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Agrichemical movement in the root-zone of claypan soils: ridge- and mulch-tillage systems compared

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Abstract

Climate, poor internal drainage in claypan soils, and cultural factors make it difficult to control agrichemical movement in the southern fringe of the Corn Belt, USA. Ridge- and mulch-tillage systems were evaluated for root-zone water quality and grain production on a claypan soil. In northcentral Missouri the Mexico silt lam (fine, montmorillonitic, mesic Udollic Ochraqualfs; FAO-Mollic Planosols) has a pronounced B_t horizon. Zero-tension pan lysimeters at 91 cm were used to monitor nitrate–nitrogen (NO_3–N) and herbicide concentrations in three farming systems: (1) a high chemical input mulch-tillage in a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation (MTH); (2) a reduced chemical input with mulch-tillage in a corn–soybean–wheat (*Triticum aestivum* L.) rotation (MTR); (3) a reduced chemical input with ridge-tillage in a corn–soybean rotation (RTR). Farming system treatments were replicated three times with lysimeters placed in two replications. By band-applying herbicide over rows, herbicide mass applied to the MTR and RTR system was 50% less than applied to MTH, where herbicides were broadcast. Only marginal benefits to root-zone water quality could be attributed to this reduced herbicide input. Leachate water flow volume and chemical concentration intercepted by the pans were influenced more by intrinsic, site-specific soil hydrology and year-to-year variation of rainfall intensity and timing than by the management. Root-zone leachate in both MTH and RTR farming systems in 1992 were below USEPA maximum contaminant levels (MCL) of 10 mg l^{-1} for NO_3–N and 3 $\mu g\ l^{-1}$ for atrazine used for drinking water. Rainfall after herbicide application was more frequent and intense in 1993, but the extent of leaching was site-specific with significant variation among plots within all treatments. For example, maximum NO_3-N and atrazine concentrations in leachate were 42 mg l^{-1} and 100 $\mu g\ l^{-1}$, respectively, in one MTH plot, and in second plot they were below 7 mg l^{-1} and 2 $\mu g\ l^{-1}$, respectively. High concentration variability also occurred between RTR plots. Nitrate–N and atrazine were consistently below their MCL on MTR plots. While herbicide movement and loss may be slightly reduced with banding, this management will have low adoption on claypan soils because of the yield-loss risks associated with the small time window allowed for field operations. The same risk is associated with split N applications.

Keywords: Nitrate; Herbicide; Leachate; Pan lysimeter; Grain production; Herbicide banding

1. Introduction

Chemical concentration in the water under ridge- and mulch-tillage farming systems have not been previously measured in the root-zone of claypan soils

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at a field scale. Claypan soils occupy about 4 million hectare in Missouri and Illinois with Major Land Resource Area 113 (U.S. Department of Agriculture, 1981), and have a unique hydrology controlled by a slow water flow in the soil matrix of the restrictive clay layer (Jamison et al., 1968). Infiltration rates vary greatly especially as related to soil moisture contents (Jamison and Thornton, 1961; McGinty, 1989). Clay content in the argillic horizon is generally >500 g kg^{-1} and is comprised of smectitic (high shrink-swell) clay minerals. Claypan soils can have significant soil cracks when dry, with maximum soil volumes of 0.06 m^3 m^{-3} (Baer et al., 1993) or 0.17 m^3 m^{-3} (Larson and Allmaras, 1971). Water flows through these desiccation cracks, as well as through pre-existing biopores and relic cracks filled with coarser textured surface soil. Evaluations of various management practices on impaired water quality are challenging under these conditions because of the scale influences on macroporous flow.

Soil testing and accurate yield goal estimation are reliable approaches to guide N fertilizer recommendations for increased nutrient uptake efficiency and reduced potential for nutrient loss into the environment. Best management practices (BMPs) for N fertilization include: (1) realistic yield goals; (2) N rate according to the soil organic matter content, previous crop, and manure application; (3) soil NO_3–N testing for determining preplant or sidedress N applications; and (4) applications of N at times that maximize the use of N and reduce off-season losses (Randall and Schmitt, 1993). Any fertility management practice that increases N uptake per unit of applied N usually reduces N loss into the environment. Multiple application (split-timing) have increased N crop-use efficiency 7–9% and decreased NO_3^-N leaching loss 23% compared with a single application of an equal amount of fertilizer (Kanwar et al., 1984).

Reduced soil erosion with conservation tillage has promoted investigation of tillage effects on water quality. Baker (1987) concluded that reduced runoff with entrained N leaves more water available for infiltration in conservation tillage systems. Leaching of NO_3–N and pesticides with minimum or no-tillage was increased in some studies (Brinsfield et al., 1987; Steenhuis et al., 1990) but not in others (Logan et al., 1994). Leaching losses were similar among various tillage systems in a corn–soybean rotation (RTR) but had greater atrazine losses for ridge-and no-tillage when continuous corn was grown (Kanwar et al., 1997). Nitrate leaching under no-tillage management was less than when soils were tilled in arid regions (Lamb et al., 1985) and more than with tilled soils in humid regions (Tyler and Thomas, 1977; Thomas et al., 1981). When Kanwar et al. (1985) applied 150 kg ha^{-1} of N to no-tillage and moldboard plowed plots, significantly greater amounts of NO_3–N remained in the top 30 cm of the no-tillage plots. Also, the amount of NO_3–N lost to leaching was almost 100 kg ha^{-1} less in the no-tillage plots.

Herbicides banded over the row and cultivation of the interrow (e. g., ridge-tillage) provides weed control as effective as applying herbicides broadcast (Mulder and Doll, 1993; Wilson, 1993; Pleasant et al., 1994; Krausz et al., 1995). Nitrate and bromide applied to the elevated ridge of a ridge-tillage reduced leaching compared to a similar application with flat tillage (Hamlette et al., 1990), as runoff was directed into the valleys between the ridges, below and away from the chemical bands. Another evaluation of ridge-tillage reported no significant differences in NO_3–N leaching compared to the other tillage systems (Kitur et al., 1984).

Crop rotation also can change rooting depth, water use patterns, crop residue quantity and quality, and N uptake, all of which can impact root-zone water quality. Rotation may decrease pest infestations and the need for chemical control. Certain crop rotations have reduced inorganic N fertilizer needs while reducing NO_3–N available for leaching (Varvel and Peterson, 1990). Also, farming systems with large chemical inputs are more likely to contaminate shallow ground water more than those with small inputs (Hubbard et al., 1986).

