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Preferential Paths of Flow under Conventional and Conservation Tillage

M.S. ANDREINI and T.S. STEENHUIS

Department of Agricultural and Biological Engineering, Cornell University, Ithaca, NY 14853 (U.S.A.)

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ABSTRACT

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Preferential solute movement through conservation and conventional tillage soil profiles was investigated by applying bromide and dye tracers to undisturbed soil columns at an application rate which did not create ponding or runoff. In both tilled and untilled soils preferential flows were established with much of the soil well below saturation. Spatial variations in the solute flows were observed by monitoring the column effluent flowing from a grid lysimeter. Dye in effluent flowing at lower water velocity was more retarded than dye traveling in higher velocity effluent.

INTRODUCTION

Pesticides and other agricultural chemicals are now acknowledged as potential groundwater pollutants and increasing concern about the presence of these chemicals in the environment has led to stricter regulation of their use. Water is nature's primary vehicle for the transport of dissolved chemicals and researchers are refining their methods for analyzing the movement and fate of pesticides in the soil to minimize the risks of groundwater contamination. Most conventional transport models are based on the convective-dispersive equation which, in most formulations, models an average flow path (Parlange et al., 1988). These models are unable to predict spatial and temporal variations of pesticide concentration sometimes found in the groundwater. These models do not explicitly consider flow through preferential paths such as wormholes, rootholes and cracks. An awareness of the phenomena was first voiced by Lawes et al. in 1882. During studies at Rothamstead he and his colleagues observed preferential flows, then called "channel" drainage, preceding the matric or "general" drainage from the saturated body of the soil. Horton (1936) asserted

that drying cracks, earthworm, insect and root hair perforations enhance infiltration. A 1940, USDA study of 68 soils found an association between infiltration rate and noncapillary porosity (Free et al., 1940). Despite an awareness that macropores and preferential flows played a role in water and solute movement, they were largely ignored for many years.

Tillage practices may have a profound effect on the amount and character of the short-circuiting observed. Conservation tillage (no-till) has been recommended as a palliative for pesticide contamination of surface water because it has been demonstrated to decrease pesticide loss via surface water by reducing runoff and its attendant erosion (Baker and Johnson, 1979). Because plowing is minimized under conservation tillage there are more continuous macropores and other preferential paths reaching directly from the surface deep into the subsoil. Conventional tillage destroys the structure of the surface soils, mixing the plow layer and covering the macropore's connection to the surface. Ehlers (1975) found that the number and percentage volume of earthworm channels near the surface (in the top 20 cm) of a plot under no-till cultivation for four years was twice that of a similar plot which had been continuously cultivated in the conventional manner. These macropores are capable of increasing the infiltration of water and dissolved chemicals (Bouma, 1976; Germann et al., 1984; Richard and Steenhuis, 1988). It is thought that rapid solute fluxes through these preferential paths bypass or short-circuit the biologically active rootzone reducing time for degradation of these potentially harmful chemicals before they reach the groundwater. As yet, there are inconclusive data regarding the influence of preferential flow through macropores on pesticide migration to groundwater (Brinsfield et al., 1987; Ritter et al., 1987). If by the year 2010 half of all the farm land in the United States is under conservation tillage (Mannering et al., 1987), its effect on groundwater contamination warrants further examination. There may be a tradeoff to be made between the contamination of our ground or surface waters. This study had two objectives. The first was to assess the effect of preferential flows on solute movement and the second was to evaluate the effect of tillage practices on those preferential flow or short-circuiting mechanisms.

MATERIALS AND METHODS

At Cornell University's Willsboro Experimental Research Farm, two experimental corn plots were established on a field which was the site of previous investigations of water and solute movement in structured soils (Richard and Steenhuis, 1988). The soil is mapped as a somewhat poorly drained Rhinebeck variant fine sandy loam formed in lacustrine sediments of reworked glacial till (Olson et al., 1982). Table I describes the soil they found in pit no. 11 adjacent to the field. This field had not been tilled for more than 20 years. The northern plot (approximately 0.33 ha) was conventionally tilled and planted in corn

TABLE I

A profile description of the somewhat poorly drained Rhinebeck variant fine sandy loam soil (Pit 11) formed in lacustrine sediments over reworked glacial till on the Willsboro Farm in Essex County (the pedon is a member of the Fine, Illitic, Mesic Aeric Ochraqualfs family)

