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Conservation tillage and macropore factors that affect water movement and the fate of chemicals

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Abstract

A thorough understanding of how conservation tillage influences water quality is predicated on knowledge of how tillage affects water movement. This paper summarizes the effects of conservation tillage on water movement and quality mainly based on long-term experiments on Luvisols at the North Appalachian Experimental Watershed near Coshocton, OH, USA. Conservation tillage can have a much larger effect on how water moves through the soil than it does on the total amount percolating to groundwater. Soil macroporosity and the proportion of rainfall moving through preferential flow paths often increase with the adoption of conservation tillage and can contribute to a reduction in surface runoff. In some medium- and fine-textured soils most of the water that moves to the subsoil during the growing season (May–October) is probably transmitted by macropores. If a heavy, intense storm occurs shortly after surface application of an agricultural chemical to soils with well-developed macroporosity, the water transmitted to the subsoil by the macropores may contain significant amounts of applied chemical, up to a few per cent, regardless of the affinity of the chemical for the soil. This amount can be reduced by an order of magnitude or more with the passage of time or if light rainstorms precede the first major leaching event. Because of movement into the soil matrix and sorption, solutes normally strongly adsorbed by the soil should only be subject to leaching in macropores in the first few storms after application. Even under extreme conditions, it is unlikely that the amount of additional adsorbed solute transported to groundwater will exceed a few per cent of the application when conservation tillage is used instead of conventional tillage. In the case of non-adsorbed solutes, such as nitrate, movement into the soil matrix will not preclude further leaching. Therefore, when recharge occurs during the dormant season thorough flushing of the soil, whether macropores are present or not, can move the remaining solutes to groundwater. Thus, the net effect of tillage treatment on leaching of non-adsorbed solutes should be minimal. Published by Elsevier Science B.V.

Keywords: Chemical transport; Groundwater; Leaching; Preferential flow; Solute transport

1. Introduction

A primary reason for adopting conservation tillage is to reduce losses of soil and agricultural chemicals in

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overland flow. Most often this is achieved by a reduction in surface runoff volume due to increased infiltration (Baker, 1987). In fact, conservation tillage is broadly defined as any tillage sequence designed to minimize loss of soil and water (SSSA, 1997). This is normally accomplished by maintaining a surface residue cover of $\geq$30% whereas tillage and planting operations that usually result in <30% residue cover are indicative of conventional tillage (SSSA, 1997). With more water entering the soil, however, the potential to contribute to groundwater quality problems is increased. An additional concern is the perception that conservation tillage relies more heavily on pesticides to control weeds, insects, and diseases than where tillage is used to suppress these problems (Hinkle, 1983). Results of a recent, multiyear, survey suggest, however, that this perception is unfounded. In a survey that covered 80% of the land resource used for corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) production in the United States, Bull et al. (1993) noted few consistent differences in pesticide usage among conventional and conservation tillage systems.

At the North Appalachian Experimental Watershed (NAEW) near Coshocton, OH, USA the effects of a variety of conservation practices on surface runoff and water quality have been investigated for nearly 60 years using small (0.5–1 ha), single-practice, gaged watersheds. This extensive database allows us to draw some general conclusions regarding the effectiveness of conservation tillage under specific soil and climatic conditions, irrespective of year-to-year variation in the weather (Edwards and Amerman, 1984).

It is well known that soil, climatic, and geologic conditions have a major impact on the hydrologic response of watersheds to various soil and crop management practices. Thus, considerable effort was made in the 1930s to locate the 424 ha NAEW where conditions would be representative of a 130 000 km^2 area comprising five Major Land Resource Areas (MLRAs N-120, N-124, N-125, N-126, N-127; USDA-SCS, 1981) that include significant portions of the states of Indiana, Kentucky, Ohio, Pennsylvania, Tennessee and West Virginia (Kelley et al., 1975).

The near-surface bedrock at the NAEW consists primarily of relatively flat-lying, interbedded, sandstones and shales and the region has not been glaciated. Consequently, the residuum-derived soils at the NAEW vary widely in texture and internal drainage with depth to bedrock averaging 1.5 m and ranging from 0 to about 3.5 m. Weathering and erosion have produced a highly dissected landscape with steep, narrow, valleys and average slope of individual small watersheds at the NAEW ranges from 6 to 23% (Kelley et al., 1975). Thus, little ponding and detention of water at the soil surface occur prior to the initiation of surface runoff. The permeability and water storage capacity of the unweathered sandstone and shale are low and most flow occurs through fractures that are more extensive and interconnected as the depth to bedrock decreases (Urban, 1965). Average, annual precipitation is 943 mm, most of which falls as rain. Although about half (55%) of the precipitation occurs during the 6 month growing season (May–October), about 90% of the rain that falls at rates of $\geq$25 mm h^{-1} occurs during this period.

At the NAEW, most of the surface runoff from conventionally tilled (i.e., moldboard plowed, disked, and harrowed) watersheds with predominantly well-drained soils occurs in the late spring and early summer (Fig. 1). During this time of the year the canopy of the row crops commonly produced in this area, corn and soybean, is insufficiently developed to protect the soil surface from raindrop impact, and high-intensity ($\geq$25 mm h^{-1}), short-duration, localized ($\leq$65 km^2), convective rainstorms frequently occur. Degradation of unprotected aggregates at the soil surface results in formation of a crust that reduces infiltration rate below rainfall rate and surface runoff ensues. More than 80% of the average annual erosion from the small watersheds is due to this type of storm

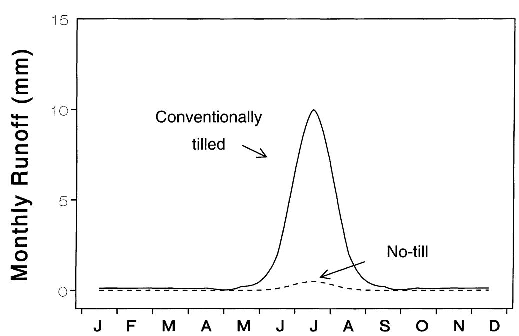

Fig. 1. Conceptualized effect of tillage on monthly surface runoff from NAEW watersheds with well-drained soils, based in part on the data presented in Edwards and Amerman (1984).

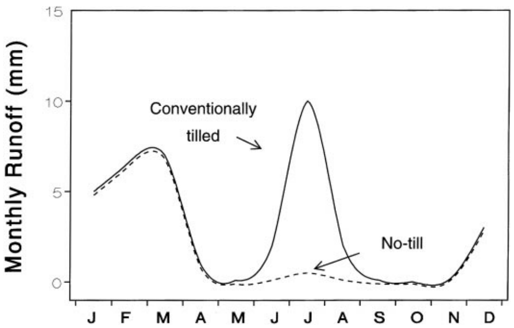

Fig. 2. Conceptualized effect of tillage on monthly surface runoff from NAEW watersheds with soils that have restricted drainage, based in part on the data presented in Edwards and Amerman (1984).

Table 1
Four-year comparison of the amount of surface runoff from a no-till watershed (WS 191, 9% slope, FAO — Haplic Luvisol) and a conventionally tilled watershed (WS 123, 6% slope, FAO — Haplic Luvisol) at the NAEW

Year	Rainfall (mm)	Runoff (mm)	
		No-till	Conventional
1979	1124	3.8	140.2
1980	1176	4.9	316.8
1981	1057	0.2	142.2
1982	889	0	113.2
Four-year total	4246	8.9	712.4
Average	1062	2.2	178.1

(Kelley et al., 1975). During the remainder of the year low-intensity, long-duration (a day or more), cyclonic rainstorms of large areal extent predominate. Under these conditions infiltration rate usually matches rainfall rate and little surface runoff occurs. When row crops are planted using no-till management (i.e., no primary or secondary tillage) the intact surface mulch protects the soil from raindrop impact, thereby reducing crust formation, and surface runoff from high intensity storms can be virtually eliminated (Fig. 1).

In the case of soils with impeded drainage the response to tillage during late spring and early summer is similar to that noted with well-drained soils (Fig. 2). Again, surface runoff can be virtually eliminated with no-till due to the residue cover that permits the maintenance of high infiltration rates at the soil surface. In the dormant season, however, relatively large volumes of surface runoff can occur regardless of tillage management. During this time of year subsoil, rather than surface, characteristics often limit infiltration, unless the soil is artificially drained. Slowly permeable subsurface horizons retard water movement, promoting development of a seasonally high water table. Under these conditions the hydraulic conductivity of the surface is irrelevant because of a lack of water storage capacity within the profile and even a low intensity rainfall can produce surface runoff. The ability of this runoff to transport sediment, however, is often limited because the flows produced by the low intensity rainfalls are usually of limited depth and velocity.

