COLLECTION AND MONITORING OF ONE-METER CUBIC SOIL MONOLITHS FOR LEACHING STUDIES

W. L. Kranz, R. S. Kanwar, C. E. Pederson

ABSTRACT. *This report presents methodology for excavating one-meter cubic undisturbed soil monoliths for detailed laboratory investigations of solute transport through the soil profile. Eight soil monoliths were collected in 1992 from three field areas that had been under consistent tillage systems since 1978. The soil was predominantly a Kenyon silt loam* (Typic Hapludoll) *with the water table maintained by subsurface drainage. Each monolith was instrumented with time-domain reflectometer (TDR) waveguides, and mini-tensiometers to monitor changes in soil water content and soil matric potential on three sides. A rainfall simulator was constructed to apply water at a rainfall intensity of 33 mm-h^{-1} to a 0.8 m × 0.8 m surface area of the monolith. A conservative tracer (KBr) was applied to the soil surface and leachate samples were collected from 36 locations at the bottom of each monolith using fiberglass wick extractors attached to 810 mm^2 areas in a 6 × 6 grid arrangement. Water application, soil water content and leachate were monitored to determine how surface tillage affected preferential flow.*

Results suggest that the soil monolith collection and transportation procedures maintained the integrity of the soil profile. Anion tracers provided an inexpensive means of simulating different nitrogen application methods. Grid cell samplers using fiberglass wicks allowed analysis of the spatial variation in leaching losses. Leachate samples provided information about the potential impact of nitrogen application method on leaching losses. When coupled with time domain reflectometry and mini-tensiometers, electronic data logging equipment can be used to monitor changes in soil volumetric water content and matric potential. ***Keywords.*** *Monoliths, Leaching, Rainfall simulation, Macropores, Tracers.*

Public concern for environmental quality issues has heightened interest in agriculture's impact on soil and water resources. Identification of agricultural chemicals in ground and surface water makes it imperative that improved management techniques prevent further chemical movement from target areas. Though nitrate-nitrogen (NO_3-N) is the most common agricultural chemical found in groundwater, other chemicals applied to the soil surface are susceptible to leaching losses. Management strategies must carefully match tillage with chemical application methods to reduce the potential for chemical losses to surface runoff and groundwater. Mismanagement could result in additional chemicals being placed on the Environmental Protection Agency's restricted use list, thereby possibly reducing crop production options.

Tillage practices may be split into three general categories: (a) conventional tillage—consisting of moldboard plowing, and one or more disk or chisel operations; (b) reduced tillage—consisting of one or more disk, chisel, or field cultivator operations; and (c) no-till—essentially zero disturbance of the soil surface. While no-till is often credited with reducing surface runoff and soil erosion, the corresponding increase in infiltration may lead to increased leaching losses. Moldboard plowing results in an increased potential for soil erosion, but the slicing action of the plow blade may block some flow pathways, thus reducing leaching losses. Therefore, moldboard plowing may still have a place in areas where surface runoff is limited and significant leaching losses are possible.

Likewise farmers apply nitrogen using several different techniques. Nitrogen application techniques include surface-broadcast, banding with the planter, knifing in liquid urea-ammonia nitrate solution or anhydrous ammonia, or application via an irrigation system. During spring planting and nitrogen application, soils are near field capacity coincidently with frequent rainfall events. Because nitrogen fertilizer formulations are readily transformed into nitrate, the opportunity for leaching exists whenever water passes through a soil. Even if the soil is dry, nitrogen applied to the soil surface may be lost if a high intensity rainfall occurs and preferential pathways exist. When water is ponded on the soil surface, it passes most freely through worm holes, freeze-thaw and moisture fluctuation cracks, or through soil deposits with permeabilities much greater than the surrounding soils. Transport of water and nitrogen can occur at rates several times greater than predicted by leaching models. If the goal is to reduce nitrogen leaching, farmers require information on the potential for leaching loss for a broad range of tillage and nitrogen application methods. One way to collect this needed information is

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Article has been reviewed and approved for publication by the Soil & Water Div. of ASAE.

Journal Paper No. 17251 of the Iowa State Agriculture and Home Economics Experiment Station, Ames, Iowa, Project No. 3415. Research was partly supported with funding from the Leopold Center for Sustainable Agriculture, Ames, Iowa, and the CSRS-USDA Project on Management Systems Evaluation Areas (MSEA). This manuscript has been assigned Journal Series No. 11780 by the Agricultural Research Division, University of Nebraska, Lincoln, Nebr.

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VOL. 41(2):333-344

through intensive monitoring of soil water and leaching losses using undisturbed soil monoliths.

Previous research has reported on determining the effect of chemical application and tillage on leaching losses to groundwater. Most investigations have used 300 mm I.D. or smaller soil columns due to their ease of collection and handling for solute transport studies. However, their small size may only represent a small portion of expected field scale variation. One-meter cubic undisturbed soil columns have been avoided due to difficulties with excavation procedures, and excessive weight for transport.

LITERATURE REVIEW

Leaching losses have been shown to vary with tillage practices (Dick et al., 1989; Germann et al., 1984; Kanwar et al., 1985), and chemical placement techniques (Baker and Timmons, 1994; Clay et al., 1994; Hamlett et al., 1990). Using 300-mm undisturbed soil cores, Boddy (1990) concluded that heavy rainfall events produced greater atrazine leaching losses from no-till than chisel or moldboard plow treatments. After six years, Dick et al. (1989) recorded twice as much leachate from a no-till treatment than for a conventional tillage treatment. Baker and Timmons (1994) found greater recovery rates for point-injected nitrogen when compared with surface-banded application methods. Clay et al. (1994) found greater leaching of nitrogen when anhydrous ammonia was knifed into the ridge when compared with application in the valley between two ridges. These studies suggest that identifying a combination of nitrogen form and nitrogen application method that limits leaching losses may be possible.

Under some conditions, solute fluxes greatly exceed those predicted by solute transport models (Everts and Kanwar, 1990; Richard and Steenhuis, 1988; Thomas and Phillips, 1979). Research using 250 to 300-mm diameter disturbed or undisturbed soil columns has pointed to preferential flow pathways to explain such findings (Boddy and Baker, 1990; Booltink and Bouma, 1991; Bouma and Wösten, 1979; Jennings, 1990; Singh and Kanwar, 1991). Preferential flow pathways may consist of earthworm and root channels (Shipitalo et al., 1990), structural cracks, old rodent burrows, or areas of the soil with significantly greater water conductivity (Beven and Germann, 1982; Kung, 1993). Shipitalo et al. (1990) found that only 17% of the soil volume contributed leachate resulting from a simulated rainfall of 30 mm. By dividing the leachate collection device into small cells, they found that a single cell often accounted for 70% of the total leachate resulting from a 60-mm water application. Singh and Kanwar (1991) noted that some 300-mm soil cores appeared to contain worm holes while others did not. Beven and Germann (1981) suggested that representative elementary volumes (REVs) be used to establish the soil sample size. In summary, based on these results, a laboratory study seeking to estimate field scale leaching processes requires a much larger volume of soil than the 300-mm diameter soil cores collected for many investigations.