Ap 0–21 cm	Very dark grayish brown (10 YR 3/2) fine sandy loam; grayish brown (10 YR 5/2) dry; moderate medium granular structure; friable; many roots; 10% coarse fragments; neutral, pH 7.1; abrupt smooth boundary.
B21t 21–42 cm	Brown (10 YR 5/3) clay loam; common medium distinct dark brown (7.5 YR 4/4) mottles; moderate fine subangular blocky structure; firm; common roots; thin patchy clay film on ped faces; very pale brown (10 YR 7/3) silt coats on ped faces; 3% coarse fragments; neutral, pH 6.7; gradual wavy boundary.
B22t 42–64 cm	Dark brown (7.5 YR 4/2) clay; few fine faint brown (7.5 YR 4/4) mottles; strong medium subangular blocky structure; firm; few roots; thin continuous clay films on ped faces; neutral, pH 6.8; clear wavy boundary.
IIB3 64–99 cm	Dark brown (7.5 YR 4/4) gravelly loam; many coarse prominent grayish brown (10 YR 5/2) and dark yellowish brown (10 YR 4/6) mottles; weak coarse subangular blocky structure; firm; 15% coarse fragments; mildly alkaline, pH 7.6; gradual wavy boundary.
IIC 99+ cm	Dark brown (10 YR 4/3) gravelly fine sandy loam; few fine faint dark grayish brown (10 YR 4/2) mottles; moderate coarse angular blocky structure; firm; 15% coarse fragments; calcareous, pH 8.6.

and the southern plot (approximately 0.40 ha) was planted in corn using conservation tillage practices. Centered on the boundary between the plots was a 20 meter wide buffer zone composed of one half conservation tillage and one half conventional tillage. This buffer was reserved for destructive sampling: dye tests, core removal and sample borings.

Large soil cores were extracted from the buffer zone and brought to the laboratory. The cores were exhumed in late August shortly after the corn had been harvested and were stored for nine months before they were tested. They were 35 cm × 35 cm square, ranging in depth from 34 cm to 46 cm. Larger than usual cores were taken to capture the representative examples of these macroporous, structured, soils. Only large undisturbed samples yield representative values when measuring K_{sat}. A sample should contain more than some minimum number of elementary structural units (Bouma, 1980). The soil in these fields is described as having moderate fine subangular blocky structure (see Table I). The size of subangular blocky structures is defined as 5–10 mm in diameter (Olson, 1981). A sample with a 35 cm × 35 cm cross section has over 1,000 structural units per centimeter depth. To remove the samples a square trench was excavated exposing a column of soil 1.2 m on a side and 1.0 m tall. The column was carefully trimmed with a shovel to the final, 35 cm × 35 cm, dimension. Prefabricated plywood boxes were slipped over the columns and a

plaster of paris seal poured between the box and the soil sample. The samples were sheared off at the base by gently pushing the boxes horizontally.

In the laboratory, the pair of cores chosen to be tested was placed on grid lysimeters. The free drainage grid lysimeters were constructed of short (5 cm deep) 2.5 and 5 cm square steel tubes brazed side by side to form flow through cells in grid pattern. There were two courses of 5 cm cells surrounding a six by six array of 2.5 cm cells at the center of the grid (see Fig. 1). The grid was filled with chipped limestone (approximately 1 cm in diameter) before the soil column was mounted on top of it. The limestone prevented the moist soil at the bottom of the columns from collapsing into the cells and plugging the funnels. It also helped to prevent the water from running laterally along any irregularities on the soil column bottom before dropping into the grid. The bottoms of the columns were trimmed flat and picked clean to minimize the effects of any smearing or disturbance of the surface during the shipment. A small funnel at the bottom of each cell of the grid lysimeter was attached to a length of plastic tubing leading to an individual sample bottle so that the flow from each cell (referred to here as local flow) could be collected, weighed and assayed for bromide and dye. A total of 152 cells (76 for each tillage regime) were sampled at each interval (approximately daily) for the duration of the tests.

A rainfall simulator was used to water the pair of soil cores simultaneously at an application rate which did not create ponding or runoff (2 cm per day). Even spatial distribution of the "rainfall" was considered important to elimi-

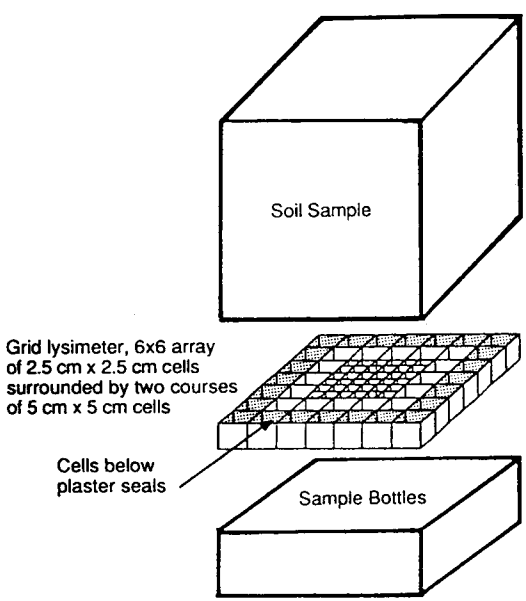


Fig. 1. Grid lysimeter.

nate the possibility of inducing preferential flow under areas of greater rainfall intensity. Induced preferences would obscure meaningful conclusions about the influence of preferential flows through macropores on the spatial distribution of the solutes exiting the column. The rainfall simulator consisted of a trolley riding back and forth on a beam which was itself riding back and forth on a set of rails perpendicular to the axis of the beam. Water dripped from two eighteen gauge catheters (one for each soil sample) mounted on the trolley. The water was pumped through plastic hoses to the catheters by a pair of peristaltic pumps. Each catheter traversed its soil column's entire surface as a result of the combination of the two perpendicular oscillations. This system was capable of delivering continuous, slow, even "rainfall" to the samples.

