraqualf with nearly identical boundary conditions to this study. They found benzoic tracers and Br concentrations reached maximums 1 to 3 h before the maximum tile discharge rate. Earlier peak concentrations for these two experiments may be because of the shallower depth to the tile drain (1- and 0.75-m deep) than in this experiment (1.2 m).

Upon reaching a maximum, the conservative tracer concentrations decreased after the cessation of irrigation. The concentrations increased and decreased again on DOY 186 and 187 when the tile discharge responded to subsequent rain events. By the end of the observation period, all of the conservative tracers except Br were again at concentrations below the detection limit of 0.1 mg L^{-1}. This parallel increase and decrease of tracer concentration and tile discharge rate was identified as *event-driven flow* by Lennartz et al. (1999) and has been identified in other studies (Kladivko et al., 1991; Jarvis et al., 1991; Laubel et al., 1999; Kung et al., 2000a,b) as a consequence of preferential flow.

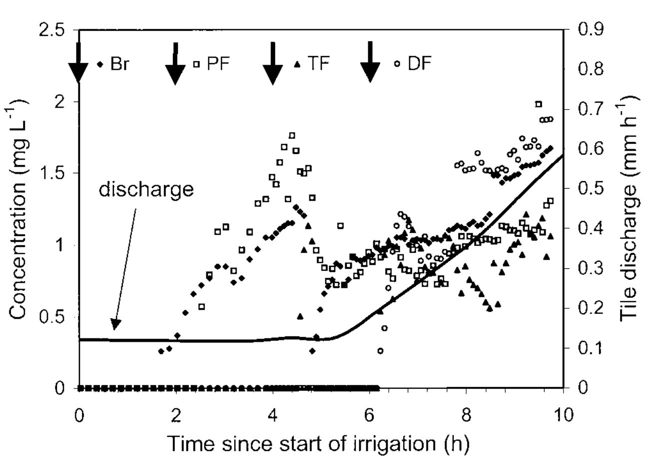

Fig. 4. Timing of conservative tracer application (arrows), tile flow rate, and conservative tracer concentrations in tile effluent versus time from start of irrigation. Only first 10 h of irrigation are shown.

Drainage results for the first 10 h of irrigation clearly show an effect of tracer application timing on tracer arrival in the tile discharge (Fig. 4). About 102 min after the start of irrigation, Br was detected in the tile effluent. First arrival of Br occurred before any measurable increase in tile discharge rate (<0.008 mm h^{-1} change). Bromide concentrations increased for 3 h then abruptly decreased even as irrigation continued, before increasing again. Assuming no lateral displacement of Br at the surface because of the lack of surface ponding, the Br contained within this first peak was equivalent to about 5 mm^2 of the 24.4-m^2 area sprayed with tracer. Thus, this first peak and breakthrough of Br could have been because of a single macropore within the tracer application strip. The subsequent increase in Br concentration would be because of the contribution of an increasing number of other preferential flow paths.

The other three conservative tracers, PF, TF, and DF, appeared in the tile effluent in the same order they were applied. To varying degrees, these tracers exhibited the same behavior as Br during the first 10 h—first increasing, then decreasing, before increasing again during the irrigation. This consistent pattern for all tracers implies that at least the most rapid pathway for chemical movement through the soil profile was active during the entire irrigation.

As the irrigation continued, tracer transport along the preferential pathways became increasingly faster. Thus, while it took a little <102 min after irrigation started before Br appeared in the tile, it took only 33 and 35 min for PF and TF, and only 15 min for DF to appear after they were applied. Assuming vertical flow only, this gives tracer velocities of between 0.000196 and 0.00133 m s^{-1}, which are in the range for tracer velocities in macropores found by Laubel et al. (1999). Moreover, the depth of applied water required to leach the tracers to the tile decreased with order of tracer application. While it took 7.1 mm of irrigation to leach Br to the tile, it took 2.3 and 2.4 mm for PF and TF, and only 1 mm of irrigation to leach DF to the tile. This is the same pattern observed by Kung et al., 2000b where markedly less time was required for tracers applied later in the irrigation to be detected in the tile discharge. The overall similarity of the leaching pattern for the different tracers while the rate of leaching accelerated during the experiment implies that while the preferential pathways may remain the same, water and tracer movement through the pathways increases as irrigation progresses and the soil becomes progressively wetter (Kung et al., 2000b).