Undisturbed soil monoliths have traditionally been used to study subsurface drainage and crop water use rates (Armijo et al., 1972; Klocke et al., 1993; Schneider and Howell, 1991). Though the collection process has varied, a bottomless container has typically been forced into the soil using a drilling mechanism, dead weight, jacks or backhoe (Brown et al., 1974; Persson and Bergström, 1991). Schneider et al. (1988) describe the design of a hydraulic pulldown assembly for jacking 3 $m^2 \times 2.4$-m deep steel boxes into a Texas soil. Soil outside the steel box was manually shaved away as the frame was pulled into the soil. The undisturbed blocks of soil were removed by crane after installing a series of pipes horizontally across the bottom of the box. The most significant problem encountered during the installation process was warping of sidewalls as the box was being installed. Klocke et al. (1993) described installation of 0.90-m diameter metal percolation lysimeters. Lysimeters were installed using a pulldown method with two 178-kN hydraulic cylinders attached to a framework. They found that some unconsolidated horizons were compacted due to friction between soil and the inside walls of the lysimeter. These projects show that soil monoliths can be acquired using different methods, but none have presented procedures that involve collecting one-meter cubic undisturbed soil monoliths for use in laboratory investigations.

Excavation, transportation, and preparation of soil monoliths for testing requires that procedures provide support for the soil pedestal without altering soil physical characteristics (Bowman et al., 1994). The main considerations are to support the soil pedestal, maintain contact between the soil and the liner, and allow the soil to shrink and swell with changing water contents. Materials such as foam, plaster-of-paris, paraffin, concrete, and polyester resin have been used for support (Murphey et al., 1981; Shipitalo et al., 1990). Bowman et al. (1994) state that plaster-of-paris is not well suited because cracks developed during the curing process and the rigidity of the material does not allow the soil to shrink and swell with changing water contents.

Anion tracers have been used to mimic nitrate leaching through the soil profile. Solute transport studies have been conducted using bromide, chloride, nitrate, fluorescent dyes, benzoic acids, herbicides, and radioactive isotopes (Agus and Cassel, 1992; Bergstrom and Johansson, 1991; Czapar et al., 1992; Everts and Kanwar, 1990; Ghodrati and Jury, 1992; Rice et al., 1991; Saffigna et al., 1977; Starr et al., 1986). Chloride and bromide have been used as tracers in nitrate leaching studies since they occur at low concentrations in most soils, analysis is inexpensive, and they travel with leaching water similar to nitrate (Saffigna et al., 1977). Czapar et al. (1992) added a mixture of alachlor, cyanazine and pendimethaline to soil columns to investigate the impact of macropores on leaching rates for strongly adsorbed solutes. Despite being strongly adsorbed, the three herbicides were transported rapidly through soils with artificially created pores. Rice et al. (1991) applied four benzoic acid tracers and bromide to a sandy loam soil to evaluate solute movement under furrow-irrigated conditions. Using a water balance approach, they found that tracer flow velocity was 2 to 2.5 times greater than predicted by a piston flow model. Though analysis costs are greater, these tracers do not occur naturally in soils.

Few soils exhibit spatial homogeneity, or constant soil water contents over time (Baker and Allmaras, 1990; Van Wesenbeeck and Kachanoski, 1988). Soil water variables, such as water potential or water content, have been used to verify water movement within the soil profile (Ahuja et al., 1976; Baker and Allmaras, 1990; Bouma et al., 1982; Topp and Davis, 1985; Williams, 1978). Most studies have recorded soil water tension rather than water content. Tensiometers have been used to record changes in water tension due to ease of measurement and the availability of instrumentation (Rice, 1969; Williams, 1978). Booltink and Bouma (1991) used a multiport valve to record soil water tensions from 21 miniature tensiometers using a single pressure transducer.

Topp et al. (1980) found that Time Domain Reflectometry (TDR) technology could be applied to measure the water content of the soil. The method is safe, accurate, nondestructive, and thought to be unaffected by differences in bulk density, solute concentration or mineral concentrations (Ledieu et al., 1986; Roth et al., 1992; Topp et al., 1980). Typical measurement errors are less than 2% (Baker and Allmaras, 1990). Time-domain reflectometry also allows frequent measurement over the time required to conduct leaching rate studies (Baker and Allmaras, 1990; Heimovaara et al., 1993; Topp and Davis, 1985).

One of the most common criticisms of laboratory studies is that bottom boundary conditions seldom mimic those found in the field. To investigate unsaturated flow through soil columns without macropores, the soil at the lower boundary must become saturated before drainage will occur. Different approaches have been employed in an attempt to bring laboratory conditions closer to those found in the field (Boll et al., 1992; Bowman et al., 1994; Phillips et al., 1995; Tindall et al., 1992). Bowman et al. (1994) presented a description of a laboratory test stand that could apply a vacuum of 0 to −34.4 kPa to the bottom of the soil block. Boll et al. (1992) used fiberglass wicks to aid extraction of water samples from soils under unsaturated conditions. Matric potentials up to −30 kPa were possible under flow rates of 6 $mL\text{-}h^{-1}$. The wicks affected the dispersion of a Br^- and a blue dye tracer much less than recorded for flow through undisturbed soils. Steenhuis et al. (1990) evaluated porous cup extractors, gravity pan lysimeters and fiberglass wick pan lysimeters under field conditions in New York. They found that fiberglass wicks placed in a grid arrangement provided more representative samples of water and solute. Thus, fiberglass wicks can draw water from a soil column at water contents below saturation without applying a vacuum.

OBJECTIVES

The overall objective of this research was to determine if a particular combination of preplant tillage and nitrogen application methods would minimize the potential for NO_3-N leaching losses to shallow groundwater due to rainfall immediately following nitrogen application. Detailed laboratory studies were conducted to meet the following specific objectives:

- Develop procedures and monitoring equipment for:
  - Excavating, and transporting one-meter cubic soil monoliths from a remote site to the laboratory;
  - Applying water and tracers to simulate chemical application techniques;
  - Monitoring water movement through the soil monolith; and
  - Collecting leachate samples from discrete soil volumes.
- Determine the importance of nitrate leaching through preferential flow pathways because of:
  - Preplant tillage; and
  - Nitrogen application method.

The objective of this manuscript is to present the methodology used to excavate and monitor the soil monoliths presented in Objective 1. The results for Objective 2 will be presented in subsequent manuscripts.

METHODS AND MATERIALS

The study was conducted in the hydraulics laboratory operated by the Agricultural and Biosystems Engineering Department at Iowa State University in Ames, Iowa. For this study eight, one-meter, cubic undisturbed soil monoliths were collected from research plots near Nashua, Iowa. The dominant soil classification was a Kenyon silt loam (*Typic Hapludoll*) classified as poorly to moderately well drained. Bulk densities ranged from 1.5 $Mg\text{-}m^{-3}$ for top 0.1 m to 1.7 $Mg\text{-}m^{-3}$ at a depth of 0.9 m. Saturated hydraulic conductivities recorded using a constant head permeameter produced results ranging from 0.045 $mm\text{-}s^{-1}$ at 0.1 m to 0.068 $mm\text{-}s^{-1}$ at 0.9 m below the soil surface.