Some combinations of soil drainage/texture, landscape, and climate early in the growing season highly restrict the opportunities for management of water quality. Hydrological properties of the Mexico soil association are spatially variable and have an extremely slow drainage that controls the opportunities for timing of fertilizer application and cultivation to reduce reliance on chemical pest control. Inconsistencies among studies regarding tillage effects on water quality underline the need for regional assessment of these variables. Furthermore, studies (Hamlette et al., 1990) emphasize the importance of designing experiments to evaluate tillage interactions between fertility and herbicide management, as modified by physical, chemical, and biological processes in a site specific mode (Bouma, 1989).

This research assessed the impact of farming systems that integrate different tillage, crops, and chemical management practices for grain production and water quality control in claypan soils (Ward et al., 1994). We hypothesized that farming with a more conservative yield goal, side-dressed N, and banded herbicides over the row would have an equivalent yield and less NO_3–N and herbicide leaching losses than a system with a high-yield goal, preplanted N, and broadcast herbicide farming system. Yields and concentrations of NO_3–N and herbicide were measured in the soil and in root-zone water for one ridge-tillage and two mulch-tillage systems from 1991 to early 1994. Farming systems were distinguished by their tillage treatment, but also have other management factors that differed.

2. Materials and methods

2.1. Farming systems and site description

Six farming systems differing in yield goal, tillage, crop rotation, and management of N and herbicide were started in the spring of 1991 at the Missouri MSEA site near Centralia, Missouri, USA. Farming systems were evaluated on 30 plots (18×189 m^2) that were arranged in a randomized complete block design with three replications (Fig. 1). Plot size and dimen-

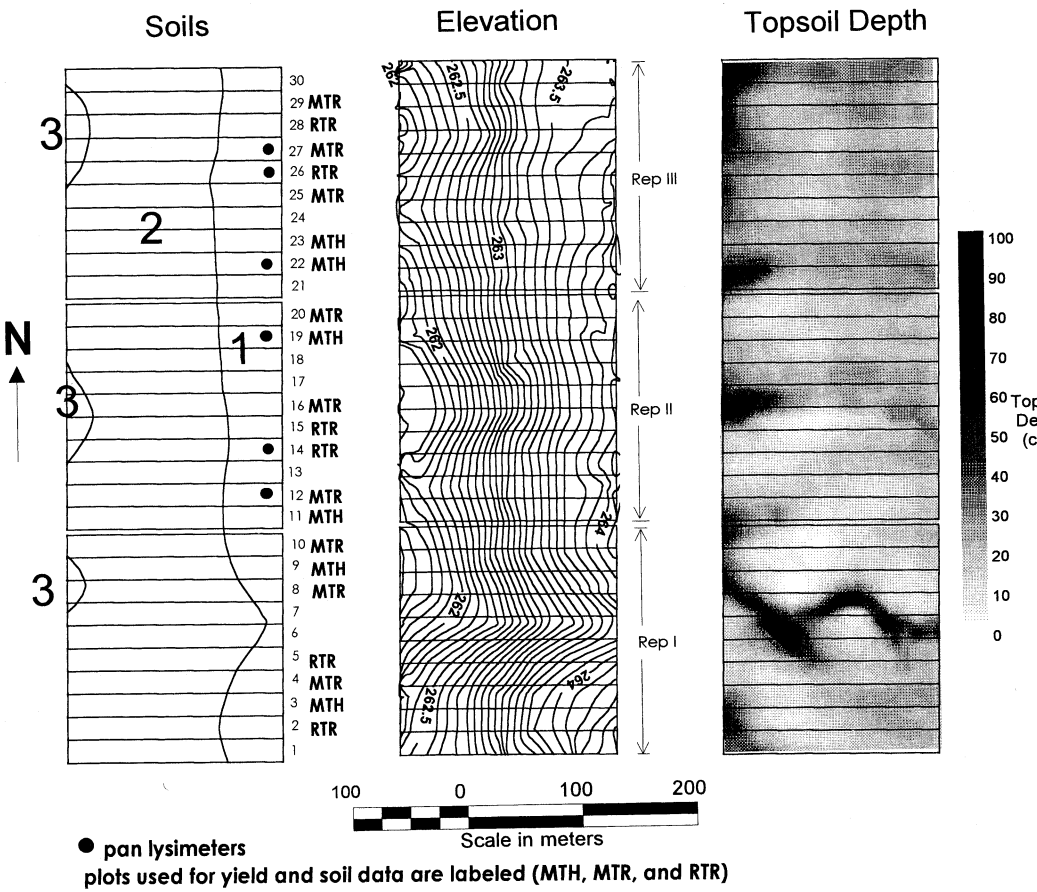

Fig. 1. Soil type, elevation, and topsoil depth over the 11 ha plot research site. Components of mapped soil complex: 1 is Adco silt loam, 0–1% slopes; 2 is Mexico si cl loam, 1–3% slope, eroded; and 3 is Mexico silt loam, overwashed, 1–2% slope.

Table 1
Properties of the Mexico silt loam, 1–3% slope, at the Missouri MSEA site near Centralia, MO

Horizon	Depth (cm)	Texture	Structure[a]	Sand ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	BD[b] at 33 kPa ($Mg\ m^{-3}$)	Matrix[c] flow ($cm\ h^{-1}$)	Water retention ($kg\ kg^{-1}$) 33 kPa	Water retention ($kg\ kg^{-1}$) 1.5 MPa	Organic carbon ($g\ kg^{-1}$)	CEC[d]	pH	Crack[e] area (%)
A_p	0–20	Sil	Wvfg	50	200	1.50	0.08–0.24	35.0	16.0	12.7	18.1	6.2	0.46
BE	20–28	Sicl	Wfsb	70	320	1.35	0.08–0.24	–	–	8.7	25.2	5.2	1.0
B_t	28–38	Sic	Wfsb	20	540	1.15	0.02–0.08	–	–	9.9	42.7	5.1	6.0
$B_{tg}1$	38–48	C	Wfsb	10	590	1.10	0.02–0.08	48.5	30.0	8.0	43.7	5.4	–
$B_{tg}2$	48–58	Sic	Wfsb	10	460	1.40	<0.02	40.0	22.5	3.8	37.7	5.5	1.5
$B_{tg}3$	58–91	Sicl	Mfsb	20	390	1.50	<0.02	–	–	1.8	36.7	5.6	–
$B_{tg}4$	91–132	Sicl	Wcp	30	330	1.50	<0.02	–	–	1.4	25.1	6.5	–

