

**Using rainfall simulation, TDR, and tracer anions to determine effects of soil properties
on nitrate leaching**

by

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ABSTRACT

Nonpoint source nutrient pollution from agricultural lands is recognized as an important environmental and social issue. One of the primary nutrient forms of concern is nitrate-nitrogen ($\text{NO}_3\text{-N}$). The issue of $\text{NO}_3\text{-N}$ leaching and the resultant contamination of surface and groundwater resources is a continuing public concern. Loads of $\text{NO}_3\text{-N}$ in subsurface drainage into surface waters in the U.S. corn-belt are among the highest in the country. Although N fertilizers applied to cropland are of considerable importance because of the yield-increasing benefits, many researchers have shown that there is a considerable potential for $\text{NO}_3\text{-N}$ leaching losses with subsurface drainage water. Because $\text{NO}_3\text{-N}$ is soluble and not adsorbed to most soils, it moves readily with water. In any case, minimizing $\text{NO}_3\text{-N}$ losses from agriculture lands is of importance in improving the environment in the Midwest and Mississippi Delta region of the country.

Two experiments were performed to evaluate $\text{NO}_3\text{-N}$ leaching features using tracer anions combined with use of non-destructive time domain reflectometry (TDR) techniques which can potentially be used to predict solute resident concentrations and subsurface leaching. A laboratory experiment was conducted to study the effects of soil bulk density in the zone of N application and soil moisture on $\text{NO}_3\text{-N}$ leaching during rainfall simulation. Simulated rainfall was applied at an intensity of 6.5 cm/h for 70 min to runoff/drainage pans with the zone of $\text{NO}_3\text{-N}$ applied in a line source which was with different levels of localized compaction (with bulk densities of 1.10, 1.33, 1.57 and 1.81 g/cm³), and initial soil moisture contents of 10 and 15% by mass. Surface runoff, subsurface drainage, and soil extract samples were analyzed for $\text{NO}_3\text{-N}$, Br (added with rainfall), and Cl (added uniformly to soil)

concentrations. TDR probes were horizontally installed either beneath the zone of $\text{NO}_3\text{-N}$ applied in a line sources for determination of resident solute transport from measured soil bulk electrical conductivity (EC_b), or just 1 cm below the soil surface to estimate solute concentrations in the “mixing zone”. It was found that for subsurface hydrology, due to differences of moisture content in preparing and packing the soil into runoff/drainage pans, the 15% soil moisture content treatment had a longer time to the beginning of drainage and less drainage volume compared to 10% soil moisture. Greater compaction caused lower concentrations and losses of $\text{NO}_3\text{-N}$ in subsurface drainage, resulting in a significant difference between bulk densities for both 10 and 15% moisture treatments. Soil volumetric water contents measured with time during rainfall simulation with TDR showed different patterns in top and subsurface soils and in the “time-to-saturation”, and a higher final soil moisture for the 10% moisture treatment than for 15%, suggesting a higher water holding capacity for the former. Significant relationships of EC_b with $\text{NO}_3\text{-N}$ for both antecedent moisture and compaction treatments provides a potential to estimate solute concentration in subsurface drainage by TDR techniques, and allows further development of modeling parameters and estimation of solute transport properties.

Further testing of TDR techniques was done in a second experiment using outdoor rainfall simulation with field lysimeters. Twelve lysimeters were laid out in a randomized block design with three replications, using two tillage practices (no-till and tillage) and two methods of N-fertilizer applications (local soil compaction and no compaction as a line source). Four TDR probes were installed in each lysimeter. Two of them were placed horizontally beneath one of three line sources added to each lysimeter, and the other two probes were vertically placed between two of the three line sources. An ISCO 3230

bubbler/pressure sensor was used in each lysimeter for water table measurement before, during, and after rainfall simulation. The results showed that local compaction in the zone of application reduced $\text{NO}_3\text{-N}$ leaching significantly in the rainfall simulation study with lysimeters; however, tillage did not have a significant effect. Soil EC_b and volumetric water content, measured by TDR, beneath the fertilizer line sources provided “real-time” information; the relationship between $\text{NO}_3\text{-N}$ and EC_b was further tested in this study, indicating $\text{NO}_3\text{-N}$ in 15 cm of top soil has a curvilinear relationship to EC_b beneath line sources that had the potential to simultaneously indicate solute leaching and water infiltration/movement in that zone.

This study could provide new information for improving N fertilizer applicators. However, future research could involve examining solute transport properties using TDR techniques combined with model simulations at the field scale. One challenge of that work includes setting modeling boundary and initial conditions when solute is involved in localized compaction zone.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Nonpoint source nutrient pollution of water resources with drainage from agricultural lands is recognized as an important environmental and social issue in Iowa, the U.S., and around the world. Researchers have found that the primary nonpoint sources of nitrogen (N) are mainly from the widespread use of N fertilizers, application of livestock manure, legumes, and mineralization of soil organic-N (Hallberg, 1987; Kiuchi et al., 1996; Goolsby et al., 1999). One of primary nutrient forms of N carried with subsurface drainage is nitrate-nitrogen ($\text{NO}_3\text{-N}$), and the loads of $\text{NO}_3\text{-N}$ in agricultural drainage to surface waters in the U.S. Corn-Belt are among the highest in the country. These N loads can negatively affect human health where such water is used for drinking water supplies, and are suspected to contribute to hypoxia in the Gulf of Mexico (Baker, 2001). Many in-field factors and management practices, including soil moisture, soil structure, tillage, and fertilizer rate and placement can play a role in protecting surface and groundwaters from pollution. However, the implementation of improved management practices requires knowledge of solute transport properties to evaluate the risk of contamination. Generally, the solute transport process can be monitored in the field. However, traditional methods for measuring solute concentrations, such as a solution sampler, either are limited to relatively narrow range of soil water contents or require destructive sampling (Dalton, et al., 1986). Although mathematical models are often used for simulation/determination of solute transport, they are

usually not thoroughly tested because of difficulty in obtaining measured values for comparison (Kachanoski et al., 1994). Time domain reflectometry (TDR) is a tool that can be used in the simultaneous measurement of soil water content (Topp et al., 1980) and bulk soil electrical conductivity, EC_b , (Dalton et al., 1984) in “real time.” It has also been shown to have potential to estimate soil solute transport (Ward et al., 1994). Although TDR has been used to obtain solute transport parameters (Lee, et al., 2000, Guar, et al., 2003), its capability to predict solute transport features in relation to in-field soil management has not been fully studied.

The overall purpose of this research was to study the effects of bulk density in the zone of NO_3 -N application and soil moisture content on NO_3 -N leaching from runoff/drainage pans during the laboratory rainfall simulation, and the effects of soil management (local compaction and tillage) in lysimeters in field rainfall simulations using TDR in combination with tracer anions. The specific objectives of this study were:

1. To study the impacts of different treatments, antecedent soil moisture content, localized soil compaction, and tillage, on the leaching characteristics of NO_3 -N beneath line source NO_3 -N application zones based on concentration and losses in subsurface drainage.
2. To compare NO_3 -N leaching from a line source with measurement of two other anions, Br in rain water and Cl mixed uniformly in the soil, in the indoor rainfall simulation, and of Br and PO_4 -P in rain water in the outdoor rainfall simulation.
3. To determine the potential of TDR methods for measuring soil moisture content and electrical conductivity in the zone beneath line source containing NO_3 -N during

rainfall simulation and surface runoff and subsurface drainage to aid in assessing $\text{NO}_3\text{-N}$ movement.

Dissertation Organization

This dissertation is organized into a literature review chapter, and two journal papers, each presented as separate additional chapters. Chapter 2 is the literature review on both development of TDR application to measurements of soil water content and EC_b , $\text{NO}_3\text{-N}$ leaching, and management to control leaching. The review examines the important factors and processes for reduction of $\text{NO}_3\text{-N}$ leaching to subsurface drainage, including soil moisture content/hydrology, soil structure/tillage, and by-pass flow/soil subsurface flow barriers to $\text{NO}_3\text{-N}$ leaching. The first paper, Chapter 3, is about using indoor runoff/drainage pan/rainfall simulation, TDR, and tracer anions to determine effects of soil properties on $\text{NO}_3\text{-N}$ leaching. The second paper, Chapter 4, describes the soil management impacts on anion transport in subsurface drainage for an outdoor lysimeter/rainfall simulation. The literature review and two papers are preceded by a general introduction and followed by general conclusions. At the very end are appendices of the raw data related to measurements made for the two paper chapters, which include indoor (laboratory) and outdoor (lysimeter) rainfall simulation, hydrology, chemical concentration, and TDR data.

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CHAPTER 2. LITERATURE REVIEW

Nitrate-nitrogen ($\text{NO}_3\text{-N}$) Loss

Nonpoint source nutrient pollution of water resources with drainage from agricultural lands is recognized as an important environmental and social issue in Iowa, the U.S., and around the world. One of primary nutrient forms of N carried with subsurface drainage is nitrate-nitrogen ($\text{NO}_3\text{-N}$), and the loads of $\text{NO}_3\text{-N}$ in agricultural drainage to surface waters in the U.S. corn-belt are among the highest in the country. The issue of nitrate-nitrogen $\text{NO}_3\text{-N}$ leaching and the resultant contamination of surface and groundwater resources is a continuing public concern (Baker, 2004). Nitrogen fertilizers applied to cropland are of considerable importance because of the yield-increasing benefits they provide (Hamlett et al., 1990). Bauwer (1990) noted that NO_3 is the main form of N in soil taken up by plants. But many researchers have shown that there is a considerable potential for $\text{NO}_3\text{-N}$ leaching losses with subsurface drainage water. Because $\text{NO}_3\text{-N}$ is very soluble and not adsorbed to soil, it moves readily with water. Baker et al. (1975) found that even with modest N fertilization of corn, in a corn-oats-con-soybean rotation, $\text{NO}_3\text{-N}$ concentrations in subsurface tile drainage often exceeded the 10 mg/L drinking water standard. Surface runoff can also carry $\text{NO}_3\text{-N}$, but losses with surface runoff are generally less than those with subsurface drainage because sufficient infiltrating water will move through the surface “mixing zone” before runoff begins to move a significant portion of the $\text{NO}_3\text{-N}$ present there to a depth where it can not be lost with runoff. That is why $\text{NO}_3\text{-N}$ concentrations in surface runoff from row-crop lands in

the Corn Belt are usually in the 2-5 mg/L range; whereas, in subsurface drainage water from the same lands, NO₃-N concentrations are usually in the 10-20 mg/L range (Baker, 2001). In any case, minimizing NO₃-N losses from agriculture lands is of considerable interest.

TDR Methodology

Time domain reflectometry (TDR) is routinely used to measure soil water content and electrical conductivity both in the laboratory and the field (Dalton et al., 1984; Nadler et al., 1991; Noborio et al., 1994; Heimovaara et al., 1995). Extended use of TDR has been studied by some researchers. Noborio et al. (1999) indicated that simultaneous measurement of soil matric potential and water content by a special ψ - θ TDR probe. Schenar et al. (2003) used a probe to estimate the heat flux related to water movement. The dependence of the dielectric constant (κ), an electrical property of soils, on volumetric water content has been determined by Topp (1980). Different soil textures can have different dielectric constants. The value of κ for air is 1 (lowest comparable to other materials), and for water at 20 °C it is 80 (highest comparable to other materials). The κ of a mixture of materials is related to an average of the κ values of its components. The basic equation used to determine κ by TDR is

$$v = c_0 k^{-0.5} \quad [2-1]$$

Where v is the velocity at which an electrical signal propagates in a cable or other wave guides, and c_0 is the velocity of light in a vacuum. Although TDR only measures the time, Eq. 2-2 can be used to convert from time to distance for displaying distance on the horizontal axis of the TDR cable tester screen. The propagation velocity v can be calculated from :

$$d = vt \quad [2-2]$$

Where d is the one-way distance, and t is the one-way travel time. From equations 2-1 and 2-2, the dielectric constant (called apparent electric constant in some literature), κ can be calculated:

$$k = \left[\frac{c_0 t_t}{2L} \right]^2 \quad [2-3]$$

Where t_t is the two-way travel time, and L is the distance between the impedance changes. In this case, $v = \frac{2L}{t_t}$. Using this equation, the volumetric water content can be measured with

TDR as described.

Due to κ of water being much larger than other soil constituents, the dielectric constant can be used for measuring soil water content (Noborio, 2001). Topp et al. (1980) developed a much used equation:

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} k - 5.5 \times 10^{-4} k^2 + 4.3 \times 10^{-6} k^3 \quad [2-4]$$

Malicki et al. (1996) developed another equation which includes soil bulk density (ρ_b):

$$\theta_v = \frac{k^{0.5} - 0.819 - 0.168\rho_b - 0.159\rho_b^2}{7.17 + 1.18\rho_b} \quad [2-5]$$

The Malicki equation reduces the variance of volumetric water content estimates to approximately one fifth of the estimates made with a calibration equation without accounting for bulk density (Noborio, 2001).

In addition, TDR can be used to detect soil bulk electrical conductivity (EC_b) with the same probe and the same volume of soil (Delton et al., 1984). TDR produces electromagnetic

(EM) waves which are launched into a wave-guide (probe), and then measures the voltage amplitudes of the reflected EM waves (Nissen et al, 1998). The reflection coefficient (ρ) is ratio between the voltage amplitude of reflected EM wave (V_R) and the voltage amplitude of EM waves originally transmitted from the cable tester (V_0). It is also a function of the impedance in the waveguide before (Z_0) and after (Z_L) a change in impedance. A TDR probe embedded in the soil can estimate impedance Z_L at the end of the waveguide with a characteristic impedance Z_0 .

$$\rho = \frac{V_R}{V_0} = \frac{Z_L - Z_0}{Z_L + Z_0} \quad [2-6]$$

ρ can be obtained by measuring V_R and V_0 shown on the TDR waveform. Z_L can then be represented by ρ and Z_0 . By measuring Z_L in soil, a simple Z_L -EC_b relationship can be established as was done by Topp et al. (1988), and Heimovaara et al. (1995):

$$EC_b = -\frac{K_c}{Z_L} f_T \quad [2-7]$$

Where f_T is a temperature factor. Vogeler (1996) introduced that f_T can be determined with Table 15 U.S. Salinity laboratory Staff, (1954). K_c is the cell constant of TDR probe, (m^{-1}). Z_L is the impedance of the sample(Ω). For determination of K_c , one only needs two pairs of values of known conductivity, EC measured by EC meter, and Z_L measured by TDR. However, higher accuracy can be obtained with more data pairs. Another similar equation is

$$EC_b = \frac{K_c}{Z - Z_{cable}} \quad [2-8]$$

Where Z_{cable} is the resistance associated with cable, connectors, and cable tester. For salinity levels less than $\approx 0.3 \text{ S m}^{-1}$, $Z_{cable} \ll Z$ in equation 2-8 and is therefore omitted (Mallants et al.,

1996). It was mentioned that when the cable resistance, $Z_{\text{cable}} = 0.2 \Omega$, was accounted for (using a 50Ω coaxial cable approximately 2 m long), a perfect linear relationship was found between solution EC and TDR-measured EC, with the slope, equal to K_c , 2.937 m^{-1} . The cell constant K_c was obtained by measuring Z when immersing the TDR probe in five different salt solutions of known conductivity ranging from 0 to 1.2 S m^{-1} (Nadler et al., 1991; Heimovaara et al., 1995). It is not necessary to take the temperature factor (equation 2-7) into account to calculate the cell constant K_c when the reference measurement with the laboratory conductivity meter is done on the same sample at the same temperature. Therefore, equations 2-7 and 2-8 can be simplified as:

$$EC_b = -K_c \frac{1}{Z_L} \quad [2-9]$$

TDR offers the possibility of determining EC_b mentioned as above. Nissen (1998) indicated that it is desirable to know the soil-water electrical conductivity (EC_w) instead of EC_b . Most models except the one by Rhoades et al. (1989) assume linearity between EC_w and EC_b at constant θ_v and at all EC_w values. In order to relate Z with C , some researchers think that it is further necessary to describe EC_b as a function of the EC_w and θ_v . For a given θ_v , the relation between EC_b and EC_w may be given in a linear form (Rhoades et al., 1976):

$$EC_b = EC_s + T\theta EC_w \quad [2-10]$$

Where EC_s is EC in the interface between cable and probe rods. Rhoades et al. (1989) interpreted T as the mobile water content fraction (soil water in the large pores).

A linear relationship is generally observed and used between the resident solute concentration, C , and EC_b for constant water contents ranging from relatively dry to

saturation, and for salinity levels ranging from 0 to approximately 50 dS m⁻¹ (Ward et al., 1994):

$$C = \alpha + \beta EC_b \quad [2-11]$$

Where α and β are constants.

Another use of TDR is determining relative solute concentration. The equation is:

$$C(x,t) = \frac{Z_{x,t}^{-1} - Z_i^{-1}}{Z_0^{-1} - Z_i^{-1}} \quad [2-12]$$

Where Z_i is the impedance before application of the tracer solution, Z_0 is the impedance associated with the reference concentration, and $Z_{x,t}$ is measured impedance. It shows that, under steady flow conditions (i.e., constant soil water content), the relative solute concentration C at a particular depth, x and time, t , can be derived from the measured impedance $Z_{x,t}$ if appropriate values of Z_i and Z_0 are available (Lee, 2000).

In order to use TDR efficiently, many researchers have indicated the factors which might affect the TDR measurement. Noborio (2001) discussed the probe type, which generally include two-rod and three-rod configurations. Patterson et al. (1985) warned that two-rod probes used in measurement of water content could increase measurement uncertainties without an impedance-matching transformer because of the risk of encountering stray voltages and currents, but many people still use two-rod probe without transformer. On the other hand, using a two-rod probe with a transformer was not suitable for measuring electrical conductivity because the signal's amplitude after the final reflection decreased due to low frequency attenuation. However, the three-rod probe generally gives simpler waveforms than does a two-rod probe (Noborio, 2001), and there is no need for using the impedance-matching transformer because it simulates a coaxial cell (Zegelin et al., 1989). In

theory, probe length does not affect the accuracy of measurement in non-conducting media. Topp (1984) suggested using probes with $L \geq 0.1$ m because determination of reflection points on TDR waveforms and calculation of κ are very sensitive to small errors in L . Small errors in determining L , especially for dry soils having small κ (2-5), induce larger uncertainties in relation to longer probes. Knight (1992) suggested that for design of two- or three-rod probes, d/s should be less than 0.1 so that not too much of the energy is concentrated around the wires. Baker et al. (1989) indicated that the volume “sampled” by a twin rod TDR probe is concentrated between the rods with the greatest sensitivity in close proximity to the surface of the rods. Topp et al. (1982) found the rods of probes packed with the air-dry soil consistently read lower θ than the rods installed after soil was moistened. It was concluded by Annan (1977) that air gaps around probes in soil could cause serious error in determination of κ . However, EC_b of soil determined by TDR is insensitive to the quality of contact between rods and soil (Nadler et al., 1991).

