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Abstract

Although numerous studies have investigated the effects of crop production practices on soil water dynamics, not much information is available on the impact of row position on solute transport. A field experiment was carried out to evaluate surface and subsurface solute transport properties in plant row, nontrafficked interrow, and trafficked interrow positions. For this purpose, a plot of 14 × 14 m in a strip-cropped field with soybean (*Glycine max* L. Merr), corn (*Zea mays* L.), and oat (*Avena* L.) was selected. After harvesting the crops, surface (top 2 cm) electrical conductivity measurements were made by time domain reflectometry at 45 locations during a chloride pulse leaching experiment. At the conclusion of the pulse leaching experiment, 120-cm deep soil cores were collected at the 45 locations to measure the soil profile chemical distributions. No crop or row position effects were observed for surface-determined pore water velocities (v), whereas profile-determined v was greater in plant row versus interrow positions when averaged over all crops. Overall, the profile-determined v was slightly greater than the surface determined v, probably because of lower effective or mobile water contents. The profile-determined dispersion coefficient (D) was smaller in row positions than interrow positions in soybean and corn, perhaps because of surface ponding in the interrow positions of the crops resulting in macropore flow. Profile-determined $D$was greater in the interrow positions of soybean than oat, again reflecting possible macropore flow. Overall, the mean soil profile dispersivity (λ = 2.97 cm) was larger than the surface soil (λ = 1.02 cm). The local surface solute transport varied by row positions, whereas profile solute transport was affected by both row position and crop, perhaps due to surface ponding producing macropore flow in the trafficked and nontrafficked interrows of soybean and the trafficked interrows of corn. Thus, a one-dimensional solute transport model with a spatially distributed flux or potential controlled upper boundary condition must be used to model this system.

Keywords

solute transport, TDR, soil water velocity, dispersivity, row position

Disciplines

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SURFACE AND SUBSURFACE SOLUTE TRANSPORT PROPERTIES AT ROW AND INTERROW POSITIONS

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Although numerous studies have investigated the effects of crop production practices on soil water dynamics, not much information is available on the impact of row position on solute transport. A field experiment was carried out to evaluate surface and subsurface solute transport properties in plant row, nontrafficked interrow, and trafficked interrow positions. For this purpose, a plot of 14 × 14 m in a strip-cropped field with soybean (*Glycine max* L. Merr), corn (*Zea mays* L.), and oat (*Avena* L.) was selected. After harvesting the crops, surface (top 2 cm) electrical conductivity measurements were made by time domain reflectometry at 45 locations during a chloride pulse leaching experiment. At the conclusion of the pulse leaching experiment, 120-cm deep soil cores were collected at the 45 locations to measure the soil profile chemical distributions. No crop or row position effects were observed for surface-determined pore water velocities (*v*), whereas profile-determined *v* was greater in plant row versus interrow positions when averaged over all crops. Overall, the profile-determined *v* was slightly greater than the surface determined *v*, probably because of lower effective or mobile water contents. The profile-determined dispersion coefficient (*D*) was smaller in row positions than interrow positions in soybean and corn, perhaps because of surface ponding in the interrow positions of the crops resulting in macropore flow. Profile-determined *D* was greater in the interrow positions of soybean than oat, again reflecting possible macropore flow. Overall, the mean soil profile dispersivity (λ = 2.97 cm) was larger than the surface soil (λ = 1.02 cm). The local surface solute transport varied by row positions, whereas profile solute transport was affected by both row position and crop, perhaps due to surface ponding producing macropore flow in the trafficked and nontrafficked interrows of soybean and the trafficked interrows of corn. Thus, a one-dimensional solute transport model with a spatially distributed flux or potential controlled upper boundary condition must be used to model this system. (Soil Science 2007;172:419–431)

Key words: Solute transport, TDR, soil water velocity, dispersivity, row position.

LANDSCAPE characteristics and soil properties vary across landscapes, and their effects on solute transport need to be assessed to reduce leaching risks to surface and ground water. Soil water movement is highly variable in both space and time especially near the soil surface, resulting in direct environmental and management implications (Starr and Timlin, 2004). To quantify the movement of solute and understand solute redistribution, the spatiotemporal variation of solute transport due to weather, soil, agronomic, and biotic factors should be considered.

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Some of the major factors that affect solute transport are soil type, topography, and crop production practices such as crop type, tillage practices, and wheel traffic. Cultivation of row crops tends to accumulate soil within the plant rows. During rainfall or sprinkler irrigation, the raised microtopography along plant rows can shed water away from the plant rows to interrows and may cause ponding (Saffigna et al., 1976). The ponding in interrows and no-ponding in plant rows can affect infiltration and solute leaching (Saffigna et al., 1976; Ghodrati and Jury, 1990; Bargar et al., 1999). Some of the solute infiltrating at interrows may spread laterally in the subsurface water to the adjacent plant rows because of lateral hydraulic gradients (Bargar et al., 1999). The subsurface lateral redistribution between interrows and plant rows and preferential flow due to biologically induced activities in plant rows may result in faster infiltration and also in deeper percolation in plant rows, than in interrows (Paltineanu and Starr, 2000).

Plants, by virtue of their roots, play an important role in determining the magnitude and even the direction of field soil water flow and solute transport. Plant root growth initially may inhibit infiltration, but decomposition of roots opens channels or macropores, which can enhance infiltration (Meek et al., 1989). Fescue roots can loosen the soil and increase hydraulic conductivity (Shirmohammadi and Skaggs, 1981). Gish and Jury (1982) reported that plant roots altered the nature of the porous medium and caused water and solutes to move through only part (65–86%) of the wetted pore space.

Wheel traffic reduces the macroporosity and bulk density of soil due to compaction and results in lower infiltration rates in wheel-trafficked interrows than in nontrafficked interrows (Ankeny et al., 1990). Blanco-Canqui et al. (2004) found that lower bulk densities in soybean resulted in greater saturated hydraulic conductivity than in corn. The effect of trafficking and cultivation practices on infiltration and hydraulic conductivity has been verified by several researchers (Meek et al., 1989; Ankeny et al., 1990; Starr, 1990; Mohanty et al., 1994; Vervoort et al., 2001; Blanco-Canqui et al., 2004).