First detection of alachlor in tile effluent occurred at the same time as Br, and atrazine was detected 10 min earlier (Fig. 5 and 6). However, because the detection limit for the herbicides was 500 times lower than for Br while only about 40 times more Br mass was applied to the plot, the detection/application ratio was about 12.5 times greater for the herbicides than for Br. Adjusting for this difference in detection sensitivity to mass applied, gives the first detection of atrazine comparable with Br about 30 min after the detection of Br and the first detection of alachlor about 40 min after the detection of Br. Thus, after accounting for the differences in application mass and detection sensitivity, herbicide transport to tile outlet was retarded compared with Br, which is expected for matrix flow given the affinity of these herbicides to sorb to soil [distribuion coefficient expressed on the basis of organic C (K_{oc}) = 91 L kg^{-1} for atrazine and K_{oc} = 157 L kg^{-1} for alachlor, Kladivko et al., 1991] and the high organic C content of these soils (20–30 g kg^{-1}, Cambardella et al., 1994). Apparently, the herbicides also interacted with the soil along the preferential flow paths and were thus retarded with respect to Br. In addition, atrazine concentrations were about two times higher than alachlor in the tile effluent throughout the monitoring period, even though slightly more alachlor was applied to the tracer strip than atrazine. In other field and watershed studies where similar soils occur, the same trend has been found with atrazine measured in subsurface drains at appreciable concentrations (>3 μg L^{-1}), while alachlor is rarely detected (Jayachandran et al., 1994; Jaynes et al., 1999;

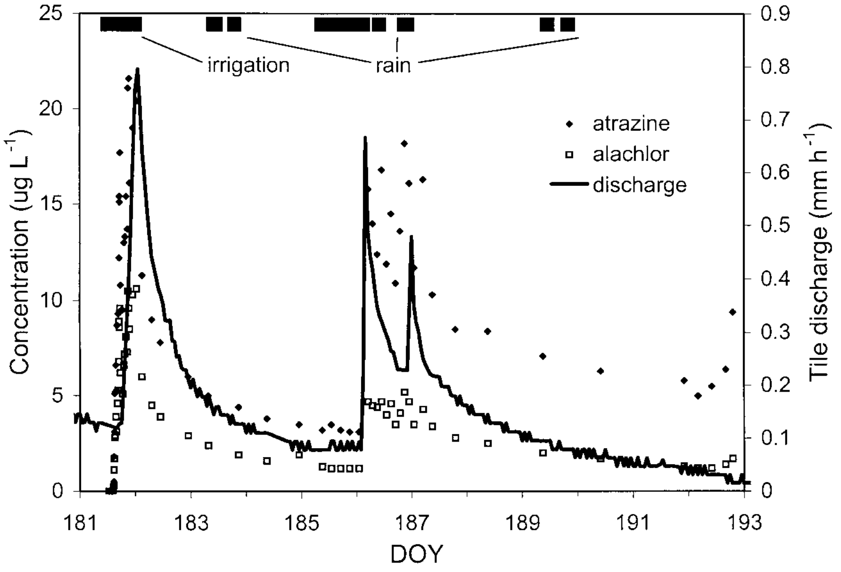

Fig. 5. Timing of irrigation and rain, tile flow rate, and herbicide concentrations in tile effluent versus day of year (DOY) for entire monitoring period.

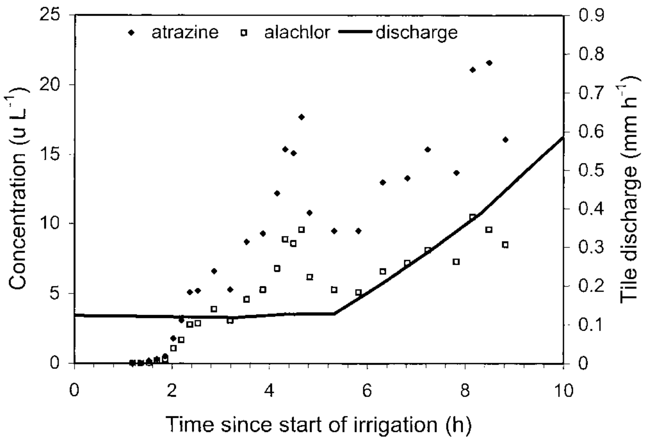

Fig. 6. Tile flow rate and herbicide concentrations in tile effluent versus time since start of irrigation. Only first 10 h of irrigation are shown.