Baker et al. (1989) found experimentally that the sensitivity using water was largely confined to a quasi-rectangular area of about 20 by 65 cm surrounding the rods with no significant variation in sensitivity along the rod length. Heimovaara et al. (1990) showed the wave form differed somewhat among the results from the use of parallel probes used by Topp et al. (1984) or Dalton et al. (1986). The reason for this is the different geometry of the probes and the lack of a balun. Each probe that is installed in the soil has its own unique reflection pattern (Heimovaara et al., 1990). Because soils are heterogeneous, one or more additional reflections can occur in a wave form, or noise might be introduced by extra connectors or other small discontinuities. Topp et al. (1980) found κ of homogeneous soils

were not strongly sensitive to temperature (10 to 36 °C), soil texture (clay to sandy loam), bulk density of soil (1.14 to 1.44 g/ cm³) for non-swelling soils, and soluble salt content for soils (moistened with salt-free water, 0.01 N CaSO₄, or 2000 ppm NaCl solution). Vogeler et al. (1996) assumed that the vertically installed probe measures the average water content and solute resident concentration over its entire length, regardless of the distribution. A horizontally installed probe, however, measures these properties at a specified depth. Jacobsen et al. (1993) found that while bulk density, clay content, and organic matter content each influence the dielectric behavior of a soil, bulk density had the largest influence on EC_b. During calibration measurements where KCl is used to increase EC, exchange between the native Ca²⁺ and added K⁺ is likely to occur (Vogeler et al., 1996). This cation exchange results in a decrease in the measured EC_w of the soil solution, compared with the electrical conductivity of the added solution, of between 63-82%, depending on the concentration of the added solute. This decrease could also be due in part to an adsorption of Cl⁻ or a double-layer effect (Rhoades et al., 1989). On the other hand, anion exclusion might occur under some conditions resulting in an increase of EC_w. The decrease/decrease of EC_w shows the importance of measuring the electrical conductivity of the soil solution, instead of assuming it to be the same as that of the added solution. However, it is impossible to determine the accurate ion concentrations of a solution with TDR unless the solution contains only one pair of ions, and it is still necessary to take samples of the soil water and compare the results of sample analysis with EC_w measurements obtained with TDR (Nissen et al., 1998).

Three basic factors affect the ion mobility in the bulk solution: the concentration of the soil solution cross section at the unsaturated state, the distance from the solid surface, and the specific geometry of the pores containing soil solution. The ion mobility very close to the

solid surface would be considerably diminished compared to the mobility at the central part of the pores, and to account for that, one may consider as an approximation an immobile zone in the immediate vicinity of a solid surface. Success or failure of TDR to accurately measure solute concentrations depends strongly on the appropriateness of the calibration procedure being used. A linear relationship between Z and C has been observed for instance by Ward et al. (1994) for different values of water content. But this determination only works well under the condition of relatively homogeneous sandy soil or repacked soil columns (Kachanoski et al., 1992; Ward et al., 1994). However, calibrations may become problematic for soils exhibiting small-scale heterogeneities due to the presence of macropores, immobile water regions, or low-permeability zones (Mallants et al., 1996). It was also noted that this is a problem if zones of low permeability and/or stagnant water are present within the sampling volume of TDR probe; the solute may then require an inordinate amount of time in order to spread uniformly by diffusion across the entire cross-section of the column. So use of water-saturated soil columns is a good idea.

TDR offers the possibility of determining the bulk soil electrical conductivity (EC_b) of the soil, which is linearly related to concentration of a certain salt solution. But Nissen (1998) thinks that it is more desirable to know the EC_w instead of EC_b in most applications within soil science.

Soil Solute Transport Modeling

Models are simplified representation of some real systems. Mathematical models are often used to study the time varying response of selected aspects of a real system. In water

quality studies, models are used widely because field experiments are costly and time consuming, and might even add to pollution of the environment. Therefore, mathematical models are often used to predict solute concentrations before management strategies are implemented (Simunek et al., 1999). The basic model form for leaching is convection-dispersion equation which assumes uniform flow velocity, constant moisture content, and linear, instantaneous, reversible equilibrium adsorption. Convection, diffusion, and dispersion are three mechanisms of solute movement in soil. When a solution different in composition or concentration from preexisting pore solution is introduced into a soil, the original solution will be replaced and displaced (Ahuja, 1990). The replacement and displacement result in a change in composition or concentration of soil solution with time. How fast and how much the change will be depends on the scale of convection, diffusion, dispersion, and soil properties. A plot of solution concentration versus time at any particular position of soil column/matrix, called a breakthrough curve (BTC), is frequently used to characterize the replacement and displacement process. Since the solute in soil is generally not visible, and is difficult to be visualized and determined, the outflow of a column BTC is commonly used to characterize solute transport from the soil. A BTC can partly explain what takes place during solute transport in soil. The situation will be complicated if surface runoff occurs during the measurements. But Ahuja et al. (1990) indicated that the transfer of chemical to runoff may be small enough that it does not change the shape and general magnitude of the chemical pulse moving downward with time. Thus, we could decouple the downward transport process from the transfer to runoff, and use the conventional transport solutions.

Numerical models can be used to quantitatively describe solute transport process.

For equilibrium transport when water is flowing uniformly at steady state through a homogeneous soil, the classical convection-dispersion equation (CDE) can be used to describe one-dimensional solute transport.

$$R \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2} - V \frac{\partial C}{\partial z} + S \quad [2-13]$$

Where C is the solute concentration at time t and distance z , v is average pore-water velocity, D is lumped diffusion and dispersion coefficient, and R is the retardation factor. The source term, S , represents degradation and/or production of solute. If the solute is non-reactive and no degradation or production occurs, S can be dropped. K_d (partitioning coefficient) = 0 and $R = 1$, if no adsorption of the solute takes place. The term v can be obtained by measuring outflow flux. More frequently, all these parameters are obtained by least-square fitting the right-hand side of the equation to a series of known $c(t,z)$ values, which are usually taken as the outflow concentrations sampled at certain time interval (Shen, 1999). However, when fitting many data points, the computation work is tremendous. Because of development of computer techniques, a large number of computer programs now exist for evaluating solute transport in porous media using analytical solutions of the convection-dispersion equation. CXTFIT (Toride et al., 1995), as one of them, has been developed to do the calculations and may be not only used to solve the direct or forward problem to determine the concentration as a function of time and/or position, but also used to solve the inverse problem by fitting mathematical solutions of theoretical transport models, based upon the convection-dispersion equation (CDE), to experimental results. Moreover, the stochastic option of XITFIT, together with parameter estimation, can be used to estimate resident concentration, versus depth

resulting from instantaneous application of a solute to the surface. The parameter estimation is demonstrated for the mean pore-water velocity, and dispersion coefficient with equilibrium and nonequilibrium solute transport. CXTFIT can be used for estimating solute transport parameters using a nonlinear least-squares parameter optimization method. This program may be used to solve the inverse problem by fitting mathematical solutions of theoretical transport models, based upon the convection-dispersion equation (CDE), to experimental results. This approach allows parameters in the transport models to be quantified. The program may also be used to solve the direct or forward problem to predict the concentration as a function of time and/or position. Three different one-dimensional transport models are included in CXTFIT: the conventional CDE; the chemical and physical nonequilibrium CDE; and a stochastic stream tube model based upon the local-scale CDE with equilibrium or nonequilibrium adsorption. The two independent stochastic parameters in the stream-tube model are the pore-water velocity, v , and either the dispersion coefficient, D , the distribution coefficient, K_d , or the nonequilibrium rate parameter, α . These pairs of stochastic parameters are described with a bivariate lognormal probability density function (pdf).

Effect of Soil Properties on Anion Leaching

Soil moisture content

In general, hydraulic conductivity increases with water content. Gusev (1979) summarized the results of several field experiments, which indicate that the infiltration rate depends considerably on the initial soil moisture content. He further reported that the initial

moisture content is the factor determining the infiltration capacity of the soil. Antecedent soil moisture can also influence solute transport through a soil profile (Jardine et al., 1990). Burcar et al. (1997) showed that higher antecedent soil moisture in the spring appears to have affected ammonium-nitrogen ($\text{NH}_4\text{-N}$) and $\text{NO}_3\text{-N}$ transport through the soil profile, and allowed $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ to move to greater depths before being sorbed from solution. The reason is the greater antecedent moisture would greatly reduce matric tension and the hydraulic gradient under moist conditions. Therefore, most flow with depth would occur through the larger macropores as a result of gravitational potential. Priebe et al. (1989) indicated that high moisture contents at the soil surface could be expected to promote such preferential leaching, which occurs when all the smaller pores are filled with water and additional water from rainfall bypasses most of the soil matrix by moving through macropores. The effect of initial soil moisture content deserves more attention in humid areas like the Corn Belt because farmers often apply urea to wet soil surfaces. However, a specific case has to be considered for changes in hydraulic conductivity during a rainfall event. Raindrops strike the soil surface with significant kinetic energy. Hudson (1995) illustrates the difference in kinetic energy associated with flowing water versus that for impacting raindrop, and rainfall has 256 times more kinetic energy than an equivalent volume of flowing runoff water. Most soils will experience soil detachment and surface sealing during rainfall if the surface is not protected from raindrop impact. Some studies have indicated that detachment resulted from matric potential increase (Cruse et al., 1977; Francis et al., 1983; Al-Durrah et al., 1981). With high detachment rates, the pores on the soil surface tend to be filled with fine soil particles which cause the surface layer bulk density to increase, and infiltration rates to decrease.

Entrapped air

In a column study by Wang et al. (1998), two infiltration conditions were: (1) when air was free to move ahead of the wetting front and leave the bottom of the column (air draining), and (2) when air was confined ahead of wetting front and hence could escape only through the soil surface (air confining). They found that the infiltration rate was always equal to, and controlled by, the rate of air outflow. The volume of residual entrapped air in the air-confining condition increased 7% on average. Finally, it was shown that the air-confining infiltration flow was fingered and unstable.

Soil compaction and strategy to reduce the leaching

Nutrient losses, as a product of concentration and mass of carrier (volume of water for subsurface drainage), can be reduced by reduction of either or both of those factors (Baker, 2004). Therefore, the amount of water available for leaching and the $\text{NO}_3\text{-N}$ concentration (affected by rate of fertilizer applied) at a given time are key factors influencing $\text{NO}_3\text{-N}$ leaching loss. It is believed that the lower loss of $\text{NO}_3\text{-N}$ in surface runoff generally occurs because $\text{NO}_3\text{-N}$ is very soluble and much of it is moved from the surface “mixing zone” down into the soil with initially infiltrating rainwater, before runoff beginning (Baker et al. 1983). A study (Baker et al., 1982) indicated that loss of N in surface runoff is very dependent on the amount and timing of runoff. They used rainfall simulation, and found that about 5 and 1% of the surface-applied $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$, respectively, were lost with 60 mm of runoff from bare plots shortly after N application. Therefore, most studies of N loss as $\text{NO}_3\text{-N}$, in general, focus on $\text{NO}_3\text{-N}$ losses by leaching.

A portion, sometimes, of the volume of leaching water may result from macroflow, often called preferential flow, or by-pass flow, which is thought to be associated with large pores, like cracks, root holes, wormholes, and macropores in structured more fine-textured soil. Recent studies, however, increasingly show that preferential flow also occurs in soils without obvious macropores (Bouwer, 1990). Nitrogen transport in the soil as $\text{NO}_3\text{-N}$ is caused by mass transport of water (advection) and diffusion and dispersion. Diffusion is a function of the concentration gradient, but dispersion and mass transport are proportional to the mass flow rate of water through the soil profile and nitrate concentration gradient. The leaching process is most frequently described by assuming the water entering any layer of soil displaces water already in that layer and that solutes initially present near the soil surface are moved downward as a “band”, or a “concentration bulge,” that is moved progressively deeper with each additional amount of water passing through the soil (Priebe et al., 1989). Leaching also could be responsible for these losses of N if significant amounts of water moved preferentially through soil macropores (i.e. cracks, channels formed by plant roots or worms (earthworm, *Lunbricus* spp.), and other relatively large voids in the soil). Such preferential movement can result in sufficient dispersion of solutes that a portion of solutes initially present at soil surface moves downward distances of a meter or more before the concentration bulge moves out of the top few centimeters. This dispersion occurs when water and solutes bypass many of the smaller pores without displacing the fluid contents of these pores. The second major reason is that some macropores having horizontal as well as vertical components were undoubtedly truncated by the cement casing. The concentration of soil solution in small pores could be higher than that of larger pores because the velocity of solution movement in small pores should be lower than that in large pores. (Ohte et al.,

1997). Soil N movement in the field has been determined by (1) deep profiles sampling, (2) tile outflow measurements, (3) vacuum extractors, and (4) lysimeters. Lysimeter studies throughout the United States have shown that N leaching losses vary widely depending on experimental treatments (Timmons et al., 1981).

Preferential flow is a general term to describe the process whereby water movement through a porous medium such as soil following “favored” routes, and bypassing other parts of the medium. The preferential movement of surface applied solutes and water through soil macropores is now being recognized as an important potential source of groundwater contamination (Ahuja et al., 1990). Two scales of preferential flow are recognized (Burcar et al., 1997): (i) macropore (≥ 1 -mm diameter) flow, which provides rapid infiltration and transfer of water with little chance for the deeper soil matrix to influence water quality during drainage; and (ii) mesopore (<1 -mm diameter) flow, which provides for lower flow velocities, allowing greater interaction at the soil-liquid interface. Under conditions of preferential matrix (mesopore) flow, a more traditional solute-soil matrix interaction should occur, thus maximizing subsurface nutrient flux. Bouma et al. (1997) indicated that soil macropores form direct conduits for water and solute movement to greater depths and circumvent small or less conductive pores. Therefore, macropore flow has two functions. It could allow rapid solute transport (probably solute coming from the soil surface), bypassing the system’s natural ability (diffusion and adsorption) to remove nutrients from the infiltrating solution (Hendrickx et al., 1991). On the other hand, macropores can also result in reduced leaching of anions. When water quickly drains through macropores, it could have little chance to interact with solutes dissolved in water within aggregates, therefore bypassing those solutes.

Localized soil compaction is one of management strategies which has been proposed to reduce N leaching from agricultural lands (Ressler et al., 1998b). The method of application or placement of applied N is receiving increased attention because the location in/within the soil relative to zones of higher water movement influences the degree of anion (including $\text{NO}_3\text{-N}$) leaching. The concept is that compacted soil can be used as a barrier to water flow above applied fertilizer, limiting/diverting water movement in/away from or around the fertilizer band (Baker et al. 1997). Kiuchi et al. (1994) measured the effects of different subsurface barriers, including plastic disks and compacted soil, on anion leaching in soil columns. All barriers placed over applied chloride (Cl) delayed column breakthrough and reduced peak concentrations of Cl. They further investigated the concept of “subsurface water-flow barriers” in field lysimeters (Kiuchi et al., 1996). They found that a compacted soil layer in situ above the anions reduced leaching by 12%.

Baker et al. (1989) reported that losses of surface-applied fertilizers through surface runoff and volatilization of NH_3 would be reduced to near zero through soil incorporation resulting from point injection. They further noted that because of the ease of application with the rolling point-injector applicator, multiple N applications could be made to more closely match in time the availability to crop needs and therefore potentially reduce leaching and denitrification losses. Baker et al. (1997) measured Br leaching from undisturbed blocks of soil where the Br was broadcast applied or point-injected with and without compaction around the point of injection, and found that there was no significant difference in water volumes percolating through the columns, but concentration and losses of Br in drainage water for the compacted point injection treatment were significantly less than those in

drainage water from soil columns for point injection without compaction or broadcast application.

Tillage and fertilizer applicators

The degree of tillage has the potential to affect both $\text{NO}_3\text{-N}$ concentrations and the volumes of surface and subsurface drainage. In general, tillage, especially extensive tillage, weakens soil structure and reduces soil pore sizes. Because well-structured soil has large pores between aggregates, practice/management that improve soil structure should improve saturated/macropore flow and infiltration. However, well-structure soil tends to increase leaching because of macropore flow. Tillage can be a factor in $\text{NO}_3\text{-N}$ leaching, with generally lower $\text{NO}_3\text{-N}$ concentrations for conservation tillage, particularly no-till, compared to moldboard plowing, but there is the potential for increased infiltration and leaching water volumes to negate the lower concentrations with conservation tillage (Baker, 2004). Use of tillage is often considered with fertilizer application. Kanwar et al. (1985, 1988) indicated that chemical incorporation associated with tillage in their studies resulted in reduced leaching compared with no-till because macropores were disrupted and there was less bypass water flow. In one extensive 3-yr study in northeast Iowa (Weed et al., 1996), average $\text{NO}_3\text{-N}$ concentrations in tile drainage water were measured as a function of crop rotation and tillage. Concentrations for no-till flat and ridge tillage were lowest of the four tillage systems studied, and moldboard plow was the highest with chisel plow almost equal the moldboard plow. When concentration data were combined with flow volume data to calculate losses, lower flows with the moldboard plow system somewhat off-set the higher concentrations such that losses were in the order no-till equal ridge-till less than moldboard plow less than

chisel plow for the corn-soybean and soybean-corn rotations; for continuous corn, the order was moldboard plow less than ridge-till less than no-till less than chisel plow. The lower concentrations with no-till are believed due to less mineralization with no soil disturbance; movement of a greater percentage of water through preferential flow-paths, possibly “bypassing” some of the $\text{NO}_3\text{-N}$ within aggregates in the no-till soil profile; and possibly some dilution due to higher average infiltration rates and drainage volumes with no-till (Weed et al., 1996; Baker, 2004). In a rainfall simulation study of water and anion movement under ridge tillage (Hamlett et al., 1990), $\text{NO}_3\text{-N}$ and Br placed in the elevated portion of the ridge had reduced leaching compared to a similar application with flat tillage. After 7.2 cm of rain a day after anion application, 89 and 94% of the applied $\text{NO}_3\text{-N}$ and Br were recovered by soil sampling the top 1.2 m of the soil profile, respectively; corresponding numbers for flat tillage were 53 and 62%.