Results of a 4 year comparison of two similar watersheds at the NAEW illustrate how effective no-till management for continuous corn production can be in reducing surface runoff (Table 1). During 1979–1982, <1% of the total precipitation was lost as surface runoff from the no-till watershed (WS 191), whereas nearly 17% of the precipitation was lost as surface runoff from the conventionally tilled watershed (WS 123). Moldboard plowing of the conventionally tilled watershed was discontinued after 4 years, partly out of concern that high rates of surface runoff and gully formation would degrade its usefulness for future studies. No-till management, however, has continued on WS 191 and the records for the past 18 years indicate that surface runoff averaged 0.2% of precipitation and never exceeded 1% (Table 2). Conservation tillage measures other than no-till appear to be similarly effective in reducing surface runoff and erosion under conditions at the NAEW (Edwards et al., 1993a).

The foregoing suggests that there may be a conflict between the goal of reducing surface water contamination through the use of conservation tillage and the maintenance of groundwater quality because of increased infiltration. During the past 10 years we have investigated the effects of conservation tillage on water quality and our research has focused on the following questions:

1. How much additional water percolates through the soil under conservation tillage than under conventional tillage and when do these differences occur?
2. Does the preservation of macropores in soils under conservation tillage contribute to increased infiltration rates and reduced surface runoff volumes

Table 2
Eighteen-year record of rainfall and surface runoff from a long-term, continuous, no-till corn, watershed (WS 191, 9% slope, FAO — Haplic Luvisol) at the NAEW

Year	Rainfall (mm)	Runoff (mm)
1979	1124	3.8
1980	1175	4.9
1981	1057	0.2
1982	889	0
1983	1028	0
1984	907	2.3
1985	929	0
1986	980	9.2
1987	841	0.2
1988	832	0
1989	964	7.4
1990	1321	0.3
1991	679	0
1992	915	0
1993	941	1.0
1994	888	0
1995	911	0
1996	1130	0
Eighteen-year total	17,551	29.3
Average	973	1.6

and what conditions promote entry of water into macropores?
3. What factors influence the chemical quality of the water that infiltrates via macropores?

2. Percolation — conventional vs. no-till

2.1. Percolation within the solum

Conservation tillage is postulated to have an adverse effect on groundwater quality because more water infiltrates than when conventional tillage is used. We have conducted several studies to investigate how much of this additional water eventually percolates through the soil.

In one study at the NAEW we monitored 75 cm long by 30 cm diameter column lysimeters placed in the field for 2 years (Shipitalo and Edwards, 1993a). These columns were obtained from a reserve area adjacent to WS 191 (Table 2) with a well-drained Rayne silt loam soil (FAO — Haplic Luvisol; USDA — fine-loamy, mixed, mesic Typic Hapudult) that had been in no-till corn for 17 years. The upper 15 cm of half the columns was mixed in the beginning of June each year to simulate tillage.

During this experiment an average of 36% more water, nearly 200 mm per year, percolated through the no-till columns than through the tilled columns. As suggested by our observations of surface runoff from watersheds with well-drained soils (Fig. 1), the differences in percolate volume were greatest during the late spring and summer months, coinciding with the largest differences in infiltration. In the months June–September the tilled columns produced only 57% of the volume of percolate produced by no-till columns. In contrast, during the remainder of the year the tilled columns produced 81% of the volume of percolate obtained from the no-till columns. In this study the columns were unvegetated and runoff was prevented. Thus, the differences among treatments were due solely to increased evaporation from the tilled columns. Had the lysimeters been vegetated, transpiration would have reduced the total amount of percolate obtained and probably reduced the differences among tillage treatments. On the other hand, had the design of columns allowed for surface runoff, the differences in percolate volume among tillage treatments probably would have been accentuated.

In a companion study, 50 cm deep pan lysimeters were used to collect percolate from adjacent no-till and moldboard plowed corn fields. The soil type was the same as in the column lysimeters and the relative differences among tillage treatments were of similar magnitude, with the pans in the no-till field yielding 31% more percolate than those in the conventionally tilled field (Shipitalo et al., 1994). The average annual difference in percolate volume, however, was reduced to 50 mm compared with the 200 mm noted with the column lysimeters, probably due mainly to transpiration. The collection of percolate by the pan and column lysimeters closely followed the rainfall pattern year-round in the no-till soil, but only during the dormant season in the tilled soil. A similar observation was made by Hall et al. (1989) in a pan lysimeter study in nearby Pennsylvania.

Surface runoff and percolate were collected from 4.8 by 1.7 m no-till and conventionally tilled lysimeters in a 6 year study at Wooster, OH, ≈75 km from the NAEW (Dick et al., 1989). A fragipan impedes water movement in the Canfield silt loam soil at this site (FAO — Fragic Luvisol; USDA — fine-loamy, mixed, mesic Aquic Fragiudalf) and percolate was collected using perforated copper pipe installed ≈40 cm below the soil surface and immediately above the fragipan. Percolate production was 2.3 times greater from the no-till than from the conventionally tilled lysimeters, with annual differences ranging from 165 to 441 mm. For each of the 6 years the difference in surface runoff was smaller than the difference in percolation, with surface runoff from the conventionally tilled lysimeters exceeding that from the no-till lysimeters by 44–154 mm annually. The differences in percolate volume were somewhat larger than those observed in the pan and column lysimeter studies at the NAEW (Shipitalo and Edwards, 1993a; Shipitalo et al., 1994). It is conceivable that the drainage system in the Wooster lysimeters may have reduced the occurrence of saturated conditions above the fragipan thereby reducing the differences in surface runoff and increasing the differences in percolation. Nevertheless, the results indicate that in some instances the effect of tillage treatment on the volume of percolate moving to shallow depths in the profile exceeds the effect on surface runoff volume.

2.2. Percolation below the solum

Unlike studies conducted using shallow lysimeters, the 4.3 m long, 1.7 m wide by 2.4 m deep monolith lysimeters at the NAEW give us the capability to evaluate the effects of tillage on percolation below the solum. The entire undisturbed soil profile is contained within these lysimeters and the bottom 1–1.5 m is composed of the fractured sandstone and shale bedrock from which the soils were derived (Fig. 3).

In a 4 year comparison with a Keene silt loam soil (FAO — Haplic Luvisol; USDA — fine-silty, mixed, mesic Aquic Hapludalf), conventionally tilled monolith lysimeters consistently yielded more surface runoff than no-till lysimeters with an average annual difference of 57 mm and a range of 10–114 mm (Chichester, 1977). Consistent differences in percolation, however, were not apparent among tillage treatments. The no-till lysimeters annually yielded from 39 mm less to 75 mm more percolate than the tilled lysimeters. During the 4 years, the no-till lysimeters yielded an average of only 6% more percolate than the tilled lysimeters. Although significant differences in percolation among tillage treatments might have been detected had more lysimeter years of data been collected, it is apparent that the relatively large differences in percolation detected at shallow depths in the aforementioned studies were not reflected in the deep percolation results. Moreover, unlike the shallow lysimeters, percolation from the deep lysimeters was rarely affected by storms during the growing season and only 14% of the total yearly percolation from the tilled and no-till lysimeters occurred during the months of May–October.

2.3. Combined effects of shallow and deep percolation

Watershed data indicate that the volume of additional water that infiltrates as a result of no-till compared with that of conventional tillage is equivalent to the reduction in surface runoff. The amount of additional water that percolates to shallow depths within the no-till soil profile, however, can exceed the difference in surface runoff. Results of the column lysimeter study indicated that reduced evaporation from the mulch-covered, no-till soil surface contributes to the supply of water available for percolation. Under our climate the differences in percolation, as well as the differences in surface runoff, are most pronounced during the growing season when potential evapotranspiration exceeds the water supply and intense rainstorms occur more frequently. Depending on soil type and the weather pattern, annual percolation to shallow depths within the profile can be up to several times greater in no-till than in tilled soil. Yet, the deep percolation data from the Coshocton lysimeters did not suggest a major effect of tillage practice on water yield. A logical explanation for this observation is that although more rainwater infiltrates no-till than conventionally tilled soil, this water remains within the solum where it can be accessed by roots and transpired. Studies in temperate and tropical regions have documented higher soil water contents in soils subject to conservation tillage than in tilled soils (Griffith et al., 1986). This additional supply of available water can contribute to the increased yields usually observed with no-till on well-drained soils if reduced soil temperatures are not a limiting factor (Griffith et al., 1986; Dick et al., 1991; Lal et al., 1994).