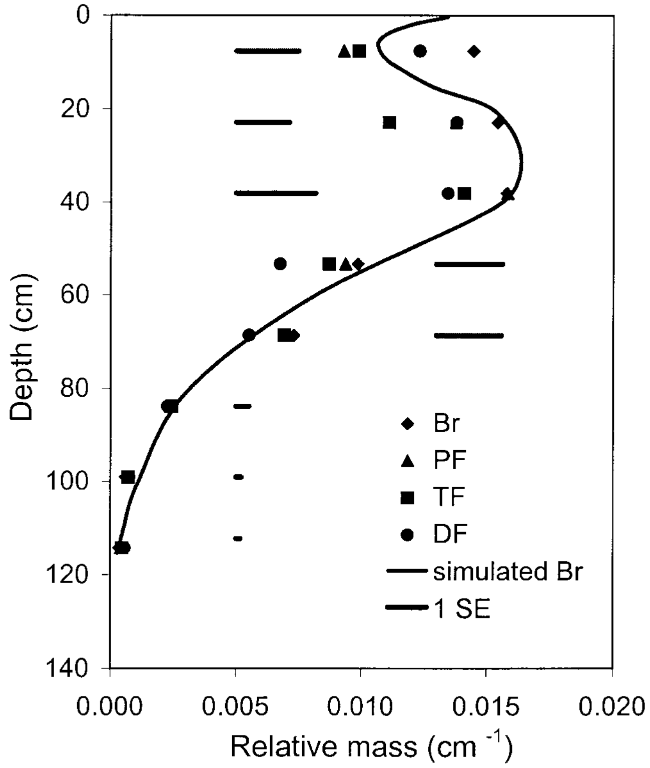

Fig. 7. Average relative mass recovered and standard error of mean (SE) of conservative tracers and simulated Br mass in soil profile 20 d after application.

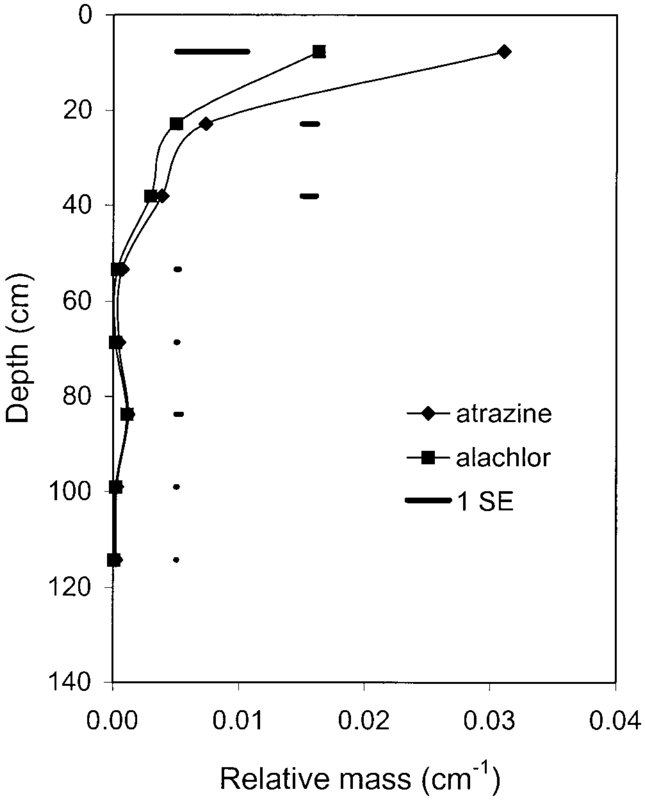

Fig. 8. Average relative mass and standard error of mean (SE) of recovered herbicides in soil profile 20 d after application.

Moorman et al., 1999). This difference was attributed by Kladivko et al. (1991) to the higher soil adsorption affinity for alachlor versus atrazine.

