Field Measurement of Soil Surface Chemical Transport Properties for Comparison of Management Zones

Management of chemicals in soil is important, yet the complexity of field soils limits prediction of management effects on transport. To date, few methods have been available for field measurement of chemical transport properties, but a recently developed dripper–time domain reflectometry technique allows rapid collection of data for determining these properties. The objective of this work was to apply this technique for comparison of chemical transport properties for different soil management zones. Experiments were conducted comparing four interrow management zones: no-till nontrafficked, no-till trafficked, chisel plow nontrafficked, and chisel plow trafficked. Drip emitters were positioned at 12 locations in each zone and used to apply water followed by a step input of CaCl$_2$ tracer solution. Breakthrough curves were measured via electrical conductivity with time domain reflectometry probes. The mobile–immobile model was fit to the breakthrough curves to determine chemical transport properties. Mean chemical transport properties were 0.34, 0.11 h$^{-1}$, 10 cm h$^{-1}$, 164 cm$^2$ h$^{-1}$, and 5 cm, for the immobile water fraction, mass exchange coefficient, average pore-water velocity, mobile dispersion coefficient, and dispersivity, respectively. All five properties showed significant differences between management zones. Differences in mass exchange and mobile dispersion coefficients coincided with differences in tillage, while differences in mean pore water velocities coincided with differences in traffic. The immobile water fraction was largest for the no-till nontrafficked zone. These results represent one of very few reports for field measurement of chemical transport properties and the first application of this approach for comparison of chemical transport properties across management zones.

Abbreviations: BTC, breakthrough curve; CPNT, chisel plow nontrafficked; CPT, chisel plow trafficked; EC, electrical conductivity; MIM, mobile–immobile model; NTNT, no-till nontrafficked; NTT, no-till trafficked; TDR, time domain reflectometry.
MATERIALS AND METHODS

Field Conditions

Research was conducted on the Iowa State University’s Agronomy and Agricultural Engineering research station near Ames. The soil at the site is mapped as Webster silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquoll, Soil Conservation Service, 1981). This soil is nearly level (slopes <2%) and is considered poorly drained under natural conditions. The soil is currently drained by a tile drainage system.

The areas selected for field measurement were adjacent plots under no-till and fall chisel plow tillage treatments. Plots had been maintained with the existing tillage scheme for at least 5 yr before this study. A rotation of corn (Zea mays L.)—fallow—soybean (Glycine max (L.) Merr.) was used in the tillage study; measurements were conducted in fallow plots following corn for both tillage treatments. The last tillage operation for the chisel plow plots was performed approximately 9 mo before the experiments. For comparison, two transects were selected in each plot. The first transect was an interrow space used for wheel traffic during all field operations, and the second transect was a nontrafficked interrow.

Drip Emitters

The dripper line setup consisted of three dripper tubes fixed together in parallel (Fig. 1). Each dripper tube was equipped with 12 identical drip emitters spaced 1.5 m apart. Each of the three dripper tubes in the line had
pressure-compensating drip emitters (Netafim USA, Fresno, CA) designed to deliver a different discharge rate: 2, 4, or 8 L h\(^{-1}\) at pressures of 55 to 83 kPa. The three dripper tubes were connected together by a polyvinyl chloride (PVC) manifold at either end of the line. The manifold consisted of a pressure gauge and independent two-way valves for each tube. This allowed one or more dripper tubes within a line to be operated simultaneously. A PVC funnel was positioned under the drip emitters at each location along the transect to direct flow from all three dripper tubes to the same position on the soil surface (Fig. 1). The combination of the three dripper tubes in the dripper line allowed water to be delivered at a range of discharge rates at each 1.5-m position along the transect. Dripper lines were held 10 cm above the soil surface with wooden stakes. Water or a salt tracer solution was supplied to the dripper lines from 1514-L (400-gallon) tanks via a pump used to produce the necessary pressure.

