Temporal Dynamics of Preferential Flow to a Field Tile

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Abstract
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Keywords
herbicides, conservative tracers, tile drainage

Disciplines
Agriculture | Bioresource and Agricultural Engineering | Water Resource Management

Comments
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Introduction

Preferential flow of water and chemicals along preferential flow paths has been shown to contribute significantly to chemical losses to subsurface drain pipes (“tiles”) and ultimately to the degradation of surface water quality (Gentry et al., 2000). Little is known about the stability of preferential flow pathways over time. 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 plow-till soils. Kluitenberg and Horton (1990) demonstrated the dependency of preferential flow on the timing of chemical and water application in laboratory soil columns and Jaynes et al. (1992) demonstrate the same effect in field soils. Much less is known about the temporal dynamics of preferential flow within a single leaching event. The objectives of this study were to quantify the contribution of preferential flow to the overall chemical movement to a field tile during the first few weeks after application and to see how the timing of chemical application relative to the start of irrigation affects preferential flow during an irrigation event.

Materials and Methods

The 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 Hapludoll). Over the years, this site has been intensively investigated (Everts and Kanwar, 1990; Jayachandran 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 within a field plot that had been under no-till continuous corn management since 1984. A solid set sprinkler irrigation system 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 field tile. Water was pumped to the sprinklers to provide a target irrigation rate of 4 mm hr⁻¹ and the volume of water was periodically measured with a mechanical flow meter and recorded versus time. Rainfall before and after the irrigation was measured onsite with a tipping bucket rain gage.

On July 1, a sequential tracer leaching experiment was initiated on the site. Thirty minutes before starting

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irrigation, we uniformly sprayed 3.5 L of water containing 2.610 kg of NaBr, 10 L of water containing 49.45 g of the herbicide atrazine, and 10 L of water containing 51.86 g of the herbicide alachlor on a 1-m strip of ground spanning the 24.4 m length of the plot. The tracer strip had previously been cleared of corn by hand to allow uniform application of tracers and irrigation. The tracer strip was offset laterally from the tile by 1.5 m to minimize potential chemical leaching through the disturbed soil above the tile. Two hours after irrigation started, 9 L of water containing 995 g of a second conservative tracer, pentafluorobenzoate (PF), was sprayed onto the tracer strip in the same manner as the Br solution. A third conservative tracer (995 g of o-trifluoromethylbenzoate, TF, in 9 L of water) and a fourth conservative tracer (994 g of difluorobenzoate, DF, in 9 L of water) were sprayed onto the tracer strip 4- and 6-hr after the start of irrigation, respectively. The benzoate tracers used in this experiment have been shown to be both conservative and to have transport properties nearly identical to Br in this soil (Jaynes, 1994).

The center of the plot was drained by a tile located 1.2-m below surface that emptied into a sump at the lower end of the plot. Flow rate from the tile was measured continuously and tile water samples were collected periodically for chemical analysis with an autosampler. 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. The soil cores were cut into 150-mm long sections and analyzed for chemical residues using an IC for conservative tracer analysis and a GC/MS for herbicide analysis following standard methods.

**Results and Discussion**

Irrigation started at DOY 181.5 and lasted until DOY 182.06 (11.3 hr). A total of 47.6 mm of water was applied at an average rate of 4.2 mm hr\(^{-1}\). During the next 20 days, an additional 69.3 mm of rain fell on the site. Tile discharge responded to the irrigation approximately 6 hr after the start of irrigation (Fig. 1 and 2) and decreased sharply starting 1 hr after irrigation ceased. Increases in drainage rate around DOY 186 and 187 were in response to several large rainfall events on those days. Drainage ceased by DOY 195 due to lack of additional water inputs and cumulative evaporation and drainage. Total water drained from the plot equaled 44.1 mm or about 40% of the total irrigation and rain. Much of the difference can be explained by canopy interception of rain and evaporation during July conditions, but some of the difference was probably due to seepage below the tile or laterally away from the tile, out of the plot.