[a] Wvfg: weak very fine granular; wfsb: weak fine subangular blocky; mfsb: moderate fine subangular blocky; wcp: weak coarse prismatic.
[b] Bulk density measured at field capacity.
[c] Matrix flow measured as a permeability.
[d] Unit for CEC are $cmol_c\ kg^{-1}$ of soil.
[e] Maximum crack area in an exposed horizontal plane.

sions were arranged to evaluate farming system effects at summit, sideslope, and footslope landscape positions. Soils were mapped (1: 5000 scale) as Mexico and Adco silt loams (Udollic Ochraqualfs; FAO-Mollic Planosols) on a 1–3% slope. The site had eroded sideslopes (thin topsoil) and depositional areas on footslopes and long pathways for concentrated water flow. Topsoil depth above the B_t horizon ranged from 5 to 90 cm over the 11 ha site (Fig. 1) as measured by the electromagnetic induction (Doolittle et al., 1994). Table 1 provides selected soil physical and chemical characteristics that suggest difficult hydrologic management of the Mexico silt loam.

Chemical inputs, tillage, and crop rotation varied between different farming systems according to the different production and water quality objectives. Only three of the six farming systems were instrumented and compared to accomplish our objectives (Table 2). The ridge-tillage (RTR) system employed a corn–soybean with reduced agrichemical inputs and corn yield goal of 6.9 Mg ha^{-1}, consistent with the long-term average yield in the region. One mulch-tillage system (MTR) was identical to the RTR system with reduced agrichemical inputs and the same corn yield goal but was in a 3-year rotation of corn–soybean–wheat. The wheat yield goal for MTR was 4.0 Mg ha^{-1}. Herbicides were banded at planting over only the row for RTR and MTR. A second mulch-tillage system (MTH) had a corn–soybean rotation with high agrichemical inputs and a high corn yield goal of 9.4 Mg ha^{-1} (average yield of best years for this area). It had overall broadcast herbicide so that the herbicide mass applied per hectare was twice that in the RTR and MTR systems. Each crop of each farming system was grown every year.

2.2. Machinery used for RTR system

Crops were planted with a 76 cm, four-row ridge-tillage planter with a single disk coulter, gauge wheels, and a 36 cm sweep attachment (plateau cleared at ridge top was 10–18 cm wide). The sweep was followed by a slot opener, seed firming wheel, disk covers, and a coil-tyne harrow. Cultivations and ridge development were performed with a ridge-type cultivator employing a single stabilizing coulter with gauge wheels, disk blades, and V-winged sweep. Approximate ridge-base dimension was 46 cm wide, and cultivation depth was 4 cm. In 1993, a starter solution of urea–ammoniumnitrate (UAN; 28-0-0) was dribbled at 21 kg ha^{-1} behind angled coulters offset from the planter slot opener. All N fertilizer in 1991 and 1992 and the remainder of N fertilizer in 1993 were dribbled behind the disk blades corn cultivation at the five–six leaf growth stage. A second cultivation was performed in corn at the nine–ten leaf growth stage if needed. Soybean were cultivated twice.

Table 2
Chemical input summary for three Missouri MSEA farming systems

Farming system	Corn N fertilization	Corn herbicides	Soybean herbicides[a]
MTH: mulch-till, corn–soybean, high agrichemical input	190 kg ha^{-1}, UAN solution incorporated with spring tillage pass	2.24 kg a.i. ha^{-1} atrazine and 2.8 kg a.i. ha^{-1} alachlor incorporated preplant with spring tillage pass	3.4 kg a.i. ha^{-1} alachlor and 0.14 kg a.i. ha^{-1}
RTR: ridge-till, corn–soybean, reduced agrichemical input	129 kg ha^{-1}, UAN solution side-dressed at five–six leaf stage (1991–92)	0.9 kg a.i. ha^{-1} atrazine and 101 kg a.i. ha^{-1} alachlor	1.40 kg a.i. ha^{-1} alachlor and 0.07 kg a.i. ha^{-1}
	21 kg ha^{-1}, starter UAN solution and 97 kg ha^{-1}, side-dressed UAN solution at the 5–6 leaf stage (1993)	Herbicides placed in a 38 cm band over the row at planting	
MTR: mulch-till, corn–soybean–wheat, reduced agrichemical input	129 kg ha^{-1}, UAN solution side-dressed at five–six leaf stage (1993)	0.9 kg a.i. ha^{-1} atrazine and 1.1 kg a.i. ha^{-1} alachor	1.40 kg a.i. ha^{-1} alachlor and 0.07 kg a.i. ha^{-1}
	21 kg ha^{-1}, starter UAN solution and 97 kg ha^{-1}, side-dressed UAN solution at the five–six leaf stage (1993) Wheat N fertilization: 28 kg ha^{-1}, fall broadcast dry urea and 56 kg ha^{-1}, spring topdress dry urea	Herbicides placed in a 38 cm band over the row at planting	

[a] Imazaquin incorporated preplant with spring tillage pass in MTH; in RTR and MTR system imazaquin placed in 38 cm band over row at planting.

2.3. *Machinery used for MTH and MTR systems*

Planting in the mulch-tillage systems was performed with the same 76 cm, four-row planter used for RTR minus sweeps. The same cultivator as in RTR was used in MTR except that the V-winged sweep was adjusted to prevent formation of ridges. Tillage in the spring was accomplished in one pass with a multiple-tool implement consisting of one row of minimum-angle, 20 cm disk blades followed by three rows of staggered, 20 cm field cultivator sweeps, and a coil-tyne harrow. Fall tillage was performed with the same implement following corn harvest when soil moisture conditions allowed (1992, 1993). Tillage was performed 15–18 cm deep in fall and 10–13 cm deep in spring with a goal of 30% surface residue cover before planting.

2.4. *Yield measurements*

Grain yield was measured with a weigh-bin fitted combine and harvested at each landscape position of summit, sideslope, and footslope. Three and four rows were harvested for corn and soybean, respectively, in 20–40 m long strips. Grain yield moisture content was adjusted to 155 g kg^{-1} and 130 g kg^{-1} moisture in corn and soybean, respectively. Yields for 1991–1993 are presented as a mean over three landscape positions. Least significant differences (LSD) for paired yield comparisons were calculated when the analysis of variance F-test gave a significant ($p<0.05$) farming system effect.