Thus, even though the herbicides moved rapidly along preferential pathways in this study, there was sufficient interaction between the herbicides and the soil to retard herbicide movement. This is in contrast to the results of Kung et al. 2000a who found rhodamine WT to appear in tile discharge at nearly the same time that Br or Cl appeared in a leaching study similar to this one conducted in New York on a sandy loam Aeric Epiaqualf. Greater interaction between the herbicides and soil at the Iowa site may be because of the higher organic and clay fraction of this soil compared with the New York soil and the greater K_{oc} for the herbicides compared with rhodamine WT (~1.5 L kg^{-1}).

The overall breakthrough patterns of the herbicides in the tile effluent were very similar to Br as well—increasing during the irrigation, decreasing during recession after irrigation ended, and again increasing and decreasing during the rainfall events of DOY 186 to 187 (Fig. 5). Variations in herbicide concentrations in tile discharge during the first 10 h of irrigation also mimicked Br (Fig. 6). Herbicide concentrations first increased, then decreased before continuing to increase during the first 6 h of irrigation. This early nonmonotonic behavior common to all of the chemical tracers represents transport along common preferential flow paths.

Soil Residues

Recovered chemical mass per unit depth was computed for each of the eight soil cores and averaged for the eight soil depth increments (Fig. 7 and 8). For the first three conservative tracers applied, the greatest mass was recovered in the 30- to 45-cm depth increment. The last conservative tracer applied, DF, had the greatest amount of mass recovered in the 15- to 30-cm depth increment. No PF, TF, or DF was recovered in the soil samples collected outside of the tracer strip. Bromide recovered outside the tracer strip was <0.01 g g^{-1} of the Br recovered from the surface layer within the tracer strip. Thus, little lateral movement of tracer in runoff occurred either during the low intensity irrigation or subsequent rainfall events.

Considerable spreading through the soil profile below the tracer strip was evident for the conservative tracers (Fig. 7). A relatively greater amount of Br mass than benzoate tracers was recovered in the top soil layer. This may have been because of Br being applied before irrigation rather than during the irrigation as with the other tracers. Kluitenberg and Horton (1990) and Jaynes et al. (1992) clearly demonstrated that spraying a conservative tracer on the soil surface immediately before irrigation allowed some of the tracer to enter less mobile soil pore space and thus leach to a shallower depth during irrigation than a tracer applied with the irrigation. The same process may have happened in this study, keeping more of the Br in the surface layer.

Herbicide mass recoveries demonstrated a different pattern than the conservative tracers (Fig. 8). Herbicide mass decreased exponentially with depth except for a slight increase in the 91- to 106-cm layer. This increase may have been because of a change in soil texture or bulk density, although earlier investigations at this site have not reported differences at this depth (Kanwar et al., 1989). The pattern of herbicide mass residues in the soil profile are consistent with a sorbing chemical, where most of the chemical is sorbed to the surface layers where soil organic C is highest. The herbicide residue data is in contrast to the tile effluent results where the herbicides arrived very rapidly. Apparently, most of the herbicide and conservative tracers moved within the soil matrix in a manner consistent with matrix flow in a porous medium without preferential flow paths. However, a small portion of the chemicals ($<1\%$) moved rapidly through preferential pathways and arrived at the tile in <2 h.

Total mass recoveries of the chemical tracers used were computed from the measured soil residues and tile effluent losses. Mass recoveries in the soil were 1.01 kg kg^{-1} for Br, 0.90 kg kg^{-1} for PF, 0.83 kg kg^{-1} for TF, 0.84 kg kg^{-1} for DF, 0.64 kg kg^{-1} for atrazine, and 0.37 kg kg^{-1} for alachlor. Mass recoveries for the conservative tracers were better than observed in similar field experiments (Jaynes et al., 1992; Starr and Glotfelty, 1990). Mass recoveries for the herbicides were considerably lower than the conservative tracers because of dissipation of the herbicides during the 20 d between application and recovery. Adjusting the expected mass remaining after 20 d using a 60-d half-life for atrazine and a 15-d half-life for alachlor (Baker et al., 1992), gives mass recoveries in the soil of 0.80 kg kg^{-1} for atrazine and 0.94 kg kg^{-1} for alachlor which are comparable with the conservative tracers.