A common application technique in the north-central region of the U.S. is knife injection of N fertilizer. It leaves a porous knife slit in the soil above the injected fertilizer which results in a soil zone more favorable to water movement than is the surrounding soil (Ressler et al., 1997). Ressler et al. (1998b) reported that a knife applicator leaves two soil zones (i) undisturbed soil with background N concentration and (ii) loose, porous, disturbed soil with an increased N concentration. The disturbed soil above the injected fertilizer commonly settles into the knife slit, leaving a depression that may channel nearby surface flow through the fertilizer band (Ressler et al., 1998b) and increase leaching. Combination of macropore disruption, compacted soil layers, and ridges at the field scale during fertilizer injection was studied, and an integrated fertilizer applicator, called local compaction and doming (LCD) was designed to limit N movement in production agriculture (Ressler et al.,

1997). Comparison of $\text{NO}_3\text{-N}$ movement for N applied with the LCD applicator with that applied with a conventional knife applicator during the corn growing season showed that the average depth of leaching with the LCD was only 60% of that with the knife. In another field study (Ressler et al., 1998b), the 83-day period in 1993 that was wetter than normal, and there was about 25 kg/ha more of both $\text{NO}_3\text{-N}$ and Br retained in the sampled soil for the LCD versus the knife applicator. In other study, (Ressler et al., 1998a) showed that determined the measurement of three fluorobenzoate tracers used to compare leaching of these anions (to the 1.2 m deep drainage collection tube) applied surface broadcast, with a conventional knife applicator, and with the LDC applicator. At the end of 6 months, leaching losses were 4, 5, and 1% of that applied by the three methods, respectively.

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CHAPTER 3. USING RAINFALL SIMULATION, TDR, AND ANION TRACERS TO DETERMINE EFFECTS OF SOIL PROPERTIES ON NITRATE LEACHING

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ABSTRACT

The objective of this research was to determine the effect of soil bulk density and antecedent moisture content on nitrate-nitrogen ($\text{NO}_3\text{-N}$) leaching from runoff/drainage pans during rainfall simulation in the laboratory in order to develop a better understanding of the leaching process and to devise improved management practices. The combined use of time domain reflectometry (TDR) and tracer anions was tested as a methodology to help develop this understanding. Measurement of bulk electrical conductivity (EC_b) and changes in volumetric moisture content in the depth of 5 cm below soil surface which was beneath the zone of $\text{NO}_3\text{-N}$ applied in a line source were made with TDR during rainfall. The line source was put in the depth of 4.1 cm (the button of line source) below the soil surface as a size of 76.2 cm long by 2.7 cm wide by 1.4-2.3 cm high for different levels of localized compaction (with bulk densities of 1.10, 1.33, 1.57, and 1.81 g/cm^3). Anions, bromide (Br) and chloride (Cl), were added to the rainwater (50 mg/L) and bulk soil (112 kg/ha), respectively, to help understand and trace water movement. From the chosen bulk density of 1.1 g/cm^3 , calculated amounts of soil were packed into runoff/drainage pans in three 2.54-cm layers, for a total soil depth of 7.62 cm. Four TDR probes were used per pan; two inserted into the soil 1 cm below

the soil surface from the side of runoff/drainage pan, and two buried 1 cm below the central line application of $\text{NO}_3\text{-N}$. Simulated rainfall was applied at an intensity of 6.5 cm/h for 70 min to the runoff/drainage pans, and surface runoff and subsurface drainage samples were collected with time. The four line source treatments with different soil compaction densities and two antecedent soil moisture contents (10 and 15%, dry weight of soil basis) were replicated three times. Measured final soil water contents were higher for the 10% moisture content treatment compared to the 15% treatment. This, plus the facts that surface runoff began much sooner for the 15% treatment than would be expected based on just the differences in moisture contents, and that subsurface drainage was delayed and with a lower volume for the 15% compared to the 10% moisture treatment, indicated that the preparation/mixing and packing of the soils to obtain the 10 and 15% moisture contents resulted in a difference in structure of the soil in the runoff/drainage pans. EC_b measured by TDR below the line sources of $\text{NO}_3\text{-N}$ varied significantly with $\text{NO}_3\text{-N}$ for both antecedent moisture and compaction treatments. The results of the study showed that the effect of increasing compaction in the line source zone was to reduce water flow in the compacted area, which reduced $\text{NO}_3\text{-N}$ leaching from the soil layer for both antecedent soil moisture contents from 34.7% (1.33 g/cm^3 treatment) to 85.3% (1.81 g/cm^3 treatment) compared to no-compaction treatment (1.1 g/cm^3). The degree of compaction necessary to significantly reduce $\text{NO}_3\text{-N}$ leaching is important information in the design of special fertilizer applicators to better manage applied N. Antecedent moisture content significantly affected the hydrology and anion leaching, with less subsurface flow, and anion losses for the 15% moisture treatment. As discussed earlier, this effect is believed due to differences in the structure of soil prepared and packed into the runoff/drainage pans at different moisture contents. TDR

techniques, combined with a model, such as the one dimensional CDE with CXTFIT model were tested, which provides a potential to estimate solute concentration via parameter estimation and solute transport properties in subsurface drainage under field conditions.

Keywords: rainfall simulation, soil compaction, antecedent moisture content, TDR, anion

Introduction

The fate and transport of dissolved substances in soil and groundwater is generating considerable interest because of concern for the quality of the subsurface environment (Simunek et al., 1999). Nonpoint source nutrient pollution from agricultural lands is recognized as an important environmental and social issue. One of the primary nutrient forms carried with subsurface drainage is nitrate-nitrogen ($\text{NO}_3\text{-N}$), and the loads of $\text{NO}_3\text{-N}$ in agricultural drainage to surface waters in the U.S. Corn-Belt are among the highest in the country. These N loads can negatively affect human health where such water is used for drinking water supplies, and are suspected to contribute to hypoxia in the Gulf of Mexico. In an early study, Baker et al. (1975) found that $\text{NO}_3\text{-N}$ concentrations in tile drainage often exceeded the 10-mg/L drinking water standard even with modest N fertilization of corn. Researchers found that the primary nonpoint source of $\text{NO}_3\text{-N}$ is agriculture, specifically from the widespread use of N fertilizers, application of livestock manure, legumes and mineralization of soil organic-N (Hallberg, 1987; Goolsby et al., 1999). Concentrations of $\text{NO}_3\text{-N}$ in streams have been found to be significantly related to the percentage of row-crops in watersheds (Schilling et al., 2002). Data show that N fertilizer use in Iowa significantly

increased from 1965 to 1981, generally averaging between 900,000 to 1.0 million t/y in the 1990's. Data also show that $\text{NO}_3\text{-N}$ concentrations in Iowa's streams have significantly increased since the mid-20th century, increasing from 2 to 6 mg/l in the Cedar River and nearly doubling in the Des Moines River (Schilling, 2003).

$\text{NO}_3\text{-N}$ is the form of N which, because of its specific physical and chemical properties, is not adsorbed to soil. It usually is the most abundant form of N in the soil water; that combined with hydrological factors and lack of adsorption will determine how much leaches. In general, it is often expressed that nutrient losses come from "excess nutrients," with the implication that if there were no excess nutrients, there would be no losses. From a recent state-wide nutrient budget done for Iowa, it is believed that currently there are on average no "excess nutrients," under the conditions and assumptions of the examples given for the corn-soybean rotation. However, in order that sufficient nutrients are available to the plants to obtain economic optimum crop yields, nutrients must be present in significant amounts during the growing season, and therefore are susceptible to loss with rainfall-runoff and subsurface drainage events that can and do happen at any time (Baker, 2004).

Many factors, including rate, method, and timing of fertilizer applications to provide nutrients for a corn-soybean system, can affect the amount of N lost by $\text{NO}_3\text{-N}$ leaching. Leaching also could be responsible for these losses of N if significant amounts of water moved preferentially through soil macropores. Because subsurface tile drainage is a common agricultural practice to remove excess moisture in the shallow soil profiles in many parts of the United States (Mohanty et al., 1997), management practices/systems for the nearly flat, tile-drained areas, such as those within Iowa, need to be more focused on N because of $\text{NO}_3\text{-N}$ leaching losses (Baker, 2001). Substantially reducing $\text{NO}_3\text{-N}$ losses from these agricultural

systems will require a combination of in-field best management practices and off-site landscape modifications.

Soil property management in the zone of application is one of the more promising in-field strategies for reducing surface water contamination, and some studies have demonstrated that localized compaction has the potential to reduce $\text{NO}_3\text{-N}$ leaching losses with tile drainage. Creating surface domes/ridges, compacting a soil layer, and macropore disruption in the zone of N application are strategies that can potentially reduce leaching (Ressler et al., 1998). An applicator using localized soil compaction and doming (LCD) was described by Ressler et al. (1997), which attempts to combine these strategies to smear and close macropores below the N-injection knife, fill and compact soil into the knife slit, and cover the fertilizer band with a surface ridge or dome. In a rainfall simulation study of water and anion movement under ridge tillage, $\text{NO}_3\text{-N}$ and Br placed in the elevated portion of the ridge had reduced leaching compared to a similar application with flat tillage (Hamlett et al., 1990). Kiuchi et al. (1994, 1996) showed that barriers placed over applied Cl delayed column breakthrough and reduced peak concentrations of Cl. In another study, Baker et al. (1997) measured Br leaching from undisturbed blocks of soil where the Br was broadcast-applied or point-injected with and without compaction around the point of injection. Compaction significantly reduced Br leaching with concentrations for the treatment on no-till blocks of soil being 7 and 11% of the uncompacted point injection and broadcast application treatments, respectively. Comparison of $\text{NO}_3\text{-N}$ applied with a LCD applicator with that applied with a conventional knife applicator during the growing season (Ressler et al, 1997) showed that the average depth of leaching for the LCD applicator was only 60% of that for

the knife. These studies focused on $\text{NO}_3\text{-N}$ leaching in subsurface drainage; however, the leaching feature just beneath the fertilizer application zone is still not fully understood.

Solute fluxes to groundwater can be predicted by fitting models to observed volume-averaged concentration data, referred to as resident concentration or to flux-averaged concentration data (Caron et al., 1999). Therefore, obtaining the observed values/raw data is first important step, which can be completed by different sampling devices/methods in field. In general, there are two kinds of the sampling methods, disturbed and undisturbed. Undisturbed method has been used by some researchers, such as porous cup sampler (Caron et al., 1999; Brye et al., 2001). However, automation of the estimation of soil resident concentration would be highly advantageous, and TDR techniques may offer this possibility (Caron et al., 1999). TDR techniques have been used to determine solute resident concentrations (Topp et al, 1980; Dalton et al., 1986; Ward et al., 1994) because concentration changes cause significant changes in the soil electrical conductivity. TDR techniques also allow the simultaneous determination of water content which can be used for estimation of drainage water flux. Many other advantages were discussed in previous studies (Ward et al., 1994) such as low costs associated with analytical determination, and that TDR method is nondestructive, fast and easily automated. Although the important limitation of using TDR techniques to measure solute concentrations is that it requires correction or calibration because it is nonspecific to ionic species, it is still widely used.

The behavior of solutes over relative long spatial and temporal scales must generally be assessed with the help of theoretical methods since it is usually not feasible to carry out experimental studies over sufficiently long distance and/or time periods. Mathematical models are often to predict solute concentrations before management strategies are

implemented (Simunek et al., 1999). For equilibrium transport when water is flowing uniformly at steady state through a homogeneous soil, the classical convection-dispersion equation (CDE) can be used to describe one-dimensional solute transport (Shen, 1999). However, when fitting many data points, the computation work is tremendous. Because of development of computer techniques, a large number of computer programs now exist for evaluating solute transport in porous media using analytical solutions of the convection-dispersion equation. CXTFIT (Toride et al., 1995), as one of them, has been developed to do the calculations and may be not only used to solve the direct or forward problem to determine the concentration as a function of time and/or position, but also used to solve the inverse problem by fitting mathematical solutions of theoretical transport models, based upon the convection-dispersion equation (CDE), to experimental results. Moreover, the stochastic option of XITFIT, together with parameter estimation, can be used to estimate resident concentration versus depth, resulting from instantaneous application of a solute to the surface. The parameter estimation is demonstrated for the mean pore-water velocity, and dispersion coefficient with equilibrium and nonequilibrium solute transport.

The overall purpose of this research was to quantify the effects of soil local compaction and antecedent soil moisture content on $\text{NO}_3\text{-N}$ leaching during laboratory rainfall simulation with the help of tracer anions and TDR measurements, and to use this information to help in the development/improvement of N application methods/equipment. Specifically, simulated rainfall containing Br was applied to soil in runoff/drainage pans with two different antecedent soil moisture contents. The soil in the pans had been treated with $\text{NO}_3\text{-N}$ (in a localized line source with different degrees of compaction) and Cl (mixed uniformly in the soil).

The general objectives were:

1. To study the impacts of two levels of antecedent soil moisture content (10 and 15%) and four levels of local soil compaction (with bulk densities of 1.10, 1.33, 1.57, and 1.81 g/cm³) in the zone of N application on the leaching characteristics of NO₃-N beneath local chemical application zones based on concentrations and losses in subsurface drainage.
2. To compare NO₃-N leaching from a local compaction zone with measurement of leaching of two other anions, Br in rain water and Cl mixed uniformly in the soil.
3. To estimate the potential of TDR methods for measuring soil moisture content and electrical conductivity during a rainfall and surface runoff and subsurface drainage and assessing anion movement.

Materials and Methods

This study was conducted in the porous media laboratory in the Agricultural and Biosystems Engineering Department at the Iowa State University. Three anions were used to study movement: bromide (Br) in rain; chloride (Cl) incorporated/incubated in soil, and NO₃-N within locally compacted soil (compacted soil bar). Simulated rainfall was applied to soil in runoff/drainage pans at 6.5 cm/h for 70 min. Measurement of the volumetric water content and bulk electrical conductivity in the soil layer beneath the zone of NO₃-N applied in a line source, and in the top 2-cm of soil were made with TDR to evaluate the effectiveness of using the combination of tracer anions and TDR to study the fate and transport of solutes in surface runoff and subsurface drainage. To determine the impact of antecedent soil moisture

content and local soil compaction on the transport of $\text{NO}_3\text{-N}$ compared to the other two anions and movement of water, two levels of antecedent soil moisture content, 10 and 15% gravimetric moisture, and four localized compaction levels of soil treated with $\text{NO}_3\text{-N}$ were placed within soil in pans for rainfall simulation. Bulk densities of 1.10, 1.33, 1.57, and 1.81 g/cm^3 were tested, for a total of eight treatments with three replications per treatment. The treatments are denoted as 10% moisture, 1.10 g/cm^3 bulk density (10-1.10); 10% moisture, 1.33 g/cm^3 bulk density (10-1.33); 10% moisture, 1.57 g/cm^3 bulk density (10-1.57); 10% moisture, 1.81 g/cm^3 bulk density (10-1.81); 15% moisture, 1.10 g/cm^3 bulk density (15-1.10); 15% moisture, 1.33 g/cm^3 bulk density (15-1.33); 15% moisture, 1.57 g/cm^3 bulk density (15-1.57); and 15% moisture, 1.81 g/cm^3 bulk density (15-1.81).

Soils

The soil for this study was obtained from the Iowa State University research farm about 8 km west of Ames. The soil was mapped as Nicollet silt loam (42% sand, 52% silt, and 6% clay) with 1 to 3% slope, which is somewhat poorly drained on slightly convex or plane slopes on knolls and swales. Soil was retrieved from the top 25 cm of a field that had been in a corn soybean rotation for several years. Prior to use in rainfall simulation, the soil was sieved on 5- and 2-mm screens to separate residue and to remove large soil aggregates. The sieved soil was analyzed for the background levels of $\text{NO}_3\text{-N}$, Cl, Br, and moisture content. The soil for 10 and 15% moisture treatments, by weight, were created by adding distilled water with Cl (as KCl) dissolved in it to the soil through a pressurized spray nozzle, while mixing the soil in a rotating concrete mixer drum for 30 min to establish homogeneity. The thoroughly mixed soil was transferred to plastic bags and stored in containers located

indoors for at least 3 days before being used. After mixing, visually there was a small difference in the aggregates that had formed during the tumbling/mixing between 10 and 15% treatment.

Runoff/drainage pans

Plastic lids of large storage containers were used as runoff/drainage pans. The dimensions of the pans were 81.2 cm long by 42.2 cm wide, resulting in 3396.2 cm² rainfall collection surface area. However, the dimensions of the soil surface area were 80.5 cm long by 41.0 cm wide resulting in a 3281 cm² surface area (Figure 3-1). A 0.95-cm inside diameter perforated polyethylene drain tube was inserted into the bottom of each pan to serve as a subsurface drain. Fine silica sand was placed in the bottom of each pan over the drain tube to a depth of 3.8 cm, and above the sand, a predetermined mass of soil (27.4 kg dry weight) was compacted in three successive layers to a 7.6 cm thickness, resulting in a dry bulk density of 1.1 g/cm³. The second layer was divided into two sublayers, and two compacted soil bars 38.1 cm long containing NO₃-N were placed end-to-end in the runoff pan between those sublayers. Sheets of cheesecloth and fiberglass screen were placed between the sand and soil layers. Plexiglas sideboards 12-cm high were attached at the rim of each pan to reduce water and sediment loss due to raindrop splash. Each pan was tilted at 4% slope, and positioned a minimum of 3.05 m below the rainfall simulator (Figure 3-2).