In contrast to the hydraulic properties, Timlin et al. (1992) found less bromide leaching in soil under soybean than corn and more leaching in interrows than in plant rows in a conventionally tilled field. The bromide leaching was affected by root water uptake and evaporation. The experiments, conducted in the presence of complex variables including evaporation and plant uptake, require measurements of numerous parameters, making it difficult to quantify solute leaching at different row positions.

It is not clear how row position influences surface and subsurface solute transport. For instance, Blanco-Canqui et al. (2004) found lower saturated hydraulic conductivity at trafficked interrow than at nontrafficked interrow positions but did not find any change in the saturated hydraulic conductivity with depth (20 cm) at different row positions. Kung (1990) and Timlin et al. (1992) found that subsurface flow and subsurface solute leaching behavior at various row positions was probably influenced by the plant root distribution or lateral flow. Several studies report increases or no trends in solute transport properties with depth (Khan and Jury, 1990; Jaynes, 1991; Jaynes and Rice, 1993; Shukla et al., 2003; Gaur et al., 2006). To date, no study has reported the surface and subsurface solute transport properties at specific row and interrow positions. Additional knowledge of the relative differences in surface and subsurface solute leaching in different row interrow positions will help to improve our understanding of the implications of crop and cultural practices. The row positions more prone to leaching in a row-cropped field can be identified by measuring surface and subsurface solute transport properties under different row positions.

Solute dispersivity is a useful measure of solute transport behavior in soil. It is directly affected by heterogeneity in flow and can, therefore, help to assess nonuniformity in surface and soil profile flow introduced by crop production practices. Solute dispersivity can be determined by fitting a solution of the one-dimensional convective-dispersive equation (CDE) to observed soil solute resident concentrations established in response to controlled boundary conditions (Toride et al., 1993). The model has been successfully applied at both the column scale (Wierenga and van Genuchten, 1989) and the field scale (Biggar and Nielsen, 1976; Roth et al., 1991).

The objective of our study was to evaluate the effect of row positions on surface and subsurface solute transport properties in a strip-cropped field. The effect of row positions (plant row, nontrafficked interrow, and wheel-trafficked interrow) on solute leaching was studied in soybean, corn, and oat.

MATERIALS AND METHODS

Site Description

The experiment was performed at the Iowa State University Agronomy and Agricultural Engineering Research Center near Ames, Iowa, during the fall season of 2002. The soil at this site is predominantly Nicollet loam (fine loamy, mixed superactive, mesic Aquic Hapludolls) in the Clarion-Nicollet-Webster soil association (Soil Conservation Services, U.S. Department of Agriculture, 1981). This glacial till-derived soil is somewhat poorly drained and moderately permeable with a slope of 2 to 3%. The bulk density ranged from 1.45 (top 7.5 cm) to 1.55 Mg m^{-3} (50-cm depth) (Azevedo et al., 1996).

A 14 × 14-m field plot centered over a subsurface drainpipe or "tile" was selected within a long-term strip-cropped field. The field was chisel plowed each fall. All field operations used five-row equipment (0.76 m row width) and controlled traffic. Each crop strip was in a crop rotation of corn-oat-soybean. Each crop strip received secondary tillage with a field cultivator before planting. The corn and soybean strips were cultivated in late June resulting in a slightly lower (1–2 cm) ground level between rows. The crops were harvested before conducting the experiment.

The measurement locations in each of the three crops occurred at three row positions: plant rows, interrows, and trafficked interrows (Fig. 1). The row-to-row spacing in corn and soybean was 0.76 m; the first plant row, third interrow (nontrafficked), and fourth interrow (trafficked) in each crop strip were selected for observations. Oat was planted in a 0.19-m row spacing using a shallow drill. The rows and interrows from the previous corn crop were used to designate measurement positions in the oat strip. The selected plant rows and interrow had five measurement locations spaced at 2 m for a total of 15 measurements in each crop for a total of 45 locations.

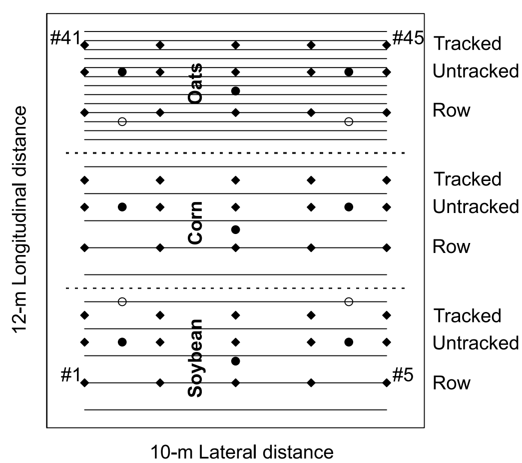

Fig. 1. Schematic of field experimental layout. Diamonds are locations where surface and profile transport parameters were measured. Filled and open circles are sprinklers and rain gauge locations, respectively. Horizontal lines indicate plant rows.

A portable irrigation system with four Gilmour oscillating sprinklers (model 9836z) was used to apply water and solute at rates between 0.2 and 0.3 cm h^{-1}. The sprinklers were switched on and off at regular intervals by an automated switch to maintain the desired irrigation rate. Nine tipping bucket rain gauges coupled with a data logger were used for monitoring the sprinkler irrigation rate. Potential evaporation was estimated based upon nearby weather station measurements (Iowa Environmental Mesonet, Iowa State University). The field plot was pre-irrigated with well water having an electrical conductivity (EC) of 0.68 dS m^{-1} and chloride content of 75 mg L^{-1} for 240 h until a steady-state water condition was attained, as evidenced by steady flow from the tile line beneath the plot. After reaching the steady-state condition, a 78-h pulse of calcium chloride ($CaCl_2$) solution (14.4 g L^{-1}) with an EC of 23 dS m^{-1} was applied through the sprinkler system followed by the application of a low concentration $CaCl_2$ solution. During and after the pulse application, surface EC measurements were made with time domain reflectometry (TDR) equipment. One day (26 h) after irrigation ceased, soil profile cores were obtained at the 45 measurement locations. Water drainage and solute transport to the subsurface drain were measured and are reported elsewhere (Gaur et al., 2006).