2.5. *Water sampling and agrichemical analysis*

Zero-tension pan lysimeters were installed at the summit of ten plots in Reps II and III (Fig. 1) during fall and winter of 1991 – Rep I was excluded due to the extreme variation in topsoil depth at the summit (Fig. 1). Lysimeter pans were constructed from the adjacent troughs (each trough was 229 cm long×25 cm wide×5 cm deep cut from a 38 cm diameter PVC sewer pipe (four troughs/pipe). Perforated (3.2 mm diameter holes) stainless steel 16-gauge

(1.6 mm thick) sheeting was fastened to the top of each trough. A piece of flat PVC was fastened on each end of the trough to contain collected water and provide mechanical stability. A drain hole was drilled on one end of the pan.

The lysimeter pans were installed after excavating a pit (3 m long, 2 m deep) perpendicular to the crop rows. Soil material was removed by the soil horizon. At 91 cm below the soil surface, soil was carefully hand-excavated approximately 50 cm back into each side wall of the pit to allow pan placement into the excavated area, approximately 25 cm from the pit wall. Excavation for pan installation was done at a slight angle to allow leachate to drain. Lysimeter pans were raised until their top surface was flush with the bottom of the soil profile before backfilling with a homogeneous mixture of removed soil and bentonite. A 13 mm tygon drain tube was attached to each pan drain and connected to a 19 l stainless steel pot located within the trench approximately 30 cm deeper than the lysimeter. Another 13 mm tygon tube was fastened to the inside wall of the pot and extended to the soil surface for sample leachate retrieval with a vacuum pump. All connections and covers were sealed with long-lasting waterproof sealant that did not interfere with chemical measurements after a period of conditioning. Each excavated trench was then carefully backfilled by horizon. Lysimeters were designed to intercept leachate from a uniform area without disrupting water upflux (e.g. capillary water) – their size compared to a representative soil volume was large enough to intercept the preferential flow channels.

Zero-tension lysimeters for soil water sampling have advantages and disadvantages. The zero-tension lysimeters were designed with a large surface area to intercept any saturated and preferential water flow. Zero-tension lysimeters collect water only if the soils are saturated or macropores are continuous from the soil surface to the lysimeter. With such macropores, creation of a 'zero-tension' zone can induce greater water flow than might occur under natural, undisturbed conditions (personal communication, S.H. Anderson, University of Missouri-Columbia).

Berms were constructed over plot borders to eliminate potential agrichemical movement in surface runoff between the treatments. To eliminate subsurface agrichemical movement in lateral interflow between the plots a 1.0 m deep trench on plot borders was dug, lined with heavy plastic, and backfilled.

Thirty piezometers were installed at summit, sideslope, and toeslope positions throughout the experimental area to measure water table elevations on a biweekly basis. Water gradients and flow lines were then calculated to describe the direction and convergence of the groundwater flow.

Plots with lysimeters for MTH and RTR were in soybean in 1992, and MTR plots were in wheat. All the instrumented plots were in corn in 1993. One year before lysimeter installation (in 1991) MTH and RTR plots were planted to corn and chemicals were applied at rates listed in Table 2. The MTR system was in soybean in 1991 and did not receive N or atrazine. The soil near all lysimeters was evaluated for horizonation and sampled for particle size (Soil Survey Laboratory Staff, 1992) and background herbicide analyses (Koskinen et al., 1991) at the time of lysimeter installation.

Each lysimeter intercepted leachate from a $25\times229\ \mathrm{cm}^2$ area of undisturbed soil beneath three adjacent 76 cm rows on each plot. When possible, lysimeters were sampled within 24 h of every rainfall event for the first 45 days after chemical application. After 45 days and until crop harvest, lysimeters were sampled within 24 h of rainfall for events >1.3 cm. Lysimeters were sampled monthly from crop harvest until chemical application the next year. Our goal was to sample lysimeters within 1 day of rainfall events, but excessive soil moisture forced additional 1–2 day delays after a few events.

Water samples were vacuum pumped directly from the 19 l stainless steel vessels (used for leachate storage) in 1.0 l amber glass bottles with teflon-lined caps and immediately refrigerated. Lysimeters and storage vessels were pumped dry at every sampling into large glass bottles for measuring the leachate volume. Samples were not taken for chemical analyses when sample volumes were less than 20 ml. Biweekly measurements from the nearby piezometers indicated that the water table was periodically above the lysimeters from late March to early May of 1992 and 1993. Water samples collected during these periods were discarded because of the potential contamination from shallow ground water. Lysimeters were purged with deionized water after the water table dropped. This procedure was completed before chemicals were applied and spring sampling was started.

Lysimeters were sampled from May 1992 through March 1994.

Water samples were filtered through 0.45 μm nylon filters within 48 h of sampling and split for NO_3–N and atrazine analyses. Samples for NO_3–N analysis were preserved at a pH below 2.0 in sulfuric acid (U.S. Environmental Protection Agency, 1983). Nitrate in a sulfanilaminide complex was measured colorimetrically with a continuous-flow autoanalyzer (Zellweger Analytics: Lachat Instruments Division, Milwaukee, WI).

Atrazine in 100 ml water samples was separated from the contaminants and concentrated by C_{18} solid-phase extraction, eluted with ethyl acetate, separated and quantified by gas chromatography using a N–P detector (Thurman et al., 1990), as previously described (Donald et al., 1998). The limit of detection (LOD) for atrazine was 0.04 $\mu g\ l^{-1}$.

2.6. Soil coring

One core per plot from the summit (downslope from lysimeters) in Reps II and III was taken in zero-contamination plastic liners (5.7 cm diameter× 122 cm long) using a hydraulic soil corer: holes were backfilled with bentonite. Cores were collected near each other (3 m diameter data) in April 1991 (baseline), April 1992, October 1992, and May 1993, and were subdivided into samples for analysis by taxonomic horizon. Soils cores were taken at random without considering herbicide banding within MTR and RTR plots. Atrazine and alachlor concentrations in soil were determined according to Koskinen et al. (1991). The LOD for each herbicide in soil was 5 $\mu g\ kg^{-1}$.

3. Results

Leachate water volume and chemical concentration are reported separately for each instrumented plot for each farming system (Figs. 2–4) – they were not averaged for two reasons. The range in leachate volumes and concentrations between the two replicate plots of the same farming system was often large and spatially indicative of claypan soil hydrology. Duplicate lysimeter plots within a farming system are referred to as plots A and B in Figs. 2–4. USEPA MCL are presented for drinking water since none are available for root-zone water quality.