Compacted soil bars

Aluminum channels were used as “forms” to hold soil in a rectangular cross-section as it was being compressed to create the compacted soil bars containing NO₃-N. The

dimensions of the aluminum channel were 38.1 cm long by 2.67 cm wide by 2.29 cm high, resulting in 101.61 cm² surface area and 232.29 cm³ volume. Each aluminum channel was packed with 255.5 g (dry weight bases) of soil to an initial bulk density of 1.1 g/cm³. A “Sintech” computer integrated testing machine by MTC Corporation was used to compress the soil bars to the desired bulk densities. The computer controlled system allowed good repeatability. Compression was performed by using a grid cell and an iron press bar attached to it with dimensions fitting the aluminum channel. The entire compaction process was controlled by using computer software integrated with the machine. By fixing the speed and varying the time of grid cell travel, the desired distances of travel were reached, which were related to bulk densities. For example, the 1.81 g/cm³ bulk density required a final soil volume of 141.17 cm³ and soil depth of 1.39 cm. Thus, the distance of travel of compression grid cell from the start at the original soil surface was 0.88 cm. Plastic wrap was placed inside the aluminum channel to reduce the friction between the soil and aluminum channel for better removal of soil after compaction. After compression to the desired densities, the aluminum channel was put in a bench clamp, and the open edge of channel was expanded a little, which allowed removal of the soil from the channel without breaking it.

TDR Setup

In this study, the TDR instrumentation included a Tektronix 1502 cable tester (model 1502B, Tektronix Corp., Redmond, OR), SDM50 multiplexer, SDM1502 interface, and TACQ program (Evelt, 1998; Lee, 2000) to obtain the Z value (equation 2-8 of chapter 2) called soil impedance. This can be converted to soil bulk electrical conductivity by calibrating TDR probe cell constant (Topp et al., 1988; Heimovaara et al., 1995; and

Mallants et al., 1996). The k value (equation 2-1 of chapter 2), called soil dielectric constant, can be converted to soil moisture content via the Topp equation (1980) or Malicki equation (1996) (equations 2-4, 2-5 of chapter 2). This was done as a function of time during the rainfall simulation experiments. In addition, the calibration curves for electrical conductivity and volumetric water content were made prior to rainfall simulation. Four TDR probes per pan were used. Two with three rods, 15-cm long were buried beneath the soil bars (Figure. 3-1). The other two were inserted into soil 1 cm below the soil surface from the side of the pan. Thus, it was assumed that the two probes in shallow soil measured the average values of electrical conductivity and moisture content in the mixing zone, and the other two probes beneath the soil bar measured these parameters in the zone of potential $\text{NO}_3\text{-N}$ leaching, although the Br and Cl anions were also used in our study.

Model

CXTFIT 2.0 (Toride et al., 1995) in STANMOD 2.2 was used to solve the inverse problem by fitting mathematical solutions of theoretical transport models, based upon the convection-dispersion equation (CDE), to experimental results. In this study, $\text{NO}_3\text{-N}$ input can not exactly match the model solute input pattern, the soil bar containing $\text{NO}_3\text{-N}$ was arbitrarily considered as “pulse” input. TDR measured data of bulk electrical conductivity beneath the soil bar were assumed to represent resident concentration of $\text{NO}_3\text{-N}$ because of little effect of macroflow (which can move Cl and Br downward) to the area just beneath the local compacted zone. Because of the change in soil moisture content before the soil reached saturation, the “pulse” concentration and application time of $\text{NO}_3\text{-N}$ were hard to predict. An alternative approach was use of relative EC_b values:

$$EC_b(\text{relative}) = \frac{EC_b(\text{observed})}{EC_b(\text{initial})} \quad [3-1]$$

$$EC_b(\text{initial}) = \frac{EC_b(\text{maximum})}{c} \quad [3-2]$$

where c is percentage of $\text{NO}_3\text{-N}$ leached for treatments during the rainfall simulation

With these data, solute transport parameters, pore velocity and dispersion coefficient, were estimated.

$\text{NO}_3\text{-N}$ application and tracer anions

Three anions, Cl, Br, and $\text{NO}_3\text{-N}$, were used to evaluate the movement of water and solutes from and through the soil to surface runoff and subsurface drainage. The Cl anion was added to soil in an amount equivalent to 112 kg/ha (as KCl) in a water solution, and the soil was stored for at least three days before being used to pack the runoff/drainage pans. The Br anion was added to rainwater at 50 mg/L (as KBr). The $\text{NO}_3\text{-N}$ anion in an amount equivalent to 112 kg/ha (as $\text{Ca}(\text{NO}_3)_2$) was added to the soil that was compacted into the soil bars. Each soil bar received 19 mL of the $\text{NO}_3\text{-N}$ solution treatment prior to compaction.

Procedure

Two runoff/drainage pans were used simultaneously during each rainfall simulation run. Before and after rainfall simulation, soil and sand samples were taken for determination of initial and final moisture contents; the total weight of the soil-water-pan system was also taken before and after simulation to cross-check water balance and water storage calculations. An indoor rainfall simulator with 12 spraying nozzles located overhead in three

lines was used to produce simulated rainfall. Rainfall was applied to the pans at the rate of 6.5 cm/h, and the nozzles were positioned 3.05 m above the runoff pans. The combination of nozzle height, operating pressure of 10 psi, and flow rate created droplet sizes and velocities similar to natural rainfall. An electronic timer that could be adjusted to attain the desired rainfall intensity controlled the sweep period of the nozzle. The intensity and volume of rainfall were measured with an aluminum channel rainfall collector placed between the two pans. Rainfall and runoff from the two pans were individually routed through transfer tubes to sample containers on electronic balances (Figure 3-2). Pan runoff samples were collected at 2-min intervals after the start of runoff, and subsurface drainage samples were taken at 4-min intervals after the start of drainage. The subsurface drain tube was left open at either end to permit venting of air from the soil and the release of subsurface water from the outlet. With the start of rainfall, a small vacuum pressure of 12 cm of water was applied to each subsurface drain tube with an electric vacuum pump to expedite sampling of subsurface drainage water.

After the rainfall simulation was ended, soil and sand from pans were separated and transferred to large plastic containers for anion extraction and analysis. Extractions were performed using a 2:1 ratio by weight of distilled water to soil/sand. Soil/sand and water were thoroughly mixed with a heavy duty electrical drill and stirring rod twice for 5 to 10 min prior to sampling.

Analysis

The surface runoff samples collected every 2 min were weighed, and then composited into samples for eventual anion analysis. The first two runoff samples were combined to

make up the first composite sample, and every four samples after that were combined to make up the rest of the composite samples for analysis. Subsurface drainage samples collected every 4 min, were retained as individual samples. Water samples were analyzed for $\text{NO}_3\text{-N}$, Br, and Cl concentrations; $\text{NO}_3\text{-N}$ was analyzed by the automated flow injection cadmium reduction method using a Lachat Quickchem 2000 Automated Ion Analyzer system. For this method, $\text{NO}_3\text{-N}$ is reduced to nitrite (NO_2) by a cadmium/copper column; then the NO_2 is diazotized with sulfanilamide and reacted with N-(1-naphthyl)-ethylenediamine dihydrochloride at a pH of 8.5 to form a colored (pink to red) azo compound, whose intensity is proportional to the amount of $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$ in the sample. Measurements were made with a colorimeter at a wavelength of 520 nm. The $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$ concentrations (hereafter referred to as just $\text{NO}_3\text{-N}$) in samples were determined by comparing sample absorbance with those obtained from a calibration curve comprised of standards containing 0.25 to 30.0 mg $\text{NO}_3\text{-N/L}$.

The Cl analyses were performed by the automated flow injection ferricyanide method using a Lachat 2000 Automated Ion Analyzer system. The Cl anion forms a soluble complex with mercuric thiocyanate. The freed thiocyanate ion reacts with iron(III) to form a red-orange colored compound whose intensity is proportional to the Cl concentration in the sample. Measurements are made with a colorimeter at a wavelength of 480 nm. The Cl concentrations in samples were determined by comparing sample absorbance with those obtained from a calibration curve comprised of standards 1.00 to 100.0 mg Cl/L.

The Br analyses were performed by the automated flow injection phenol red method using a Lachat 2000 Automated Ion Analyzer system. Chloramine-T reagent oxidizes Br to bromine which is then brominated with phenol red (buffered at a pH of 4.5-4.7) to form a

reddish to brown colored compound whose intensity is proportional to the Br concentration in the sample. Measurements were made with a colorimeter at 590 nm. The Br concentration in samples were determined by comparing absorbance of the sample with a calibration curve based on absorbances of standards containing 1.0 to 60.0 mg Br/L.

A complete randomized block design was used with three blocks and 24 experimental units (EU), each block being four local compaction levels and two antecedent moisture contents, and an EU being a runoff/drainage pan of soil. A 2x4 factorial was used and analysis of variance (ANOVA) was performed. The Statistical Analysis System (SAS) was used for effect tests of moisture content of soil and bulk density on hydrology, and solute concentrations and losses in surface runoff, subsurface drainage, soil/sand.

Results and Discussion

Calibration results of volumetric water content and bulk electrical conductivity

Figure 3-3 shows the calibration curve of volumetric water contents measured by TDR using equations 2-4 and 2-5 listed in literature review versus moisture contents determined gravimetrically for the Nicollet soil separately. The TDR method underestimated the gravimetric soil water content from 0.03 to 0.08% using Malicki and Topp equations, respectively. The reason for underestimation is low bulk density mentioned above. The result from Malicki equation is better than Topp equation. Also because of consideration of bulk density factor in Malicki equation, Therefore, Malicki equation was used with TDR measurements in our study to estimate moisture contents, using the calibration equation:

$$\theta_{v1} = 0.9127\theta_{v2} + 0.0517 \quad [3-3]$$

where θ_{v1} is the volumetric water content determined by TDR, and θ_{v2} is the volumetric water content determined gravimetrically. The other calibration was made during the rainfall simulation to compare with the equation 3-3. For 10 and 15% moisture treatments, initial and final volumetric water content measured by TDR (twice with probes in top soil and beneath the soil bar) were compared with antecedent and final soil moisture contents in runoff/drainage pans determined gravimetrically (Figures 3-4, 3-5, and 3-6). In Figure 3-4, average TDR signal of eight treatments in initial stage and final stage of rainfall simulation were compared to volumetric water content gravimetrically determined, resulting in the following equation:

$$\theta_{v1} = 0.9953\theta_{v2} + 0.0792 \quad [3-4]$$

This result suggested that some factors affect the TDR method during rainfall simulation, causing greater underestimation for this in situ calibration than for the calibration prior to rainfall simulation. In top soil, TDR values (side probes) for the 10% moisture treatment were underestimated less than for the 15% moisture treatment at the start of rainfall (Figure 3-5), possibly due to a soil structure effect (following the mixing of the 10 and 15% antecedent moisture content soils). However, compared to dry soil at the start of rainfall, TDR values for 10 and 15% moisture treatments (low probes) and in wet soil at the end of rainfall were more (Figure 3-6), indicating greater measurement uncertainties for moisture content using two-rod probes.

In this experiment, equation 2.8 in literature review, $EC_b = K_c / (Z - Z_{cable})$ was used for determination of soil EC_b . For salinity levels less than 0.3 S/m, in this equation $Z_{cable} \ll Z$,

and therefore can be omitted (Mallant et al., 1996). The determination of the cell constant was described by Nadler et al. (1991) and Mallant et al. (1996). It was obtained by measuring $1/Z$ when immersing the TDR probe in five different salt solutions of known conductivity ranging from 0 to 1.2 S/m. Solutions of 0, 0.02, 0.04, 0.06, and 0.08% of KCl were used in this experiment, and the eight probes used were immersed in these five solutions, with two duplications, one by one. A conductivity meter (Accumet, Model 30, Fisher Scientific) was used for determination of solution EC (table A-3). The range of EC is 0 to 0.15 S/m which were less than 0.3 S/m. Therefore, Z_{cable} in equation 2.8 was omitted in calculation of EC. A linear relationship was found between solution EC and TDR measured EC, with slope $K_c = 41.263 \text{ mS/cm}$. Figure 3-7 shows the results for EC calibration. A linear relationship was estimated between solution EC and TDR measured EC:

$$EC_1 = 41.263EC_2 - 0.0159 \quad [3-5]$$

where EC_1 is the value from the EC meter, and EC_2 is from the TDR. Statistical analysis of the calibration data for each individual probe indicated that there were no significant differences among the eight probes used.

Soil volumetric water content and bulk electrical conductivity

Table 3-3 shows the initial and final volumetric water contents in runoff/drainage pans determined with side and low probes. Figure 3-8 shows the volumetric water content in runoff/drainage pans determined by the side probes with time. The water content begins from the initial value, and increases quickly to the highest final value. At the same time, the matric potential can be expected to become very low to zero as rain continues to fall, and the soil is saturated. However, the final water content for the 15% moisture treatment was significantly

lower than 10% (Table 3-3) which could have resulted from differences during the soil mixing process and surface sealing before and during rainfall simulation. Figure 3-9 shows the EC_b in runoff/drainage pans by the side probes with time. The curves are clearly bell-shaped. Before soil saturation (shown in Figure 3-8) changes in EC_b were dependent on both soil moisture and solute concentration changes with time (see Eq. 2-10 in literature review). However, after soil saturation, the water content was constant, and EC_b was related to solute concentration (see Eq. 2-9, 2-11 in literature review), changes with time. Both EC_b in 1 cm below the surface of soil and EC_w in surface runoff were measured by TDR and EC meter, respectively (Figure 3-19). Statistical analysis indicates that there was no significant difference between EC_b measured with TDR in the top soil layer and the electrical conductivity of surface runoff samples (EC_w) after time-to-peak EC_b value. This information can be utilized to estimate solute resident and flux concentrations by directly using EC_b , rather than via EC_w . Priebe, et al. (1989) indicated that the leaching process is most frequently described by assuming the water entering any layer of soil displaces water already in that layer and that solutes initially present near the soil surface are moved downward. Therefore, if the difference between EC_b and EC_w is small enough, such as no significant difference statistically, EC_b could provide a simplified method for quick determination of solute concentrations in real time. Figure 3-10 shows the volumetric water content of soil below the soil bars in runoff/drainage pans determined by the low probes with time. This provides information on the hydraulic conductivity of the soil layer under the soil bar. This layer is protected from the forces of raindrop impact and water content is greater than surface during the rain event (Table 3-3). However, when water flow through the surface soil layer to lower layers, the soil in lower layers becomes wetter (matric potential increases), and water is

conducted to deeper layers. Thus the matric potential of low layer decreases (water content lows down slightly) after beginning of drainage.

Figure 3-11 shows the EC_b in runoff/drainage pans determined by low probes with time. The curves are also bell-shaped. There was significant difference of EC_b between low compaction and high compaction treatments.

Water results

Table 3-1 presents hydrological data related to timing and volumes of surface runoff and subsurface drainage, as well as water stored in soil and sand layer, during and after rainfall simulations. The average measured amounts of rainfall applied to the runoff/drainage pans for the two moisture treatments, 10 and 15%, were 7.6 and 7.9 cm, respectively; they were intended to be equal and were not significantly different. Of the rainfall applied, on average 44.1, 22.2, and 30.5% runoff, drained from the bottom of the pans, or was stored in the soil for the 10% moisture treatment. Corresponding values for the 15% moisture treatment were 64.6, 7.8, and 19.6%. An overview of the hydrology of the runoff/drainage pans as a function of time is given in figure 3-12. This graph shows input of rain water as well as three “fates” which are the infiltration into the soil (a), accumulated subsurface drainage from the soil (b), and water stored within the soil (c), averaged by treatment. Surface runoff is equal to rainfall minus infiltration. The 5% difference is moisture treatments to 0.42 cm of water in the 7.62 cm layer of soil. The 10.5 min difference is time to surface runoff (21.8-11.3) at 6.5 cm/h translates to 1.14 cm of water. Comparing three values shows that runoff for the 15% moisture treatment began much sooner than would be expected related to the 10% moisture treatment based on moisture content difference alone. As discussed earlier, the mixing and

packing processes likely caused some soil structure difference. As shown, the antecedent soil moisture treatment affected infiltration, subsurface drainage, and storage. Soil pans with the 10% moisture treatment had more infiltration and subsurface drainage than those with 15%. The average drainage for the 10 and 15% moisture treatments were 22.2 and 7.8% of total rain, respectively; and the average times for drainage to begin were 28.7 and 43.7 min, respectively. On average, 3.11 and 4.74 cm of water at 6.5 cm/h was applied before drainage began for the 10 and 15% moisture treatments, respectively. The average total volumes of water retained by the soil/sand were 2.93 cm and 2.21 cm for 10% and 15% moisture treatments, respectively. As just discussed for surface runoff, these results go beyond just the effect of a difference in moisture content. It was expected that subsurface drainage would begin sooner and with a greater volume for the 15% moisture treatment. And there would be no reason to expect that the difference in volumes stored, 0.72 cm, would be different than the initial difference of 0.41 cm. Again this is evidence of a difference in soil structure between the treatments.

This unexpected behavior was in contrast to the expected behavior found by Guo et al. (1999) and Camara et al. (2001) for similar rainfall simulation studies. Guo et al. studied the effect of tillage practices, and Camara et al. (2001) used a soil surface cover to evaluate effects on surface runoff and subsurface drainage. They found that the factors (surface cover or no-tillage) delayed and decreased surface runoff and speeded up and increased subsurface drainage. Their results also were similar to that of Stamm et al. (2001). They found the 20% antecedent moisture treatment did not produce greater volumes of surface runoff in screen treatments than 10% moisture treatment. Nasritdinov et al. (2003) concluded that the rainfall energy falling on the soil with higher antecedent soil moisture increased sealing of the soil

surface during the rainfall and decreased the water infiltration into the soil, resulting in more surface runoff and also less subsurface drainage. But under surface cover condition, the aggregates and resulting greater fraction of larger pores generated in mixing process and protected against the dispersive energy of raindrops by screen, may have caused rapid movement of water through the soil during the simulation (Stamm et al., 2001).

The results obtained in this study could be further explained by possible differences in soil pore sizes. Bouwer (1990) indicated that preferential flow was thought to be associated with large pores, like cracks, root holes, wormholes, and macropores in structured clay soil. Infiltration, especially for large rainfalls, is controlled by saturated flow, when all pores are filled with water. Water moves primarily through the larger pore spaces and is held loosely (or not at all) by the soil particles. During the preparation of soil at the 15% moisture content, it was observed that small aggregates were formed during the tumbling/mixing process when packed in the runoff/drainage pans, which may form some large pores between aggregates. However, at the soil surface, small particles may be by the rainfall energy and fill in these pore spaces or entrap air with them, which could slow infiltration, and also greatly reduce subsurface drainage.