Test plots contained tile drains installed 1.2 m deep at a spacing of 117 m. The research plots had received consistent tillage practices in a corn-soybean crop rotation over a 15-year period. Plans were to collect soil monoliths from three replications of the moldboard plow, chisel plow, and ridge-till treatments. However, only two replications of the ridge-till treatment were collected because the soil pedestal collapsed while placing the metal box for the third replication. Each monolith collected had been planted to corn the previous year.

SOIL MONOLITHS

The framework for the soil monoliths was sheared from 1.22 m × 2.43 m × 6.4-mm steel plates into 1.0 m square pieces at a local metal shop. Sidewall supports of L51 × 51 × 6.4 steel were welded to the plate metal at 0, 0.3 m, and 0.6 m above the bottom of the box. The sidewalls were connected by 25 mm × 6.4-mm steel bolts at each corner to allow them to be easily dismantled if the need arose. Metal supports consisting of 300-mm lengths of L51 × 51 × 6.4 steel were attached at the upper corners to permit lifting of the monolith. All metal surfaces were cleaned and roughened using a wire brush before applying a coat of primer and a coat of epoxy paint with an air-powered spray painter.

Areas where the monoliths were to be excavated were isolated after the plot area was tilled and planted to soybeans. Surface areas approximately 2 m square were covered with plastic film to protect the soil surface from rainfall. Field excavation and collection of the monoliths used an eight-step approach that included: (1) isolating the soil pedestal; (2) sliding a metal box over the pedestal; (3) filling the void between the soil and metal box with plaster-of-paris; (4) installing steel pipes across the bottom of the box frame; (5) attaching the pipes to the bottom of the box; (6) covering exposed soil surfaces with plastic; (7) lifting the monolith and placing it on a semi-trailer; (8) transporting the monoliths approximately 190 km to Ames, Iowa.

Figure 1–Method used to isolate the soil monolith showing trencher slots on the right and left sides and a backhoe used to remove soil from either end of the monolith.

The soil pedestal was isolated by trenching a 150-mm wide slot along two sides to a depth of approximately 1.2 m using a commercially available trenching machine. A straight-edged spade was used to create a flat sidewall for the remaining two sides after a backhoe carefully removed soil to within 0.3 m of the pedestal (fig. 1). Each soil pedestal had dimensions of approximately 0.92 m on a side. Once the pedestal had been isolated, the metal box was lowered over the pedestal using a backhoe. Dental grade plaster-of-paris was poured into the opening between the box and the pedestal and allowed to harden for five to six days. Then three, 38-mm standard steel pipes were driven horizontally through the soil just below the metal box. Angle iron was used to attach the pipes to the bottom of the box to ensure that the soil did not slide out of the metal frame. The encased soil monolith was lifted with a front-end loader which severed the soil pedestal from the underlying soil profile. The top and bottom of the monoliths were covered with plastic to maintain the original soil water content conditions. Monoliths were loaded on a semi-trailer equipped with air shocks and transported to Ames for storage under low light and temperature conditions until laboratory testing.

Each soil monolith was prepared for testing by removing the pipes from the bottom of the frame and shaving excess soil away leaving a nearly flat surface at the bottom. This was accomplished by tilting the box on its side using an overhead chain hoist. Care was taken to ensure that macropores were not sealed during this process. After soil shaving, a crosshatched metal frame made of L38 × 38 × 6.4 steel was attached to the bottom of the monolith to keep the soil from sliding out. Angle iron sections were welded to isolate the center grid cells from the buffer cells (fig. 3a and 3c). The 540-mm square center of the plate represented the soil volume of interest and the outside 230-mm wide areas along the edges acted as boundaries.

TEST STAND DEVELOPMENT FOR MONOLITH SUPPORT IN THE LABORATORY

The test stand was developed to straddle the shallow end of a sump installed in the hydraulics laboratory. This allowed the soil monolith to be mounted on the stand and the leachate collection apparatus to be contained in the sump (fig. 2). Based on estimates of the monolith weight and position on the test stand, pieces of L51 × 51 × 3.1 standard steel were welded to the existing steel pipe framework to provide the additional strength. Four 190-mm cast iron wheels had been installed on the test stand for mobility. The monoliths were supported by four 19-mm steel rods positioned vertically through 101 × 101 × 6.4-mm square tubing welded to the top of the stand and 50 × 101 × 6.4-mm rectangular tubing at the bottom. Each support rod contained 300 mm × 13 mm turn buckles to allow the monolith to be leveled. However, due to the weight of the monolith, turn buckle adjustment had to occur before final attachment of the monolith to the test stand. The bottom supports were held in place by two 50 × 50 × 6.4-mm square tubing with 13-mm threaded steel rod running through the center (fig. 2).

CONSTRUCTION OF RAINFALL SIMULATOR

A rainfall simulator panel was constructed of aluminum and ultra high molecular weight plastic. Water was delivered through 320 stainless-steel hypodermic needles installed in a 50-mm square grid. Emitters, 25 mm long with an inside diameter of 0.58 mm were selected to apply water at approximately 33 mm-h^{-1} based upon calibration tests. The application rate was controlled using a bypass flow control valve and readings from a positive displacement flow meter (model 234-200, MAX Machinery, Inc.). From the flow meter, water passed through a sediment filter (0.5 mm removal rating). A distribution manifold with outlets directing water to five positions on the upper side of the panel was used to supply water to the simulator panel (fig. 2). To improve water application uniformity, the simulator panel was attached to a rotating-cam drive mechanism with an offset of 50 mm. This caused each emitter to make a 50-mm circle at 8 to 12 rpm. Water uniformity tests showed a Christiansen Uniformity Coefficient of approximately 90%.

The soil surface area receiving simulated rainfall was isolated with a 1.2-m square galvanized steel shroud (fig. 2). The shroud had a 0.8-m square box with 300-mm sidewalls to isolate a specific soil surface area to receive water. The sidewalls also prevented surface ponding from leaving the application area. Troughs were attached to the outside-upper edge of the 0.8-m box to direct water delivered outside the box into a plastic bucket where it was weighed. Thin sheets of polyethylene plastic film were attached to the rainfall simulator panel to insure that all water leaving the rainfall panel landed on the soil surface or on the side drains. The shroud and plastic film allowed an accounting of all water passing through the simulator panel.

GRID SAMPLER FOR COLLECTING LEACHATE AT THE BOTTOM OF THE MONOLITH

A grid sampler modeled after Boll et al. (1992) was developed using ultra high molecular weight plastic (UHMW). This type of plastic is inert, extremely durable, and easily machined for specific uses. The bottom plate was fabricated from 19-mm thick sheet cut to 1.1 m square. A spade-bit was fabricated to drill a drain-hole, spring contact plate, and drainage funnel in one operation (fig. 3b). Each cell was equipped with a soil contact plate, funnel, stainless steel spring, fiberglass wick, drainage tube and water sample bottle (fig. 3c). The contact plates were constructed of 70-mm square pieces of the UHMW plastic.