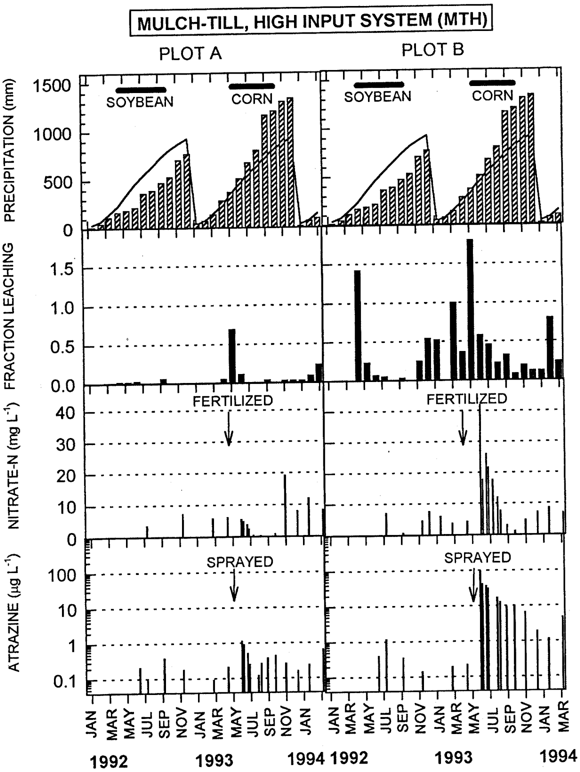

Fig. 2. Cumulative monthly precipitation (53-year mean is plotted as solid line), leachate (fraction of previous 30-days precipitation), NO_3–N and atrazine concentrations from 1992 to early 1994 for the high input, mulch-tillage system (MTH). Baseline for atrazine plot is limit of detection (0.04 $\mu g\ l^{-1}$).

3.1. Precipitation

Cumulative monthly precipitation for 1992 and 1993 is compared with the 53-year mean in Figs. 2–4. Precipitation in 1992 was less than the long-term average in January, April, May, June, and August. Precipitation in 1993 was near or above normal in all months except May and October.

3.2. Initial soil NO_3–N and atrazine at lysimeter installation

Residual soil NO_3–N concentrations in 91 cm soil cores after 1 year of each farming system averaged

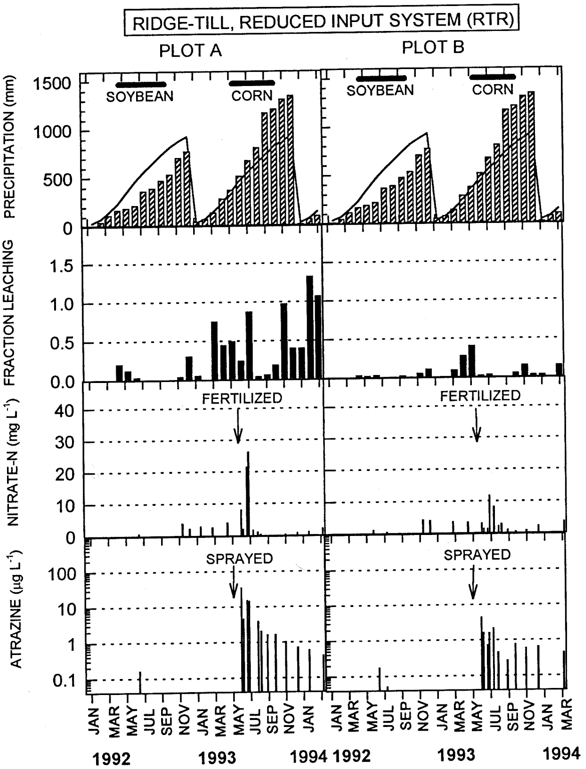

Fig. 3. Cumulative monthly precipitation (53-year mean is plotted as solid line), leachate (fraction of previous 30-days precipitation), NO_3–N and atrazine concentrations from 1992 to early 1994 for the reduced input, ridge-tillage system (RTR). Baseline for atrazine plot is limit of detection (0.04 µg l^{-1}).

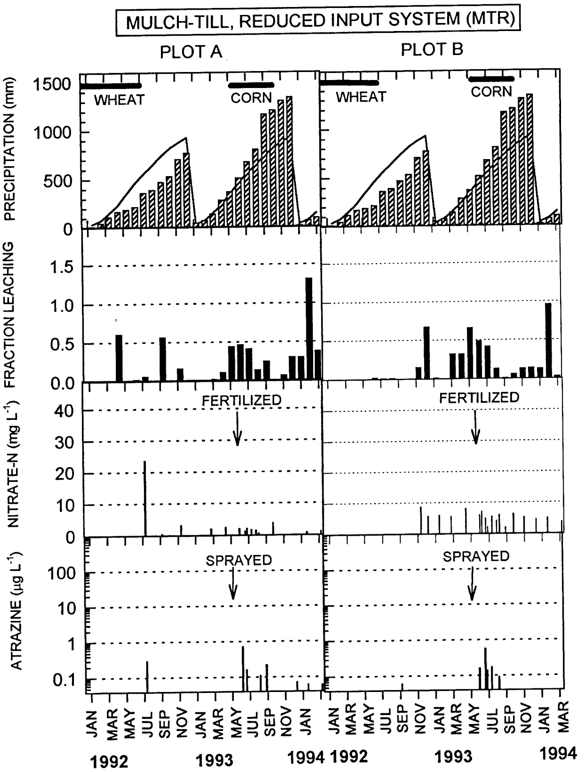

Fig. 4. Cumulative monthly precipitation (53-year mean is plotted as solid line), leachate (fraction of previous 30-days precipitation), NO_3–N and atrazine concentrations from 1992 to early 1994 for the reduced input, mulch-tillage system (MTR). Baseline for atrazine plot is limit of detection (0.04 µg l^{-1}).

128, 81, and 63 kg ha^{-1} for MTH, RTR, and MTR farming systems, respectively. These concentrations where the lysimeters were installed illustrate the capricious nature of high-yield goal planning. More NO_3–N likely accumulated in MTH because high N rates were applied for a higher yield goal but corn yields were low due to drought-like conditions in 1991. The MTR farming system was in soybean in 1991 and did not receive atrazine and N fertilizer. Background soil atrazine concentrations averaged 40 µg kg^{-1} in the surface horizon (A_p) of the MTH farming system, representing an almost year-long carryover from that applied in spring of 1991. Residual atrazine was observed (5.6 µg kg^{-1}) on only one of the RTR plots (where atrazine was band applied) and neither of the MTR plots (1991 in soybean).