Because of compacted soil bars added as line source of $\text{NO}_3\text{-N}$ represented only 3% of the soil surface area and only 0.9% of the soil volume for the 1.1 g/cm^3 density (even less for the other three greater densities), the effect of bulk density treatment did not have a significant effect on surface runoff and subsurface drainage start times and volumes.

Tracer results

Figure 3-13 shows the “breakthrough curves” or anion concentrations with cumulative drainage (expressed in cm and pore volume) for Cl, Br, and NO₃-N leached through the 7.62 cm soil layer (plus through the 3.8 cm sand layer) for the 10 and 15% moisture treatments during the rainfall simulation. Several obvious differences are notable. Br and Cl anions for the 10% moisture treatment moved to the drains faster per unit drainage (steeper slopes) than for the 15% moisture treatment for all four soil compaction treatments. The Br arrived earlier with drainage for the 10% moisture treatment than for the 15% moisture treatment because of the difference in the time-to-drainage shown in Table 3-1. The immediate arrival of Cl with subsurface drainage could be expected because it is uniformly present in the 7.62 cm soil layer. However, the immediate arrival of some Br, applied with rain water, could be attributed to water flow in relative large pores. Large pores allow water to flow more rapidly than if all the water in the entire soil matrix was being displaced. More evidence of large pore flow can be also seen in Figure 3-13. For the 10% moisture treatment, drainage averaged 0.40 pore volume transported 59, 21, and 98% of NO₃-N, Br, and Cl with subsurface flow from the soil layer for the 70-min rainfall event. The corresponding values for the 15% moisture treatment were 0.18 pore volume and 18, 3, and 70% of the NO₃-N, Br, and Cl. The slower (less steep slope) arrival of solutes for the 15% moisture treatment compared to 10% moisture treatment could be attributed to removal of some of the solute from the flow channels by transverse diffusion into stagnant regions of soil layer while the pulse is passing more slowly through the soil layer with a gradual release of solute back to the flow channels by diffusion after the pulse (for Cl and NO₃-N) has passed through the system. However, Br, and Cl concentrations in subsurface drainage weren’t affected by compaction treatment

(Figure 3-18) because it only represents 3% of the soil surface area and only 0.9% of the soil volume for the 1.1 g/cm³ density (even less for the other three greater densities).

While soil for the 15% moisture treatment was “aggregated” to some degree in contrast to the 10% moisture treatment because of the tumbling/mixing process, the finer pore sizes generated within the aggregates could hold a substantial volume of water, but this water could be relatively stagnant compared to that flowing in the large channels between aggregates. The leaching patterns were also varied as affected by the tracer input method. The drainage rate rose rapidly with time once drainage began during the rain, and reached a steady state, resulting in a cumulative drainage volume that increased linearly with time (Figure 3-12). Considering anion leaching under this drainage condition, Br applied with rainfall water was a “step” input, and its leaching fraction shows nearly linear increase with cumulative drainage. Leaching of Cl incorporated in soil and NO₃-N placed in a compacted soil zone was non-linear with cumulative drainage. However, NO₃-N for the high bulk density treatments showed less leaching compared with the low bulk density treatments for both the 10 and 15% moisture treatments. Averaging over both soil moisture content treatments, NO₃-N loss with subsurface drainage at 1.81 g/cm³ bulk density was only one-fourth as much as at 1.1 g/cm³ bulk density.

From Figure 3-13, for the 10% moisture treatment, Cl for all compaction treatments and NO₃-N for the low compaction treatment were transported much more rapidly than one would expect. Subsurface drainage being 22.2% of applied rain water (equivalent to only average 0.40 pore volume) caused 96% of the Cl to be leached. One factor that could have increased Cl leaching relative to NO₃-N and Br are chemical application/location (NO₃-N within the soil bar, and Br added to the soil surface with time in rainwater with potential for

storage with rain water when it goes into soil. Anion exclusion may be an important mechanism for soil with high charge (Schoen et al, 1999; Logsdon et al., 2002), and may be another factor resulting in the larger amount of Cl leaching with a small amount of water. In addition, after addition of Cl, the soil was stored only three days which may not have been enough time for diffusion, and equilibration within the soil, especially for the soil at 10% moisture treatment which may not have been wet enough to allow complete Cl diffusion within soil aggregates. Although the leaching features of the three anions in subsurface drainage was discussed, the amounts of anions in the sand also need to be considered because they represent what is leached from the soil layer. Figure 3-14 shows the total leaching including the fraction in the sand. Obviously, leaching “retained” in sand for the 15% moisture treatment is higher than that for the 10% moisture treatment for all three anions.

Results of EC_b measurements of the surface soil layer by TDR, and EC_w measurements of surface runoff water samples with an EC meter (Figure 3-19) showed that EC_b was not significantly different from EC_w of surface runoff. That implied that EC_b values can be related directly to solute concentrations in this study. This and the trend of EC_b with time can be explained by using the “mixing theory” and a knowledge of the importance of moisture content on EC_b . After its peak value, EC_b was not dependent on soil water content because of soil saturation as indicated by TDR measured volumetric water contents which had approached their highest value (near but not quite equal to the soil porosity) by the time of peak EC_b . Under saturated conditions, soil, solutes and water can be completely mixed in top 2 cm of soil. Figure 3-15 shows, for each compaction level of the two soil moisture treatments, the concentrations of three anions in subsurface drainage and EC_b beneath the local compaction zone measured by TDR with time. Two characteristics can be observed.

First, the general solute movement follows a bell-curved leaching pattern with different magnitude and amplitude affected by antecedent moisture content and chemical application routings. The data suggest that different water flow paths or “mobile” and “immobile” waters exist. Water flowed rapidly through the larger pores (bypass flow) and reached the bottom of soil more quickly for the 10% moisture treatment. This resulted in a rapid concentration increase and high concentrations. A rainfall simulation study using 30-cm columns (Baker et al., 1997) indicated that the immediate appearance and large concentrations of Br must result from water movement through the columns through macropores. On the other hand, matrix flow water takes much a longer time to reach the bottom of soil, therefore the Br concentration in matrix flow is lower. The EC_b curve change was broader for the 15% moisture treatments than for the bypass flow for 10% moisture treatment (Figure 3-15). Baker et al. (1997) discussed that possibly some of the initial infiltration with greater Br concentrations wetted the soil by filling empty pore space. Besides a release of some of that water as the soil drained, Br could diffuse into, and later from, more immobile water. Compaction treatments did not affect the pattern of Cl and Br concentrations for 10 or 15% moisture treatments. The soil antecedent moisture treatment did. However, NO_3-N concentrations in drainage were significantly affected by both compaction and soil moisture treatments. Second, tracer movements were detected earlier with TDR. The lag time between EC beneath the soil bars and the tracer concentrations in drainage may reflect the travel time for water and solute moving from soil matrix through the sand layer to become drainage.

Modeling

Figure 3-16 shows changes in the total equivalent of $\text{NO}_3\text{-N}$, Cl and Br with time for all treatments, compared to EC in drainage measured by an EC meter. The trend of the total equivalent matched that for EC in drainage very well. This result indicates that EC in drainage can be used for estimation of solutes in drainage under one dominant anion condition. If assuming resident EC_b beneath compacted line source can represent the total equivalent of solutes (in this study, $\text{NO}_3\text{-N}$ could be a dominant solute when macroflow with Br and Cl bypasses this zone), EC_b can be related to EC_w in subsurface drainage by model. However, only parameter estimation was tried in this study.

The one-dimensional convection-dispersion model (CXTFIT) was used to test whether the observed EC_b valued can be well fitted by predicted values. The model results shows that, for 1.10 compaction treatment, the increase/decrease in resident chemical concentrations (could be, arbitrarily, $\text{NO}_3\text{-N}$ as mentioned earlier) changed with the moisture treatments, and EC_b concentration was changed faster for the 10-1.10 treatment than for the 15-1.10 treatment before/after the peak values (Figure 3-17). The mean V and D determined by CXTFIT were 0.35 cm/min and 1.18 cm^2/min for the 10-1.10 treatments, and 0.07 cm/min and 0.60 cm^2/min for the 15-1.10 treatment, respectively. The coefficients of determination, R^2 , for the inverse curve fitting by CXTFIT were 0.90 and 0.94, respectively, indicating good match with the observed data. However, the simulated relative value of EC_b did not match the observed values for compaction treatments higher than 1.10 for both 10% and 15% moisture treatments. Summarily, CXTFIT model could be used in this study in low compaction treatment. Arbitrary defined $\text{NO}_3\text{-N}$ input pattern (localized compaction line sources) in this study, different with standard input pattern of CXTFIT, needs to be further

confirmed by more studies. Assumption that EC_b beneath compaction line sources could represent NO_3-N in this zone needs evidence by analysis of the NO_3-N concentration (a relative study carried by authors in field lysimeter shows NO_3-N as the dominant solute in top layer of soil with higher concentrations). The inability of the convection-dispersion type model to reproduce EC_b higher compaction treatment confirms that a portion of tracers were leached via local compacted zone - a mechanism is not included in the model. And a fact-the observed EC_b patterns were a consequence of "limited leaching" caused by local compaction factor was not simulated by this model.

Summary and Conclusions

Leaching of NO_3-N is one of the greatest water quality problems in row-crop production of Iowa. Subsurface drainage of otherwise poorly drained/wet soils is necessary for optimum crop production. Practices which reduce NO_3-N leaching losses while maintaining regular drainage are desired. It is very difficult to reduce the losses associated with matrix flow. However, it may be possible to minimize the losses due to by-pass flow. Applications of N with localized compacted soil may result in much less leaching than with other application methods. This is especially true when heavy rainfall occurs soon after N application. It is even more important when the chemical applied is water-soluble and not bound to or attached to the soil particles or soil organic matter.

An approach has been tested in this study, which combined measurement of EC_b and volumetric water contents by the TDR technique in surface soil layer during rainfall

simulation in order to predict subsurface leaching as affected by soil properties. Soil runoff/drainage pans under rainfall simulation were used to study the effect of antecedent soil moisture and localized compacted zones with $\text{NO}_3\text{-N}$ within them on $\text{NO}_3\text{-N}$ leaching. The compaction treatment was imposed in the soil in the form of compacted soil bars placed 3.8 cm below the soil surface. Compacted soil bars represented only 3% of the soil surface area and at most 0.9% of the soil volume in the pan. Movement of Cl anion added with water to the soil prior to packing in the pans, and of Br added to rainfall was also measured.

For subsurface hydrology, 15% soil moisture content had a longer time to the beginning of drainage and less drainage volumes. This was opposite of what was expected and may be due to possible differences in soil mixing and packing process, and greater surface sealing with rainfall energy of unprotected surface soil at the higher antecedent moisture content. Due to the small percentage of soil surface area and soil volume occupied by the compacted soil bars, compaction treatments had no significant effect on subsurface hydrology.

Higher compaction caused lower concentrations and losses of NO_3N in subsurface drainage, resulting in a significant difference between bulk densities for both the 10 and 15% moisture treatments. The 10% moisture treatment produced greater $\text{NO}_3\text{-N}$ losses due to greater volume of drainage for that treatment. Higher bulk densities and moisture retained greater amounts of $\text{NO}_3\text{-N}$ in soil.

As “tracers”, Cl and Br leaching results help in understanding the effect of different solute source/location on leaching patterns. Their leaching/losses were greater for the low moisture treatments. On a percent-of applied basis, Br from surface application in rain only leached a little in part because of soil surface condition effect (sealing caused from rainfall).

However, Cl, as a soil incorporated source, had a higher leaching level than that of NO₃-N and Br for both antecedent soil moisture and local compaction treatments, which was mainly attributed to macro flow.

TDR measured soil volumetric water contents indicated the time-trends in top and subsurface soils and the “time-to-saturation”, and confirmed a higher final soil moisture for the 10% moisture treatment than for the 15%, suggesting higher water hold capacity for the former, and therefore a difference in structure for the packed soils. Only EC_b beneath compacted line source and NO₃-N in subsurface drainage significantly changed with time (Br and Cl were not affected by compaction treatment), indicating both were affected by compaction treatment. It provides a potential to estimate NO₃-N concentration with TDR in the zone just beneath the compacted line source.

In this study, higher degree of soil localized compaction did reduce NO₃-N leaching. Although higher antecedent soil moisture also reduced NO₃-N leaching, it probably did so because of some unique effects on the hydrology of the packed soil in runoff/drainage pans. EC_b in the top soil could be a realistic estimation of NO₃-N transport from soil matrix to subsurface drainage. These findings suggest that fertilizer placement in a local compacted zone, can offer desired results to reduce NO₃-N leaching. The information from this study is useful to the region with an environmental goal to reduce NO₃-N leaching.

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Table 3-1 Water amount, and beginning time of surface runoff and subsurface drainage

	Rainfall cm	surface runoff cm	beginning time min	subsurface drainage cm	beginning time min	stored in soil cm	stored in sand cm
Antecedent moisture (%)							
10	7.56a	3.35b	21.8a	1.69a	28.7a	2.32a	0.61a
15	7.94a	5.10a	11.3b	0.62b	43.7b	1.55b	0.66a
Bulk density (g/cm³)							
1.10	7.71a	4.35a	16.5a	1.19a	30.6a	1.97a	0.40a
1.33	7.73a	4.11a	16.7a	1.20a	36.5a	1.92a	0.39a
1.57	7.74a	4.10a	16.5a	1.17a	36.3a	1.91a	0.38a
1.81	7.75a	4.34a	16.5a	1.10a	36.8a	1.93a	0.40a

Table 3-2 Average nutrient concentrations and losses with subsurface drainage

	drainage cm	Conc.				Loss					
		NO ₃ -N	Br	Cl	EC _b	NO ₃ -N	Br	Cl	NO ₃ -N	Br	Cl
		-----mg/L-----				mS/cm	-----kg/ha-----			-----% applied-----	
Antecedent moisture (%)											
10	1.7a	368.4a	49.3a	674.9b	0.46a	63.7a	8.3a	112.5a	56.9a	21.9a	100.1a
15	0.6b	329.6a	21.8b	1256.0a	0.58a	20.7b	1.5b	78.9b	18.5b	3.9b	70.4b
Bulk density (g/cm ³)											
1.1	1.2a	656.3a	35.4a	945.5a	0.64a	82.1a	4.9a	97.0a	73.3a	13.1a	86.8a
1.33	1.2a	432.2a	34.1a	955.8a	0.75a	53.6b	5.1a	95.5a	47.9b	13.4a	85.3a
1.57	1.2a	176.8b	38.8a	921.2a	0.32b	21.1c	5.1a	95.6a	18.8c	13.4a	85.4a
1.81	1.1a	130.5b	33.9a	1039.5a	0.31b	12.1c	4.4a	94.7a	10.8c	11.7a	84.6a

Table 3-3 Volumetric water content determined by TDR (side probe was horizontally inserted 1 cm below the surface of soil, and low probe was horizontally inserted beneath compacted line sources) and gravimetrically after rainfall was ceased and subsurface drainage had stopped (5-10 min after rainfall ceased)

antecedent moisture			
method	10	15	mean
	-----%-----		
TDR side	0.338	0.294	0.316c
TDR low	0.522	0.488	0.505a
oven	0.412	0.373	0.393b
mean	0.424a	0.385b	
compaction			
1.10	0.422	0.377	0.400a
1.33	0.419	0.418	0.418a
1.57	0.446	0.385	0.415a
1.81	0.410	0.360	0.385a
mean	0.424a	0.385b	

Means with the same letter are not significantly at $\alpha=0.05$ level

TDR side			
antecedent moisture			
compaction	10	15	mean
	-----%-----		
1.10	0.333	0.283	0.308a
1.33	0.335	0.298	0.316a
1.57	0.337	0.301	0.319a
1.81	0.348	0.294	0.321a
mean	0.338a	0.294b	

Table 3-3 continued

TDR low				
antecedent moisture				
		10	15	mean
compaction		-----%-----		
1.10	g/cm ³	0.513	0.475	0.494a
1.33		0.513	0.583	0.548a
1.57		0.595	0.474	0.535a
1.81		0.468	0.419	0.443a
mean		0.522a	0.488a	

oven				
antecedent moisture				
		10	15	mean
compaction		%		
1.1	g/cm ³	0.419	0.373	0.396a
1.33		0.408	0.373	0.391a
1.57		0.406	0.379	0.393a
1.81		0.414	0.367	0.391a
mean		0.412a	0.373b	

Table 3-4 Anion concentrations in soil water and sand water at the end of rainfall simulation

		in soil		
		Br	Cl	NO3-N
		mg/L		
10%	1.10	42.33	10.16	12.42
	1.33	44.15	11.73	100.56
	1.57	46.88	21.11	342.47
	1.81	43.51	18.96	348.61
15%	1.10	59.50	75.52	323.50
	1.33	64.51	58.46	387.31
	1.57	61.67	67.91	628.96
	1.81	58.59	86.23	659.59
		in sand		
10%	1.10	41.04	56.19	65.49
	1.33	39.42	46.52	108.91
	1.57	39.15	55.82	65.69
	1.81	44.43	55.80	19.32
15%	1.10	34.25	464.24	384.05
	1.33	37.19	503.19	430.43
	1.57	34.01	348.97	61.54
	1.81	32.35	434.77	65.81
		in last drainage sample		
10%	1.10	51.63	72.92	281.15
	1.33	49.29	34.76	417.26
	1.57	50.52	51.69	101.71
	1.81	49.47	60.52	38.76
15%	1.10	34.13	851.48	1024.53
	1.33	26.66	1096.28	579.89
	1.57	41.01	783.46	118.41
	1.81	39.96	891.22	133.66