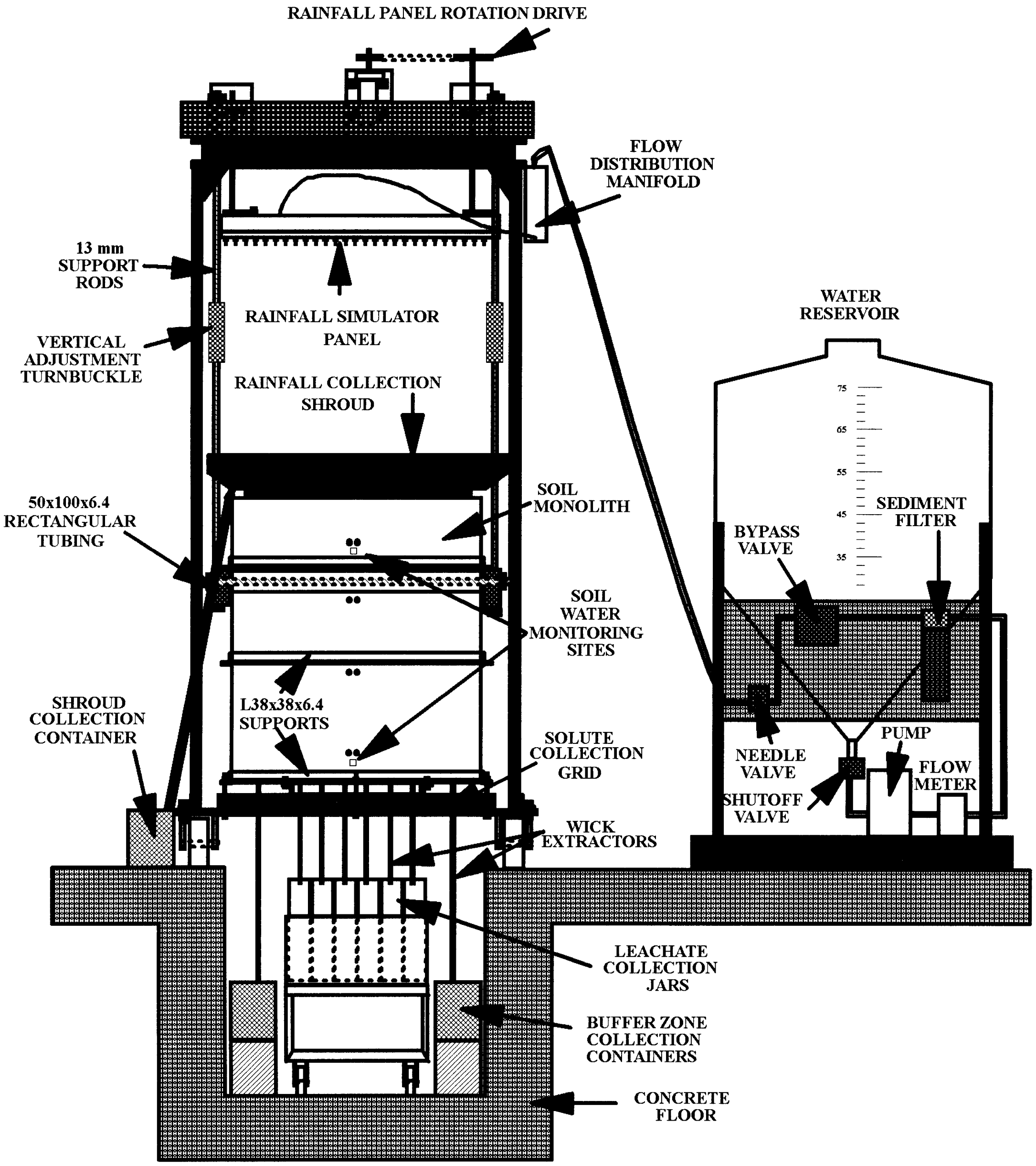

Figure 2–Schematic drawing of the test stand used to study nitrate leaching losses from one-meter cubic soil monoliths.

Slots were cut into the bottom plate in a grid for installation of 30 mm × 3.2 mm UHMW plastic sidewalls. The strips were cut to allow them to be interlocked when attached to the bottom plate. Dividing walls prevented commingling of drainage samples. A clear silicon sealant was used on all joints.

The grid sampler consisted of eight, 230 mm wide border cells on the outside edge of the sampler (fig. 3a). These cells were used as buffer for the center of the box and to help conduct mass balance for each tracer. A 6 × 6 matrix of 90 mm × 90 mm grid cells defined the sample area of the monolith. The grid sampler was raised into position and bolted to the bottom of the monolith (fig. 3b). The bolts were tightened until spring tension held the soil contact pads in place. Pieces of 25-mm thick stryofoam were cut to fit and attached between the grid sampler and the monolith base to prevent evaporation loss at the bottom boundary. Leachate from the small cells was collected into 0.75-L glass jars placed in a grid box to allow sets of sample jars to be easily removed and replaced by another set. The box holding the jars was placed on a cart that could be rolled from under the monolith at each sampling interval.

INSTALLATION OF TENSIOMETERS AND TDR WAVEGUIDES

Tensiometers. Soil water monitoring instrumentation was inserted through holes drilled in the metal sidewalls and plaster-of-paris seals. Holes were drilled at 150, 350, 550, and 750 mm soil depths on three sides of the monolith (fig. 3a). Miniature tensiometer cups (6 mm O.D. × 28 mm long) were attached with epoxy to 3 mm I.D. polyethylene tubes running from the tensiometer cup to a wooden box that housed the pressure transducers.

Pressure transducers were attached to each tensiometer and monitored by a data logger at 10-min intervals during water application and 30-min intervals between application events. Polyethylene tubing (400 mm × 6 mm I.D.) was