Surface TDR Measurements

The TDR equipment consisted of two-rod probes (3.8 mm in diameter and 100 mm long), a cable tester (model 1502B, Tektronix, Redmond, Oregon), and a computer programmed to store and analyze the data. The probes were connected to the cable tester via a multiplexer (SDMX 50; Campbell Scientific, Logan, Utah). At all 45 measurement locations, the TDR probes were inserted at an approximately 11-degree angle from the surface to maximum depths of 2 to 3 cm. The diagonal insertion from surface minimized soil disturbance as compared with horizontal installation. During a steady-state, isothermal pulse input, the relative resident solute concentration, $R(t)$, can be represented as (Lee et al., 2000):

$$R(t) = \frac{C(t) - C_i}{C_0 - C_i} = \frac{EC(t) - EC_i}{EC_0 - EC_i} \quad [1]$$

where C_i is background solute concentration, C_0 is input solute concentration, EC_I is TDR-measured apparent EC for C_i, and EC_0 is TDR bulk EC corresponding to C_0. Under steady-state conditions, because of the linear relationship between EC and C, one can determine normalized resident concentration, $R(t)$ by using Eq. (1). In this study, EC(t), as a function of time, was determined with the aid of the Win TDR99 (Or et al., 1998) computer program. It was assumed that each TDR probe measured the average bulk soil EC of the soil surrounding the probe.

Subsurface Measurements

One day after irrigation ceased, soil cores were collected from all 45 TDR locations. A hydraulic sampling device was used to collect 3.81-cm diameter, 120-cm long cores in zero-contaminated clear butyrate tubes. Each sample was obtained in a single tube entering from the surface to a depth of 120 cm. The soil cores were later sectioned into 10-cm depth increments, and each increment was split into two subsamples. In all soil cores, one subsample was used to determine the gravimetric water content, and the other subsample was diluted about fivefold with water. The diluted subsample was shaken for 30 min and allowed to settle. The supernatant was then filtered through no. 42 filter paper and analyzed for EC with an Accumet conductivity meter (model 30; Hudson, Massachusetts) and for Cl concentration with a Dionex DX-120 Ion Chromatograph (Sunnyvale, California). Both relative EC and relative Cl concentrations were found to be similar; therefore, only Cl breakthrough curves were used for the data analysis.

Data Analysis

Examples of the TDR-determined $R(t)$ at the surface versus cumulative irrigation during the pulse application are shown in Figure 2. The observed $R(t)$ did not display the expected asymptotic behavior during the chemical application period ($0 < t < t_0$, Lee et al., 2002). Instead, the TDR measurements exhibited diurnal fluctuations in $R(t)$. These fluctuations can partly be attributed to interruptions in tracer input caused by sprinkler malfunctioning during the first two nights of tracer application. Other potential causes were diurnal fluctuation of surface temperature and variation in the input concentration due to evaporation from the sprinkler water drops and surface soil water. Electrolytic conductivity increases approximately 2% $°C^{-1}$. Soil surface temperature fluctuations were not measured, but they were likely dampened by the saturated condition of the surface. A fluctuation of 5 °C could explain a 10% fluctuation in $R(t)$. An evaporation effect was independently supported by surface soil samples that were collected at the time of peak TDR EC readings before switching from chemical to water application ($t = t_0$). The surface soil samples collected by a core sampler (1.5 m deep and 6.5 cm diameter) at TDR locations had 13% greater chloride concentration than the input solute concentration. This 13% excess chloride concentration was nearly balanced by 10% potential evaporation estimated from the nearby weather station. Because the switch from high Cl concentration to low Cl concentration occurred in late afternoon, the majority of the $R(t)$ curve step down ($t > t_0$) occurred during the night when evaporation was minimum. Thus, to reduce the effects of sprinkler malfunctioning and diurnal fluctuations of temperature and evaporation, only the falling portions ($t > t_0$) of the curves were selected for analysis. We assumed that after 16 pore volumes (I_0) of tracer solution input the chemical was uniformly distributed in the top 2-cm soil layer around the TDR probes. Subsequently, the TDR EC readings were normalized with respect to the EC in the soil at each location when $t = t_0$ (i.e., $EC(t_0) = EC_0$). The program CXTFIT (Toride et al., 1993) was used to curve fit the appropriate analytical solution to the one-dimensional CDE to the measured $R(t)$ data. The best fit of the CDE to the data was obtained by optimizing the pore water velocity, v, and the dispersion coefficient, D, parameters.

The cumulative irrigation during chemical application (I_0) and the total input (I) at each measurement location were determined by spatially interpolating the measured irrigation at the tipping rain gauge locations (Fig. 1). A regularized spline method was used to make the interpolations. Mass recovery and center of mass were determined for the chemical distribution in each of the 45 soil cores. In addition, the subsurface solute transport properties, v, D, and

t_0, were estimated using CXTFIT for each location by curve-fitting the one-dimensional CDE solution to profile chloride concentration distributions measured in the deep soil cores. Simultaneous fitting of t_0 is required because t_0 determines the mass balance of tracer applied, and mass balance is an implicit fitting parameter in the least squares method. Fitting the mass balance adjusted for any variations in sampling efficiency, systematic biases in the analytical procedures caused by interferences in the soil solution, and spatial variation in water flow infiltration under heterogeneous soil conditions (Jaynes and Rice, 1993). In addition, the CDE model assumed that pore water velocity, v, was constant over time. The t_0 was fitted by setting a constant total irrigation period of 196 h in the CXTFIT method, which included the tracer and water application times and the 26 h of redistribution from the end of irrigation to soil sampling. Thus, fitted t_0 and v incorporated the adjustments for the slightly variable irrigation rates during chemical and water application by assuming a constant input rate during the entire pulse (t). Wierenga (1977) has demonstrated the validity of this approach for describing solute transport during nonsteady infiltration and drainage events.