Mass recovered in tile discharge was considerably lower than in the soil, equaling 0.03 kg kg^{-1} for Br, 0.05 kg kg^{-1} for PF and TF and 0.07 kg kg^{-1} for DF. Less relative mass was recovered for Br perhaps because it was applied before irrigation started as noted earlier. Relatively more DF was recovered in the tile discharge, which parallels the more rapid travel time of this tracer which was applied last. Greater loss of DF in tile discharge may have been because of greater transport along preferential pathways during the latter stages of the irrigation.

Herbicide mass recoveries in the tile effluent were considerably lower than the conservative tracers. Mass recovery of atrazine in the effluent was 0.007 kg kg^{-1} and 0.003 kg kg^{-1} was recovered for alachlor. Kladivko et al. (1991) also observed more atrazine leaching to subsurface drains than alachlor and attributed it to the greater adsorption affinity of alachlor to soil. Thus, although the herbicides traveled along preferential flow pathways quickly, interaction between the herbicide and the soil did occur.

Overall mass recoveries for Br were 1.04 kg kg^{-1}, 0.94 kg kg^{-1} for PF, 0.88 kg kg^{-1} for TF, and 0.91 kg kg^{-1} for DF after summing soil residues and losses in tile effluent. Adjusting for degradation of the herbicides gives overall mass recoveries of 0.81 kg kg^{-1} for atrazine and 0.94 kg kg^{-1} for alachlor. These recoveries are excellent compared with other field studies given the uncertainties in half-lives and the other possible dissipation pathways such as volatilization that were not considered. Thus, comparable mass recoveries were found for all of the chemical tracers used. However, relatively more mass was lost in tile effluent for the conservative tracers than for the herbicides. Nevertheless, during no-till corn production, atrazine leaching to tiles in this soil has been found to periodically exceed 3 $\mu g\ L^{-1}$, the maximum contaminant level set for drinking water by the US EPA, with the transport process attributed to preferential flow within the soil (Jayachandran et al., 1994).

Modeling

The rapid arrival of the chemical tracers can only be explained by the presence of preferential pathways in this soil. However, the pattern of increasing and decreasing chemical concentration in tile effluent in response to the irrigation and rainfall events was somewhat surprising. This pattern may have been the result of the geometry of the experimental design—a narrow tracer strip offset from above the tile within a much larger irrigated and drained area subject to intermittent irrigation and rain. A simulation using the two-dimensional, variably saturated, convective–dispersive, numerical model HYDRUS–2D (Šimůnek et al., 1999) was used to test whether the patterns observed were due in some way to the geometry or boundary conditions of the experimental design.

Model results for the residual mass of Br in the soil under the center of the tracer strip 20 d after tracer application are included in Fig. 7. Overall, the simulated mass profile matched the measured profile within observation error except near the surface where more Br was found in the field. The simulated water discharge from the tile reproduced the measured patterns (results not shown), but predicted ~50% greater total volume discharged over the first 14 d than measured which should have contributed to greater predicted chemical leaching. However, even with more drainage, the simulated concentrations of Br in the tile effluent were much less than those measured (Fig. 3). Inability of the convective–

dispersive type model to reproduce the tracer concentration pattern observed in the tile effluent while matching soil residue data well, confirms that a small portion of the tracers were leached via preferential pathways—a mechanism not included in the model—and that observed effluent concentration patterns were a consequence of preferential leaching within the soil profile.

SUMMARY AND CONCLUSIONS

We conducted a sequential tracer, field leaching study to investigate the temporal behavior of preferential flow during a 21-d period. Breakthrough of conservative tracers and herbicides to a tile drain at 1.2-m depth occurred in <2 hr after the start of irrigation. These rapid transport times indicate that a fraction of chemical transport is via preferential flow paths. Model simulations using a two-dimensional, convective–dispersive model reproduced soil residue patterns for Br well but not Br concentrations in tile effluent. Lack of model agreement with observed effluent concentrations reenforces the conclusion that solutes in tile discharge were not because of matrix flow.

Herbicides applied with Br also arrived at the tile within the first 2 h of the irrigation indicating transport via preferential pathways. However, relatively less herbicide mass and comparatively later arrival times of herbicides than Br indicated that there was interaction between the herbicides and the soil along the preferential pathways. Conservative tracers applied during the latter stages of irrigation arrived at the tile faster than tracers applied either immediately before or during early stages of the irrigation. The last tracer, applied 6 h after the start of irrigation, took only 15 min and 1 mm of irrigation water to travel the 120 cm between the soil surface and the tile. Overall, transport of solutes along preferential pathways appears complicated by the existence of pathways with different solute transport velocities and by a temporal trend of increasing transport velocities as irrigation progresses. These characteristics of preferential flow need to be incorporated into conceptual and numerical models of solute transport in these soils.