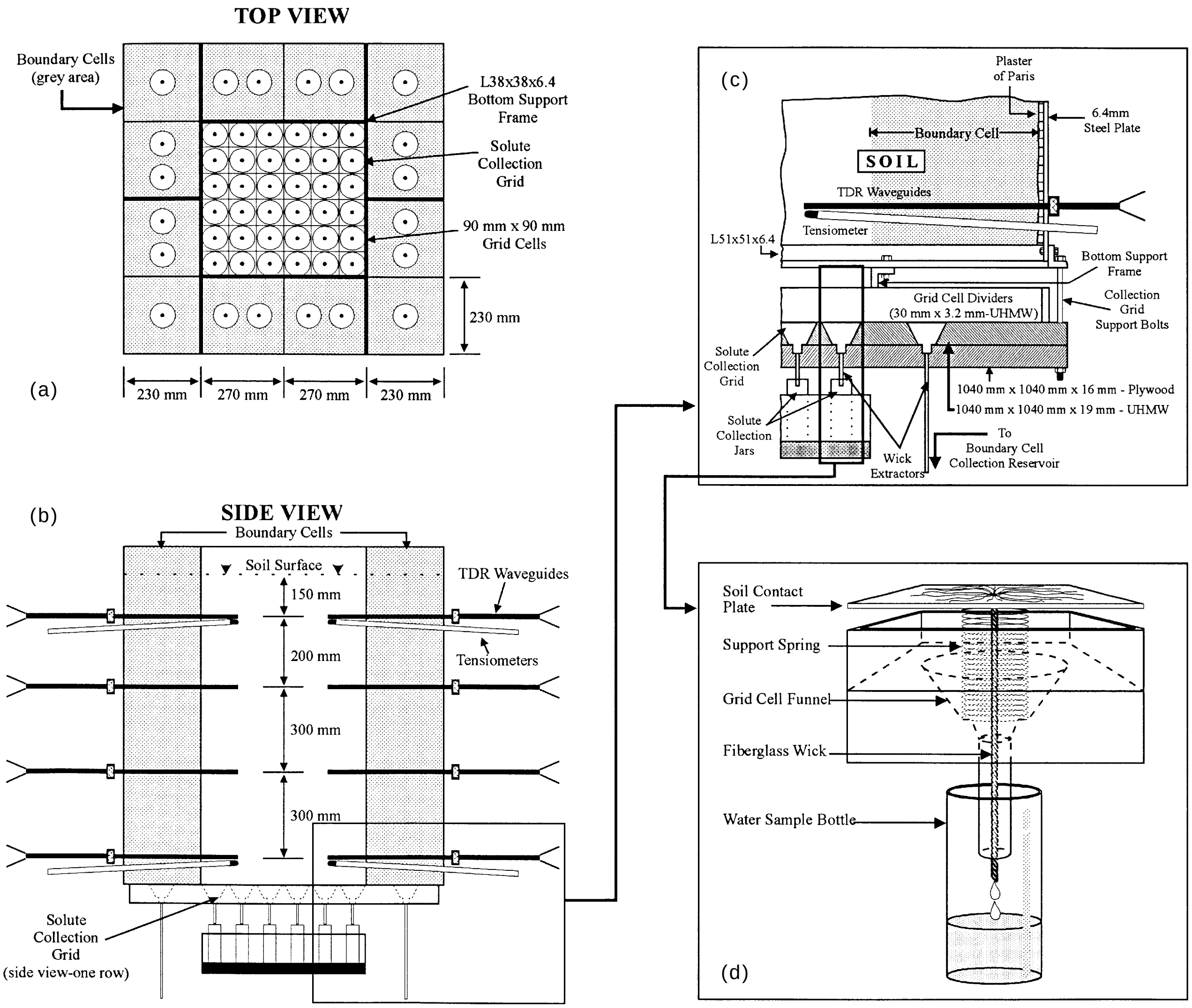

Figure 3–(a) Schematic drawing showing a top view of a soil monolith with boundary cells, solute collection grid, and bottom support frame. (b) Schematic drawing showing a side view of a soil monolith with boundary cells, solute collection grid, and soil water content measurement instrumentation. (c) Detailed schematic of soil water content measurement instrumentation, solute collection components, plaster-of-paris seal, and side walls of a soil monolith. (d) Detailed schematic of a grid cell used to collect leachate at the bottom of the soil monolith showing the contact plate, support spring, funnel, fiberglass wick, and water sample bottle.

slipped over the tensiometer tubing to aid in installing the tensiometers into the soil and to protect the tubing from damage. Due to a limited supply of transducers, tensiometers were installed through two side walls of each box at 150 mm and 750 mm below the soil surface (fig. 3a). Additional sampling depths could be added if the pressure transducer output signals are routed through multiplexing devices. An electric drill with a 9.5-mm wood bit was used to drill holes into the soil to a position 200 mm inside the sidewall. The hole was drilled on a slight angle upward so that water could not accumulate near the ceramic tensiometer cup.

Time Domain Reflectometers. Soil volumetric water content was monitored at 12 locations (4 depths × 3 sides) in the monolith using TDR. Waveguides were installed next to the tensiometer cups (fig. 3b). The TDR waveguides consisted of two, 300 mm × 3.1-mm parallel stainless steel rods equipped with an impedance matching balun as described by Spaans and Baker (1993). The waveguides were manufactured by Midwest Special Services of St. Paul, Minnesota. Similar to the tensiometer cups, a 200-mm deep hole was drilled into the soil for each waveguide so that 100 mm of each waveguide was in contact with the soil. Two hundred millimeters of each waveguide were covered with heat shrink tape to provide electrical isolation as the probe passed through the metal sidewall.

A calibration test was conducted for the TDR probes to account for the reduction in soil contact length. Connection between the waveguides and Campbell Scientific Model 1502B cable tester was provided using 7.6-m lengths of coaxial cable and a two tiered multiplexing system. The cable tester was linked to a data logger using software provided by the manufacturer. Complete waveforms were downloaded to a laptop computer for analysis.

A separate data logger recorded TDR waveforms so that soil matric potential and water content data could be recorded simultaneously. Wave forms were recorded at 20-min intervals during water application, and at 60 min intervals for the remainder of the test.

EXPERIMENTAL PROCEDURES

Each monolith received a water application of approximately 150 mm to insure that the soil was near field capacity. The application water was obtained from a rural well with a mean anion concentration of 3.8 mg-L^{-1} chloride, 1.2 mg-L^{-1} bromide, 0.0 mg-L^{-1} iodide, 4.3 mg-L^{-1} nitrate, and 60.5 mg-L^{-1} sulfate. In all cases, leachate was collected from all but two to three grid positions following this water application. Soil surface conditions were preserved by a double layer of fiberglass screen.

Anion tracers were applied to mimic nitrogen applied using a slot with compaction method, surface broadcast, and with water. Tracers were applied approximately 24 h after the rainfall event applied to bring the soil to field capacity. Bromide was applied as a slot with compaction treatment, chloride as the surface broadcast treatment, and iodide as the with-water treatment. Each tracer was applied at a rate equal to 225 kg-ha^{-1}. Thus, 29.5 g of potassium iodide, 47.2 g of potassium chloride, and 68.2 g of potassium bromide were applied to each monolith.

The slot with soil compaction treatment was modeled after the concept presented in Baker et al., 1997. The treatment consisted of opening a slot across the midpoint of the monolith, adding the potassium bromide tracer to the slot, and compacting the soil over the application zone to direct infiltrating water around the application zone. Potassium bromide solution was applied to the slot using a plastic specimen washing bottle. The bottle was moved by hand back and forth across the soil surface at nearly constant speed. Five to six passes were made with the bottle. Paper towels were placed at the edge of the monolith to collect the solute that would otherwise be applied to the plaster-of-paris. The towels were weighed before and after the application to determine the mass of the tracer absorbed. Soil compaction over the slot was achieved using two 203 mm × 38-mm wagon wheels mounted at 45° from vertical, and a 20-kg steel weight (fig. 4). The apparatus was moved across the monolith directly above the slot opening.

The potassium chloride tracer was applied to the soil surface using four sprayer nozzles mounted on a short spray boom. Pressure was supplied by a hand spray can attached to the spray nozzles. The spray boom was attached to a garage door opener set to make two passes across the monolith and stop. This sequence was repeated until 1.5 L of the solute was applied to the soil surface. This required approximately six passes across the monolith. As before, paper towels were used to collect the spray that would otherwise have been delivered to the plaster-of-paris. The towels were weighed before and after the application to determine the mass of tracer reaching the soil.