After the rainfall simulator design was finalized, uniformity tests were conducted. To measure uniformity, 25 plastic bottles, 19 cm deep, with 4.52 cm diameter mouths were placed in a five-by-five array where the soil cores would eventually be placed. After the rainfall simulator was run for several hours, the water in each bottle was measured. The simulator's performance was evaluated by calculating the uniformity coefficient,

$$C_u = 100 * \{1.0 - (x/mn)\}, \quad (1)$$

where n is the number of observations, m is the mean value of the observations and x is the deviation of the individual observation from the mean value (Christiansen, 1942). Uniformity Test no. 1 was conducted immediately before the cores were sprinkled. To assure ourselves that the simulator continued to deliver uniform "rain" uniformity Test No. 2 took place immediately after the sprinkling ended. A summary of the results of rainfall uniformity tests is presented in Table II. This rainfall simulator design proved to be very reliable; it can continuously for months. The rainfall rate remained constant at extremely low application rates. More importantly, the spatial and temporal distribution of the rainfall was very even.

Two tracers were used in these experiments: bromide and FD&C Blue Dye

TABLE II

Rainfall simulator uniformity tests

Test number	Column	Date	Flow rate (cm/day)	Uniformity coefficient (%)
Before experiments				
1	No-till	5/19/88	2.0	94.6
1	Tilled	5/19/88	1.9	90.7
After experiments				
2	No-till	6/6/88	2.0	96.6
2	Tilled	6/6/88	1.9	94.4

No. 1. Bromide was chosen to measure the water's velocity because bromide anions move at approximately the same rate as the water through negatively charged clay soils. A commercial food coloring, Warner Jenkinson Company, FD&C Blue Dye no. 1, was chosen as a safe surrogate for adsorbed solutes (specifically pesticides). Food coloring is easily handled and the concentration of a dye solution can be measured quickly with a spectrophotometer.

Since the nature of the adsorption of a specific organic chemical to a specific media is difficult to predict, small scale packed column studies were conducted to understand the character Blue Dye No. 1 adsorption to Willsboro's soil and to help choose the appropriate dye and bromide concentrations for the undisturbed column studies. These preliminary tests indicated that a 1.0% dye solution (by weight) had a retardation factor of approximately 5.6 when pumped through a column of soil particles sieved to a size between 0.425 mm to 0.890 mm. During these tests the bromide breakthrough curves were very symmetrical, but the dye curves exhibited tailing. Since the bromide exhibited very little tailing this asymmetry is probably an artifact of the adsorption–desorption process of the dye and not the result of dispersion. The breakthroughs showed no anomalous behavior which would arouse the suspicion that density effects were a major concern. As a result of these experiments and previous field experience (Richard, 1988b) a 0.1 *M* bromide, 1.0% blue dye solution was chosen for the undisturbed column experiments.

Two undisturbed columns were tested simultaneously: one taken from the no-till plot and one taken from the tilled plot. The columns were sprinkled continuously at the 2 cm/day rate. After 10 days, the total daily flows exiting the bottom of the columns were approximately equal to the daily quantity of the water applied at the surface (2 cm/day) and a pulse of 0.1 *M* bromide, 1.0% FD&C No. 1 Blue Dye solution was applied for 24 hours. Following this pulse "clean" water was applied for 30 days. During this 30 day period effluent was collected from each flowing cell (some cells remained dry for the duration of the experiment). At the outset there was uncertainty as to the optimal sampling interval. Samples were collected more frequently at first and the interval subsequently lengthened as it became apparent that longer intervals could be used without sacrificing detail. The sample bottles were collected and replaced three times the first day, twice the second day, every day from the third until the twelfth day and every other day from the twelfth until the thirtieth day. The effluent samples from each of the cells were weighed and analyzed for bromide and blue dye concentration. The bromide concentrations were measured using a bromide specific electrode. The blue dye concentrations were measured with a spectrophotometer. From these data, breakthrough curves for each cell were generated.

At the end of the thirty day period a 1.0% blue dye solution was applied until darker effluent began to emerge from the columns to re-stain the preferential flow paths. Then the columns were removed from the test apparatus and dis-

sected by cutting successive horizontal slices from the columns' bottom surfaces. The dye patterns at the bottom of each layer were observed.

RESULTS AND DISCUSSION

Water and solute flow through the undisturbed columns was not piston-like. Although water was applied evenly at the surface of the columns and at a low enough rate to assure that there was no ponding or overland flow, large spatial variations of the solute outflows were recorded during this experiment. These macroporous, structured soils engender preferential flows which affect the velocity of a solute's passage through the profile even at a 2 cm/day sprinkling rate. Figures 2a, b show the cumulative volume of water that passed through the sample during the tests as a function of location at the bottom of the columns. These three-dimensional graphs and the subsequent ones do not include flow through the outermost layer of sampling cells. These cells were below the soil and plaster interface at the periphery of the columns. To minimize the distracting influence of flow through the plaster or through gaps in the seal either between plaster and the soil or between the plaster and the plywood, these measurements were not plotted (they were included in the mass balance calculations). The plaster seals were approximately half a cell thick. The soil above the peripheral cells (see Fig. 1) accounted for 25% of the samples' cross sectional area, but these cells accounted for 16.3% of the flow through the no-till column and 8.7% of the flow through the tilled column. The edge flows were not excessive which indicates that the plaster seals were reasonably tight and impermeable.