3.3. *Water flow in root zone*

Rain fall in 1993 exceeded that in 1992 by 58 cm; the larger fraction leaching indicated that more water moved through the root-zone into lysimeters (Figs. 2 and 3, and Fig. 4). When soils were wet in the spring, water frequently moved into lysimeters within 24 h after rainfall. An increased leaching occurred in Plot A in September and Plot A and B in November 1992 on the MTR system following wheat harvest in July (Fig. 4), where weed control following wheat harvest in July allowed summer and early fall rains to recharge the root-zone. There was very little rainfall and almost no leachate collected from any system in August or October 1992. As expected, leachate volume decreased during maximum crop evapotranspiration of both years (July through September).

Between January 1992 and March 1994 the fraction of precipitation moving past the root-zone varied greatly between replicate plots within each farming system (Plots A and B in Figs. 2–4). Little variability in the soil horizonation and texture among all plots was observed where lysimeters were installed. Soil horizonation matched a typical Mexico silt loam pedon (Table 1) with depths to characteristic horizons ranging $\leq$5 cm between lysimeters. Clay content ranged from 560–650 g kg^{-1} in the claypan. Topsoil depth above the B_t horizon was between 20 and 25 cm for all lysimeter locations (Fig. 1). Neither horizonation nor soil texture readily explains the variability in soil water percolation between plots of the same system. Root-zone water flow into 1.0 m^2 lysimeters at a similar depth and location varied between 300 and 5000 ml after 5 cm water was applied (Tindall and Vencill, 1995).

The presence or absence of the preferential flow pathways unique to each lysimeter location was closely related to root-zone water flow into lysimeters. During lysimeter installation, root and insect channels, and relic cracks were observed in the A_p and B_t soil horizons. Low permeability of the soil matrix (Table 1) likely forced preferential flow of water through these macropores. Variability in soil water movement affected NO_3–N and atrazine concentrations in root-zone water samples (discussed in the next sections).

Leachate as a fraction of the monthly precipitation was less than 0.5 for most months (Figs. 2–4), but exceeded 1.0 for at least 1 month and one plot of each farming system. Values of fraction leached >1.0 suggests that the lysimeters were receiving water from a drainage area greater than their collection surface. This possibility exists because these lysimeters did not have sidewall barriers and the B_t horizon could induce flow. Also, since leaching occurred within days after precipitation and this calculation is based on monthly amounts, the fraction leached may be high when a wet month is followed by a dry month.

3.4. No_3–N concentration in the root-zone and lysimeters

Significant NO_3–N leaching may have occurred in post-harvest wheat fields although little NO_3–N leached in plots nearby, containing actively-growing, transpiring crops. Lysimeter-instrumented MTH and RTR plots were in soybean while MTR plots were in wheat in 1992. Despite high soil NO_3–N accumulation from 1991, NO_3–N concentrations in leachate were below the MCL of 10 mg l^{-1} for all systems in 1992 (Figs. 2–4). The only exception was one measurement (23 mg l^{-1}) from a MTR plot immediately after a 5 cm rainfall following wheat harvest (Fig. 4).

After the plots were fertilized with N, NO_3–N concentrations in root-zone water rose to levels greater than the MCL for several sampling dates (Figs. 2–4). Lysimeter-instrumented plots from all farming systems had corn in 1993. Nitrogen fertilizer was applied to MTH plots on 26 Mat, one day before planting. A sample containing 42 mg NO_3–N l^{-1} was collected from one MTH plot (Fig. 2, Plot B) on 9 June after a 5 cm rainfall. Nitrate concentrations between 10 and 30 mg l^{-1} were collected from this plot until mid-August. Higher NO_3–N concentrations correlated with greater leachate volumes on this particular plot. In contrast, NO_3–N concentrations of Plot A of the same MTH system remained below 7 mg l^{-1} and leachate volumes were much less throughout this same time period.

Nitrate–N concentrations increased in RTR and MTH plots after N fertilizer was sidedressed (21 June) and subsequent rainfall (Fig. 3). Because of the rainfall within 2 weeks of application, NO_3–N concentrations exceeded the 10 mg l^{-1} MCL in both RTR plots. Nitrate concentrations were higher on Plot A (a maximum of 27 mg l^{-1}) than on Plot B, corresponding with greater leachate volumes (Fig. 3). The MTR and RTR farming systems received equivalent chemical inputs and leached similar volumes in 1993, but nitrate concentrations in MTR remained below the MCL (Fig. 4).

3.5. Atrazine concentrations in root-zone and lysimeters

Little atrazine moved below the root-zone into lysimeters in 1992. There were occasional detections, yet all but one were below 1 μg l^{-1} (Figs. 2–4). Since no atrazine was applied in 1992 to plots with lysimeters, detections were from residual atrazine from the 1991 growing season, or from the 1990 growing season for the MTR system. Atrazine was detected more frequently in water samples from MTH plots where 2.24 kg a.i. ha^{-1} was applied to corn in 1991 than from RTR plots where 0.9 kg a.i. ha^{-1} was banded over corn rows in 1991.

Atrazine concentrations, as with NO_3–N, significantly increased in root-zone water following application to corn plots in 1993 (Figs. 2–4). Atrazine concentrations ranged between 1 and 100 μg l^{-1} for MTR Plots A and B, respectively, following rainfall in early June (Fig. 2). The highest atrazine and NO_3–N concentration were measured on the same MTH plot, Plot B. Atrazine concentrations of RTR reached 34 μg l^{-1} on Plot A and only 4 μg l^{-1} on plot B during the same period (Fig. 3). Atrazine concentrations remained below the 3 μg l^{-1} MCL and both MTR plots. Agrichemical concentrations tended to be higher when more water moved in lysimeters for both MTH and RTR systems (Figs. 2 and 3). Leachate volume was more strongly correlated with NO_3–N concentration (r=0.63) when soils were wet early in the growing season (1 June through 15 July) than over the entire year (r=0.29). These correlations indicated greater macropore water flow and chemical transport to the lysimeter when the soil was saturated during late spring and early summer. As the soil dried and matric water potential decreased, water intercepted by shallow macropores was quickly absorbed by the soil matrix and preferential transport past the root-zone was reduced. Also, as the growing season progressed, atrazine was either adsorbed or irreversibly bound to soil and degraded while NO_3–N was taken up by plants, immobilized into soil organic matter, or denitrified. Thus the soil concentration of these chemicals decreased with time and the correlation between flow and chemical concentration decreased during the fall and winter periods when the soil was again saturated.