Before water was applied, all loose residue was removed from the soil surface and surface conditions were photographed (Fig. 2). Conditions such as the percentage of residue cover, surface cracking, and tire imprints were recorded. Samples were also collected at 12 evenly spaced locations along each transect to determine the soil bulk density. For this measurement, a sample was collected from the 0- to 4-cm depth increment at each location using a 6-cm-diameter ring. Bulk density was computed as the ratio between the oven-dry mass of the sample and the sample volume.

A small piece of scrubber sponge (3 by 3 by 0.5 cm) was positioned under the drip emitters to lessen water impact on the soil surface and protect any existing soil crust. The scrubber sponge was selected to ensure minimal water absorption during dripper discharge. Water was applied beginning with the 2 L h\(^{-1}\) emitter. The discharge rate was increased incrementally using different combinations of the dripper tubes in each dripper line until a steady-state ponded area with at least an 8-cm diameter could be achieved at each location along the transect. The steady-state ponded area for each dripper and each discharge rate was measured by hand and recorded. Emitter discharge rates were also measured several times by hand to determine the actual water application rate. The dripper discharge rates used for measurement of the BTCs were approximately 2, 8, 2, and 4 L h\(^{-1}\) for the NTT, NTNT, CPT, and CPNT transects, respectively.

Fig. 1. A dripper transect (left) and an individual dripper during measurement (right).

Fig. 2. Soil surface conditions for no-till (A) with and (B) without residue and for chisel plow (C) with and (D) without residue.
Fig. 3. Examples of the Jaynes et al. (1995) approach for determining chemical transport parameters ($R = \text{relative resident concentration}$ and $t^* = \text{scaled time}$).

### Tracer Experiment

After a steady-state ponded area had been achieved, TDR probes were installed centered under the ponded area at each dripper position. The TDR system consisted of two-rod probes (0.38-cm diameter, 10 cm long, and 2-cm spacing), a cable tester (Model 1502B, Tektronix Corp., Redmond, OR), a computer, and a computer program (WinTDR 98; Or et al., 1998) to store and analyze the data. The 12 probes were connected to the cable tester via a multiplexer setup. The TDR probes were inserted at an angle of ~11° from the surface to a depth of ~2 cm. This insertion method limits surface soil disturbance, but requires the assumption that measurements represent the midpoint depth of the probes (Gaur et al., 2006). Before application of the tracer, TDR data were collected while the drippers supplied a constant input of water. This continued until a constant EC was measured, which was used to establish ECa.

A tracer solution consisting of 0.05 $M$ CaCl$_2$ was applied as a step input into the drippers. This was accomplished by switching supply tanks for the drippers and quickly flushing the dripper lines through an outlet at the end of the lines. Collection of BTC data took approximately 2 h, but the time required varied with location and tillage scheme. After collecting BTC data, each location along the transect was sampled. The samples were collected from the surface to 2-cm depth in the area where each TDR probe was installed using 8-cm-diameter brass rings. These samples were taken to the laboratory for analysis. The actual midpoint depth of the TDR probes at each location was determined through excavation.

Each soil sample was split into two subsamples. One subsample was used to determine the gravimetric water content, and the other subsample was diluted five times with water. The diluted subsample was shaken and allowed to settle. The supernatant was subsequently analyzed with a conductivity meter (Model 30, Accumet, Hudson, MA) to determine $C(t)$ of the final soil water solution (i.e., corresponding to the final TDR measurement). Samples obtained from the tracer solution and the background water input solution were also analyzed in the laboratory to determine $C_0$ and $C_i$, respectively.

### Breakthrough Curves and Analysis

From the final soil value of $C(t)$, $C_0$, and $C_i$, it was possible to determine the final value of $R(t)$ in Eq.[3]. Subsequently, the value of ECa, was computed using this final value of $R(t)$, the corresponding ECa(t), and ECa. Values for ECa and ECa were then used to normalize $R(t)$ with respect to the real-time ECa values measured with the TDR probes (Gaur et al., 2003). The normalized $R(t)$ values represent the relative resident concentrations of the surface ~2-cm soil layer where the TDR probe was installed. The relative resident concentration BTCs were used to estimate the MIM solute transport parameters $\theta_{im}$, $\alpha$, $D_m$, and $v$.