Figures 3a through 6c show selected daily dye and bromide fluxes as a function of location at the bottom of the columns. These particular graphs were chosen to show the solute flux as the breakthroughs began, peaked and ended. The data presented in these graphs has been smoothed by the graphing routine used. This smoothing allows the graphs to be easily read, but is not intended to suggest that these are mesopore flows and not macropore flows at discrete locations. The solute flow is nonuniform in space. Water flowed from only 16 of the 52 center cells under the no-till column and from only 21 of the 52 center cells under the tilled column. The coefficients of variation among the total solute volumes which passed through the individual grid cells were: 2.3 for the no-till column bromide, 2.5 for the no-till column dye, 2.8 for the tilled column bromide, 3.0 for the tilled column dye.

The columns were dissected immediately after the second application of the dye solution had ceased, to observe where it appeared that the dye had traveled. The surface (to a depth of approximately 1 cm) of the no-till column was uniformly dyed and very moist (moisture content was 34% by weight). It appears that local saturation very near the surface was responsible for the initiation of macropore or nonequilibrium flows through the remainder of the soil

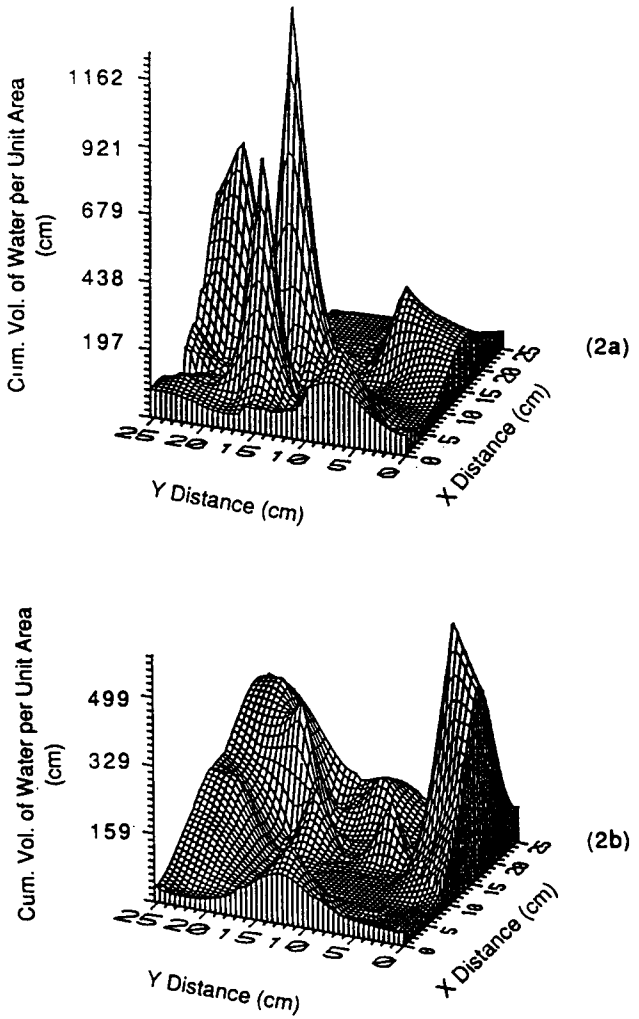
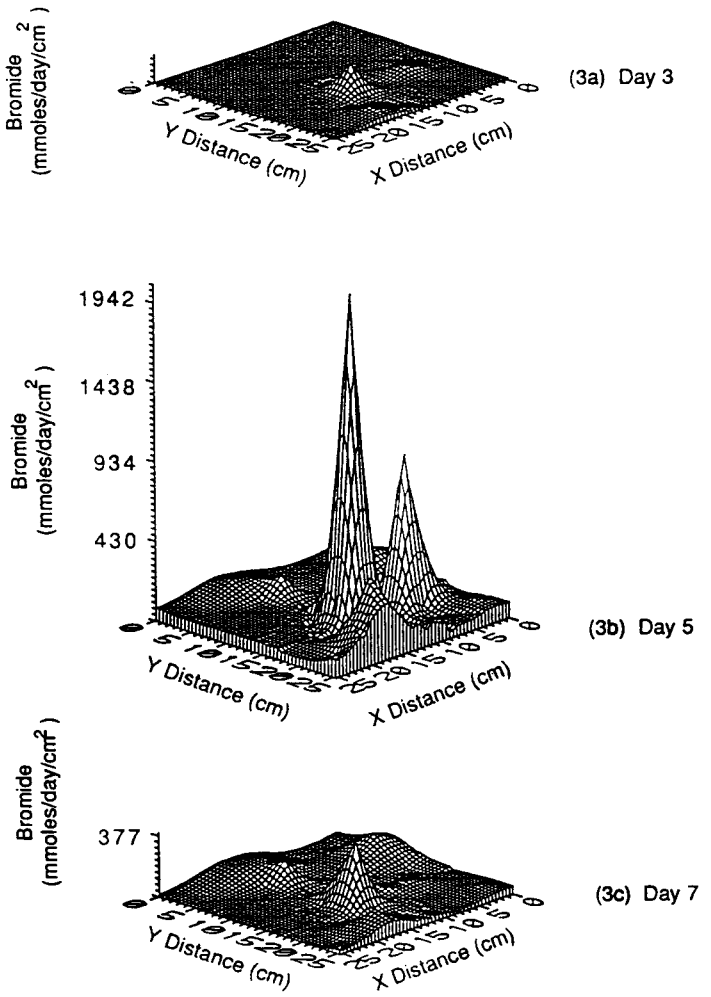