3.6. Soil characterization and analysis

Conclusions about herbicide leaching reached by sampling with lysimeters were tested by measuring herbicides in soil cores. Soil samples for baseline characterization were collected over the 30-plot area in April 1991 before agrichemical application. No cores contained atrazine >5 μg kg^{-1}, and only four of 296 samples contained alachlor detects. Soil samples were collected every 6 months (as weather permitted) from April 1991 to April 1994 at the summit field location (Fig. 1) for all plots and analyzed for NO_3–N, atrazine, and alachlor concentrations. From 360 samples collected from the MTH, MTR, and RTR plots, only 40 (11%) contained atrazine and/or alachlor concentrations higher than the LOD (5.0 μg kg^{-1}) (Table 3). Most detections (79%) were in soil of the Ap horizon, evidence that there was little

Table 3
Herbicide detections in soil subjected to three farming systems at the Missouri MSEA for 1992 and 1993

Horizon layer	Soil horizon[a]	Level of detection	MTH		RTR		MTR	
			Atrazine	Alachlor	Atrazine	Alachlor	Atrazine	Alachlor
		(μg kg^{-1})	Number of samples					
1	Ap	<Detection[b]	6	12	16	18	18	25
		5–10	3	2	3	2	8	2
		10–20	4	3	2	1	1	0
		20–40	2	1	0	0	0	0
		40–80	2	0	0	0	0	0
		80–200	1	0	0	0	0	0
2	BE or B_t1	<Detection[b]	14	17	21	21	25	27
		5–10	3	1	0	0	1	0
		10–20	0	0	0	0	1	0
		20–40	1	0	0	0	0	0
3, 4, 5	$B_{tg}2$, $B_{tg}3$, $B_{tg}4$	<Detection[b]	64	66	62	62	99	100
		5–10	1	0	0	0	1	0
		10–20	1	0	0	0	0	0

[a] See Table 1 for horizon properties.

[b] Concentration below detection limit.

Table 4
Corn and soybean grain production from MTH, RTR, and MTR farming systems at the Missouri MSEA for 1991, 1992, and 1993

Farming system	1991		1992		1993	
	Corn	Soybean	Corn	Soybean	Corn	Soybean
	(Mg ha^{-1})					
MTH	5.23	2.59	9.19	2.37	7.92	3.28
RTR	5.21	2.71	6.99	2.23	6.01	3.40
MTR[a]	5.30	2.46	6.87	2.02	6.04	3.02
LSD[b]	NS	NS	2.13	NS	0.92	0.25

[a] Wheat yield not reported.

[b] When treatment *F*-test is significant ($p<0.05$).

movement of herbicides in soil past the soil layer in which the herbicides were applied.

Herbicides were detected about two–three times more frequently for the MTH farming system than for either the MTR or RTR farming systems (Table 3). All seven soil samples with herbicide concentration >20 μg kg^{-1} were collected from MTH plots. Herbicide concentrations were low in MTR and RTR farming systems because less herbicide was applied by banding over the row than when broadcast-applied in MTH. Herbicides were not detected below 76 cm in soil cores, but when herbicide was detected in subsurface soil horizons, soil from the horizon (s) directly above almost always had measurable herbicide (Table 3).

3.7. Grain yields

Grain yields reflect adverse water stress, unpredictable herbicide activation, and inability to access fields for side-dress N application and weed control (cultivation and/or herbicidal). Excessive early spring rains delayed site preparation and planting of corn and soybean into late May and early June 1991. Cropping history suggested that the corn yields were reduced between 20% and 30%. Grain yields of corn or soybean were not significantly different among farming systems (Table 4). Since corn yields were similar among farming systems while N fertilizer rate varied, N not accounted for in the grain and stover was about 130 kg ha^{-1} for MTH, about twice that of RTR and MTR farming systems (Kitchen and Hughes, 1993).

While corn was water stressed in June 1992, timely July rains and unseasonably cool nighttime temperatures in July and August contributed to corn grain yields 20–40% higher than long-term averages. Sparse early season precipitation, however, was not sufficient to activate soil-applied herbicides in the RTR and MTR systems. Weed competition was not rated, but visually evaluated weed control was much poorer with these two farming systems (personal communication, W.W. Donald, Agricultural Research Service, Columbia, MO). Cultivation helped but weeds persisted in the row in spite of the herbicide band at planting (Table 2). Post-emergence herbicides were not considered a good option due to water stress in the crop. Corn yields under MTH were at least 2.0 Mg ha^{-1} greater than under the two systems with banded herbicide, because of reduced or less weed competition. Soybean yield was not significantly different between farming systems even though control was poorer in RTR and MTR than MTH.

Spring and summer rainfall were well above average for 1993 (Figs. 2–4), but planting was delayed until late May and wet summer conditions favored soil and plant-borne diseases. Corn leaf chlorosis during grain fill suggested inadequate N, especially in RTR and MTR. No more than 10% of applied N had leached during the 12-month period. While not measured, denitrifying conditions in these poorly drained soils throughout the growing season likely explain the inadequate N and significant corn-yield loss. Consequently, the MTH farming system, with over 70 kg ha^{-1} more N fertilizer, produced the highest corn yield (Table 4). Soybean yield was slightly higher in the RTR than in the MTR farming system. For this extremely wet year, ridging helped to shed excess water into the interrows and allowed ridges to dry between incessant rains, but there were limited windows of time available (data not shown) for cultivation in the RTR and MTR farming systems.

4. Discussion

Water elevation in nearby wells and piezometers and on neighboring fields changed rapidly within days after precipitation (Blanchard et al., 1993) demonstrating that poorly drained claypan soils are ‘leaky’. Preferential and bypass flow dominates over matrix flow. Tindall and Vencill (1995) concluded, from variations in flow, agrichemical transport, and rapid lysimeter response, that claypan soils are characterized by preferential flowpaths. Dimensions, extent, connectivity, and temporal changes in preferential flow pathways are difficult to characterize; variability of flow and chemical concentration between lysimeters suggests that spatial patterns of root-zone preferential flow pathways are at a scale greater than the lysimeter sampling area. Current methods for monitoring water flow and chemicals in the root-zone may not adequately capture average preferential flow.