Initial estimates of $\theta_{im}$ and $\alpha$ were obtained using the Jaynes et al. (1995) approach from Eq. [4] (Fig. 3). For this fitting, we neglected the early time data, following the underlying assumption in this approach that the tracer front has advanced sufficiently so that dispersion effects are negligible (Lee et al., 2000). Implementation of Eq. [4], in turn, requires a priori estimates of $v$ and $\theta$ at each measurement location. The volumetric water content was determined from gravimetric samples collected at the conclusion of the experiments using (Al-Jabri et al., 2002a)

$$\theta = \frac{\theta_g \rho_s}{\theta_g \rho_s + 1}$$

where $\theta_g$ (kg kg$^{-1}$) is the gravimetric water content and $\rho_s$ is the particle density (2.65 g cm$^{-3}$). Initial estimates of $v$ were determined from surface measurements of the ponded area under each dripper, the rate of water input from the drippers, and $\theta$. Because water spreads as it moves through the profile, $v$ decreases as water proceeds downward. Based on the work of Wooding (1968), however, the ratio of $v$ at the TDR depth to $v$ at the surface can be estimated (cf., Al-Jabri et al., 2006). For our initial estimate of $v$, we assumed a ratio of 0.6 between $v$ at the lower end of the TDR probe and surface-measured $v$.

After obtaining these initial estimates for $\theta_{im}$, $\alpha$, and $v$, inverse fitting was performed with CXTFIT (Toride et al., 1999) to determine final values for all parameters based on the relative resident concentrations. For fitting, $v$ was given an upper bound equal to the surface $v$. We chose to fit $\theta$ despite the available estimate from the surface, because of the associated uncertainty in changes in $v$ with depth. Others have also suggested that an optimized $v$ may be appropriate to reflect the TDR sampling zone of the measured BTCs (Mallants et al., 1994; Gaur et al., 2003). The parameters $\theta_{im}$ and $\alpha$ were established from the initial estimate of Eq. [4], but were allowed to vary ±10% in fitting. The parameter $D_m$ was not bounded in fitting.

### RESULTS AND DISCUSSION

#### Soil Surface Conditions

Soil surface conditions varied by tillage treatment (Fig. 2). For the NTNT transects, the surface was covered by residue ranging in size from fine fibers to whole corn stalks. Surface cover was visually estimated to average 80% along the transect before residue removal. After the removal of residue, it could be observed that the soil surface was relatively loose. For the TNT transect, residue was also abundant; however, some residue was partially incorporated into the surface in the tire track depressions caused by a previous field operation during moist conditions. This partially incorporated residue was left in place so as not to disturb the soil. After removal of the loose residue, the soil surface showed obvious indication of tire treads with some depressions and more tightly consolidated material.

The chisel plow transect showed significantly less cover than did the no-till plots but with slightly more large, incorpo-
rated residue (Fig. 2). Residue cover in the CPNT transect was estimated to be <30% in all cases and <10% at five of the 12 measurement locations. After removal of any existing loose residue, the soil surface appeared to be slightly crusted, with a crust 2 to 3 cm thick. The CPT transect again showed depressions as evidence of field traffic, but with less obvious compaction from treads than were observed for the no-till traffic transect.

In addition to these more qualitative comparisons, soil dry bulk density was also measured along each transect. Bulk densities varied by transect with mean bulk densities of 1.31, 1.58, 1.40, and 1.50 Mg m\(^{-3}\) for the NTNT, NTT, CPNT, and CPT zones, respectively. Differences in bulk density were significant at the 95% confidence level (Table 1). Bulk density trends followed the qualitative observations. The surface was most pristine for the NTNT transect, showed some crusting for the chisel plow transects, and was most compacted from traffic along the NTT transect.