Fig. 2a. The cumulative volume of water per unit area that flowed through the tilled soil column after 30 days as a function of location.
Fig. 2b. The cumulative volume of water per unit area that flowed through the no-till soil column after 30 days as a function of location.

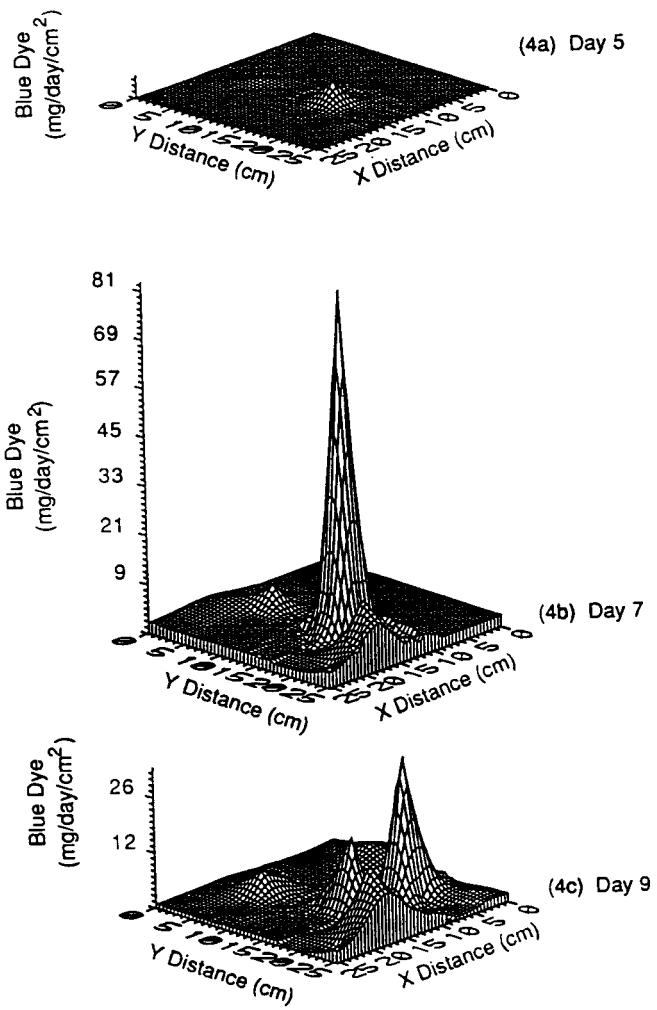
profile. The surface of a slice 20 cm deep had some areas which were undyed and others only lightly dyed. However, the distinction between the dyed and undyed zones was not sharply delineated. Two more slices: one at 28 cm depth and a third at 34 cm exhibited similar patterns. Finally, at the bottom of the column (46 cm deep) a distinct dye pattern had emerged; two large areas of the sample were undyed, showing no evidence that dye flowed through them.



Figs. 3a–c. Fluxes of bromide through the tilled column as a function of location.

Those areas with no measurable flows were not dyed at all. Those areas above cells where large flows were recorded were saturated and dyed dark blue.