For the first application, water was applied at a rate of approximately 33 mm-h^{-1} until approximately 90 mm of water were applied. This rate and duration of rainfall simulates a 10-year, 6-h storm for central Iowa. Twenty-four hours later, an additional 430 mm were applied to help define breakthrough curves for each tracer. This brought the total water application after tracer application to approximately 520 mm or 1.1 pore volumes for the Kenyon silt loam.

Water sample collection started with the first flush and continued for 24 h after the cessation of water application. The first flush was identified as the time when approximately 20% of the grid points were producing leachate. After the first flush, solute samples were collected at 15-min intervals for hours 0 to 2, at 30-min intervals for hours 2 to 4, and at 60-min intervals for hours 4 to 7. Samples were immediately refrigerated until being transported to the laboratory for analysis.

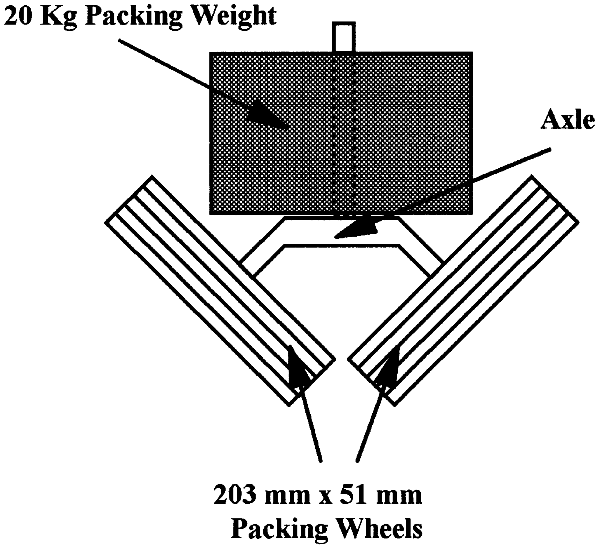

Figure 4–Line drawing of packing wheel apparatus used for the slot application with compaction treatment.

The water sample collection scheme was developed to collect more information than necessary to establish leachate mass and distribution of leachate concentrations with time. Eight sets of samples were analyzed for chloride, bromide, iodide, nitrate, and sulfate for each grid position. Incremental leaching losses for each grid position were determined by multiplying the sample concentration by the leachate volume collected since the last sampling time. The outside set of grid boxes was used only for mass balance determinations.

Nitrate and sulfate were evaluated to provide two independent estimates of how nitrogen contained in the soil matrix would respond to water application. In addition, the ion chromatography results provided concentrations for both anions during a single analysis. Analysis for nitrate and sulfate ions would allow the comparison of leaching rates for newly applied nitrogen based on tracer applications with leaching rates of residual nitrogen based the levels contained in the soil prior to conducting the rainfall simulations.

After the leaching study was completed, soil samples were collected for use in mass balance calculations and to provide a distribution of tracers remaining in the soil profile. One side of the monolith box was removed to allow access to the soil pedestal. The soil was dissected horizontally at 100-mm intervals to allow the soil to be photographed for image analysis. In addition, the monolith was dissected to confirm visually that soil cracks had not resulted from the excavation and transportation procedures. Subsamples were collected from five to six locations of the exposed horizontal area. Subsamples were combined and mixed before collecting a single sample for laboratory analysis.

Tensiometer data were summarized by calculating the average value for two tensiometers installed at the same depth. Water was determined by dividing the accumulated flow between sampling times by the time since the last sample. Cumulative distributions were determined by sorting the total leaching loss for each cell by volume and dividing by accumulated volume. Data are presented for the total bromide leaching loss by grid cell.

RESULTS AND DISCUSSION

Data collected during previous laboratory experiments using varying sized soil columns have been analyzed and presented in many ways. Unlike standard treatment-based research investigations, studies of spatial variation in soil leaching rates frequently do not lend themselves to traditional statistical analyses. For example, measurement of leachate using a grid sampler makes it unrealistic to calculate a treatment mean for the leachate volume or mass leached for each grid cell. Though the mean value could be easily calculated, preferential flow pathways occur without regard to the position of the grid sampler and may contain variation dictated by the type and extent of a flow pathway. For example, Cell A4 in Replication 1 might be influenced by a preferential flow pathway and Cell A4 in Replication 2 may not. To take the mean merely masks the preferential flow phenomenon making it unlikely that statistical differences will be identified.

The use of grid samplers can also be used to develop gross estimates of leaching rates for a surface tillage treatment. By summing leachate volumes and tracer mass from all grid positions, mean leaching rates can be established and evaluated using traditional statistical techniques. Therefore, data from one replication of the ridge tillage treatment are presented as an example of the information that can be collected from one-meter cubic soil monoliths during rainfall simulation studies. Leaching results are limited to the slot application of the bromide tracer since it provides the most graphic example of tracer movement through the soil.

SOIL WATER MEASUREMENT

The goal of the soil water content measurement system was to monitor changes in soil volumetric water content using TDR and soil matric potential using tensiometers during a water application event. Though soil water content could have been monitored at many sites, the main points of interest occur near the bottom of the tillage layer and at a depth close to the bottom of the crop root zone. These two positions allow gross measurements of solute transport times resulting from water application to the soil surface. In addition, the surface layer location can be used to identify tillage effects.

Soil matric potentials show a quick response to water application (fig. 5). Even at a depth of 750 mm, tensiometers responded within 180 min of water application began. A response time of 180 min places the transport times within the range of saturated hydraulic conductivities reported by Singh (1994). The data also suggest that none of the tensiometer cups were installed directly into preferential flow pathways.

SPATIAL VARIATION IN WATER AND SOLUTE TRANSPORT

Spatial variation in leaching rates was evaluated using three data summarization techniques: (1) comparison of water flux; (2) plotting cumulative leachate volume distribution curves; and (3) plotting mass of tracer loss from the grid sampler. The following paragraphs provide discussion on the existence of preferential flow pathways in this soil.

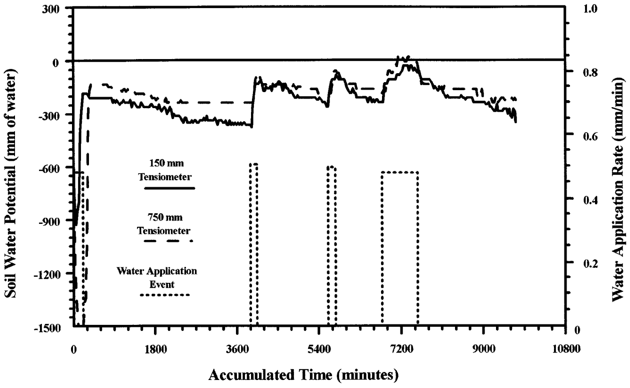

Figure 5–Response of soil water potential at soil depths of 150 mm and 750 mm during four water application events.