To compare the variations in dispersion and velocity on a common basis, the dispersivity, λ ($= D/v$), was used to characterize the solute leaching in the rows and interrows. A one-way analysis of variance was used to test for differences among solute transport properties at row and interrow positions. The Waller-Duncan k ratio test was used to compare the effects of row and interrow positions on solute transport properties (SAS, 1996). Equality of transport parameters determined from surface and profile data was tested using a two-sample paired t test for means of the log-transformed data (SAS, 1996).

RESULTS

On average, a total of 33.7 ± 11.4 cm net irrigation (I) was applied during the leaching experiment. During tracer application, the on and off times for sprinkler operation were set to 30 sec each, resulting in an irrigation rate of 0.23 ± 0.10 cm h^{-1}. The chemical tracer was applied for 78 h for a total net water (irrigation–evaporation) depth of 16.3 ± 6.0 cm (I_0). Because water was starting to pond on the plot surface, the off time for the sprinklers was increased during the water application phase to reduce the irrigation rate to 0.21 ± 0.08 cm h^{-1}. Water was applied for 92 h for a total of I_w = 17.4 ± 7.8 cm of net water application recorded by the rain gauges. Even after decreasing the irrigation rate, ponding could not be avoided in the interrows of

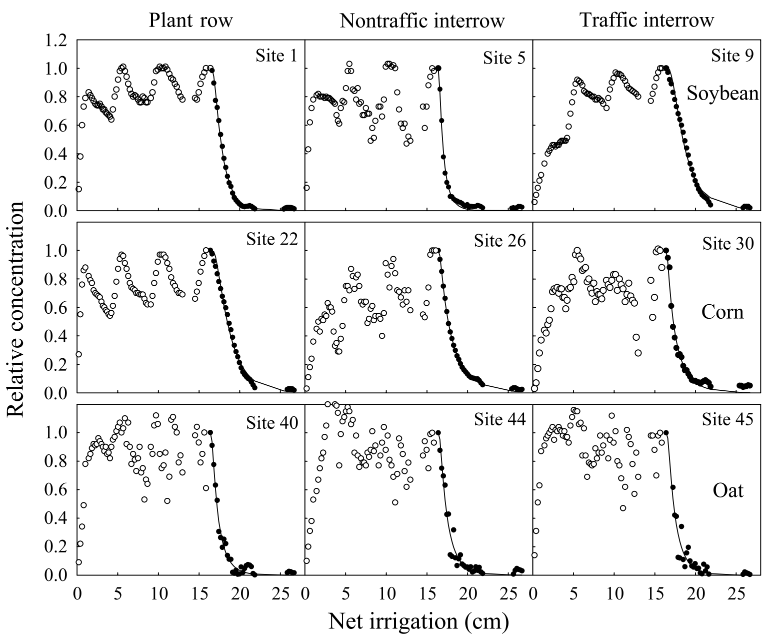

Fig. 2. Measured and fitted surface resident concentrations (both circles refer to observed concentration and solid lines refer to the fitted concentration with solid circles).

TABLE 1

Surface solute transport properties determined from TDR resident concentrations under different crop and row positions

Parameters	Crop	Row positions			Mean	$P > F$
		Plant row	Nontrafficked Interrow	Trafficked Interrow		
Pore velocity, v (cm h^{-1})	Soybean	0.26 (0.18–0.38)†	0.39 (0.23–0.49)	0.31 (0.23–0.40)	0.31 (0.26–0.38)	0.235
	Corn	0.34 (0.24–0.50)	0.38 (0.28–0.51)	0.45 (0.30–0.69)	0.39 (0.33–0.45)	0.308
	Oat	0.33 (0.28–0.39)	0.33 (0.23–0.49)	0.29 (0.17–0.49)	0.32 (0.27–0.37)	0.536
	Mean	0.31 (0.27–0.36)	0.36 (0.31–0.43)	0.34 (0.28–0.42)	0.34 (0.31–0.37	0.334
	$P > F$	0.183	0.096	0.737	0.104	
Dispersion coefficient, D (cm^2 h^{-1})	Soybean	0.13 b (0.07–0.25)‡	0.43 a (0.17–1.04)	0.36 a (0.19–0.68)	0.30 (0.20–0.45)	0.030
	Corn	0.28 b (0.06–1.36)	0.64 a (0.30–1.38)	0.80 a (0.27–2.35)	0.64 (0.33–1.23)	0.038
	Oat	0.35 (0.18–0.67)	0.25 (0.13–0.50)	0.34 (0.13–0.92)	0.31 (0.22–0.43)	0.693
	Mean	0.25 b (0.15–0.41)	0.43 ab (0.29–0.63)	0.46 a (0.30–0.71)	0.38 (0.30–0.49)	0.015
	$P > F$	0.179	0.118	0.154	0.488	
Dispersivity, λ (cm)	Soybean	0.50 b (0.36–0.70)	1.02 aAB (0.58–1.80)	1.12 a (0.73–1.72)	0.88 (0.67–1.15)	0.011
	Corn	0.62 b (0.18–2.12)	1.60 aA (0.91–2.83)	1.62 a (0.77–3.42)	1.38 (0.81–2.34)	0.019
	Oat	1.03 (0.60–1.75)	0.72 B (0.49–1.04)	1.06 (0.59–1.88)	0.92 (0.73–1.15)	0.377
	Mean	0.72 b (0.48–1.06)	1.10 a (0.83–1.44)	1.22 a (0.95–1.57)	1.02 (0.84–1.23)	0.014
	$P > F$	0.112	0.041	0.352	0.826	

All statistics were computed using log-transformed data.

†The values in parentheses refer to confidence limit with 95% probability.