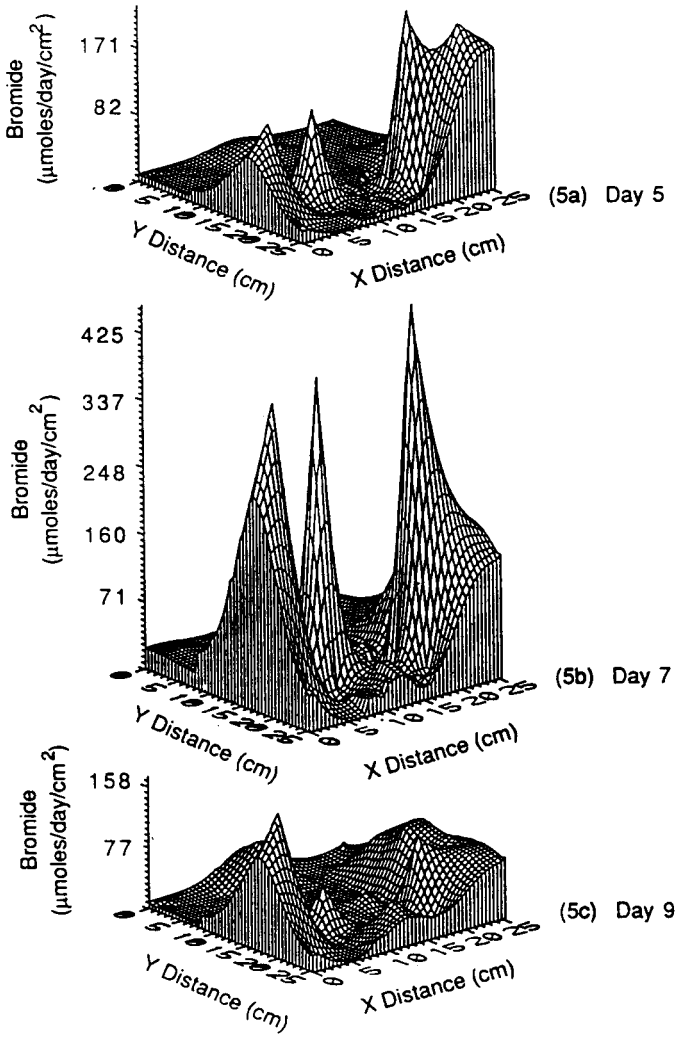
From the surface to a depth of 15 cm the tilled column was uniformly dyed and very moist (moisture content was 32%). Positive pressure in a soil matrix above a wetting front may supply water to macropores (Beven and Germann, 1982). It appeared that the areas of local saturation necessary to initiate preferential flow may have developed at the bottom of the tilled surface layer. As the water passed through the till pan into the undisturbed soil, patterns of preferential flow began to emerge. A slice 8 cm below the till pan (23 cm depth) shows undyed zones and zones of a very intense blue hue. The surface of the



Figs. 4a–c. Fluxes of blue dye through the tilled column as a function of location.

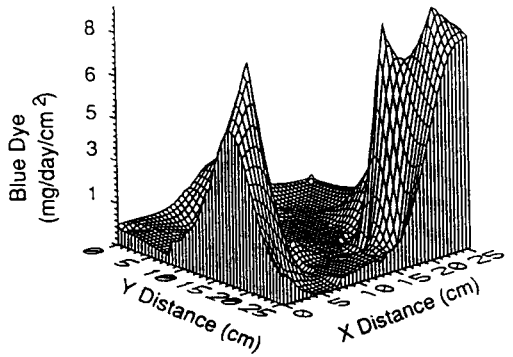
next slice 5 cm deeper (28 cm depth) exhibited more distinct differentiation between the dyed and undyed zones. At the bottom of the column there were very distinct zones which appeared to never have been dyed and other zones dyed a dark blue. The dye pattern observed at the bottom of the columns appeared to be consistent with the preferential flow patterns recorded by the grid lysimeter. Areas of high flow were dyed blue and areas without significant flows were undyed. It seemed that the cellular collection technique was capable of recording the flows as they exited the columns.

The tillage treatments shared common characteristics. The top surfaces of the columns were uniformly dyed. Near the top of the undisturbed soils the

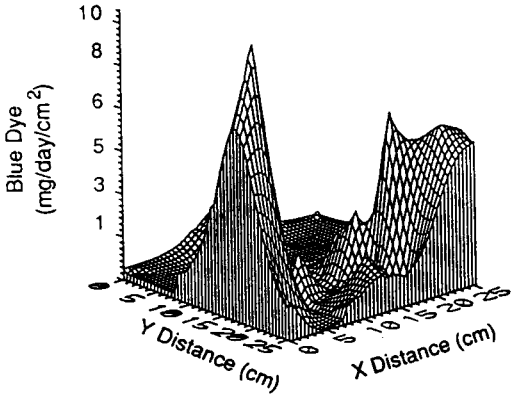


Figs. 5a–c. Fluxes of bromide through the no-till column as a function of location.

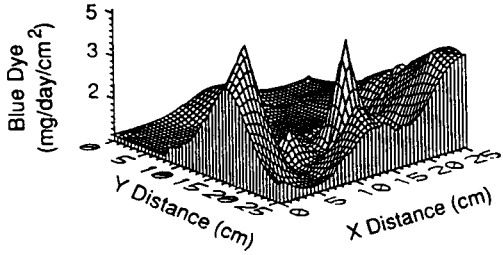
exact paths the water followed through were difficult to ascertain. With depth there were increasingly distinct differences between dyed and undyed areas. The majority of the water and solutes were observed to be coming through preferential flow paths or zones. Those areas above cells where large flows were recorded were saturated and dark blue. Those areas with no measurable flows were unsaturated and undyed. There were observable dyed macropores in the dyed areas but the soil near them was also very moist and dyed blue. It is difficult to conclude whether a given preferential flow is exclusively the result of specific macropores or of a group of mesopores in the same area. But the



(6a) Day 8



(6b) Day 11



(6c) Day 16

Figs. 6a–c. Fluxes of blue dye through the no-till column as a function of location.

preferential flow paths are quite evident and they terminate over grid lysimeter cells from which large quantities of solution flowed.