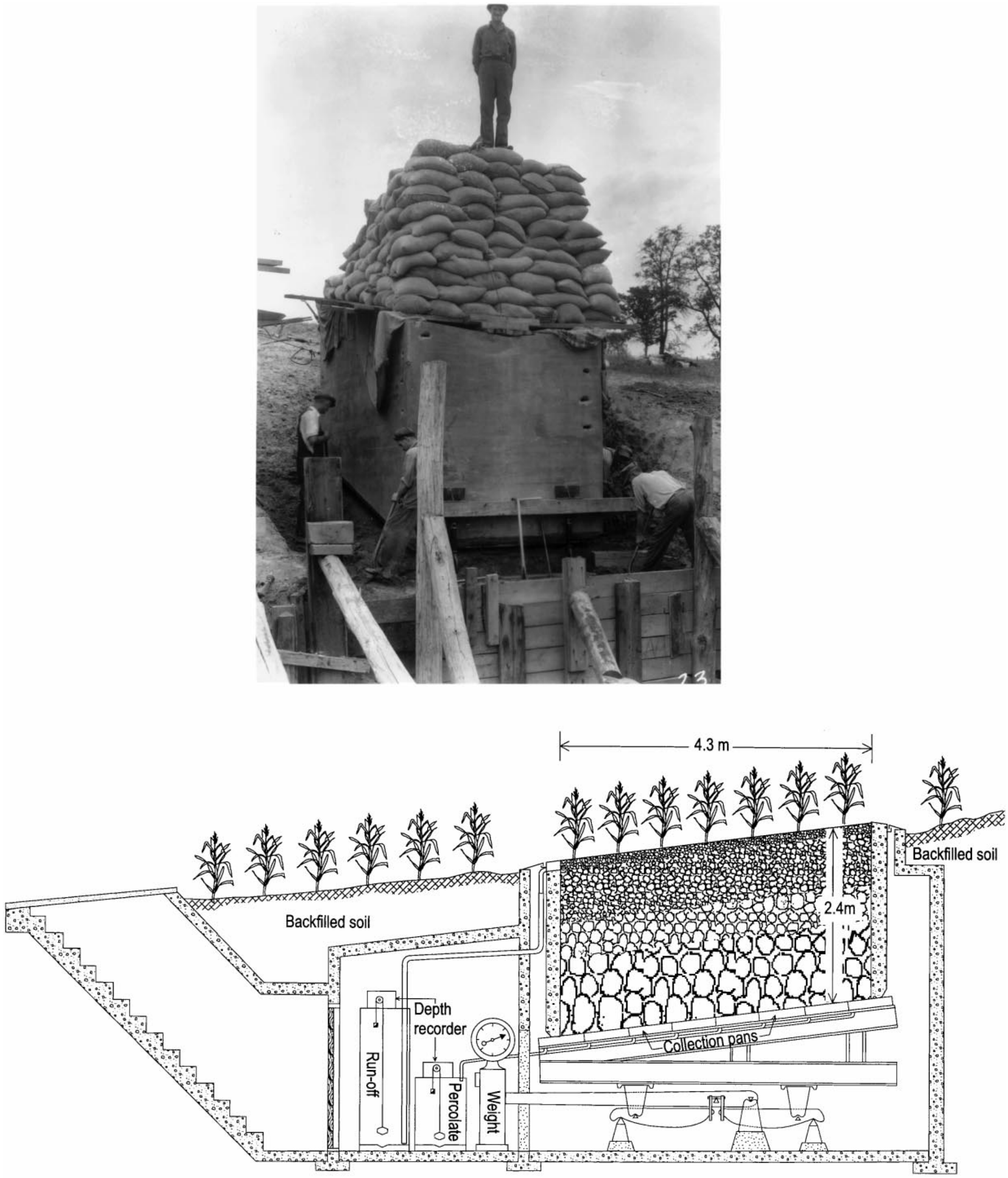

Fig. 3. Construction of one of the 11 monolith lysimeters at the NAEW, August 1936 and a schematic of their design (modified from Kohnke et al., 1940).

A re-analysis of the Coshocton lysimeter data of Chichester and Smith (1978) by Rose et al. (1983) supports a conclusion that the effect of conservation tillage on the volume of water percolating through the soil diminishes with depth because of storage and transpiration. Water movement in the monolith lysimeters was monitored using a single application of ^{15}N labeled nitrate fertilizer as a tracer. Labeled nitrate concentration peaked in the first dormant season after application and successively diminishing peaks were noted in subsequent dormant seasons. The model of Rose et al. (1983) suggested that preferential flow moved the tracer into the profile where it was temporarily stored within macropores or diffused into the matrix. The labeled nitrate was then subject to removal during the winter recharge season when water traveled the entire 2.4 m depth of the lysimeters.

3. Macropores, infiltration, and percolation

3.1. Tillage effects on soil porosity

Although the effect of conservation tillage on the amount of percolate available to transport solutes to groundwater appears to be small, this does not preclude a large effect on solute transport. How the water moves through the soil may have a larger impact on chemical transport than the total amount of percolate.

An increase in soil bulk density, thus a decrease in total porosity, is often noted when soil under reduced tillage is compared to soil that has been frequently tilled. Edwards et al. (1988) noted that the bulk density of the Ap horizon of a long-term, no-till, watershed (WS 191) at the NAEW averaged 1.6 mg m^{-3}. If conventionally tilled, the bulk density of this horizon would be $\approx$1.0 mg m^{-3} shortly after tillage and reconsolidate to $\approx$1.3 mg m^{-3} by the end of the growing season. This observation is typical, as Rawls et al. (1983) noted that most soils exhibit an increase in total porosity when moldboard plowed followed by gradual reconsolidation, with coarse-textured soils normally exhibiting a greater response than clayey soils. With less total pore space, infiltration and water storage capacity of the no-till soil should be less than that of tilled soil. Yet the data presented in Table 1 indicate that little surface runoff occurred from this watershed compared to a similar watershed that was conventionally tilled. Therefore, the remaining pores in the no-till soil must be more effective in transmitting water than those in the plowed soil. Undoubtedly, the maintenance of a continuous residue cover that helped to prevent crust formation was a factor contributing to the reduction in surface runoff and the increased effectiveness of the remaining porosity. Based on air permeability measurements, however, Roseberg and McCoy (1992) noted that although tillage creates greater total porosity, macropore continuity can be reduced. Edwards et al. (1988) observed that large numbers of continuous macropores formed by burrowing earthworms were present in the no-till watershed (WS 191) and they speculated that these contributed to the high infiltration rates.

Researchers at other locations have also noted an increase in macroporosity concurrent with a reduction in tillage intensity (Ehlers, 1975; Boone et al., 1976; Gantzer and Blake, 1978; Shipitalo and Protz, 1987; Moran et al., 1988; Drees et al., 1994; Pagliai et al., 1995). In these instances the increase in macroporosity was attributed to the preservation of root and earthworm-formed macropores that are normally disrupted by tillage. Moreover, the increased residue cover of no-till soil may produce a cooler and wetter environment near the soil surface that is more favorable for faunal activity than when the soil was tilled, which may result in a faster rate of formation of this type of biopore (Edwards and Bohlen, 1996, pp. 268–299).

3.2. Effects of macropores on water movement

3.2.1. Column and pan lysimeters

Additional objectives of our research program have been to determine if the preservation of macroporosity observed with conservation tillage contributes to increased infiltration and reduced surface runoff, and to determine the conditions that promote entry of water into macropores. In particular, we investigated whether biopores $\geq$5 mm diameter, formed by the earthworm *Lumbricus terrestris* L., with an estimated density of 1.6 million ha^{-1} in Watershed 191 (Edwards et al., 1988), increased the infiltration of natural rainfall.

In the column lysimeter study (Shipitalo and Edwards, 1993a) not only did no-till columns produce more percolate than tilled columns but percolate accumulated more rapidly. Furthermore, storms

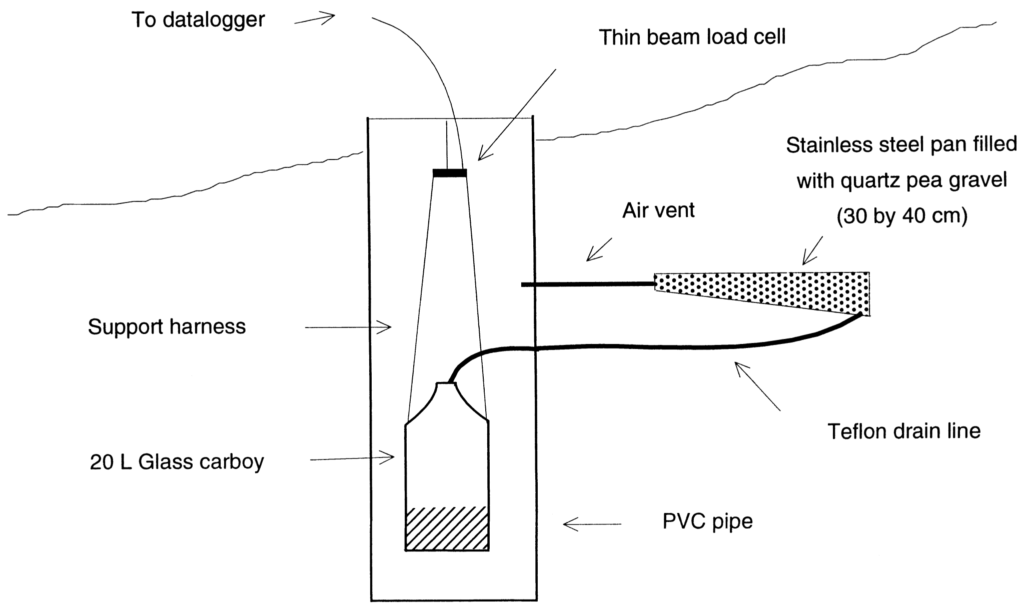

Fig. 4. Schematic of a pan lysimeter designed to electronically record the rate of percolate accumulation.

during the summer that produced percolate from no-till columns often did not produce percolate from tilled columns. Hall et al. (1989) also noted that percolate accumulated faster and more frequently in pan lysimeters in a no-till Typic Hapludalf (FAO — Haplic Luvisol) than when this soil was tilled. Since transmission of water during rainfall is characteristic of macropore flow (Thomas and Phillips, 1979), the implication of these results is that disruption of macropore continuity by tillage reduced the contribution of macropores to the total flow.