‡Where $P \leq 0.05$ for F statistic; means within a column followed by the same capital letter and means within a row followed by the same lowercase letter are not significantly different using the Waller-Duncan K ratio test.

the soybean and somewhat in the corn. No ponding was observed in the oat strip.

Surface Solute Transport Properties From TDR

During water application after tracer application ($t > t_0$), the decrease in surface $R(t)$ measured by TDR was rapid, and $R(t)$ approached zero at all sites after the application of 7 cm of water (Fig. 2). The coefficients of determination, R^2, for the fitted $R(t)$ curves ranged from 0.88 to 0.99. Several researchers (Biggar and Nielsen, 1976; Jaynes, 1991; Jaynes and Rice, 1993; Gupte et al., 1996; Jacques et al., 1997) have found that solute transport properties including pore water velocities and dispersivities are best described by lognormal distributions. Kolmogorov-Smirnov and goodness-of-fit tests verified that surface v, D, and λ were best represented by lognormal distributions; thus, all statistics were computed on log-transformed data.

On average, the fitted local-scale surface v, D, and λ were found to be 0.34 cm h^{-1}, 0.38 cm^2 h^{-1}, and 1.02 cm, respectively. The mobile water content estimated as a ratio of applied water rate to fitted v was found to be 0.55, whereas the measured average volumetric water content at the surface was 0.49. Before switching back to the low concentration Cl solution, the high concentration tracer solution was still ponded in interrows at some locations. The initial mixing time of the low with the high concentration solution possibly delayed the leaching curve, which may have reduced v and caused the apparent mobile water content to exceed the measured water content.

The surface solute transport properties were affected differently by rows and interrows in each crop (Table 1). Pore water velocity ranged from 0.17 to 0.63 cm h^{-1}, but there were no significant differences in v by either crop or row position. The dispersion coefficient, D, ranged from 0.04 to 1.39 cm^2 h^{-1} and was significantly affected by row position in corn and soybean, but not oat. In both corn and soybean, D was smaller in the plant row than in either the trafficked or nontrafficked interrow positions. Dispersivity, λ, ranged in value from 0.14 to 2.73 cm and, as with D, showed significant row effects in corn and soybean, but not oat. Smaller values for λ were observed in plant rows than in the interrows in corn and soybean. No significant differences were observed for surface v, D, or λ between the nontrafficked and trafficked interrows.

Solute Transport Within Soil Profiles

Because of spatial nonuniformity in the application of applied water, the amount of irrigation during chemical (I_0) application varied among crops. The chemical input, I_0, was comparatively less in corn (15.4 cm) than in soybean (16.6 cm) and oat (17.3 cm). The water application after the tracer application, I_w, was greater in corn, particularly in corn plant row (22.6 cm), than in soybean and oat. As a result, I was slightly larger in the corn than in soybean and oat. Overall, both I_0 and I did not vary significantly among row and interrows. The corn plant row received the largest irrigation (I) of 38.0 cm.

The high degree of variability in vertical solute movement at different locations within the study plot may be illustrated by the extremes in the shapes of the solute distributions (Fig. 3). The peak relative resident chloride concentrations varied from 0.25 to 0.96, with an average value of 0.70 ± 0.05. Some double-peak breakthrough curves were observed in the soybean (sites 5, 11, and 15). The soybean strip experienced more surface ponding in the interrow positions than corn, whereas ponding never occurred in the oat strip. Fracture or other macropore flow fed by the ponded water may have led to bypassing of some of the soil volume and contributed to the occurrence of the double peaks.

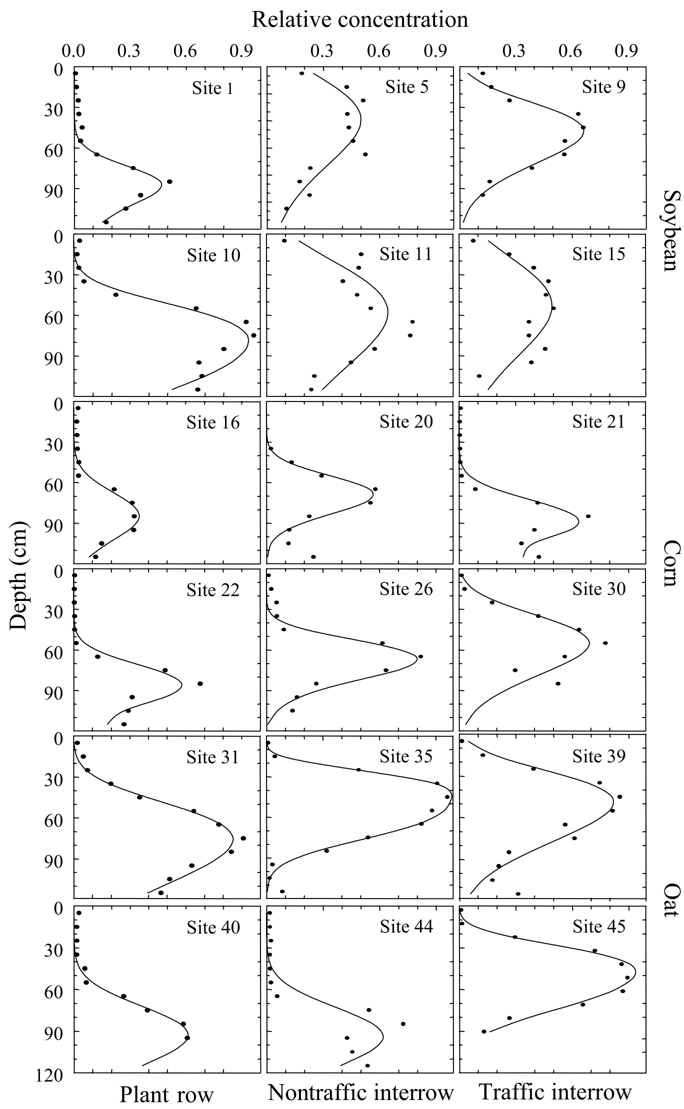

Fig. 3. Measured and fitted subsurface resident concentrations (circles refer to observed relative concentration and solid lines refer to the fitted relative concentration).