A mass balance was calculated for both the bromide and blue dye (see Table III). The bromide and dye quantities from each cell were summed over the duration of the experiment and compared with the quantities applied during the pulse. Eighty-five percent of the bromide from the no-till column and 92% of the bromide from the tilled column was accounted for, but there were still significant quantities of blue dye continuing to emerge from the columns at the end of the 30 day tests. It appeared that larger percentages of the dye remained in the columns than did the bromide.

TABLE III

Mass balance

	Bromide (Mmoles)		ED&C blue dye no. 1 (grams)	
	No-till	Tilled	No-till	Tilled
Pulse (input)	270,000	249,000	25.5	23.5
Effluent (output)	231,000	228,000	14.3	13.7
Percentage of pulse	85%	92%	56%	58%

A computer program, CXTFIT, by Parker and van Genuchten (1984) was used to estimate the velocity, retardation and dispersion. It uses the least squares inversion method to fit the convective-dispersive equation's solution to the experimental BTC's. The transport equation with a linear adsorption isotherm written for flux averaged concentrations without decay or production of the solute is

$$R\frac{\partial c_f}{\partial t}=D\frac{\partial^2 c_f}{\partial x^2}-v\frac{\partial c_f}{\partial x} \tag{2}$$

where the initial and boundary conditions are

$$c_f(x,0)=c_i \tag{3}$$

$$\frac{\partial c_f}{\partial x}(\infty,t)=\text{finite} \tag{4}$$

$$c_f(0,t)=\begin{cases} c_0 & 0<t<t_0 \\ 0 & t\geq t_0 \end{cases} \tag{5}$$

and where c_f is the flux-averaged concentration (ML^{-3}), x is the distance (L), t is the time (T), R is the retardation factor (dimensionless), D is the hydrodynamic dispersion coefficient reflecting the combined effects of diffusion and mechanical dispersion (L^2T^{-1}), v is the average pore water velocity (LT^{-1}).

The local or cell water velocities and dye retardation factors were found in the following fashion. The bromide was assumed to have moved at the local velocity of the water emerging from each cell. The computer model was fitted to the bromide BTC with the retardation factor fixed at one to find the local water velocity. After the water velocity was determined the model was fitted to the dye BTC with the velocity fixed at its previously determined value to determine a local dye retardation factor for the cell. Lower velocity paths were associated with higher retardation factors and higher velocity paths with lower retardation factors. Figure 7, a plot of local retardation factor versus local water velocity, illustrates this relationship.

Figures 8 and 9 show the total breakthrough curves for both the bromide and

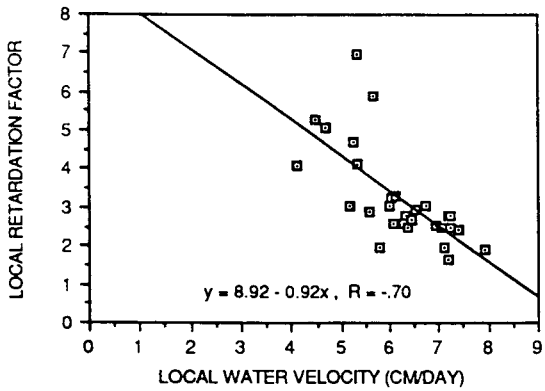


Fig. 7. A plot of local retardation factor vs. local water velocity.

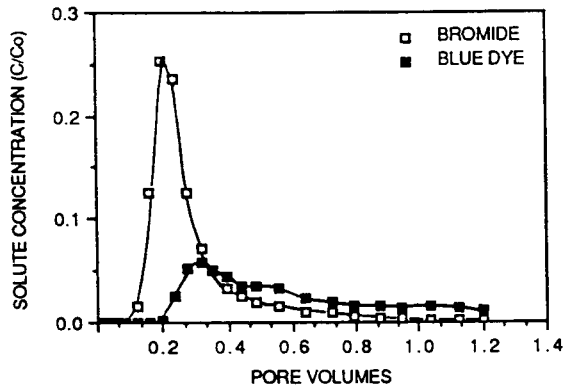


Fig. 8. A plot of the tilled bromide and blue dye breakthrough curves.

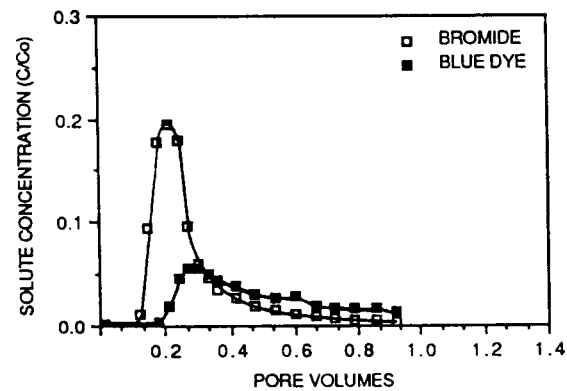


Fig. 9. A plot of the no-till bromide and blue dye breakthrough curves.

the blue dye. These curves were generated by agglomerating the cell measurements to reconstruct for the entire column a total or conventional breakthrough curve. The dye observations suggested that the breakthroughs should take place well in advance of a pore volume. The bromide peaks came through after approximately 0.2 pore volumes of water had exited the columns. The dye breakthroughs followed the bromide, peaking at 0.3 pore volumes, and exhibited considerable tailing.