The conservative tracers in the tile water all exhibited two marked peaks in concentration during the observation period (Fig. 1). The concentrations peaked about 1.5 d after the start of irrigation and about 12 hr after tile discharge had reached its maximum. After reaching a maximum, the conservative tracer concentrations decreased after cessation of the irrigation until the tile discharge increased again in response to subsequent rain events, when the concentrations again increased then declined in response. By the end of the observation period, all of the conservative tracers except Br were at concentrations below the detection limit of 0.1 mg L\(^{-1}\).

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About 102 min after the start of irrigation, Br was
detected in the tile effluent (Fig. 2). First arrival of Br occurred before any measurable increase in drainage rate due to the irrigation. Bromide concentrations increased for 3 hr then abruptly decreased even as irrigation continued, before increasing again. 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 first increasing, then decreasing, before increasing again during the irrigation. This consistent behavior for all tracers implies multiple classes of preferential pathways for chemical movement through the soil profile, with each class having its own characteristic travel time for these conditions.

As the irrigation continued, tracer transport along preferential pathways became increasingly faster. Thus, while it took a little less than 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. 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 water applied 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.

Initial detection of alachlor in tile effluent occurred at the same time as Br, and atrazine was detected 10 min earlier (Fig. 3). However, the detection-to-application ratio for the herbicides was about 25 times greater than for Br in this experiment. Adjusting for this ratio means that detection of herbicide concentrations comparable to Br occurred 35 min after Br for atrazine and 45 min after Br for alachlor. Retardation of herbicide movement in the soil matrix compared to Br is expected given the affinity of these herbicides to sorb to soil (K_{oc} = 91 L kg⁻¹ for atrazine and = 157 L kg⁻¹ for alachlor) and the high organic carbon content of these soils (20 - 30 g kg⁻¹). Apparently, the herbicides were retarded with respect to Br along the preferential pathways. 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. Monitoring studies of fields and watersheds where these soils occur have shown the same trend, with atrazine measured in subsurface drains at appreciable concentrations (> 3 µg L⁻¹), while alachlor was rarely found (Jaynes et al., 1999) and is attributed by Kladivko et al. (1991) to the higher adsorption affinity of alachlor. 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 and reduce herbicide movement.

**Soil Residues.** Chemical mass per unit depth was computed for each of the eight soil cores and averaged for the eight soil depth increments (Fig. 4). For the first three conservative tracers applied, the greatest mass was recovered in the 30 to 45 cm depth increment. For the last conservative tracer applied, DF, the greatest amount of mass was recovered in the 15 to 30 cm depth increment. Considerable spreading throughout the soil profile below the tracer strip was evident for the conservative tracers (Fig. 4a). A relatively greater amount of Br mass than benzoate tracers was recovered in the top soil layer. This may have been caused by Br being...
applied before irrigation started 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.

Herbicide mass recoveries demonstrated a different pattern than the conservative tracers (Fig. 4b). Herbicide mass decreased exponentially with depth. 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 carbon 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 convective - dispersive behavior in a porous media. However, a small portion of the chemicals (< 1%) moved rapidly through preferential pathways and arrived at the tile in less than 2 hr. 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. 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. Relatively more mass was lost in tile effluent for the conservative tracers (> 3%) than for the herbicides (< 1%). Nevertheless, herbicide leaching to tiles in this soil, primarily by the same preferential mechanisms illustrated in this study, is of sufficient magnitude under normal herbicide management practices to be of environmental and health concern (Jayachandran et al., 1994).

Conclusions

Rapid transport times of conservative tracers to a tile drain indicate that a small fraction of chemical transport is through preferential flow paths. Herbicides applied with Br also arrived at the tile within the first 2-hr of the irrigation indicating a fraction of the 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. Transport along the preferential flow pathways appeared to accelerate as the irrigation progressed with the last tracer applied taking only 15 min and 1 mm of irrigation water to travel the 1.2-m distance between the soil surface and the tile. Overall, transport of solutes along preferential pathways appears complicated by the existence of pathways with varying solute transport velocities and by a temporal trend of decreasing transport times as the irrigation progresses. These characteristics of preferential flow need to be addressed in conceptual and numerical models of solute transport in these soils.

References

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