Table 1. Measured properties including bulk density, proportion of water in the immobile domain (\(\theta_{im}/\theta\)), first-order mass exchange coefficient (\(\alpha\)), pore water velocity (\(v\)), dispersion coefficient (\(D_m\)), and dispersivity (\(\gamma\)) for the four management zones. Each value represents 12 measurements; standard deviations are shown parenthetically.

<table>
<thead>
<tr>
<th>Management zone†</th>
<th>Bulk density</th>
<th>(\theta_{im}/\theta)</th>
<th>(\alpha)‡</th>
<th>(v)‡</th>
<th>(D_m)‡</th>
<th>(\gamma)‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTNT</td>
<td>1.32c(\pm)0.18</td>
<td>0.28b(\pm)0.11</td>
<td>0.13a(\pm)0.16</td>
<td>19a(\pm)20</td>
<td>330a(\pm)1694</td>
<td>6ab(\pm)9</td>
</tr>
<tr>
<td>NTT</td>
<td>1.58a(\pm)0.27</td>
<td>0.47a(\pm)0.19</td>
<td>0.11a(\pm)0.16</td>
<td>3c(\pm)3</td>
<td>307ab(\pm)4560</td>
<td>13a(\pm)0.38</td>
</tr>
<tr>
<td>CPNT</td>
<td>1.40bc(\pm)0.09</td>
<td>0.26b(\pm)0.10</td>
<td>0.05b(\pm)0.14</td>
<td>12a(\pm)12</td>
<td>144ab(\pm)1255</td>
<td>3bc(\pm)7</td>
</tr>
<tr>
<td>CPT</td>
<td>1.50ab(\pm)0.13</td>
<td>0.32b(\pm)0.13</td>
<td>0.05b(\pm)0.22</td>
<td>6b(\pm)5</td>
<td>20b(\pm)62</td>
<td>1c(\pm)1</td>
</tr>
</tbody>
</table>

† Management zones are no-till nontrafficked (NTNT), no-till trafficked (NTT), chisel plow nontrafficked (CPNT), and chisel plow trafficked (CPT).
‡ Statistical analysis performed using log transforms.
§ Values shown in the same column followed by the same letter were not significantly different at \(\alpha = 0.05\).

Breakthrough Curves

Representative examples of BTCs from each of the four management zones are shown in Fig. 4 to 7. Breakthrough generally occurred more rapidly in the nontrafficked transects, thus data collection time varied slightly between treatments. Several inferences can be made from the shapes of the BTCs. First, because the relative concentration in all cases remained well below one as the slope of the BTCs approached zero, the BTCs are indicative of mobile–immobile transfer (i.e., preferential flow). In other words, a fraction of the soil water is not readily involved in the solute transfer. Of particular note was
the much lower maximum relative concentration observed for the NTT zone (Fig. 5).

In all four management zones, the slopes of the BTCs decrease with time, but never reach a constant concentration (Fig. 4–7). Thus, it can also be inferred that there is significant exchange between the mobile and immobile water fractions: the parameter $\alpha$ from Eq. [2] would be expected to be nonzero. The tail slopes of the BTCs tended to be larger for the no-till zones (Fig. 4–5) than for the chisel plow zones (Fig. 6–7), but in all four cases slopes were non-zero. This differs from the assumption used by Clothier et al. (1992) of limited interaction between mobile and immobile fractions and suggests that the Jaynes et al. (1995) approach, Eq. [4], is more appropriate for this data set.

Table 2. Chemical transport properties including the proportion of water in the immobile domain ($\theta_{\text{im}}/\theta$), first-order mass exchange coefficient ($\alpha$), pore water velocity ($v$), dispersion coefficient ($D_m$), and dispersivity ($\gamma$) across all management zones. Values represent 48 measurements.