To confirm these observations, Shipitalo and Edwards (1993b) devised a method to electronically record the rate of percolate accumulation in pan lysimeters installed 50 cm deep in the field (Fig. 4). The response observed for a storm on 11 July 1993 that produced 27.4 mm of rain was typical of that observed for high intensity thunderstorms (Fig. 5). Percolate accumulation began 1 h after the start of the storm and shortly after the rainfall intensity began to increase rapidly. After the storm was over percolate accumulation was negligible. In total, the pan lysimeter captured 17% of the rainfall. Based on antecedent soil water content and water holding capacity, however, the soil above the pan should have been able to retain all the rainfall. Thus, the water that was collected in the pan lysimeter must have bypassed the matrix.

3.2.2. Flow in earthworm burrows

To determine if earthworm-formed macropores could contribute to bypass flow, Edwards et al. (1989) developed a method to monitor the flow in individual $\geq$5 mm diameter burrows by inserting a tight-fitting tube into the base of holes intercepted from the sidewall of an open pit. The tube led to a

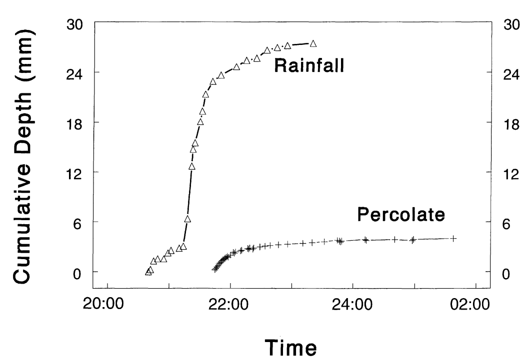

Fig. 5. Cumulative rainfall as a result of a storm on 11 July 1993 and rate of percolate accumulation in a recording pan lysimeter installed 50 cm below the soil surface.

sample bottle and another tube was routed from the bottle to the soil surface. Afterwards, the pit was refilled and a hand-held vacuum pump was used to remove any accumulated water from the bottle after each rainfall.

Fifty earthworm burrows adjacent to a long-term, no-till watershed (WS 191) were instrumented in this manner and flow was monitored from June to October 1987 (Edwards et al., 1989). The results indicated conclusively that the earthworm burrows functioned as preferential flow paths with the monitored burrows collecting up to 10% of the rainfall from individual storms and an average of 13 times more water than expected based on the diameter of their openings. The number of burrows that produced percolate and the amount of flow were a function of storm characteristics. High intensity rainfalls and dry soil surface conditions fostered flow in the monitored burrows, but low intensity storms did not yield percolate. The number of burrows that produced percolate and the volume per burrow increased with rainfall amount, whereas the percentage of rainfall captured by the burrows decreased. The results of a laboratory study supported these findings. When 30 mm of simulated rain was applied at a range of intensities to undisturbed soil blocks obtained from a no-till field, percolation began sooner and both percolate volume and the area of soil yielding percolate at the base of the blocks increased with rainfall intensity (Edwards et al., 1992).

3.2.3. Contribution of earthworm burrows to bulk flow

In the preceding study, burrows were monitored only during the growing season and total percolation was not assessed. In order to determine the potential contribution of the $\geq$5 mm diameter earthworm burrows to total percolation, burrow samplers and pan lysimeters were installed side-by-side in six no-till fields and a conventionally tilled field and monitored for 11 months (Shipitalo et al., 1994). In all instances the monitored earthworm burrows functioned as preferential flow paths collecting more water than an equivalent area of bulk soil as indicated by the catch in the pan lysimeters. This comparison also indicated that burrows in the tilled field contributed less to total percolation than those in the no-till fields, suggesting that disruption of burrow continuity by tillage reduced their effectiveness as flow paths. Based on an estimated 1.6 million burrows ha^{-1} (Edwards et al., 1988), $\geq$5 mm diameter macropores transmitted 1.0–4.1% of the rainfall at the no-till sites, but only 0.25% at the tilled site during the period investigated. A direct comparison of the efficiency of the monitored burrows to the pan lysimeters indicated that they were 8.2–53.7 times more effective in transmitting water than the bulk soil at the no-till sites, but only 2.7 times more effective at the tilled site.

Only $\geq$5 mm diameter biopores could be investigated using the burrow samplers and this size range may represent only a small fraction of the total macropores noted in no-till soil (Edwards et al., 1988). The large macropores we were able to monitor may be more efficient in transmitting water than those of smaller diameter. Nevertheless, given the rapid response to high intensity rainfall noted during the growing season in the no-till column and pan lysimeters, most of the flow during this time of the year must have been gravity flow in macropores. During times of the year when the soil approaches saturation, the soil matrix becomes increasingly involved, but laboratory studies suggest that macropores continue to dominate the flow processes in no-till soil (Shipitalo and Edwards, 1996).

3.2.4. Water movement out of macropores

Although the monolith lysimeter data suggested that little of the additional percolate during the growing season ultimately moves below the profile (Chichester, 1977), during the dormant season a direct connection of the macropore flow system in the soil to the preferential flow system in the fractured bedrock below is indicated. When spatial variability of flow from the base of the monolith lysimeters was assessed using eight separate collection pans (Fig. 3), rapid response to intense rainfall was noted for some pans during the dormant season (Edwards et al., 1995, 1997). Response of other pans was delayed and percolate accumulation occurred days to weeks after rainfall.

3.3. Combined effects of macropore and fracture flow

The effects of conservation tillage on water flow in the monolith lysimeters, and under field conditions, in general, are summarized in Fig. 6. During the growing

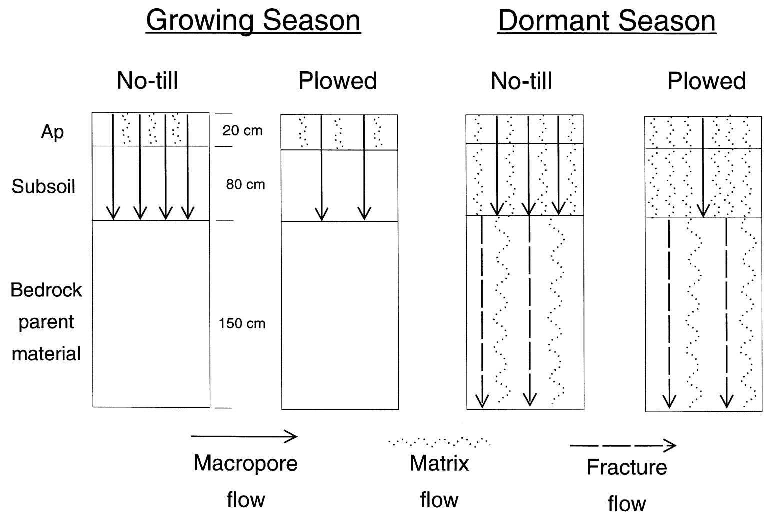

Fig. 6. Patterns of water movement in soil during the growing and dormant seasons as affected by tillage, based on studies conducted at the NAEW.

season more water infiltrates no-till soil than tilled soil due to decreased surface runoff losses. Unless the season is unusually wet, any water percolating much below the Ap horizon travels in macropores. Macropore flow is more prevalent in no-till soil than in tilled soil due to the increased formation and preservation of biopores and a greater supply of water due to decreased surface runoff and evaporation. Little water from storms during the growing season moves out of the profile or through the fractured bedrock parent material. On the other hand, infiltration is similar for no-till and tilled soil during the dormant season. Due to wetter soil conditions and lower intensity storms a greater proportion of the percolation is through capillary-sized matrix porosity, but macroporosity still accounts for a large percentage of the flow in the no-till soil. Percolate moves through the entire depth of the soil profile and, whether delivered to the top of the parent material by matrix or macropore flow, some of this water enters the fracture system of the bedrock and is quickly transmitted to the base of the lysimeters. The remaining flow saturates the soil and underlying bedrock and slowly releases water. Water within the fractured bedrock is beyond the rooting zone and unavailable for plant growth during the following growing season.