TABLE 2

Mass recovery and center of mass determined from the soil profile concentration distribution in different crop and row positions

Parameters	Crop	Row positions			Mean	$P > F$
		Plant row	Nontrafficked Interrow	Trafficked Interrow		
Mass recovery (%)	Soybean	66 (10.7)[†]	80 (8.6)	60 (14.0) AB	69 (6.5)	0.463
	Corn	37 (3.6) b[‡]	52 (8.9) b	80 (11.6) Aa	57 (6.7)	0.013
	Oat	60 (19.6)	50 (17.4)	41 (5.1) B	50 (8.5)	0.676
	Mean	55 (8.2)	61 (7.5)	60 (6.7)	59 (4.3)	0.805
	$P > F$	0.335	0.198	0.039	0.201	
Center of mass (cm)	Soybean	80 (6.3) a	56 (2.8) b	57 (4.5) b	64 (3.9)	0.007
	Corn	85 (2.9) a	70 (3.4) b	69 (6.0) b	75 (3.1)	0.037
	Oat	78 (3.2) a	67 (7.7) ab	53 (6.9) b	66 (4.4)	0.041
	Mean	81 (2.5) a	64 (3.2) b	59 (6.3) b	68 (2.3)	0.001
	$P > F$	0.527	0.181	0.179	0.133	

[†]The values in parentheses refer to standard errors.
[‡]Where $P \leq 0.05$ for F statistic; means within a column followed by the same capital letter and means within a row followed by the same lowercase letter are not significantly different using the Waller-Duncan K ratio test.

The solute mass recovered per unit area as a percentage of the total applied mass may be used to gauge the solute distribution in the study area. The mass recovery was determined to assess the chemical distribution within the study area (Table 2). On average, the measured solute mass recovery was found to be 59 ± 29% ranging from 14 to 131%. The mass recovery indicated that some of the applied solute moved laterally with surface or subsurface flow. Mass recoveries greater than 100% may be indicative of lateral redistribution of the solute. The shapes of some of the concentration distributions also indicated that some solute moved below the sampling depth (e.g., sites 10, 11, 22, 31, 40, and 44). Overall, corn (57%) and oat (50%) had lower mass recovery than soybean (69%). The mass recovery was possibly affected by the relative amounts of chemical (I_0) and water (I) applied. The larger I in corn than in soybean contributed partly to deeper leaching. The plant row (37%) and nontrafficked interrow (52%) positions under the corn crop had significantly less mass recovery than in trafficked interrows (80%) positions. No significant difference in mass recoveries was determined among row/interrow positions within the soybean and oat.

The depth to the center of solute mass is another gauge of solute travel distance. In general, the centers of mass of individual profile resident concentration curves were located between 33 and 96 cm, with an average value of 68 ± 4 cm (Table 2). No significant differences in the locations of the centers of mass were observed under different crops with average values of 64, 75, and 66 cm under soybean, corn, and oat, respectively. The centers of mass were found to be deeper under plant rows (81 cm) than under nontrafficked interrows (65 cm) and trafficked interrows (59 cm). The deepest mean center of mass was observed under corn plant row (85 cm) positions followed by soybean (80 cm) and oat plant row positions (78 cm). The center of mass per unit of I also indicated the fastest movement of chemical was under the corn plant-row, suggesting that solute leaching was affected by the row and interrow positions in addition to the irrigation input. The trafficked interrow positions in oat (53 cm) had the shallowest center of mass. Both mass recovery and centers of mass suggested that the deepest solute leaching occurred below plant rows.

Subsurface Solute Transport Properties From Core Data

The observed and fitted resident chemical concentration distributions are shown in Figure 3. Except for 4 of the 45 locations, the R^2 of fitted curves ranged from 0.63 to 0.99, with an average value of 0.91. The CDE model was unable to provide good fits to the four double-peaked resident concentration curves in soybean, and estimates for these locations were not included in the analysis. Overall, the adjusted amount of tracer solution applied, I_0, was 13% less than the actual application. The fitted I_0 was lower than applied I_0 for corn and oat, which had lower mass recovery than soybean. The chemical concentration distribution in many curves indicated that substantial amounts of chemical had moved below the sampling depth of 120 cm. Subsequently, the fitted I_0 was unable to account for the missing chemical.

The distribution of v values was normal, but D had a lognormal distribution. The distribution of λ was not clearly normal or lognormal (Kolmogorov-Smirnov and goodness-of-fit tests). However, the distribution for λ values was positively skewed, indicating that the distribution was closer to being lognormal than normal. To be consistent with the surface measurements, all statistical comparisons were conducted with lognormal transformations of the subsurface transport properties. The profile solute transport properties for different row positions are summarized in Table 3.

Overall, the mean values of fitted profile v, D, and λ were found to be 0.44 cm h^{-1} (0.40–0.47 cm h^{-1}), 1.23 cm^2 h^{-1} (0.97–1.57 cm h^{-1}), and 2.97 cm (2.32–3.80 cm), respectively. The ratio of average applied flux rate and fitted v indicated that the mobile water content was 0.40. The porosities of the soil profile at this site have been reported to range from 0.47 (top 7.5 cm soil) to 0.42 (50 cm) (Kanwar et al., 1989; Azevedo et al., 1996). The average top 2-cm water content was 0.49. The water content in the soil profile measured one day after irrigation ceased was 0.32 indicating that the mobile water content was close to the actual satiated water content. The effective (mobile) solute transport volume varied among row and interrow positions, indicating that the entire soil pore volume was not contributing to the solute transport. Particularly, v in plant rows was significantly greater than in the interrows in soybean and oat and when averaged across the three crops. This difference was attributed to either greater infiltration (van Wesenbeeck and Kachanoski, 1988; Ankeny et al., 1990) or less mobile water volume in plant rows than in interrows (Gish and Jury, 1982) (i.e., bypass flow).