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Spatial Analysis of Machine-Wheel Traffic Effects on Soil Physical Properties

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ABSTRACT

Infiltration in irrigation furrows exhibits spatial variation from furrow to furrow within a field. One major contributing factor is the effect of multiple levels of machine-wheel traffic on soil physical properties. The purpose of this study was to determine the effect of machine-wheel traffic levels within equipment passes on a field basis. Variations in satiated hydraulic conductivity (K_s), penetrometer resistance (R_p), and bulk density (ρ_b) due to nine, eight-row equipment passes were studied in three transects, crossing 72 furrows perpendicular to crop rows, on a Hord silt loam (fine-silty, mixed, mesic, Pachic Haplustoll). Mean values, spatial patterns, and regression relationships between properties were determined. Spectral analysis was used to fit cosine curves to property data that showed significant periods at 2.7, 8.0, and 72 furrows. An additional period of 24 furrows was seen in the R_p and ρ_b data. All properties tested showed significant mean differences due to wheel traffic from equipment passes. Within the equipment passes it was possible to further separate treatment means for all soil properties. Results in wheel tracked furrows were different from all other treatments. Linear regression of log K_s and R_p in a 72-furrow transect shows 58% of log K_s variability is explained by changes in R_p. Predicted vs. measured log K_s in two transects shows predictions somewhat high, although the slope of the linear regression is 0.95, nearly parallel to a 1:1 line.

An understanding of infiltration variability on a field basis is needed for efficient management of surface irrigation systems. Primary sources of this variability are soil infiltration characteristics, which are both temporally and spatially varied, and the decreasing infiltration opportunity time with water advance along furrows (Tarboton and Wallender, 1989; Letey et al., 1984). Maximum application efficiency is inversely related to the magnitude of furrow infiltration variability; differences in infiltration are usually highest during the first irrigation event.

Furrow-to-furrow infiltration variability causes nonuniform water infiltration, furrow stream advance rates, and runoff rates. Both infiltration rate and the infiltration opportunity time determine infiltration depth at any location. Large spatial variability in infiltration has been established in many studies; coefficients of variation (CV) commonly range between 20 and 60%. The consequences of furrow-to-furrow inflow and infiltration variability are excessive runoff and deep percolation, while a portion of the field receives inadequate water (Trout, 1990).

One cause of variation in soil infiltration rates is wheel traffic patterns (Voorhees, 1977; Allen and Musick, 1997). Hillel (1980) stated that soil compaction in modern agriculture has been most commonly caused by machinery wheels, tracks, and soil-engaging tools. Research has shown that it is common for water infiltration in wheel-tracks to be reduced to approximately 50% of the infiltration without traffic (Lindstrom and Voorhees, 1980; Young and Voorhees, 1982; Ankeny et al., 1990; Allen and Musick, 1997). Kemper et al. (1982) measured reductions in infiltration rates from 12 to 80%. Kemper et al. (1982) and Allen and Musick (1997) found water content of the soil at the time of compaction had a significant impact on infiltration, as did the compacting loads. Ankeny et al. (1990) concluded that compaction primarily destroys the large pores. Allen and Musick (1997) found water advance rates in traffic furrows were twice as large as rates in nontraffic furrows, requiring extra management to avoid excessive runoff.

Lindstrom et al. (1981) found after 10 yr of wheel traffic, increased bulk density (ρ_b), and associated reduction of soil porosity in wheel traffic interrows resulted in lower saturated hydraulic conductivity. Young and Voorhees (1982) also found wheel traffic compaction can significantly reduce total pore volume and saturated hydraulic conductivity.

Wheel traffic can increase penetrometer resistance (R_p) to a depth of 30 cm (Voorhees et al., 1978, 1986; Voorhees, 1979). Young and Voorhees (1982) found increases in R_p as deep as 45 cm below wheel tracks. Because compaction decreases the total porosity of the

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