Note that although Fig. 6 suggests abrupt horizon boundaries and a clear distinction between macropore flow and matrix flow this is probably never the case. Macropore flow does not necessarily begin at the soil surface and may terminate at any depth. Likewise, matrix flow can start where macropore flow ends. A compacted layer within the soil, such as often occurs at the transition from the plow layer to the subsoil, may initiate macropore flow (Phillips et al., 1989; Andreini and Steenhuis, 1990; Gjettermann et al., 1997), and planar voids may transmit water to vertical macropores (Drees et al., 1994).

While the scenario proposed above is probably applicable to most soils and other areas with similar climates, there are likely to be some important exceptions. Where the water table is shallow, macropore flow during the growing season can move directly to groundwater. Likewise, macropores can transmit water directly to mole or tile drains (Kladivko et al., 1991; Harris et al., 1994). Similarly, if a flow-restricting horizon occurs at a relatively shallow depth, macropore flow may resurface down slope as a spring or seep and contribute to runoff as subsurface return flow. If the soil is coarse-textured or conservation tillage has not been established long enough for major differences in pore structure to develop, then the differences among tillage treatments should be minimal. In some soils, enhanced aggregation and aggregate stability associated with conservation tillage may create structural pores that serve the same role in fostering preferential flow as the biologically formed macropores noted in our soils (Quisenberry et al., 1994).

4. Macropores and water quality

4.1. Complicating factors — use of tracers

Ultimately, the primary concern with conservation tillage is not how much additional water moves through the soil or the pathways of water flow, but how conservation tillage affects the quality of the water moving to groundwater. Knowing how conservation tillage alters water movement, however, allows us to concentrate on the factors most likely to influence chemical movement.

Experimentally, it is difficult to establish the direct effect of tillage treatment on chemical migration in macropores because of a number of complicating factors. In the field, fertilizer and pesticide application methods and formulations may differ among tillage treatments. These materials are often mechanically incorporated in conventionally tilled soil, but are frequently surface-applied or receive limited incorporation in order to preserve the integrity of the surface mulch in soils subject to conservation tillage. Plant uptake, volatilization, mineralization, immobilization, and degradation rates can all be affected by tillage (Doran, 1980; Groffman, 1984). For this reason we have used strontium bromide hexahydrate ($SrBr_2{\cdot}6H_2O$) as a tracer in many of our field and laboratory studies. The movement of Sr^{2+} provides information on the effect of tillage on the transport of reactive solutes that are subject to adsorption by the soil cation exchange complex. On the other hand, Br^- is a conservative tracer that mimics the behavior of NO_3^-, but is not subject to transformation.

4.2. Seasonal patterns of chemical transport in the field

In a 2 year column lysimeter experiment, NH_4NO_3 and $SrBr_2$ were applied to tilled and no-till columns each spring (Shipitalo and Edwards, 1993a). Total annual losses of the two anions (NO_3^- and Br^-) were unaffected by tillage. By the end of each year most of the applied Br^- had leached from the soil, but both anions leached more rapidly from the no-till than from the tilled soil. Differences in NO_3^- and Br^- losses among tillage treatments reached a maximum in the months of October–December after which the differences diminished. Bromide concentration was highest in the leachate from the first storm that produced percolate after tracer application to the no-till lysimeters, but peaked several months later in the tilled columns. Losses of NH_4^+ and Sr^{2+} in the percolate were 6.6 and 2.6 times greater, respectively, from the no-till than from the tilled columns. Most of the differences among tillage treatments in losses of these two cations were attributable to the first few rainfalls after chemical application. As with Br^-, Sr^{2+} concentration was highest in the first percolate obtained from the no-till columns, but Sr^{2+} concentration decreased more sharply in subsequent events and yearly losses averaged <2% of the amount applied.

Nearly identical patterns of chemical movement were noted in the pan lysimeter-burrow sampler experiment where $SrBr_2$ was spread on the soil surface surrounding the pans and earthworm burrow samplers in tilled and no-till fields (Shipitalo et al., 1994). Both Br^- and Sr^{2+} were detected in the first percolate obtained from the burrow samplers and transport of these tracers was 2.0–5.6 times more efficient in the monitored $\geq$5 mm diameter macropores than in the bulk soil.

These results are consistent with the model presented in Fig. 6. Leaching of the conservative tracer (Br^-) was more rapid in the no-till than in the tilled soil because the first few rainfalls probably washed some of the surface-applied $SrBr_2$ off the crop residue and rapidly transmitted it through the soil via macropore flow. The remaining Br^- was probably washed into the matrix porosity of the soil. In the case of the tilled soil, a smaller proportion of the flow occurred in macropores and the first few rainfalls probably washed most of the Br^- into the soil matrix. During the dormant season, matrix flow became more prevalent in both tilled and no-till soils and Br^- or NO_3^- remaining in the soil was subject to leaching. Losses of the reactive tracer (Sr^{2+}) were greater in no-till than in tilled soil because macropore flow was more prevalent in the no-till soil. Furthermore, interaction of the Sr^{2+} with the cation exchange complex would have greatly reduced its being leached by matrix-type flow during the dormant season.

The consequence of these results is that although conservation tillage and macropore flow may promote slightly more rapid leaching of non-reactive solutes, such as NO_3^-, than when the soil is conventionally tilled, the overall effect on yearly losses is likely to be minimal. In fact, the results of the monolith lysimeter study by Chichester and Smith (1978) indicated no effect of tillage on NO_3^- losses in deep percolation. Conservation tillage and macropore flow, however, may increase the relative movement of strongly absorbed chemicals, such as pesticides, to lower depths within the soil. The characteristics of the first few storms after chemical application appear to influence the magnitude of the tillage effect.

4.3. Storm and soil characteristics affecting macropore flow and chemical transport

4.3.1. Methodology

To investigate the effects of storm and soil characteristics on chemical mobility in macropores, undisturbed 30 by 30 by 30 cm blocks of soil were removed from no-till corn fields using the methods outlined in Shipitalo et al. (1990) and Shipitalo and Edwards (1996). The locations of macropores in the base of the blocks were mapped using a grid that corresponded to the dimensions of a 64-cell grid lysimeter used to collect percolate (Fig. 7). In the laboratory, a rainfall simulator was used to apply water at any desired rate and the accumulation of percolate was noted in relationship to the location of macropores on the maps. Results indicated that storm intensity, duration, sequence, and timing, as well as water content of the soil, all affected macropore flow and chemical transport. Rapid movement of water entirely through the 30 cm blocks, at times within 2–4 min of the start of rainfall, was invariably linked to the presence of one or more macropores in the cells that produced percolate.

4.3.2. Rainfall intensity

High intensity rainfall resulted in greater water movement in macropores, hence greater transport of chemicals freshly applied to the soil surface, than low intensity rainfall (Edwards et al., 1992). Percolate production and transport of freshly applied atrazine, Br^-, and Sr^{2+} were 12–14 times greater in blocks that received 30 mm of simulated rain in 15 min than in blocks that received the same rainfall amount in 120 min. Similar observations have been made by numerous other researchers (Germann et al., 1984; Coles and Trudgill, 1985; Smith et al., 1985; Bicki and Guo, 1991; Jarvis et al., 1991; Trojan and Linden, 1992; Sigua et al., 1993; Li and Ghodrati, 1994; Quisenberry et al., 1994; Wopereis et al., 1994; Gjettermann, 1997), suggesting that a positive correlation between rainfall intensity and water and solute transport holds for a wide range of soil types and chemicals.

4.3.3. Storm sequence

Storm sequence can also have a large effect on chemical movement in macropores in no-till soil (Shipitalo et al., 1990). A light rainfall of 5 mm in 60 min did not affect the amount of percolate produced in a subsequent 30 mm, 30 min rainfall, but reduced atrazine, Br^-, and Sr^{2+} transport 2-, 7-, and 10-fold, respectively, compared with blocks that did not receive this initial, light rain. In a similar study, Golabi et al. (1995) noted that a light rainfall preceding a heavy rainfall reduced Cl^- concentrations and total losses in no-till as well as tilled soil. In this instance, the effect was more pronounced in tilled than in no-till soil with a 2-fold reduction in both concentration and losses noted.