<table>
<thead>
<tr>
<th></th>
<th>$\theta_{\text{im}}/\theta$</th>
<th>$\alpha$</th>
<th>$v$</th>
<th>$D_m$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.34</td>
<td>0.11</td>
<td>10</td>
<td>164</td>
<td>5</td>
</tr>
<tr>
<td>SD</td>
<td>0.16</td>
<td>0.32</td>
<td>14</td>
<td>1395</td>
<td>11</td>
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<tr>
<td>Max.</td>
<td>0.89</td>
<td>0.50</td>
<td>70</td>
<td>1915</td>
<td>58</td>
</tr>
<tr>
<td>Min.</td>
<td>0.04</td>
<td>0.001</td>
<td>1</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>CV, %</td>
<td>47</td>
<td>303</td>
<td>140</td>
<td>851</td>
<td>219</td>
</tr>
</tbody>
</table>

† Lognormal distribution.

Chemical Transport Properties

Chemical transport properties determined from the fitting of the MIM to BTCs are summarized in Table 2. Similar to Al-Jabri et al. (2006), the parameter $\theta_{\text{im}}/\theta$ was normally distributed, while $\alpha$, $D_m$, and $v$ were lognormally distributed. An additional parameter, the dispersivity ($\gamma = D_m/v_m$, cm), is also shown and was characterized by a lognormal distribution. The arithmetic mean for $\theta_{\text{im}}/\theta$ and log-normal means for $\alpha$, $v$, $D_m$, and $\gamma$ across all treatments were 0.34, 0.11 h$^{-1}$, 10 cm h$^{-1}$, 164 cm$^2$ h$^{-1}$, and 5 cm, respectively. Few field measurements are available from the literature for comparison to these data. For $\theta_{\text{im}}/\theta$, Al-Jabri et al. (2006) reported a mean value of 0.23, while Jaynes et al. (1995), Casey et al. (1998) and Al-Jabri et al. (2002a, 2002b) observed larger mean values of 0.69, 0.43, 0.57, and 0.58, respectively. For $\alpha$, reported values are commonly 0.08 h$^{-1}$ (cf., Al-Jabri et al., 2006, Casey et al., 1999), which is similar to the mean observed here. A possible explanation for the slightly larger values we observed may be slight mixing of the solute input with water ponded at the surface before application of the tracer. This would have a net effect similar to increasing the concentration of the tracer with time and could result in slightly elevated values for $\alpha$; however, this effect was not observed in the results of Al-Jabri et al. (2006) using a similar approach, and is also not consistent with results observed for all treatments tested here.
Thus, our observed \( \alpha \) values are probably related to these particular soil conditions.

Al-Jabri et al. (2006) provided one of very few reports for field measurement of the remaining three parameters \( v, D_m \), and \( \gamma \), though their study was conducted exclusively under no-till conditions and with measurements in plant rows rather than interrows. Their mean values were 45 cm h\(^{-1}\) (59 cm h\(^{-1}\) in the mobile region), 1220 cm\(^2\) h\(^{-1}\), and 21 cm, respectively. Our mean values for \( v, D_m \), and \( \gamma \) are smaller (Table 2), but fall within the reported range of Al-Jabri et al. (2006) for all parameters and are consistent in that our lower observed \( v \) corresponds to a lower observed \( D_m \).

Parameters for the four soil management zones are summarized in Table 1. Analysis of variance indicated significant differences between management zones for all parameters at the 0.95 probability level. Properties were compared by management zone with a Student’s \( t \)-test using \( \alpha = 0.05 \) (Table 1). For \( \theta_{\text{im}}/\theta \), the NTT zone showed the highest value, while the remaining three management zones were similar. Values for \( \alpha \) were grouped according to tillage treatment with the no-till conditions providing higher values. Alternateley, the trend in \( v \) more closely followed traffic: the nontrafficked zones had the highest \( v \), while the trafficked zones had lower values for \( v \). The mobile dispersion coefficient, \( D_m \), was highest for the NTNT zone, intermediate for the NTT and CPNT zones, and lowest for the CPT zone.