Both D and λ varied by crop and row positions (Table 3). The largest D values were found in interrow positions in soybean, and when averaged across all row positions, D in soybean was significantly greater than D in corn or oat. D was also more variable in the soybean than in the other two crops and the four locations that could not be fit with the CDE equation were in soybean interrow positions. Both of these results may have because of the higher incidence of surface ponding in the soybean interrows leading to preferential flow down fractures or biopores. Dispersivity

TABLE 3

Soil profile solute transport properties determined from soil profile resident concentration distribution under different crop and row positions

Parameters	Crop	Row positions			Mean	$P > F$
		Plant row	Nontrafficked Interrow	Trafficked Interrow		
Pore velocity, v (cm h^{-1})	Soybean	0.53 a (0.43–0.65)[†]	0.39 b (0.21–0.69)	0.33 b (0.22–0.49)	0.43 (0.36–0.52)	0.018
	Corn	0.48 (0.42–0.54)	0.41 (0.36–0.47)	0.45 (0.38–0.54)	0.45 (0.42–0.48)	0.211
	Oat	0.53 a (0.43–0.65)[‡]	0.43 ab (0.34–0.53)	0.33 b (0.21–0.54)	0.43 (0.36–0.52)	0.018
	Mean	0.51 a (0.48–0.55)	0.41 b (0.37–0.45)	0.38 b (0.31–0.46)	0.44 (0.40–0.47)	0.002
	$P > F$	0.334	0.657	0.115	0.669	
Dispersion coefficient, D (cm^2 h^{-1})	Soybean	0.96 AB (0.51–1.78)	5.77 A (0.28–120.)	3.21 A (0.65–15.9)	2.41 A (1.30–4.47)	0.106
	Corn	0.58 B (0.39–0.85)	0.76 B (0.34–1.68)	1.70 AB (0.72–3.98)	0.96 B (0.66–1.40)	0.059
	Oat	1.24 Aa (0.93–1.65)	0.61 Bb (0.37–0.99)	0.74 Bb (0.34–1.61)	0.87 B (0.64–1.17)	0.037
	Mean	0.92 (0.71–1.20)	1.31 (0.74–2.32)	1.64 (0.99–2.72)	1.23 (0.97–1.57)	0.311
	$P > F$	0.017	0.028	0.034	0.001	
Dispersivity, λ (cm)	Soybean	1.91 b (0.94–3.85)	15.9 Aa (0.72–355.)	9.60 Aa (2.21–41.6)	6.80 A (3.29–14.1)	0.036
	Corn	1.20 b (0.86–1.66)	1.79 Bab (0.87–3.68)	3.74 ABa (1.62–8.64)	2.13 B (1.49–3.06)	0.043
	Oat	2.37 (1.71–3.28)	1.38 B (1.05–1.81)	2.34 B (1.14–4.80)	2.00 B (1.58–2.54)	0.127
	Mean	1.81 (1.40–2.34)	3.27 (1.84–5.81)	4.40 (2.72–7.12)	2.97 (2.32–3.80)	0.060
	$P > F$	0.053	0.015	0.034	0.001	

All statistics were computed using log-transformed data.

[†]The values in parentheses refer to confidence limit with 95% probability.

[‡]Where $P \leq 0.05$ for F statistic; means within a column followed by the same capital letter and means within a row followed by the same lowercase letter are not significantly different using the Waller-Duncan K ratio test.

TABLE 4

P values for *t* test of surface and subsurface solute transport properties being equal by crop and row position

Parameter	Crop	Row positions			All Row Positions
		Plant row	Nontrafficked Interrow	Trafficked Interrow	
Pore velocity, v (cm h^{-1})	Soybean	0.002	0.756	0.326	0.036
	Corn	0.061	0.444	0.778	0.043
	Oat	0.004	0.123	0.478	0.004
	All crops	<0.001	0.252	0.204	<0.001
Dispersion coefficient, D (cm^2 h^{-1})	Soybean	0.002	0.722	0.001	<0.001
	Corn	0.073	0.087	0.337	0.032
	Oat	0.004	0.026	0.026	<0.001
	All crops	<0.001	0.010	0.002	<0.001
Dispersivity, λ (cm)	Soybean	0.005	0.093	0.002	<0.001
	Corn	0.077	0.900	0.283	0.037
	Oat	0.004	0.010	0.008	<0.001
	All crops	<0.001	0.022	0.002	<0.001

All statistics were computed using log-transformed data.

essentially mirrored D, varying by row position in soybean and corn and by crop in trafficked and nontrafficked interrows. As with D, λ was greater in the interrow position of soybean and trafficked interrows of corn than at any of the other positions.

Comparison of Surface and Soil Profile Solute Transport Properties

Overall, the mean fitted surface v (0.34 cm h^{-1}) was smaller than the soil profile value (0.44 cm h^{-1}) at 95% probability level (Table 4). Similarly, D (0.38 cm^2 h^{-1}) and λ (1.02 cm) from surface measurements were significantly less than D (1.23 cm^2 h^{-1}) and λ (2.97 cm) from subsurface measurements. For v, the two sets of measurements were different when averaged across all row positions, but this was primarily because of the significant difference in measurements taken in the row position, with no significant differences found for either interrow position for any crop (Table 4). For D and λ, the measurements were different when averaged over either all crops or all row positions. However, there were row position by crop combinations for which the two sets of measurements were not different (all row positions in corn and the nontrafficked interrow for soybean).