4.3.4. Soil water content

The effects of antecedent soil water content were not as large as those observed with rainfall intensity and storm sequence (Shipitalo and Edwards, 1996). No significant differences in total amount of chemical transported were detected when simulated rain was applied to relatively dry soil blocks (θ=0.11 kg kg^{-1}) compared with wet blocks (θ=0.21 kg kg^{-1}) obtained from a no-till corn field. Movement of water and tracers applied in the simulated rain indicated, nevertheless, that matrix porosity was increasingly involved in the flow processes as soil water content increased. As a result of less interaction of the applied rainwater with the soil matrix, average concentrations of reactive, surface-applied, constituents (Sr^{2+}, atrazine, and alachlor) were 1.6–3.5 times higher in percolate from the dry blocks than from the wet blocks. As might be expected, concentration of the unreactive, surface-applied, tracer (Br^-) was unaffected by soil water content because it is not subject to sorption and moves readily in both macropore and matrix flow.

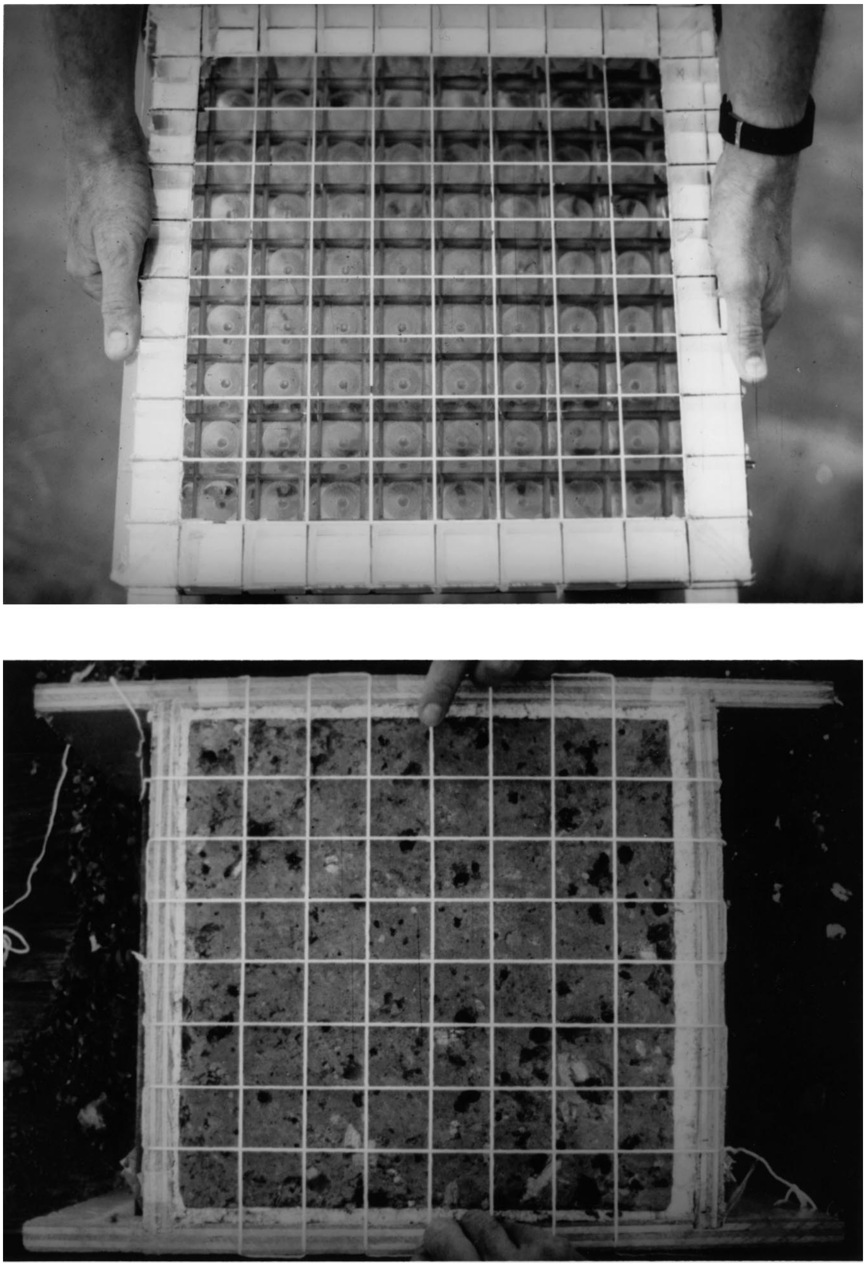

Fig. 7. Sixty-four cell grid lysimeter used to collect percolate from undisturbed soil blocks and typical macropore distribution observed at the base of a no-till soil block. Each cell is 3.75 by 3.75 cm^2.

In field studies, Flury et al. (1994, 1995) noted that initial water content did not have a pronounced effect on preferential flow, although solutes tended to move deeper in wet, well-structured, soils than when the soil was dry. White et al. (1986), however, noted considerably greater leaching losses of two herbicides dissolved in simulated rain applied to dry soil than when applied to soil that had been pre-wetted. An interaction between texture and soil water content was noted by Bergstrom and Jarvis (1993) with macropore flow resulting in greater herbicide leaching in dry, clayey, soil than in wet or sandy soil.

4.3.5. Storm timing

Rainfall timing relative to chemical application can have a major influence on the amount of chemical transmitted in macropores because of diffusion, adsorption, degradation, volatilization, and plant uptake. A 24 h delay in application of simulated rainfall following surface application of atrazine reduced transport by $\approx$50% compared with blocks that received the same size and duration storm 1 h after the herbicide was applied (Edwards et al., 1993b). With a 2 week delay, atrazine transport was less than one third of that noted with a 1 h delay. Field support for this phenomenon comes from Isensee et al. (1990). They postulated that high atrazine concentrations found in shallow groundwater beneath a no-till corn field in November were due to a high intensity storm shortly after herbicide application in May. Preferential flow due to this storm apparently moved atrazine below the rooting zone where degradation was slowed and it remained available for further leaching in the fall. In a laboratory study Francis et al. (1988) attributed less leaching of Cl^- (applied 48 h prior to simulated rainfall) compared with NO_3^- (applied immediately prior to rainfall) to diffusion of the Cl^- into soil aggregates where it was less accessible to be leached by macropore flow. McLay et al. (1991) reached a similar conclusion in a study where they compared the effect of application time on NO_3^- and SO_4^{2-} movement. Also, Logsdon (1995) noted dye movement in artificial macropores if applied just ahead of infiltration, but not when applied 24 h earlier.

4.3.6. Breakthrough time

In all our soil block studies, the highest concentrations of surface-applied, reactive solutes were associated with cells that broke through early and produced large volumes of percolate. When solute concentrations were monitored as a function of time for individual cells, the highest concentrations were frequently noted in the first percolate sample from a particular cell (Shipitalo and Edwards, 1996). To investigate how interaction of rain with surface-applied herbicides affects the amounts potentially available to enter macropores, water that accumulated in surface microdepressions in corn fields was collected during simulated rainstorms (Edwards et al., 1997). Atrazine and alachlor concentrations in this water decreased rapidly with time during storms and from storm-to-storm. Highest concentrations were noted in the first samples collected and the first storm after herbicide application. Within 30 min a 4-fold average decrease in concentration was noted. Average herbicide concentrations in water accumulated in surface microdepressions of no-till soil 32 days later were 15% of the day 1 concentrations and continued to decrease during the simulated rainfall. Together with the block studies these results suggested that significant transport of herbicides in macropores is probably limited to the early parts of the first few storms following application.

5. Summary and conclusions

The effects of conservation tillage on water and chemical movement depend on a number of site-specific environmental factors, including drainage, slope, soil texture, porosity and aggregation and, most importantly, the weather. Nevertheless, experiments conducted at the NAEW suggest some general conclusions on the effects of conservation tillage on water and chemical movement under our soil and climatic conditions.

Conservation tillage can reduce surface runoff and increase infiltration, most notably during the growing season when high intensity rainstorms frequently occur and potential evapotranspiration is highest. The amount of additional water percolating into the subsoil can exceed the reduction in surface runoff due to reduced evaporation. Because of increased macropore formation and preservation, the proportion of rainfall that enters and flows in macropores is greater with conservation tillage than with conventional tillage. In our soils macropore flow is predominately associated with earthworm-formed biopores, but in different soils other types of biopores and structural pores can play a similar role.

Since only a small fraction of the soil volume is involved in macropore flow, the velocity at which the water moves through the soil and the depth of penetration are much greater than when the entire volume of the soil is involved in the flow process. Consequently, the amount of soil that a dissolved solute encounters and its contact time with the soil are also reduced. High intensity rainfalls combined with dry conditions at the soil surface increase the relative contribution of macropores to infiltration. Most of the additional percolate is stored within the rooting zone and is transpired. Little reaches the groundwater during the growing season unless the water table is shallow.