Collection of leachate samples over discrete intervals allows estimation of the mass flux and establishes the first flush time for each cell location. The time to the first flush was not recorded for each grid cell but was estimated using the criteria of five to six grid cells with drainage. For this monolith, the first flush was recorded at 67 min after water application began. This response time is less than indicated by tensiometer data and shows that preferential flow pathways did exist. Data analyses produced a range in leaching depth of 31 to 1048 mm, mean of 424 mm, median of 392 mm, and the standard deviation of 249 mm.

Figure 6 shows water flux results for two cells representing the extremes. The solid line gives results from Cell C5 and the dotted line is from Cell A2. During rainfall simulations, the flux for Cell A2 was nearly always greater than the water application rate. The flux for one sample interval near the 5,760-min mark was approximately 1.2 mm/min compared with the water application rate of approximately 0.4 mm/min. This shows that this cell contained one or more preferential flow pathways.

Cell C5 depicts the other extreme. The flux was always less than 0.1 mm/min compared with a water application rate near 0.4 mm/min. Water did move through the soil, but at a much reduced rate compared with Cell A2. The water

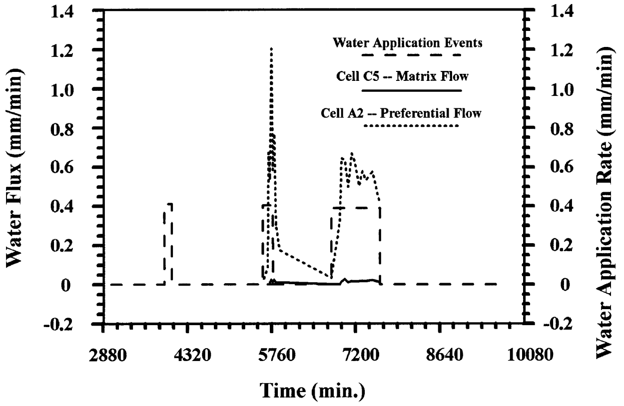

Figure 6–Comparison of water flux for grid cells exhibiting preferential flow (Cell A2) and matrix flow (Cell C5) characteristics.

flux for Cell C5 also lacks the definite peak in flux shown by Cell A2. Therefore, it can be concluded that Cell C5 is more indicative of matrix flow.

Evaluations for the influence of preferential flow pathways have used cumulative distribution plotting methods (Bowman et al., 1994). By plotting cumulative leachate volumes versus cumulative grid cell area, the curve shape can suggest the existence of preferential flow pathways. Since each cell represented an area of 8100 mm^2, if leaching were homogenous, the resulting plot would be linear. However, if leaching varies greatly, the response will be more curvilinear with the slope decreasing with the increase in the cumulative drainage area. The latter case is depicted in figure 7. Note that 50% of the surface area of the sampler produced approximately 70% of the leachate. The cumulative distribution response provides more evidence to the existence of preferential flow pathways.

If tracers are applied to the soil surface and leachate samples from each cell are analyzed, calculation of mass transport and spatial distributions are possible. Figure 8 presents leaching loss data following 520 mm of water application for the bromide tracer. Leaching losses recorded for some cells were in excess of the 225 kg-ha^{-1} application rate. This is possible because though the average bromide application rate was 225 kg-ha^{-1}, the tracer was applied in a 50-mm wide slot. This meant that the tracer application within the slot area was approximately 20 times greater than 225 kg-ha^{-1}.

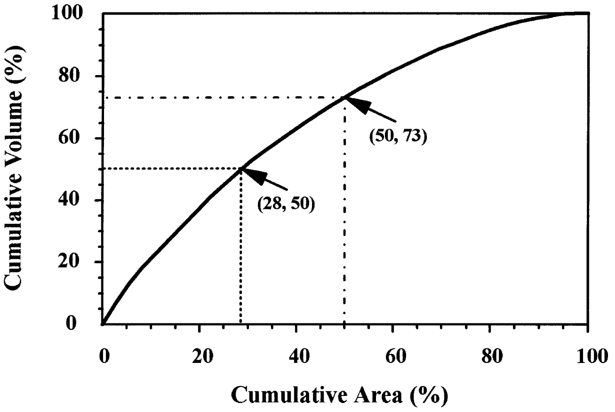

Figure 7–Cumulative distribution of leachate recorded during 520 mm of water application for replication no. 2 of the ridge tillage treatment.

Many cells had little leaching loss though more than 800 mm of solute were collected from others cells (sum of data in fig. 9 and 10). Cell A2 had 868 mm of drainage collected during all water application events, yet the total bromide loss for the cell was less than 20 kg-ha^{-1} (fig. 8). Cell D5, located directly below the slot, had a total bromide loss of 1350 kg-ha^{-1} in approximately 630 mm of drainage. Because the bromide tracer was slot applied across the midpoint of the monolith, the distribution of leaching losses was skewed to the left of the mean with a range of 1350 kg-ha^{-1}, a mean of 191 kg-ha^{-1}, and a median of 55 kg-ha^{-1}. The standard deviation of accumulated leaching losses recorded for the 36 grid cells was 301 kg-ha^{-1}. Hence, both water and dissolved chemical must be available for leaching to be a significant loss to the groundwater.

PREFERENTIAL FLOW PATHWAYS

Preferential flow pathways may be influenced by the intensity and duration of a rainfall event. Intense rainfalls develop ponding on the soil surface allowing the larger more well-connected pathways to transport water quickly through the root zone. Rainfall events with lower intensities and long duration cause small discontinuous pathways to contribute to leaching losses. Data collected from a grid sampler can be used to demonstrate the variation in leaching that occurs during a sequence of water application events and how different types of pathways contribute to leaching. Figures 9 and 10 show total leachate volumes measured during water applications of 90 mm and 430 mm by a rainfall simulator, respectively. The water application

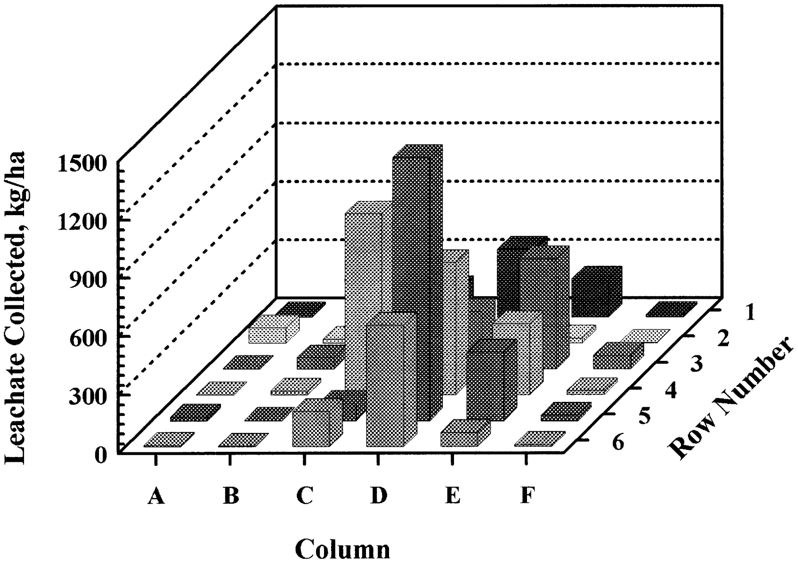

Figure 8–Distribution of total bromide leaching loss during 520 mm of simulated rainfall on a ridge tillage treatment. Shades of gray delineate row position only.