The interpretation of the total BTC's is better understood by examining the examples of tilled column cells 25 and 50 (see Fig. 10). These two cells were representative of both extremes of the flow path velocity spectrum; cell 25 had a low flow rate (5.2 cm/day) and cell 50 had a high flow rate (7.2 cm/day). In cell 50, the bromide peak came two days sooner and the blue dye peak came nine days sooner than through cell 25. The maximum dye concentration in cell 50 (0.162 mol/l) was approximately four times as high as in cell 25 (0.045 mol/l). Almost 25 times as much water flowed through cell 50 (8439 cm^3) as through cell 25 (343 cm^3). The BTC's from cell 25 were wider, more dispersed, than those of cell 50; and the concentration of dye in the tail of the cell 25 BTC (after 25 days) was approximately double that in the cell 50 BTC.

The total breakthroughs from the undisturbed columns exhibited appreciable dispersion and tailing of both the bromide curves and the dye curves. The breakthrough curves of the individual cells had various velocities and peak concentrations. Samples taken from individual cells at the bottom end of a column will rarely if ever contain the flow from a unique, uniform velocity path because paths intersect one another as they descend through the column. Therefore, the effluent at any one point no matter how small the size of the sampling grid will contain water which traveled at an assemblage of velocities (generally the variations in local pore water velocities are assumed to be log-

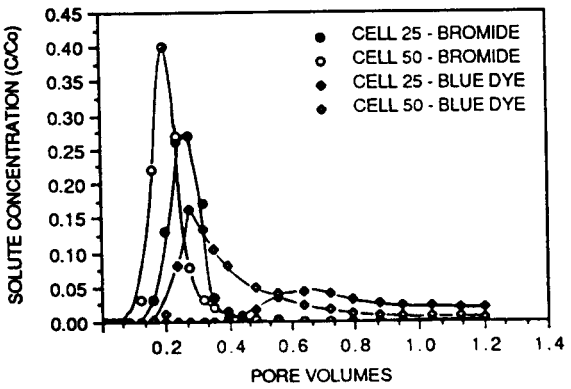


Fig. 10. A plot of the bromide and blue dye breakthrough curves for cells 25 and 50 of the tilled column.

TABLE IV

Total column breakthrough

	No-till	Tilled
Water velocity (cm/day)	6.36	6.14
Retardation factor	2.82	4.06
Dye velocity (cm/day)	2.25	1.51
Dispersion coefficient (cm^2/day):		
Bromide	13.1	9.7
Dye	61.1	77.2

normally distributed) to arrive at the bottom of the column. The dispersion and tailing of the total BTC's is a combination of the contributions from the velocity differences among the cell BTC's and result of the dispersion and tailing of the individual cell BTC's comprising it.

During the field study low concentrations of alachlor and atrazine were detected in the groundwater beneath the no-till plot within one month after application, while the groundwater samples from below the conventionally tilled plot contained no alachlor and only low concentrations of atrazine after seven months (Steenhuis et al., 1989).

The computer model was fitted to the total BTC's of the laboratory columns (see Table IV). The descent of the blue dye was retarded in both samples and their BTC's were similar. At first sight it is surprising that there is no greater difference in the transport of bromide and dye tracers between the tilled and no-till columns. However, considering the observations from the field experiments carried out at the same time, the similarity of the results for the two tillage practices can be understood. In the tilled soil there was no macropore flow at all through the tilled layer shortly after application. However, later in the season macropore flow through the plow layer was again established as worms formed holes through the plow layers. Our cores were taken in the late summer and both tillage practices had some continuous macropores. Because of the low flow rate used in the experiments the very few macropores established by the end of the growing season in the tilled soil could easily carry all the flow not carried by the matrix. Our results may have been different (i.e., a greater percentage of flow through the macropores in the no-till if the flow rate had been higher or if the soil cores were exhumed a shorter time after the soil was tilled. Care in extrapolating our results to other environmental conditions (such as application of pesticides directly after plowing) under no-till or conventional tillage is warranted. Although the dye patterns observed in the laboratory and field studies were similar, the apparent differences between the pesticide velocities found in the field study were not reflected in the total dye BTC's.

CONCLUSION

Using grid lysimeters interesting observations are possible which cannot be made if the column effluent is collected as a single sample per time period. Although there is an increasing awareness of the importance of preferential flows, spatial variations such as those recorded in this experiment had not previously been measured in this fashion. While some of the salient features of preferential flows seen in this experiment have been surmised by acute observers it is evident that the complexity of solute movement in heterogeneous structured soils makes it very difficult to quantify the effects of the various factors involved. An association between higher water velocities and lower levels of retardation was demonstrated. It was observed that the dyed flow paths led to the areas where water and solute exited the column. In the no-till column, nearly the entire depth of the profile was short-circuited by preferential flow, but in the tilled column the solute passed through the mixed, unstructured plow layer before the profile below the plow pan was short-circuited.

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