Surface-applied agricultural chemicals are most susceptible to transport in macropores in the first few storms after application because diffusion, adsorption, degradation, volatilization and plant uptake reduce the amount available for transport as time progresses. Thus, any delay between the time of application and the occurrence of heavy rainfall, or any intervening light rainfalls, can reduce chemical transport in macropore flow. Although macropore flow may contribute to slightly faster leaching of non-adsorbed solutes, the overall effect of conservation tillage is probably negligible because any solute remaining in the soil at the end of the growing season will be subject to leaching during the dormant season. Adsorbed chemicals can be moved deeper in the profile than expected due to macropore flow and are subject to leaching to groundwater. The differences among tillage treatments are likely to be no more than a few per cent of the application, even under extreme circumstances (i.e., a heavy, intense, storm immediately following surface application). Flury (1996) estimated that under a worst case scenario annual pesticide leaching losses might reach 5% of the applied mass compared to <0.1–1% under more normal conditions. The probability of a rainfall with a long return period occurring shortly after pesticide application, however, is much greater than the estimated return period for such an event (Fawcett et al., 1994) because return periods are usually based on the annual probability of occurrence.

An understanding of the factors that influence how much of an adsorbed solute, moved to the subsoil by macropore flow shortly after application, is ultimately leached to groundwater represents a critical gap in our knowledge. It is likely that sorption and degradation will further reduce the amounts available for transmission to groundwater. In the case of earthworm-formed macropores, deposition of organic matter in the burrow linings can increase pesticide sorption (Stehouwer et al., 1993, 1994), and greater aeration and nutrient supply can stimulate microbial activity, enhancing biodegradation compared to the soil matrix (Pivetz and Steenhuis, 1995).

The challenge is to manage the soil with respect to solute transport, both surface and subsurface. Conservation tillage practices should be refined to take advantage of macropore flow. Tilling the soil to reduce subsurface transport is not a desirable option as it will increase the potential for chemical losses in surface runoff, frequently cited as a more serious concern (Fawcett et al., 1994). In most circumstances, conservation tillage and macropore flow probably contribute little additional nitrate to groundwater. Management strategies that increase N-use efficiency such as nitrification inhibitors, slow-release formulations, soil testing, and site-specific applications should minimize nitrate losses to groundwater (Power and Schepers, 1989).

Downward transport of a chemical that is normally strongly adsorbed by the soil is possible during the period between its surface application and the first storm producing significant macropore flow. Chemical applications can be avoided when such storms are imminent, but this management strategy is not always practical and is limited by our ability to predict the weather. Use of application equipment and procedures or chemical formulations that reduce the amount of chemical available for transport in macropores can affect the potential impact of conservation tillage on groundwater quality. Fortunately, most management practices designed to reduce herbicide losses in surface runoff, such as sub-residue placement, reduced application rates, banding, and slow-release formulations (Baker and Mickelson, 1994), should also be effective in reducing losses in subsurface macropore flow.

References

Andreini, M.S., Steenhuis, T.S., 1990. Preferential paths of flow under conventional and conservation tillage. Geoderma 46, 85–102.

Baker, J.L., 1987. Hydrologic effects of conservation tillage and their importance relative to water quality. In: Logan, T.J., Davidson, J.M., Baker, J.L., Overcash, M.R. (Eds.), Effects of Conservation Tillage on Groundwater Quality. Lewis, Chelsea, MI, pp. 113–124.

Baker, J.L., Mickelson, S.K., 1994. Application technology and best management practices for minimizing herbicide runoff. Weed Technol. 8, 862–869.

Bergstrom, L.F., Jarvis, N.J., 1993. Leaching of dichlorprop, bentazon, and ^{36}Cl in undisturbed field lysimeters of different agricultural soils. Weed Sci. 41, 251–261.

Bicki, T.J., Guo, L., 1991. Tillage and simulated rainfall intensity effect on bromide movement in an Argiudoll. Soil Sci. Soc. Am. J. 55, 794–799.

Boone, F.R., Slager, S., Miedema, R., Eleveld, R., 1976. Some influences of zero-tillage on the structure and stability of a fine-textured river levee soil. Neth. J. Agric. Res. 24, 105–119.

Bull, L., Delvo, H., Sandretto, C., Lindamood, B., 1993. Analysis of pesticide use by tillage system in 1990, 1991, and 1992 corn and soybeans. In: Agricultural Resources: Inputs Situation and Outlook Report. Econ. Res. Ser. Report AR-32, pp. 41–54.

Chichester, F.W., 1977. Effects of increased fertilizer rates on nitrogen content of runoff and percolate. J. Environ. Qual. 6, 211–217.

Chichester, F.W., Smith, S.J., 1978. Disposition of 15N-labeled fertilizer nitrate applied during corn culture in field lysimeters. J. Environ. Qual. 7, 227–233.

Coles, N., Trudgill, S., 1985. The movement of nitrate fertiliser from the soil surface to drainage waters by preferential flow in weakly structured soils, Slapton, S. Devon. Agric. Ecosyst. Environ. 13, 241–259.

Dick, W.A., McCoy, E.L., Edwards, W.M., Lal, R., 1991. Continuous application of no-tillage to Ohio soils. Agron. J. 83, 65–73.

Dick, W.A., Roseberg, R.J., McCoy, E.L., Edwards, W.M., Haghiri, F., 1989. Surface hydrologic response of soils to no-tillage. Soil Sci. Soc. Am. J. 53, 1520–1526.

Doran, J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44, 765–771.

Drees, L.R., Karathanasis, A.D., Wilding, L.P., Blevins, R.L., 1994. Micromorphological characteristics of long-term no-till and conventionally tilled soils. Soil Sci. Soc. Am. J. 58, 508–517.

Edwards, W.M., Amerman, C.R., 1984. Subsoil characteristics influence hydrologic response to no-tillage. Trans. ASAE 27, 1055–1058.

Edwards, C.A., Bohlen, P.J., 1996. Biology and Ecology of Earthworms, 3rd Edition. Chapman & Hall, London, 426 pp.

Edwards, W.M., Bonta, J.V., Shipitalo, M.J., Owens, L.B., 1995. Parent material affects preferential flow in Coshocton lysimeters. Agronomy Abstracts, p. 201.

Edwards, W.M., Norton, L.D., Redmond, C.E., 1988. Characterizing macropores that affect infiltration into nontilled soil. Soil Sci. Soc. Am. J. 52, 483–487.

Edwards, W.M., Riess, F., Bonta, J.V., Shipitalo, M.J., Owens, L.B., 1997. Preferential flow in Coshocton lysimeters shows importance to sustained production. In: Proceedings of the Seventh Gumpensteiner Lysimeter Conference 'Lysimeters and Sustainable Landuse' BAL Gumpenstein, Austria, pp. 1–10.

Edwards, W.M., Shipitalo, M.J., Dick, W.A., Owens, L.B., 1992. Rainfall intensity affects transport of water and chemicals through macropores in no-till soil. Soil Sci. Soc. Am. J. 56, 52–58.

Edwards, W.M., Shipitalo, M.J., Lal, R., Owens, L.B., 1997. Rapid changes in concentration of herbicides in corn field surface depressions. J. Soil Water Conser. 52, 277–281.

Edwards, W.M., Shipitalo, M.J., Owens, L.B., Dick, W.A., 1993b. Factors affecting preferential flow of water and atrazine through earthworm burrows under continuous no-till corn. J. Environ. Qual. 22, 453–457.

Edwards, W.M., Shipitalo, M.J., Owens, L.B., Norton, L.D., 1989. Water and nitrate movement in earthworm burrows within long-term no-till cornfields. J. Soil Water Conser. 44, 240–243.

Edwards, W.M., Triplett, G.B., Van Doren, D.M., Owens, L.B., Redmond, C.E., Dick, W.A., 1993a. Tillage studies with a corn–soybean rotation: hydrology and sediment loss. Soil Sci. Soc. Am. J. 57, 1051–1055.

Ehlers, W., 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Sci. 119, 242–249.

Fawcett, R.S., Christensen, B.R., Tierney, D.P., 1994. The impact of conservation tillage on pesticide runoff into surface water: a review and analysis. J. Soil Water Conser. 49, 126–135.

Flury, M., 1996. Experimental evidence of transport of pesticides through field soils — a review. J. Environ. Qual. 25, 25–45.

Flury, M., Flühler, H., Jury, W.A., Leuenberger, J., 1994. Susceptibility of soils to preferential flow of water: a field study. Water Resour. Res. 30, 1945–1954.

Flury, M., Leuenberger, J., Studer, B., Flühler, H., 1995. Transport of anions and herbicides in a loamy and a sandy field soil. Water Resour. Res. 31, 823–835.