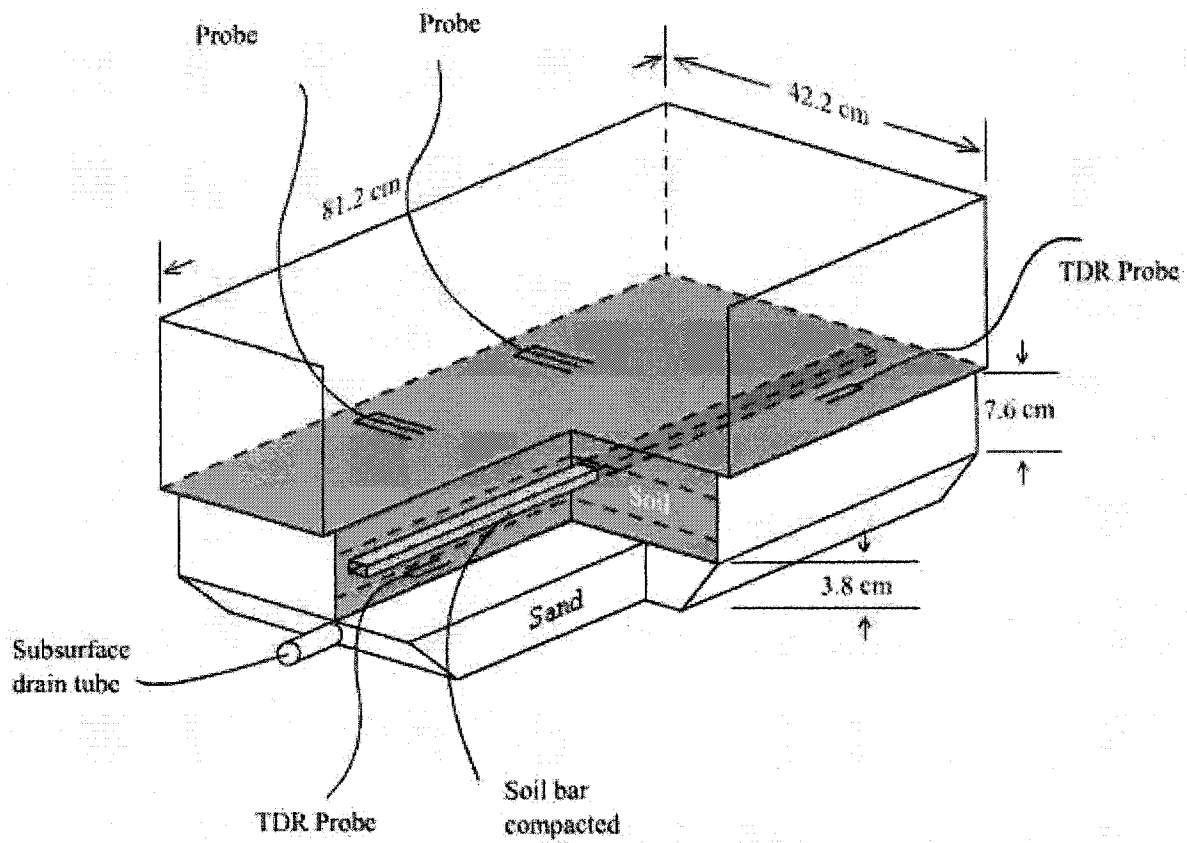


Figure 3-1 Schematic diagram of runoff/drainage pan

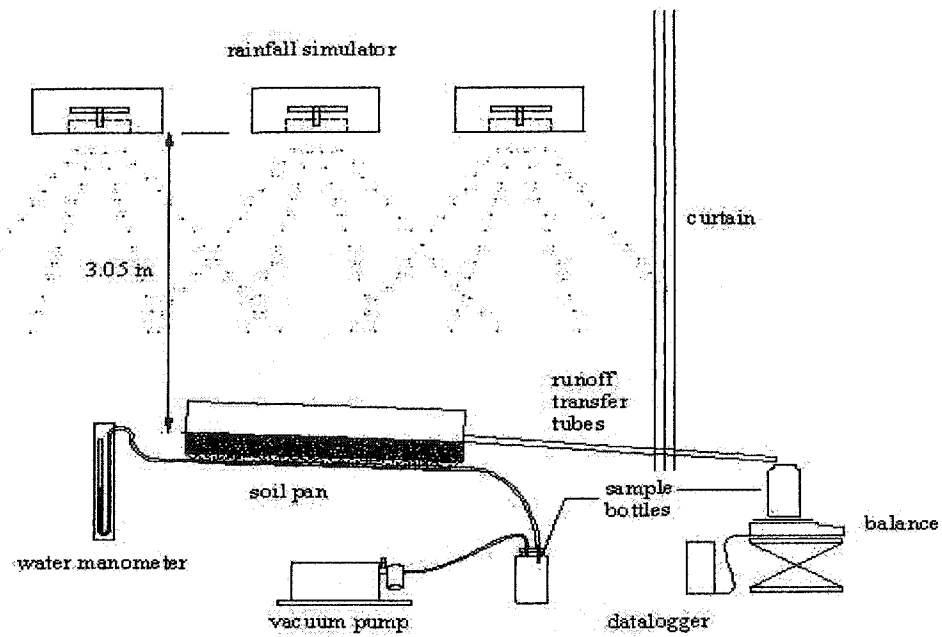


Figure 3-2 Rainfall simulator, runoff and subsurface drainage collection apparatus.

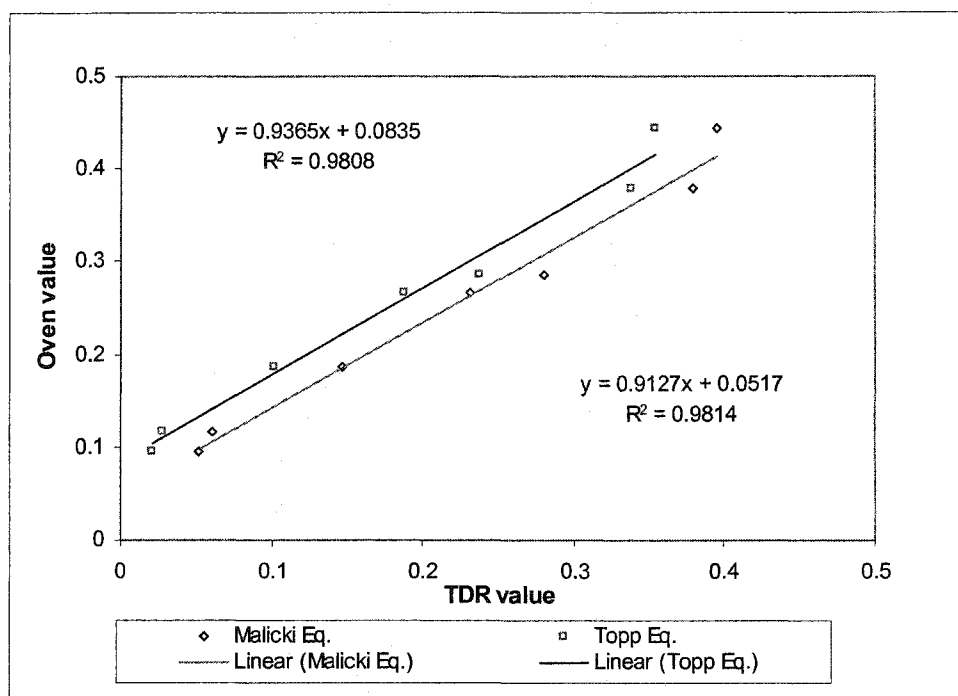


Figure 3-3 Volumetric water content determined gravimetrically (oven value) versus by TDR with Malicki and Topp equations in separate soil samples.

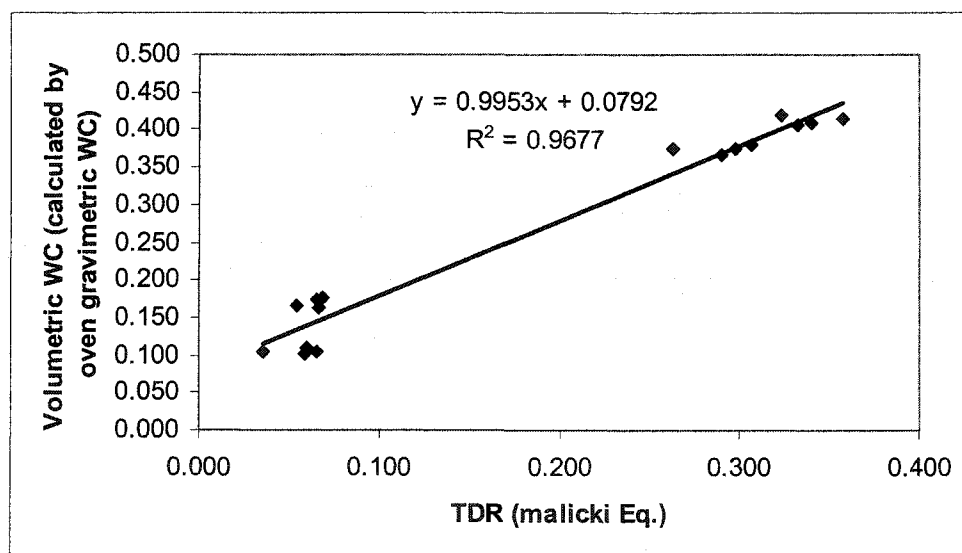


Figure 3-4 Volumetric water content determined gravimetrically (oven value) versus by TDR with Malicki equation with initial and final data in runoff/drainage pans.

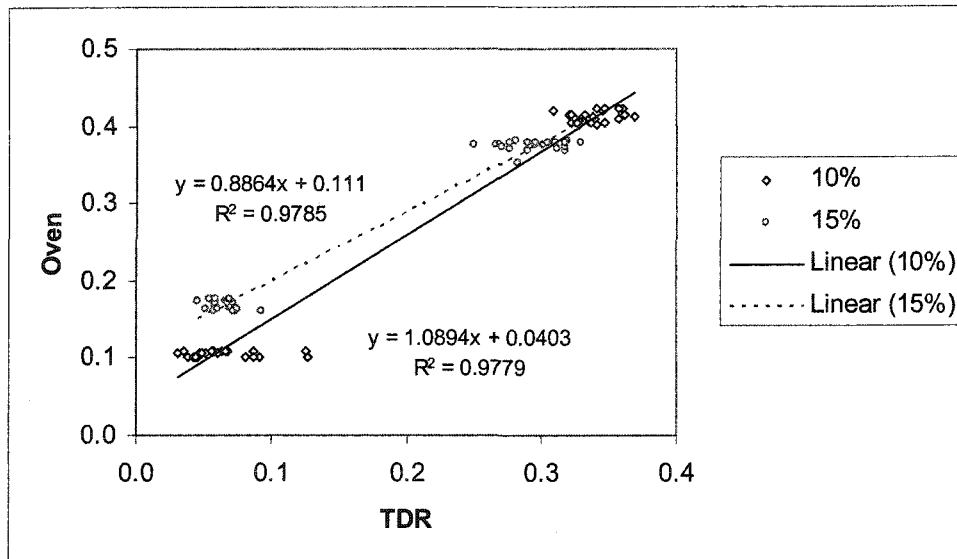


Figure 3-5 Volumetric water content determined gravimetrically (oven value) versus by TDR probes horizontally inserted 1 cm below the surface of soil with Malicki equation with initial and final data in runoff/drainage pans.

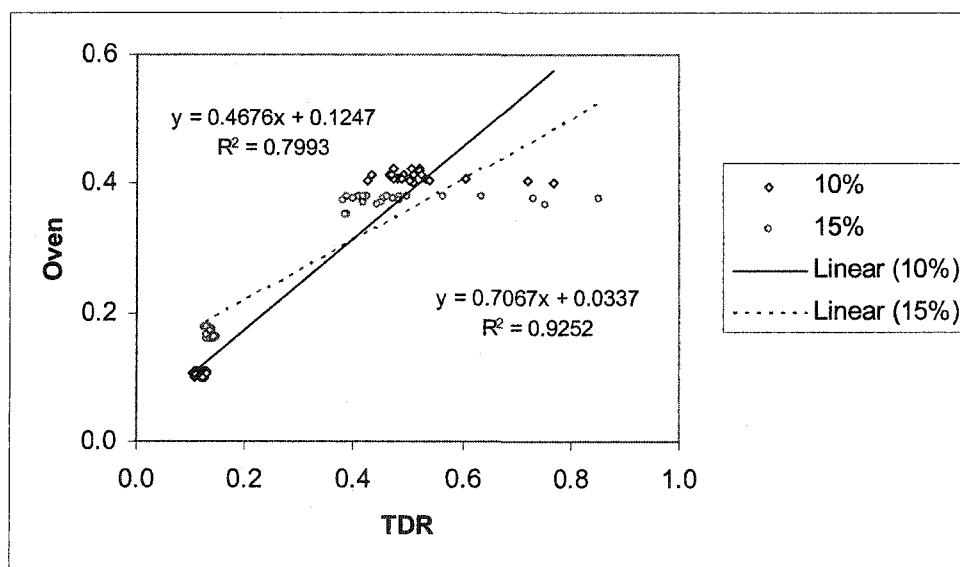


Figure 3-6 Volumetric water content determined gravimetrically (oven value) versus by TDR probes horizontally inserted beneath compacted line sources with Malicki equation with initial and final data in runoff/drainage pans.

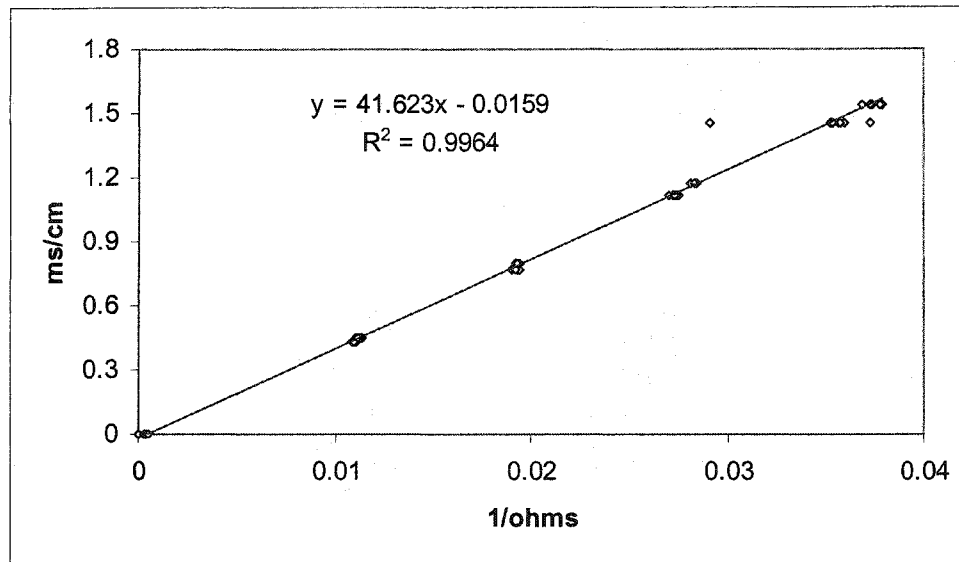


Figure 3-7 EC measured by TDR calibrated with EC measured by a EC meter in separate solutions.

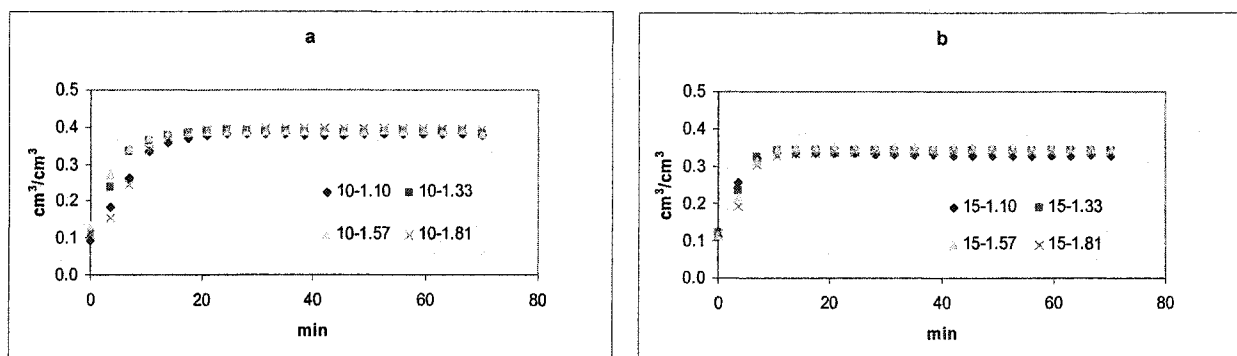


Figure 3-8 Volumetric water content measured by TDR probes horizontally inserted 1 cm below the surface of soil for 10% (a), and 15% (b) moisture treatment calibrated by Malicki equation in Figure 3-3.

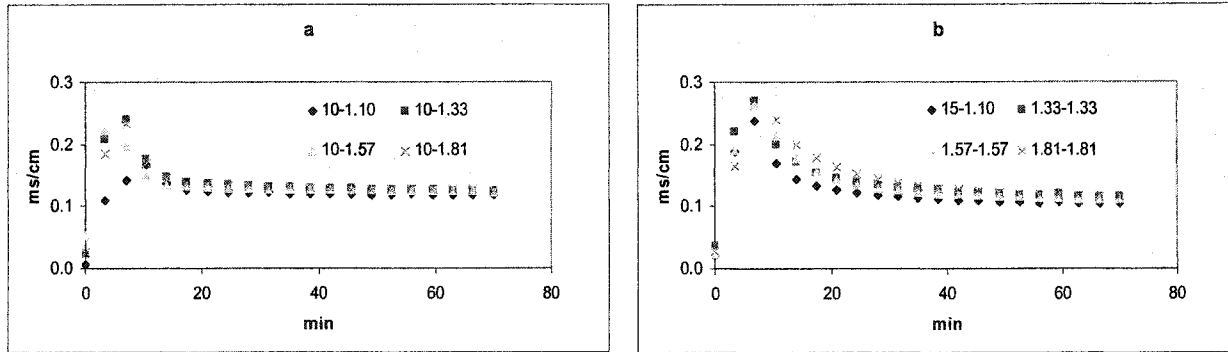


Figure 3-9 EC_b measured by TDR probes horizontally inserted 1 cm below the surface of soil for 10% (a), and 15% (b) moisture treatment calibrated by Figure 3-7.