Statistical differences between properties are consistent with differences between management for the four zones. The no-till zones would be expected to provide a wider pore-size distribution than the more uniform chiseling plow zones. Consequently, the \( \alpha \) value is higher for the no-till zones with a larger contribution from both small and dead-end pores throughout breakthrough, while the chisel plow zones provide more uniform breakthrough but through only a portion of the pore space. Continued compaction without loosening, however, relegates solute transport to a smaller fraction (i.e., higher \( \theta_{\text{im}}/\theta \)) of the NTT zone, which has a lower total porosity and thereby probably less large pores. This tightly compacted zone also has the lowest \( \gamma \), while the nontrafficked zones show higher \( \gamma \) consistent with less compaction or disturbance. The mobile dispersion coefficient, \( D_m \), differs slightly from the trend in \( v \). The pattern in \( v_m \) (data not shown in Table 1), however, also differs slightly from \( v \). Lognormal mean \( v_m \) was 27, 8, 17, and 10 cm h\(^{-1}\), in the NTNT, NTT, CPNT, and CPT zones, respectively. Given the smaller mobile fraction for the NTT zone, \( v_m \) is similar between management zones with only the NTNT zone statistically different from all other zones. Thus, again we expect that the relatively high values for \( D_m \) in the no-till zones are related to pore-size distribution: A large fraction of solute is conducted through relatively large pores in the no-till zones while the more uniform pore-size distributions in the chisel plow zones provide slightly lower mobile dispersion coefficients.

Overall, properties suggest differences in preferential flow patterns between the four zones. Mass exchange coefficients of both no-till zones indicate exchange between mobile and immobile fractions, but the greater macroporosity of the NTNT zone provides the potential for rapid chemical transport, which can be observed from \( v \). The NTT zone, with its larger immobile fraction, provides less uniform chemical transport through the soil, but the consequence of less macroporosity is a lower \( v \). This zone may provide a problem for chemical delivery to plants in that its nonuniform chemical transport through the profile (transport to a smaller fraction of the soil) is compounded by its high bulk density, which would probably limit root proliferation. Alternatively, the chisel plow zones provide more uniform, less rapid (as compared with NTNT) chemical transport through a fraction of the pore space.

**CONCLUSIONS**

Soil management such as tillage and wheel traffic can impact soil solute transport properties. Understanding of these impacts can be improved by measurement and comparison of solute transport properties, yet to date very few data are available. The method of Al-Jabri et al. (2006) provides a relatively simple means for collection of data to make this comparison.

The method, as demonstrated here, consists of collecting field-measured BTCs at multiple locations simultaneously in a relatively simple tracer experiment: water was applied through drip emitters for several hours followed by application of a CaCl\(_2\) conservative salt tracer solution. Relative concentration vs. time was determined using surface-installed TDR probes for measuring EC\(_a\). Laboratory analysis was required only to determine input, background, and final EC values. The MIM was then fit to the relative concentration vs. time data to determine the solute transport parameters. The fitting procedure used here combined the approach of Jaynes et al. (1995) for estimating \( \theta_{\text{im}}/\theta \) and \( \alpha \), with the inverse fitting of CXTFIT for final determination of parameters, but other approaches are possible.

Results indicate significant differences between the chemical transport properties for all four management zones. Mass exchange between the mobile and immobile domains and mobile dispersion coefficients were similar according to tillage, while mean pore-water velocity was similar according to traffic. The trend in the immobile water fraction showed the combined effect of both tillage and traffic. Detailed comparison and interpretation of differences between management zones requires additional data collection, but future implementation of this technique offers new opportunities for such work.

**REFERENCES**


Clothier, B.E., M.B. Kirkham, and J.E. McLean. 1992. In situ measurements...