Francis, G.S., Cameron, K.C., Kemp, R.A., 1988. A comparison of soil porosity and solute leaching after six years of direct drilling or conventional cultivation. Aust. J. Soil Res. 26, 637–649.

Gantzer, C.J., Blake, G.R., 1978. Physical characteristics of Le Sueur clay loam soil following no-till and conventional tillage. Agron. J. 70, 853–857.

Germann, P.F., Edwards, W.M., Owens, L.B., 1984. Profiles of bromide and increased soil moisture after infiltration into soils with macropores. Soil Sci. Soc. Am. J. 48, 237–244.

Gjettermann, B., Nielsen, K.L., Petersen, C.T., Jensen, H.E., Hansen, S., 1997. Preferential flow in sandy loam soils as affected by irrigation intensity. Soil Technol. 11, 139–152.

Golabi, M.H., Radcliffe, D.E., Hargrove, W.L., Tollner, E.W., 1995. Macropore effects in conventional and no-tillage soils. J. Soil Water Conser. 50, 205–210.

Griffith, D.R., Mannering, J.V., Box, J.E., 1986. Soil and moisture management with reduced village. In: Sprague, M.A., Triplett, G.B. (Eds.), No-Tillage and Surface Tillage Agriculture — The Tillage Revolution. Wiley-Interscience, New York, pp. 19–57.

Groffman, P.M., 1984. Nitrification and denitrification in conventional and no-tillage soils. Soil Sci. Soc. Am. J. 49, 329–334.

Hall, J.K., Murray, M.R., Hartwig, N.L., 1989. Herbicide leaching and distribution in tilled and untilled soil. J. Environ. Qual. 18, 439–445.

Harris, G.L., Nicholls, P.H., Bailey, S.W., Howse, K.R., Mason, D.J., 1994. Factors influencing the loss of pesticides in drainage from a cracking clay soil. J. Hydro. 159, 235–253.

Hinkle, M.K., 1983. Problems with conservation tillage. J. Soil Water Conser. 38, 201–206.

Isensee, A.R., Nash, R.G., Helling, C.S., 1990. Effect of conventional vs. no-tillage on pesticide leaching to shallow groundwater. J. Environ. Qual. 19, 434–440.

Jarvis, N.J., Bergstrom, L., Dik, P.E., 1991. Modelling water and solute transport in macroporous soil. II. chloride breakthrough under non-steady flow. J. Soil Sci. 42, 71–81.

Kelley, G.E., Edwards, W.M., Harrold, L.L., McGuinness, J.L., 1975. Soils of the North Appalachian Experimental Watershed. USDA Misc. Publ. No. 1296. US Gov. Print. Office, Washington, DC, 145 pp.

Kladivko, E.J., Van Scoyoc, G.E., Monke, E.J., Oates, K.M., Pask, W., 1991. Pesticide and nutrient movement into subsurface tile drains on a silt loam soil in Indiana. J. Environ. Qual. 20, 264–270.

Kohnke, H., Dreibelbis, F.R., Davidson, J.M., 1940. A survey and discussion of lysimeters and a bibliography on their construction and performance. USDA Misc. Publ. No. 372. US Gov. Print. Office, Washington, DC, pp. 67.

Lal, R., Logan, T.J., Shipitalo, M.J., Eckert, D.J., Dick, W.A., 1994. Conservation tillage in the corn belt of the USA. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis, Ann Arbor, MI, pp. 73–114.

Li, Y., Ghodrati, M., 1994. Preferential transport of nitrate through soil columns containing root channels. Soil Sci. Soc. Am. J. 58, 653–659.

Logsdon, S.D., 1995. Flow mechanisms through continuous and buried macropores. Soil Sci. 160, 237–242.

McLay, C.D.A., Cameron, K.C., McLaren, R.G., 1991. Effect of time of application and continuity of rainfall on leaching of surface-applied nutrients. Aust. J. Soil Res. 29, 1–9.

Moran, C.J., Koppi, A.J., Murphy, B.W., McBratney, A.B., 1988. Comparison of the macropore structure of a sandy loam surface soil horizon subjected to two tillage treatments. Soil Use and Mgmt. 4, 96–102.

Pagliai, M., Raglione, M., Panini, T., Maletta, M., La Marca, M., 1995. The structure of two alluvial soils in Italy after 10 years of conventional and minimum tillage. Soil Till. Res. 34, 209–223.

Phillips, R.E., Quisenberry, V.L., Zeleznik, J.M., Dunn, G.H., 1989. Mechanism of water entry into simulated macropores. Soil Sci. Soc. Am. J. 53, 1629–1635.

Pivetz, B.E., Steenhuis, T.S., 1995. Soil matrix and macropore biodegradation of 2,4-D. J. Environ. Qual. 24, 564–570.

Power, J.F., Schepers, J.S., 1989. Nitrate contamination of groundwater in North America. Agric. Ecosyst. Environ. 26, 165–187.

Quisenberry, V.L., Phillips, R.E., Zeleznik, J.M., 1994. Spatial distribution of water and chloride macropore flow in a well-structured soil. Soil Sci. Soc. Am. J. 58, 1294–1300.

Rawls, W.J., Brakensiek, D.L., Soni, B., 1983. Agricultural management effects on soil water processes. Part I: Soil water retention and Green and Ampt infiltration parameters. Trans. ASAE 26, 1747–1752.

Rose, C.W., Chichester, F.W., Phillips, I., 1983. Nitrogen-15-labeled nitrate transport in a soil with fissured shale substratum. J. Environ. Qual. 12, 249–252.

Roseberg, R.J., McCoy, E.L., 1992. Tillage- and traffic-induced changes in macroporosity and macropore continuity: air permeability assessment. Soil Sci. Soc. Am. J. 56, 1261–1267.

Shipitalo, M.J., Edwards, W.M., 1993a. Seasonal patterns of water and chemical movement in tilled and no-till column lysimeters. Soil Sci. Soc. Am. J. 57, 218–223.

Shipitalo, M.J., Edwards, W.M., 1993b. Recording pan lysimeter for preferential flow and chemical transport studies. Agronomy Abstracts, p. 49.

Shipitalo, M.J., Edwards, W.M., 1996. Effects of initial water content on macropore/matrix flow and transport of surface-applied chemicals. J. Environ. Qual. 25, 662–670.

Shipitalo, M.J., Edwards, W.M., Dick, W.A., Owens, L.B., 1990. Initial storm effects on macropore transport of surface-applied chemicals in no-till soil. Soil Sci. Soc. Am. J. 54, 1530–1536.

Shipitalo, M.J., Edwards, W.M., Redmond, C.E., 1994. Comparison of water movement and quality in earthworm burrows and pan lysimeters. J. Environ. Qual. 23, 1345–1351.

Shipitalo, M.J., Protz, R., 1987. Comparison of morphology and porosity of a soil under conventional and zero tillage. Can. J. Soil Sci. 67, 445–456.

Sigua, G.C., Isensee, A.R., Sadeghi, A.M., 1993. Influence of rainfall intensity and crop residue on leaching of atrazine through intact no-till soil cores. Soil Sci. 156, 225–232.

Smith, M.S., Thomas, G.W., White, R.E., Ritonga, D., 1985. Transport of *Escherichia coli* through intact and disturbed soil columns. J. Environ. Qual. 14, 87–91.

SSSA, 1997. Glossary of Soil Science Terms. Soil Science Society of America, Madison, WI, 134 pp.

Stehouwer, R.C., Dick, W.A., Traina, S.J., 1993. Characteristics of earthworm burrow lining affecting atrazine sorption. J. Environ. Qual. 22, 181–185.

Stehouwer, R.C., Dick, W.A., Traina, S.J., 1994. Sorption and retention of herbicides in vertically oriented earthworm and artificial burrows. J. Environ. Qual. 23, 286–292.

Thomas, G.W., Phillips, R.E., 1979. Consequences of water movement in macropores. J. Environ. Qual. 8, 149–152.

Trojan, M.D., Linden, D.R., 1992. Microrelief and rainfall effects on water and solute movement in earthworm burrows. Soil Sci. Soc. Am. J. 56, 727–733.

Urban, J.B., 1965. Geologic and hydrologic significance of springs and seeps in eastern Ohio. J. Soil Water Conserv. 20, 178–179.

USDA-SCS, 1981. Land resource regions and Major Land Resource Areas of the United States. United States Department of Agriculture-Soil Conservation Service, Handbook 296. US Gov. Print. Office, Washington, DC.

White, R.E., Dyson, J.S., Gerstl, Z., Yaron, B., 1986. Leaching of herbicides through undisturbed cores of a structured clay soil. Soil Sci. Soc. Am. J. 50, 277–283.

Wopereis, M.C.S., Bouma, J., Kropff, M.J., Sanidad, W., 1994. Reducing bypass flow through a dry, cracked and previously puddled rice soil. Soil Till. Res. 29, 1–11.