Herbicide measurement in soil cores inadequately estimated herbicide leaching in these claypan soils. Although atrazine was detected frequently at high concentration in root-zone water, it was detected infrequently and at low concentration in soil samples. Several factors may explain this difference. First, the soil analytical LOD was greater than for water ($5.0\,\mu g\,kg^{-1}$ vs. $0.04\,\mu g\,l^{-1}$, respectively). Second, soil was sampled at least 5–6 months after herbicide application, well after atrazine concentrations peaked in the lysimeters. Measured lysimeter atrazine concentrations during fall soil sampling were near or below the equivalent LOD for atrazine in soil of all farming systems. Third, soil core area (the area represented by a soil core) was 225 times less than the lysimeter collection surface. The likelihood of sampling preferential flow paths with soil coring was much less than with the lysimeters. Fourth, dissolved herbicides moved rapidly past the root-zone with spring and early summer rains, bypassing the soil matrix.

Root-zone water flow measurements between point observations are particularly variable on high shrink–swell clay soils (Bouma, 1989), such as with this study. Under these soil conditions, locating optimal sample and ped volumes that constitute a ‘representative sample volume’ of the soil is difficult. With irregularities in the morphological features of the flow system, flow-rate values and standard deviations are higher with a smaller sample size (Lauren et al., 1987).

Atrazine and NO_3–N were frequently detected at high concentrations on MTH plots because more of these chemicals were applied in that system (Table 2). But as both large and small leaching volumes were observed for the same farming systems on the same sampling dates, we conclude that site-specific soil hydrology (including occurrence of cracks, filled cracks, and biopores) better explains the major differences in NO_3–N and atrazine concentrations in root-zone water than chemical rate(s) or tillage.

From water flow and NO_3–N concentration measurements, estimated masses of NO_3–N leached from N fertilization in 1993 through March 1994 were 19, 11 and 8 kg ha^{-1} for MTH, RTR, and MTR, respectively. These values corresponded to 10.0%, 8.7%, and 6.8% of the fertilizer applied to MTH, RTR, and MTR systems, respectively. Clay et al. (1992) collected 5.8% of the N fertilizer applied to a ridge-tillage system in root-zone leachate immediately following 15 cm of rainfall on a sandy loam soil. Leaching losses of N in 1993 were less than 10% of the fertilizer applied even though there was 91 cm of rain between June and November. Bypass flow and N loss through denitrification best explain these results.

While the measured chemical contamination of root-zone may help screen farm management effects, ground water sampling may provide a more integrated, larger-scale picture of management effects. Monitoring shallow (4–18 m) ground water under fields at the Missouri MSEA watershed has detected atrazine in only 7% of the samples and at relatively low concentrations ($<0.2\,\mu g\,l^{-1}$) (Blanchard and Donald, 1997). Difference between root-zone and ground water atrazine concentrations may be caused by progressive atrazine adsorption and binding to soil, atrazine degradation with increasing depth, absence of hydraulic gradients to move leached atrazine past the vadose zone and mixing of atrazine-contaminated water with uncontaminated water. Lysimeter NO_3–N concentrations were similar to ground water concentrations (Blanchard et al., 1995).

Root-zone water contamination by herbicides and nitrate was not greatly decreased by the lower agrichemical-input RTR and MTR systems compared to the MTH system. While there may be a slight benefit in root-zone water quality with the lower input systems (ignoring effects on surface water contamination), the greater reliance upon cultivation increases risk for weed pressure and reduced yields when climatic conditions are unfavorable for field traffic.

Many producers are unwilling to risk weed control by reliance on cultivation plus banded herbicide, since erratic weather conditions may prevent cultivation. In a year with a dry early summer (e.g., 1992), weed competition was severe because preplant herbicides were not activated. For a year with a wetter-than-normal early summer (e.g., 1993), suitable windows of time to complete cultivation may not occur. From our experience on claypan soils, with any rainfall >2 cm during the first 8 weeks of the growing season requires a minimum of 4–6 days of dry weather before cultivation can be done without severe soil compaction problems. For this area there is a 50% probability of receiving $\geq$2.0 cm of rain within a 24 h period during each week of the first 3 weeks of June (Shaw et al., 1960), the primary window of time for corn cultivation.

Surveys conducted in 1992 and 1993 show that 41% of the producers in the claypan soil region of Missouri who had tried herbicide banding plus cultivation (like RTR or MTR) for weed control have stopped and have no plans to retry the practice again (Rikoon et al., 1996). The surveys further showed that producers who abandon banding plus cultivation have larger farms and rely heavily on custom herbicide application. Custom applications do not usually band-apply herbicides as they must operate before planting. Barriers to adoption of herbicide banding included time and labor requirements, custom labor constraints, loss of control over operation, and potential risks to yields and profitability

Banding plus cultivation with ridge-tillage is done on less than 3% of cropped claypan soil fields (1994 data, Conservation Technology Information Center, West Lafayette, IN)). Management systems like RTR and MTR are risk-prone on these poorly-drained soils. More producers in the claypan region have recently adopted close-seeded soybean with post-emergence herbicides, a practice that is not compatible with herbicide banding plus ridge-tillage cultivation. From this 3-year assessment, RTR and MTR were not productive farming systems and did not significantly reduce NO_3–N and herbicide contamination of root zone water on claypan soils.

5. Summary and conclusions

Atrazine and NO_3–N were detected more frequently at high concentrations in root-zone water in the high chemical, input mulch-tillage system (MTH) than in either reduced chemical input systems (MTR, RTR). Nitrate–N and atrazine concentrations exceeded their MCLs on two systems (MTH and RTR) following chemical application. Concentration continued to exceed the MCLs during the growing season in the high input system (MTH). Less chemical leaching and hydrologic variability was observed in the 3-year rotation, reduced chemical-input system (MTR).

Variability between plots within a farming system precludes evidence that one farming system has significant water quality advantage over another. Water flow and chemical concentration were influenced more by intrinsic, site-specific soil hydrology than by surface tillage or input rates of different systems. No measured soil properties explained differences in water flow among lysimeter-instrumented plots. Water moved rapidly into lysimeters after rainfall events following chemical application. Preferential flow is a prominent characteristic of claypan soil hydrology that influences herbicide and N contamination of ground water in Midwestern claypan regions. Research to quantify spatial and temporal distribution of preferential flow in claypan soils may help to predict shallow water vulnerability. Meanwhile, adoption of chemical and tillage best management practices may improve chemical use efficiency but will not fully resolve shallow ground water contamination associated with intrinsic soil and landscape hydrology. Adoption of RTR and MTR farming systems will remain low on soils because of the greater risk for yield loss due to poor weed control.

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