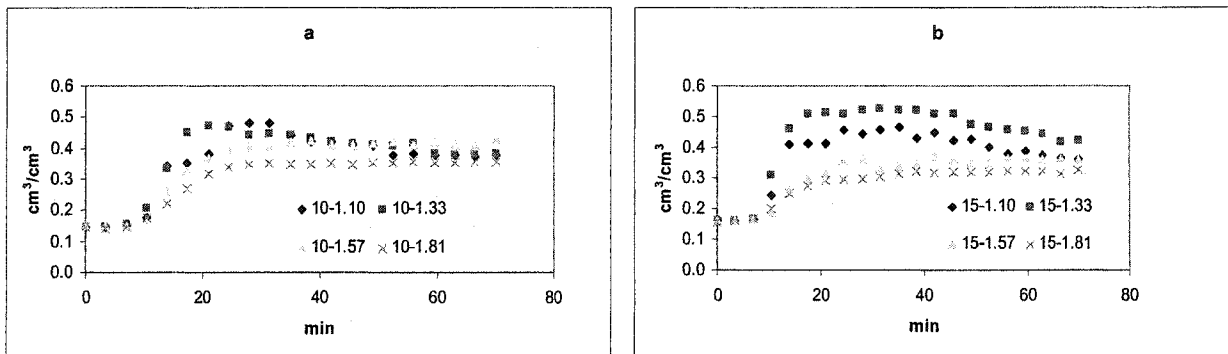


Figure 3-10 Volumetric water content measured by TDR probes horizontally inserted beneath compacted line sources for 10% (a), and 15% (b) moisture treatment calibrated by Malicki equation in Figure 3-3.

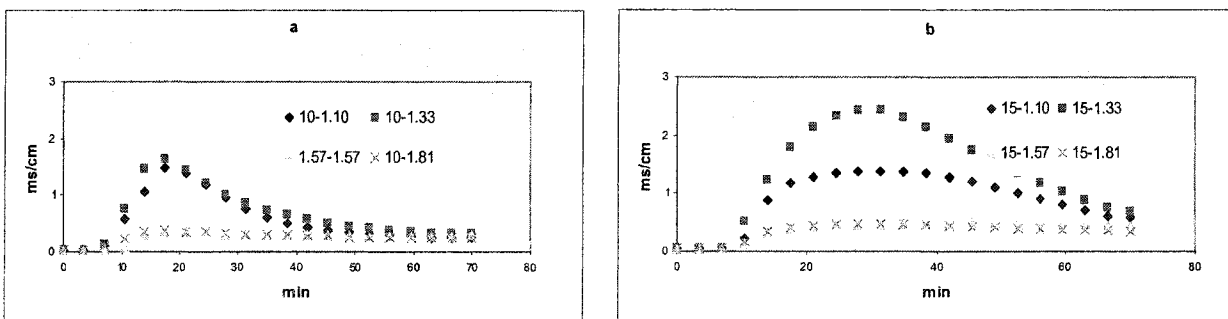


Figure 3-11 EC_b measured by TDR probes horizontally inserted beneath compacted line sources for 10% (a), and 15% (b) moisture treatment calibrated by 3-7.

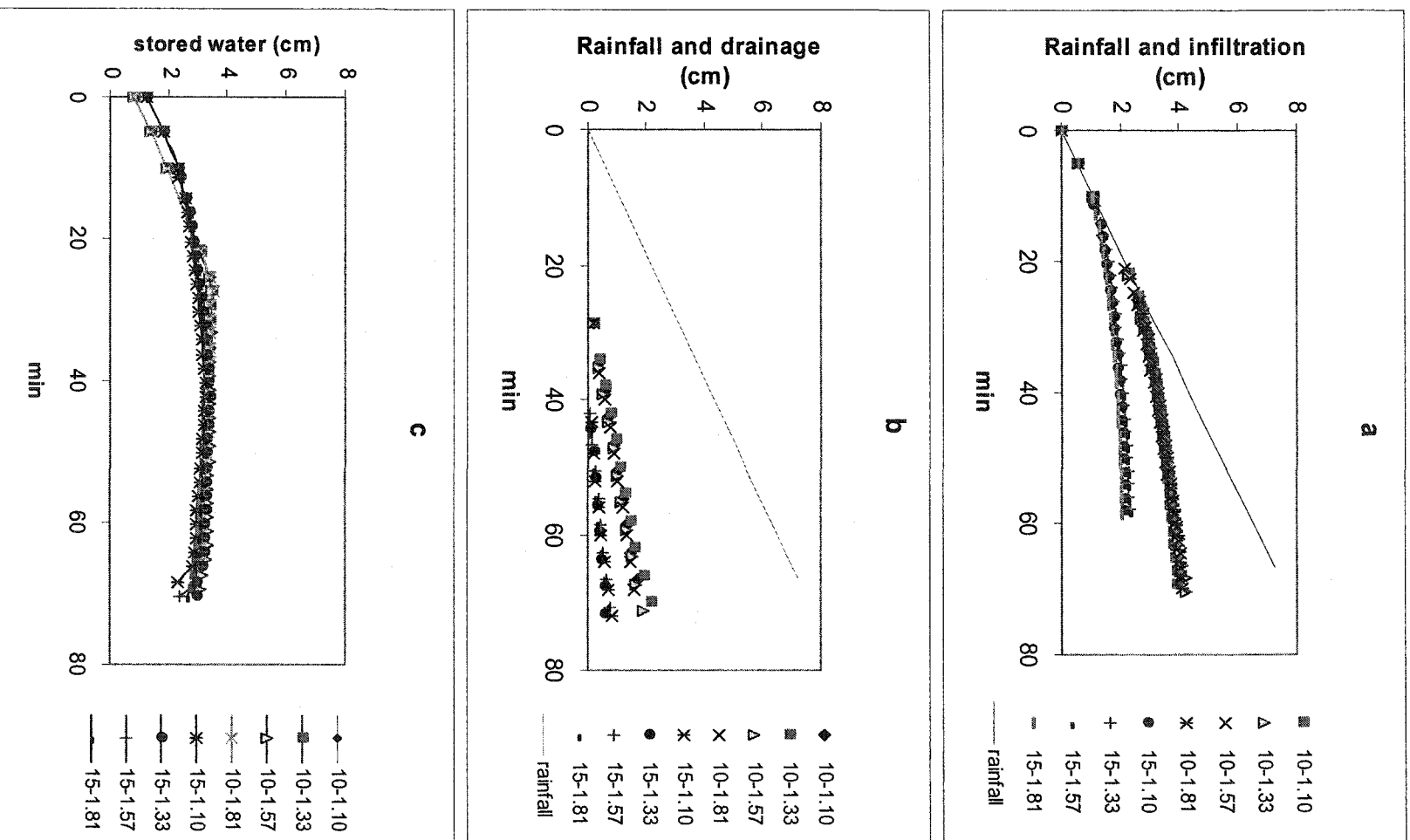


Figure 3-12 Cumulative rainfall and outflows/storage with time

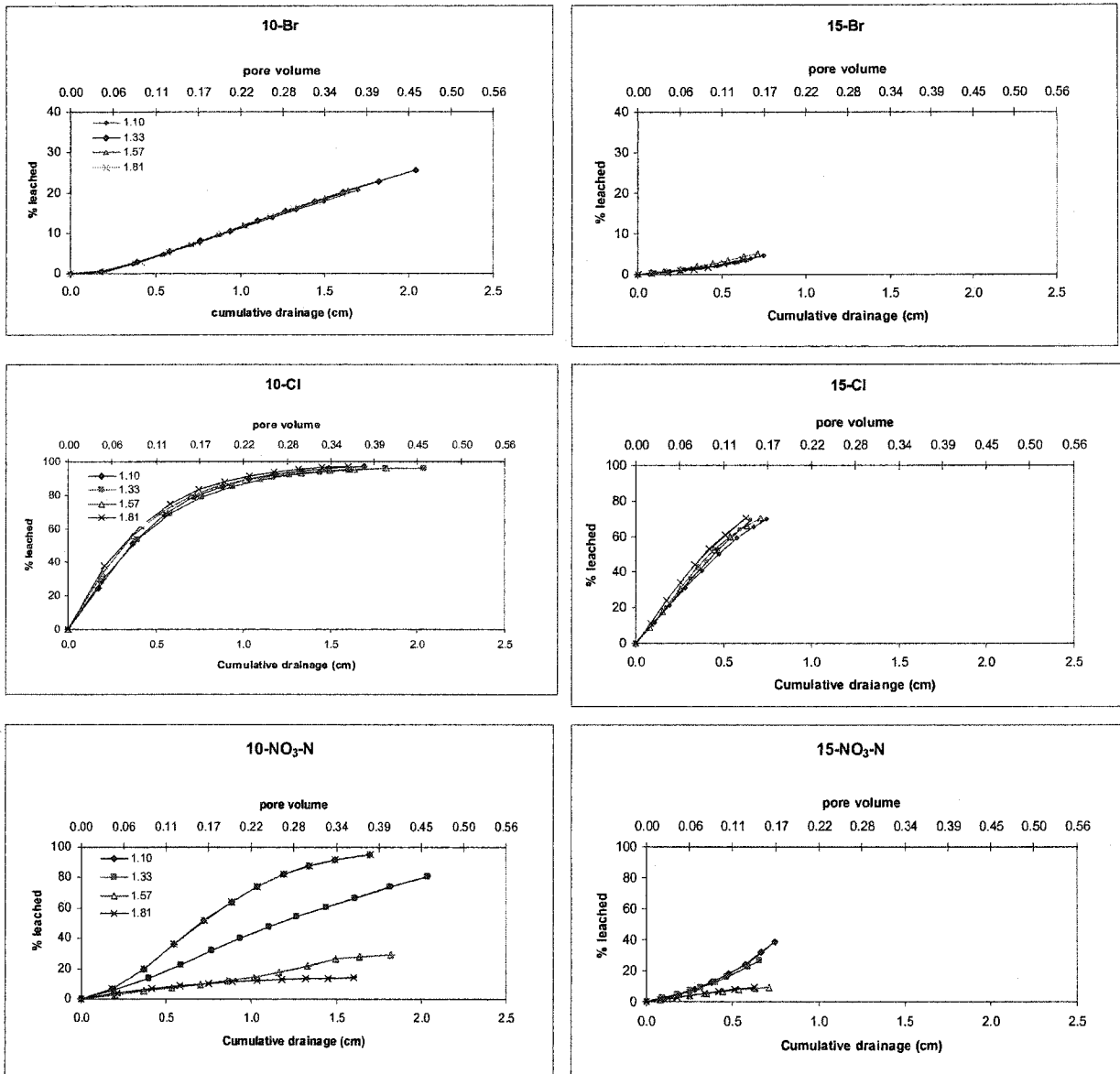


Figure 3-13 Cumulative mass fraction of Br, Cl and NO₃-N that leached with subsurface drainage

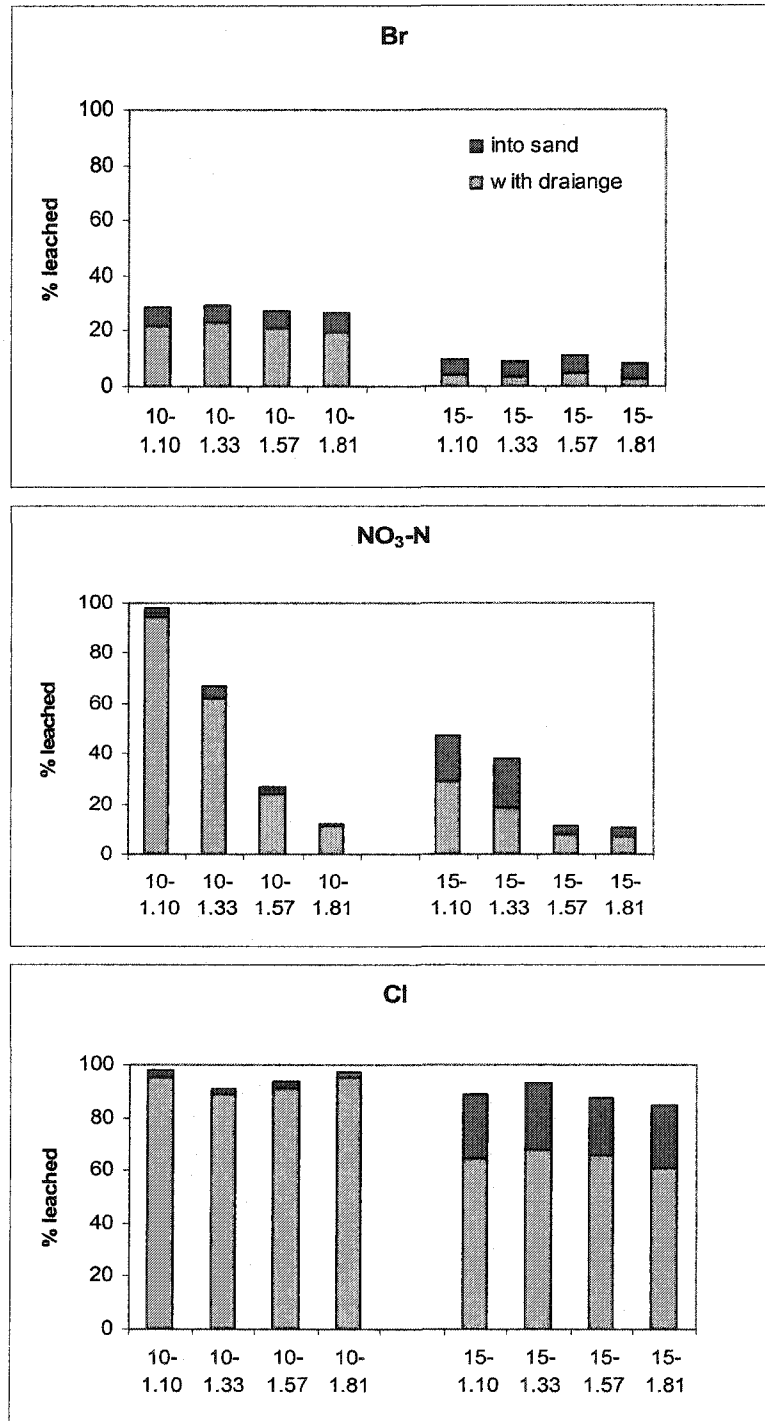


Figure 3-14 Anion leaching fractions in sand and subsurface drainage at the end of rainfall simulation

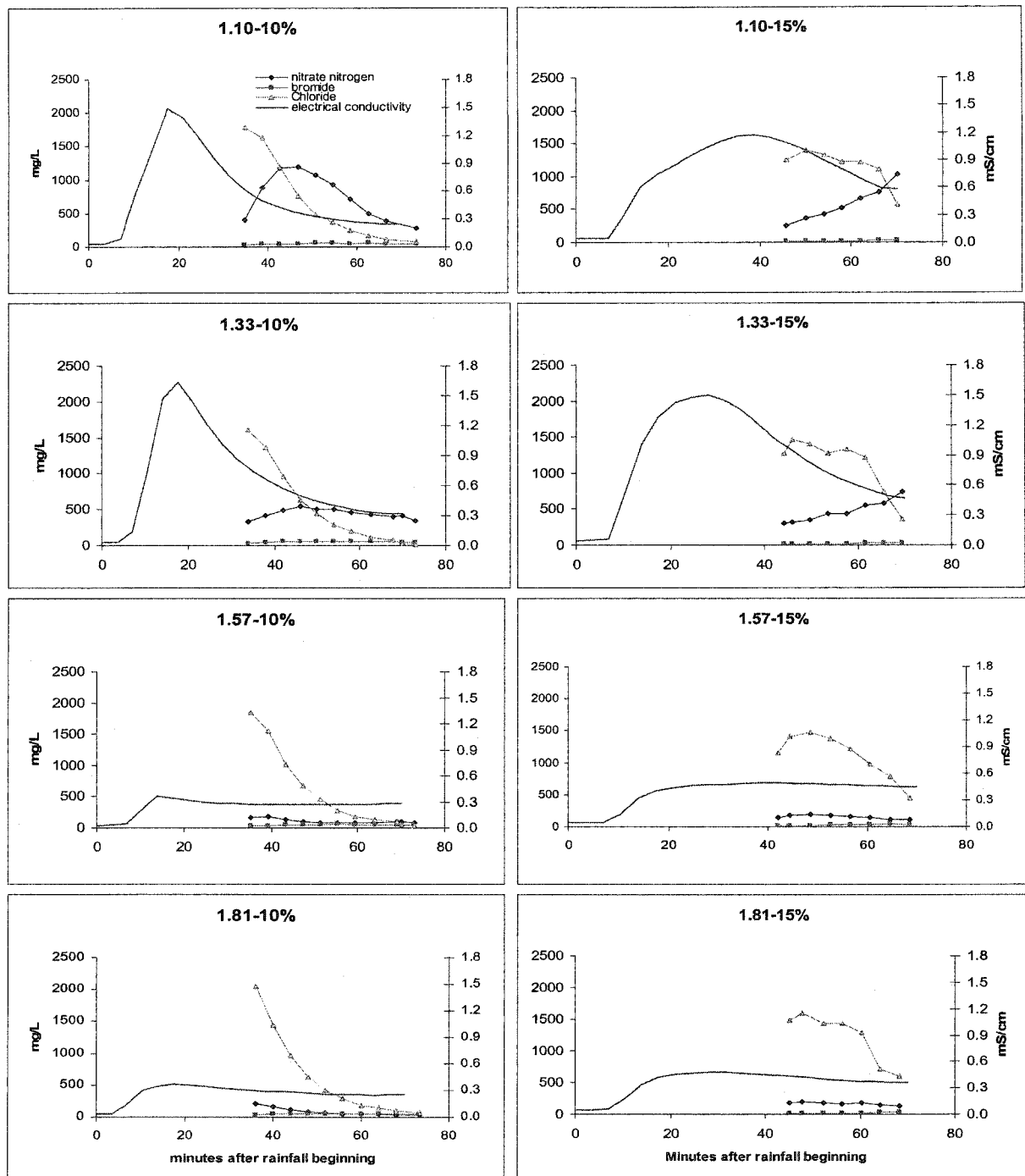
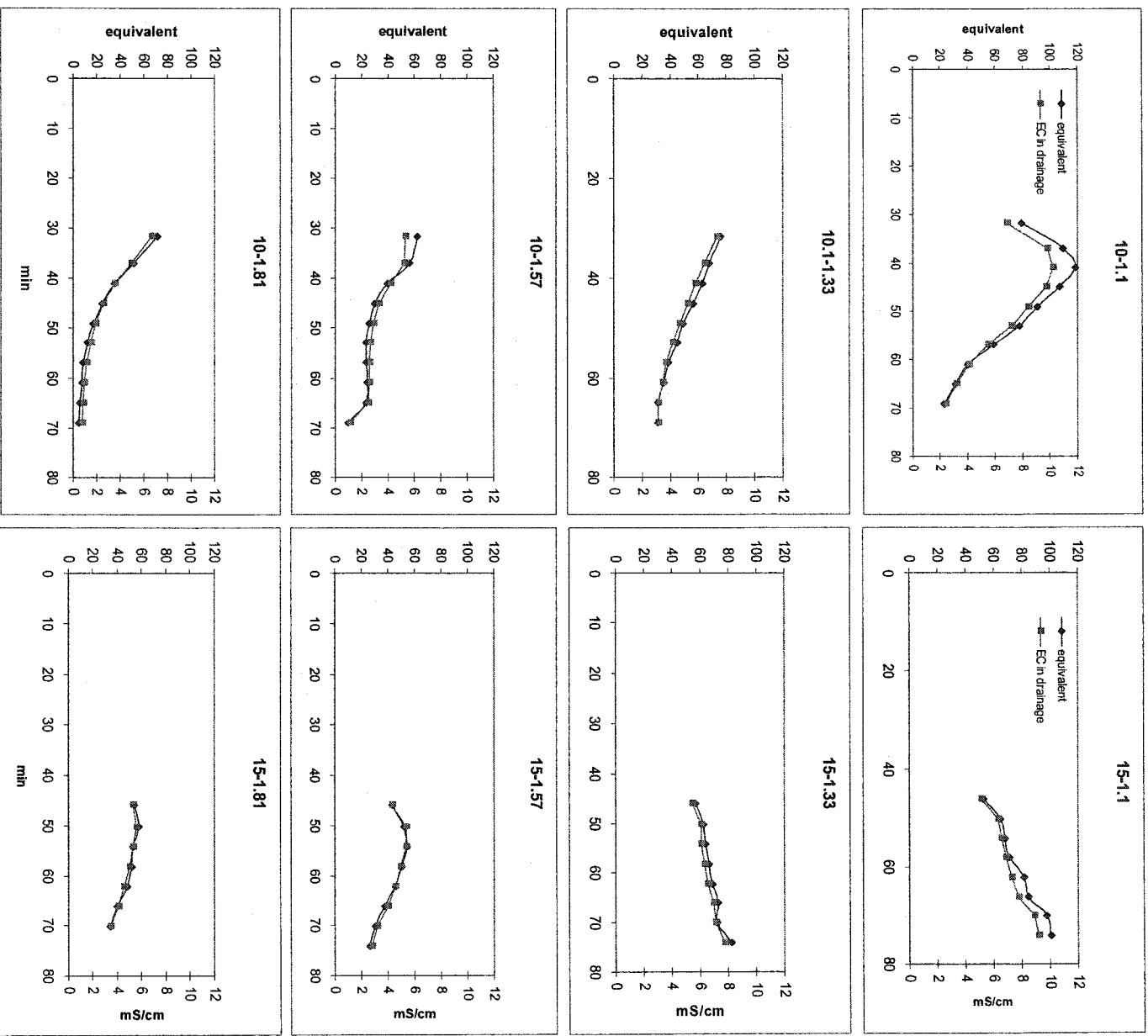