DISCUSSION

In corn and soybean, both surface and subsurface solute transport properties demonstrated significant effects caused by row and interrows. The effect of row and interrow positions was not significant on surface v (Table 1). The profile v was larger in plant rows than in interrows (Table 3). The plant rows in corn and soybean also showed smaller surface and profile λ than in trafficked interrows. The differences in v and λ values can be attributed to infiltration, transport volumes, and the presence or absence of surface ponding conditions in interrows and plant rows. The large profile v particularly in plant rows also indicated that the mobile water content was smaller in plant rows probably because of larger root density in plant rows as compared with interrows (Gish and Jury, 1982). Past studies have also reported greater infiltration rate (Ankeny et al., 1990; Mohanty et al., 1994) and leaching (Saffigna et al., 1976; Gish and Jury, 1982) in plant rows than in interrows. While working in a field with much greater surface relief, Jaynes and Swan (1999) observed less leaching below ridges (plant rows) than in interrows in uncropped ridge-tilled soil. Their tracer moved vertically in plant rows but the tracer showed more pronounced lateral spreading and preferential flow under the interrows. The differences in leaching patterns in these different studies were probably because of the water application methods and presence of growing crops. Crop canopy alters the distribution of rainfall/sprinkler application reaching the soil surface. A study conducted by Saffigna et al. (1976) found that stem flow might be related to increased water flow in soil zones directly below plant rows. In our study, the plant canopy and stem flow were absent. Ghodrati and Jury (1990) measured shallower leaching under ponded conditions than under nonponding sprinkler irrigation. Jacques et al. (1997) reported λ of 6.14 cm at 90 cm depth under no ponding condition and 65 cm for similar soil under ponded condition (observed by Mallants et al., 1996). Jaynes et al. (1988) also found that field-scale λ measured under flooded irrigation was larger than the field-scale λ under intermittent irrigation. The larger λ under ponding conditions is probably because of solute transport through macropores and to a larger variability in saturated hydraulic conductivity than in unsaturated conductivity (Mohanty et al., 1996). There was no ponding in our oat strip, and the oat strip did not have significant differences in v and λ among row positions.

Neither surface nor subsurface solute transport properties exhibited significant effects of trafficking on solute leaching in interrows (Table 1). Numerous studies have reported that trafficking reduced hydraulic conductivity and infiltration rate due to increased surface bulk density (Meek et al., 1989; Ankeny et al., 1990; Starr, 1990; Mohanty et al., 1994; Vervoort et al., 2001). The differences among studies in the effect of traffic can be attributed to differences in experimental conditions, especially the flux rates and timing of measurements. Our study used a smaller flux rate than the other reported studies. Our study was conducted late in the cropping season, whereas some of the other studies investigated effects of traffic early in the growing season (Meek et al., 1989; Starr, 1990).

The generally larger λ in the soil profile versus the surface soil for each combination of crop by row position indicated that the soil profile λ was influenced by factors below the soil surface. Jacques et al. (1997) also reported an increase in λ with depth that ranged from 1.1 to 6.1 cm at 30 and 90 cm depths, respectively. They also found an increase in variability of λ with depth. Similarly, Khan and Jury (1990) reported a linear increase in λ with increasing column length due to an increase in lateral mixing at the flux rates of 4 and 8 cm day^{-1}. In contrast, Jaynes and Rice (1993) found a decrease in dispersivity up to 1.8 m depth particularly under flooded irrigation and attributed this to greater vertical spreading of solute during the infiltration phase rather than the percolation phase of the experiment. Gaur et al. (2003) observed that surface dispersivity (1-cm depth) was similar to dispersivity at the 30-cm depth within a disturbed soil profile. Gaur et al. (2006) determined subsurface dispersivity by using solute flux concentration in a tile located at 110 cm depth that was found to be larger (8 cm) than the surface dispersivity (1 cm). In an undisturbed soil column study, Lee et al. (2002) also observed similar or smaller dispersivities at 2-cm depth than at 20-cm depth in undisturbed soil columns.

Our findings suggest that the surface solute transport could be described by a one-dimensional CDE model whose transport parameters were essentially unaffected by crop. However, D was significantly different for the different row positions, being greater in the interrow positions and lowest in the row. This study was conducted in the latter part of the growing season when soil was relatively settled as opposed to immediately after tillage. We would expect that surface solute transport parameters would differ among interrow positions because of traffic if measured immediately after tillage operations.

The subsurface solute transport properties indicated that v was generally greater in the rows than interrows. This implies a lower mobile or effective water content below the rows than between rows. Prevalence of crop roots may account for the more rapid solute movement below rows. In contrast to v, D in the subsurface was, in general, greater in the interrow positions of soybean and trafficked interrows of corn. This may have been because of surface ponding during the experiment leading to macropore flow and nonmatrix type solute transport.

The significant row position by crop variability in subsurface solute transport parameters suggests that for accurate solute transport predictions, one needs a model with spatially distributed parameters. The study was helpful in distinguishing surface and subsurface solute transport patterns at row/interrow positions after harvest. This information is important for the management of row positions to reduce solute transport. Further observations of the temporal distributions of solute transport properties at different row positions will enhance our understanding and predictive capability of chemical transport through row-cropped soil.

SUMMARY

Solute transport properties were determined at the soil surface (top 2 cm) and in 120-cm deep soil profiles. The fitted soil profile pore water velocity was greater than the fitted surface soil

pore water velocity when averaged over all measurement locations. The mean estimated soil profile dispersivity (2.97) was larger than the estimated soil surface value (1.02 cm). Both surface and subsurface solute transport properties demonstrated the effect of row position. The soil profile concentration distributions indicated larger pore water velocities and deeper leaching in plant rows than in interrows. The depth of chemical movement was affected by different mobile water contents in rows and interrows. In addition, the surface and profile dispersivities were smaller in the plant rows than in interrows for corn and soybean. The soil profile resident concentration distribution patterns suggested that, in addition to row and interrow position effects, the heterogeneity in flow and flow in macropores open to a free water surface in ponded interrow positions influenced the solute concentration distributions. The findings suggested that the surface solute transport was primarily one-dimensional and demonstrated an effect of row and interrow positions, whereas solute transport within soil profiles was more complex. Based upon these observations, the surface solute transport at different row positions is amenable to description by one-dimensional solute transport models. However, a model with a spatially distributed upper boundary condition to distinguish between flux and head control may be needed to represent spatially variable ponding.

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