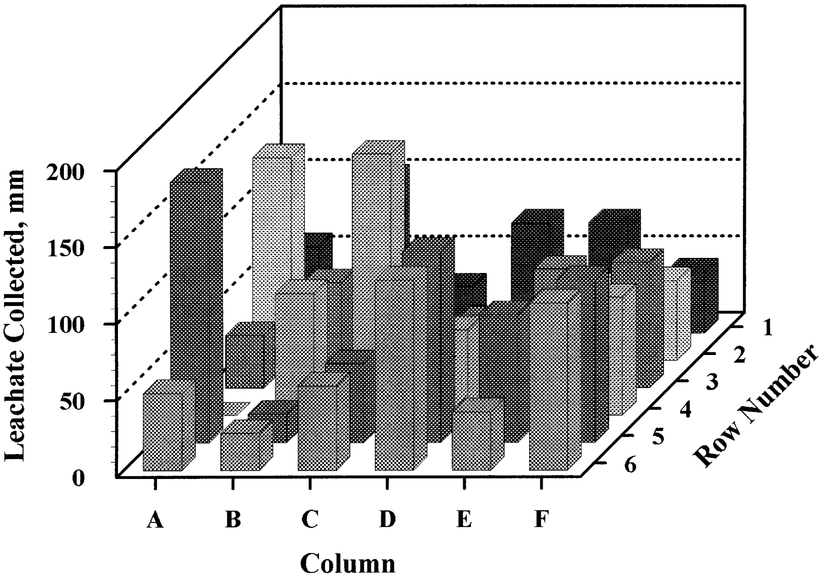

Figure 9–Distribution of leachate collected during 90 mm of simulated rainfall on a ridge tillage treatment. Shades of gray delineate row position only.

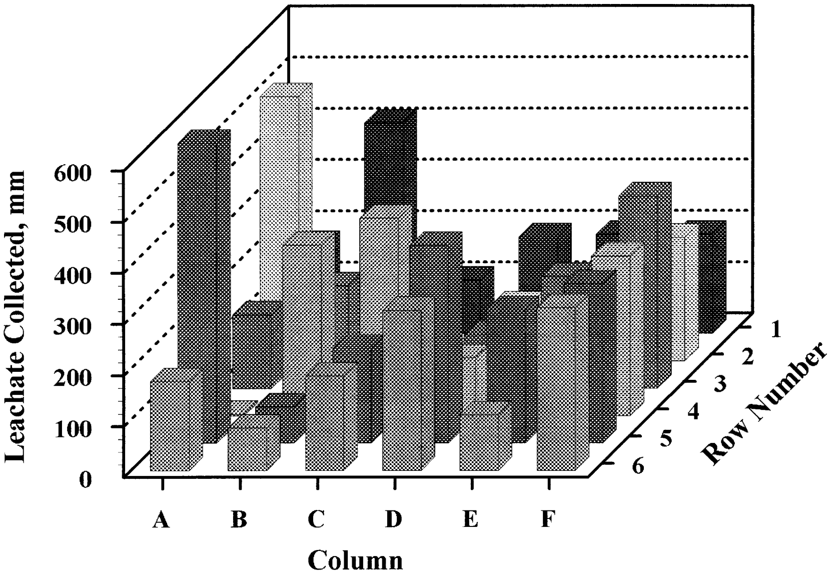

Figure 10–Distribution of leachate collected during 430 mm of simulated rainfall on a ridge tillage treatment. Shades of gray delineate row position only.

rates were enough to develop some ponding but not enough to cover the soil surface with water.

The manner in which water was transported through nearly 1 m of soil during water application provided insight into the size and connectivity of the preferential flow pathways. Often, cells that produced the greatest volumes from the 90 mm event also produced the greatest volumes following an additional application of 430 mm. Cells A2 and C4 (fig. 9) could be examples of preferential flow pathways that had access to near the soil surface and have connectivity through the entire depth of the profile. Thus, the total leaching loss was greater for both short and long duration storms. Other cells produced greater volumes after the addition of 430 mm of rain water. Cells B1 and F3 are examples of cells that may be below preferential flow pathways, but the pathways may not be connected to the soil surface. Thus, these cells required a significant water application before they could convey large volumes of leachate.

Other cells seemed unaffected by how much water was applied. For cells D4 and C6, the major mode of transport appears to be through the soil matrix. Leaching rates were more constant and were less likely to be affected by the intensity or duration of water application. Cells B5 and C2 produced little leachate, while Cell A4 produced less than 1 mm of leachate (fig. 10). This likely results due to the rocks that are common throughout glacial till soils. When the soil monoliths were dissected rocks, gravel, and rodent burrows were identified. It is hypothesized that water would be directed around a rock similar to an umbrella effect. The umbrella effect may have caused Cells A5 and C4 to produce a greater leachate volume. This extreme variation in leachate volume among the grid cells suggests that a range in preferential flow pathways existed in this soil monolith.

SUMMARY

One-meter cubic soil monoliths were excavated from plot areas with a 15-year tillage history and transported to the laboratory for an intensive leaching study. A rainfall simulator panel was constructed and used to apply water at a rate of 33 mm h^{-1} for two application events of 90 mm and 430 mm. Electronically recorded tensiometers and time domain reflectometer waveguides were installed through the sidewalls of the monoliths to monitor changes in soil water content during water application. Tensiometers responded to water application within 180 min of the initiation of water application. The response time suggested transport rates within the range of hydraulic conductivities reported by Singh (1994).

A grid sampler using fiberglass wicks was attached to the bottom of the soil block to develop water tension at the bottom soil-air interface. Variation among solute samples collected by the grid sampler exhibited evidence of preferential flow pathways. Drainage from the bottom of the monolith began after approximately 60 min of water application though tensiometers responded in 180 min. Total leachate collected from individual cells ranged from 31 mm to 1048 mm with a standard deviation of 249 mm. The cumulative distribution curve for leachate volume versus area sampled showed that 70% of the leachate was collected from 50% of the sampler area. These data supported the existence of preferential flow and confirmed results reported by other researchers (Bowman et al., 1994; Shipitalo et al., 1990).

Nearly all of the slot applied bromide tracer that reached the bottom of the monolith was found in a 270-mm wide band. Leaching loss due to 520 mm of water application ranged from 0 kg-ha^{-1} to 1350 kg-ha^{-1} with a median leaching loss of 55 kg-ha^{-1}. Leaching losses for individual cells did not appear to be highly correlated with leachate volume. These results verify that preferential flow pathways exist in this soil.

ACKNOWLEDGMENT. The authors acknowledge the support of the Agricultural and Biosystems Engineering Department of Iowa State University, and the University of Nebraska Agricultural Research Division, the Nebraska Water Center, Biological Systems Engineering Department and the Northeast Research and Extension Center of the University of Nebraska. Mention of trade names or commercial products is made for illustration only and does not constitute their endorsement by the authors, Iowa State University, or the University of Nebraska.

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