Figure 3-15 EC_b beneath the soil bar and Cl, Br, and NO_3 -N in drainage with time

Figure 3-16 EC_b and total equivalent in drainage with time

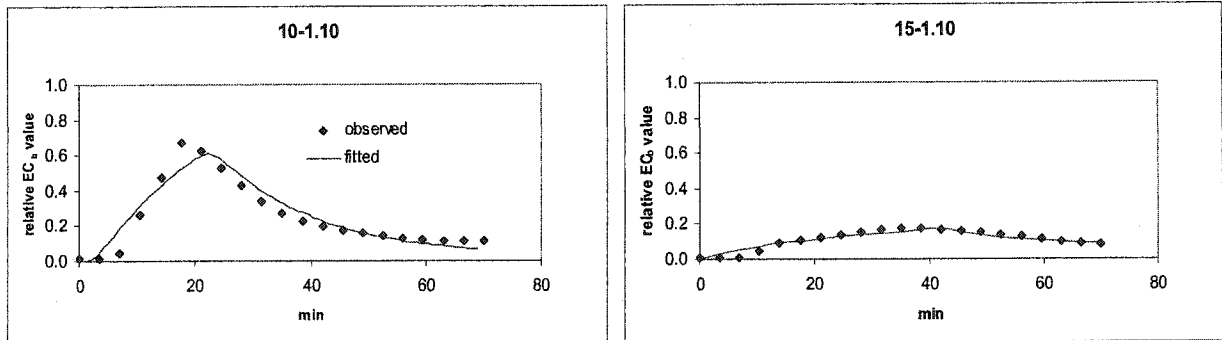


Figure 3-17 Relative EC_e observed by TDR fitted value by CXTFIT with time.

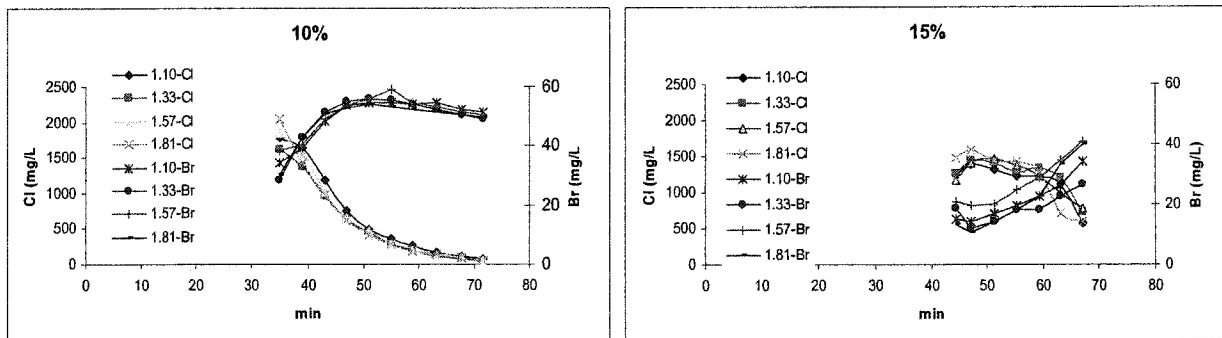


Figure 3-18 Br and Cl concentrations with rainfall simulation time for moisture treatments.

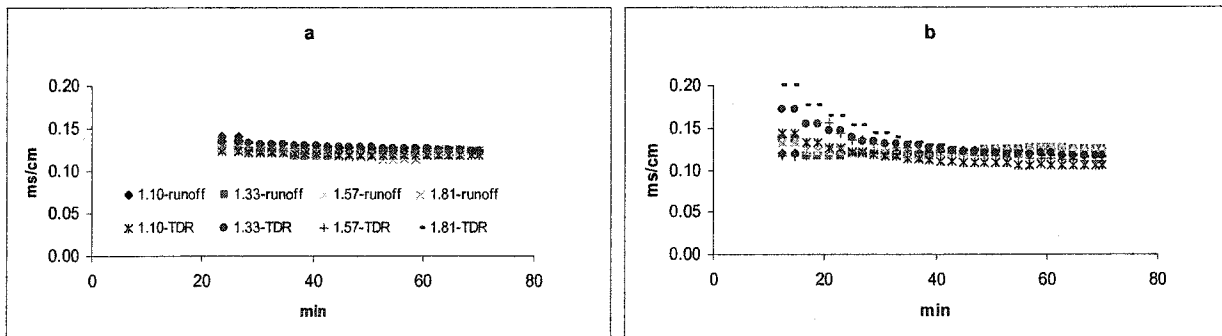


Figure 3-19 EC_b in 1 cm below soil surface and EC_w in surface runoff for 10% moisture treatment (a), and 15% moisture treatment (b).

CHAPTER 4. SOIL MANAGEMENT IMPACTS ON ANION TRANSPORT WITH SUBSURFACE DRAINAGE

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Jian Zhou James L. Baker

ABSTRACT

Soil compaction and tillage may affect the transport of anionic nutrients from surface soil to subsurface drains. The impacts of local soil compaction in the zone of $\text{NO}_3\text{-N}$ application and tillage methods on transport of anions with subsurface drainage water were studied in lysimeters using rainfall simulation. The lysimeters received 100 kg $\text{NO}_3\text{-N/ha}$, in compacted soil bars or as line sources with $\text{NO}_3\text{-N}$ in solution added to uncompacted soil in three parallel lines separated by 76.2 cm. Simulated rainfall, with 50 mg/L Br and 10 mg/L $\text{PO}_4\text{-P}$, was applied at an intensity of 5 cm/h for 60 min. Time domain reflectometry (TDR) probes were installed horizontally beneath the soil bar or solution line source and vertically between two of the three parallel line sources to measure soil moisture and bulk electrical conductivity (EC_b). An ISCO 3230 bubbler/pressure sensor was used in each lysimeter for water table measurement before, during and after rainfall simulation. For the compacted soil bar treatment only 0.54% of applied $\text{NO}_3\text{-N}$ leached with drainage; the corresponding value for the no compaction treatment was over four times greater at 2.35%. Tillage treatment did not affect $\text{NO}_3\text{-N}$ leaching. But no till treatment held a greater amount of $\text{NO}_3\text{-N}$ in the soil

profile than the tillage treatment. Soil EC_b results also indicated that localized soil compaction reduced NO_3-N leaching relative to no compaction. Moreover, the relationship between NO_3-N and EC_b was tested in this study, indicating NO_3-N in 15 cm of top soil is curvilinear related to EC_b beneath line sources. Results of this study are helpful in quantifying soluble anions transport to subsurface drainage, and developing improved management practices to reduce NO_3-N subsurface drainage losses.

Keywords. rainfall simulation, lysimeter, TDR, water table, nutrients

Introduction

Nitrogen

One of the major water quality degradation problems from nonpoint sources of pollution in agriculture results from off-site transport of nutrients as a consequence of excess precipitation and the resulting surface runoff and/or subsurface drainage. One of primary nutrient forms carried with subsurface drainage is nitrate-nitrogen (NO_3-N). Nitrate leaching refers to NO_3-N in water moving downward through the soil profile and out of the rooting zone. Nitrate is the form of N most likely lost by this process because it is not adsorbed to soil by cation exchange reactions, and usually is the most abundant form of N in the soil water that moves. Leaching of N is undesirable because it represents an economic and energy loss and is a potential threat to water supplies. The amount of N lost by leaching varies greatly with number, intensity, and times of rainfall events; amount and location of NO_3-N in the soil when conditions are favorable for leaching; cropping and tillage; and soil texture.

Tillage

Tillage disrupts continuous macropores (particularly those vertically oriented), which provide pathways that can rapidly transport water and solutes deep into soils in a short time (Ressler et al., 1998). The degree of tillage has the potential to affect both $\text{NO}_3\text{-N}$ concentrations and the volumes of surface runoff and subsurface drainage, where tillage can range from complete inversion with the moldboard plow to no tillage at all (Baker, 2004). In no-till cropland, infiltrating water tends to flow preferentially from the soil surface into macropores with openings at the surface. Some studies, including one in Iowa (Weed et al., 1996), have shown that movement of a greater percentage of water through preferential flow-paths, possibly causing “by-passing” some of the N in the no-till profile, and possibly some dilution due to higher average infiltration rates and drainage volumes with no-till, result in no-till plots having lower $\text{NO}_3\text{-N}$ concentrations in subsurface drainage compared to plowed plots. However, when concentration data were combined with flow volume data to calculate losses in that study, somewhat lower flows from continuous corn with tillage, such as moldboard plow, somewhat off-set the higher concentrations, although losses were in the order no-till less than tillage for the corn-soybean and soybean-corn rotations.

Localized soil compaction

Creating a surface dome/ridge, compacting a soil layer, and disrupting macropores in the zone of N application are strategies that can reduce leaching of applied $\text{NO}_3\text{-N}$ (Ressler et al., 1998). An applicator using localized soil compaction and doming (LCD) was described by Ressler et al. (1997), which attempts to combine these strategies to smear and close

macropores below the N-injection knife, fill and compact soil into the knife slit, and cover the fertilizer band with a surface ridge or dome.

In a rainfall simulation study of water and anion movement under ridge tillage, $\text{NO}_3\text{-N}$ and bromide (Br) placed in the elevated portion of the ridge reduced anion leaching compared to a similar application with flat tillage (Hamlett et al., 1990). Kiuchi et al. (1994) showed impermeable barriers placed over applied chloride (Cl) delayed column breakthrough and reduced peak concentrations of Cl. In another study, Baker et al. (1997) measured Br leaching from undisturbed blocks of soil where the Br was broadcast-applied or point-injected with and without compaction around the point of injection. Compaction significantly reduced Br leaching, with concentrations for the treatment on no-till blocks of soil being 7 and 11% of the uncompacted point injection and broadcast application treatments, respectively. Comparison of $\text{NO}_3\text{-N}$ applied with a LCD applicator with that applied with a conventional knife applicator during the growing season (Ressler et al, 1997) showed that under natural rainfall the average depth of leaching for the $\text{NO}_3\text{-N}$ applied with the LCD applicator was only 60% of that for the knife applicator.

Entrapped air

Cropland that is susceptible to seasonal or intermittent high water table conditions during the growing season usually requires subsurface drainage installation which serves to lower the water table to a level equal to the drain depth. This water table management is needed to control soil-water conditions in the profile of agricultural soils. However, one of the factors possibly affecting infiltration and water table changes is air entrapment; a factor that is still not fully understood. Wang et al. (1998) indicated that soil air compression during

an irrigation experiment can lead to a substantial decrease in the rate of infiltration. Some rainfall could cause the soil surface to be quickly sealed by water, leading to immediate compression of air below the wetting front. Air can be confined ahead of the wetting front, escaping only through the soil surface (air confining). If ponding occurs, water infiltration into an air-confined medium is negatively affected by that ponding on the soil surface. In addition, the air pressure between the saturated top layer and a “water table” near the bottom of a soil column could cause water to flow out of the column at a higher rate. Thus air entrapment could be an important factor in lysimeter studies of infiltration. For example, following the addition of water or a solution to the surface, the air pressure inside a lysimeter may increase, resulting in a near-immediate water discharge from the bottom if discharge is possible. Wang et al (1998) also mentioned that the amount of water then being discharged could be misinterpreted as fluid breakthrough from the applied water, or a decrease in water table could be misinterpreted as direct evaporation from the soil surface. In addition, uneven distribution of air pressure and fluctuation in the entrapped soil air pressure are two important points affecting water table elevation change. Uneven distribution of air pressure in subsoil could cause the shallow groundwater table to decrease or increase locally. One study showed that preferential flow is affected by air compression ahead of the wetting front. When the air pressure ahead of the wetting front reached an “air-breaking” value, soil air escaped from the surface, leading to an immediate decrease in the air pressure and increase in the infiltration rate. When the air pressure fell below a certain air-closing value, air escape stopped, the infiltration rate decreased again, and the air pressure increased. This cyclic process repeated itself during the entire infiltration period.

Use of time domain reflectometry (TDR)

Soil volumetric water content can be determined by dielectric constant (k) measurements using TDR (Topp, 1980):

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} k - 5.5 \times 10^{-4} k^2 + 4.3 \times 10^{-6} k^3 \quad [4-1]$$

Malicki et al. (1996) developed another equation which includes soil bulk density (ρ_b):

$$\theta_v = \frac{k^{0.5} - 0.819 - 0.168\rho_b - 0.159\rho_b^2}{7.17 + 1.18\rho_b} \quad [4-2]$$

Simultaneously, the reflected electromagnetic (EM) waves of TDR can be used to measure bulk electric conductivity (EC_b) via soil impedance change (Topp et al., 1988; Heimovaara et al., 1995; Zhou, et al., 2003). A linear relationship (equation 4-3) can be developed between the soil resident solute concentrations and EC_b through calibration (Nadler et al., 1991; Ward et al., 1994; Heimovaara et al., 1995; Mallants et al., 1996; Lee et al., 2000; Zhou et al., 2002):

$$C = \alpha + \beta EC_b \quad [4-3]$$

Where α and β is are calibration constants. The EC_b can be related to the impedance, Z (Ω) of an electromagnetic wave that travels through the soil using the equation (Topp et al., 1988; Heimovaara et al., 1995, Mallants et al., 1996):

$$EC_b = \frac{K_c}{Z - Z_{cable}} \quad [4-4]$$

Where K_c is the cell constant of the TDR probe, and Z_{cable} is the resistance associated with cable, connectors, and cable tester which can be omitted for salinity levels less than ≈ 0.3

S/m , $Z_{\text{cable}} \ll Z$, and therefore was omitted. Although Eq. 4-4 shows that the EC_b may be calculated directly from the TDR-measured Z if the cell constant for TDR probe, K_c , and Z_{cable} are known. Many researchers also describe EC_b as a function of the EC_w and θ . For a given θ , the relation between EC_b and EC_w may be given in a linear form (Rhoades et al., 1976). While many field studies, used traditional sampling methods, lose some “information” occurring between sampling intervals. TDR has the advantage that it can be used for continuous monitoring in real time during rainfall/drainage events.

Anion tracers

Many researchers have used anion tracers, such as Br and Cl, to evaluate the movement of water and solutes in the soil profile. Br and Cl are highly water soluble and have minimal soil adsorption and precipitation tendencies under normal field conditions.

Objectives

One objective of this study was to estimate changes in $NO_3\text{-N}$ concentrations beneath local chemical application zones based on EC_b measured with TDR. The second objective was to determine $NO_3\text{-N}$ concentrations in subsurface drainage from treatments with different tillage (till and no-till) and different chemical placement treatments (located in a compacted soil bar or applied in solution to uncompacted soil). The third objective was to estimate soil air effects on infiltration and percolation by measuring water table changes with time during rainfall simulation.

Materials and Methods

The rainfall simulation experiment was carried out in non-weighing lysimeters at the Agronomy and Agricultural Engineering Research Center, 11 km west of Ames, IA (Figure 4-2). The lysimeters were 1.37 m deep and 0.97 m wide by 2.29 m long (see Figure 4-1); and the soil in the area is mapped as Nicollet silt loam (a fine-loamy, mixed, mesic Aquic Hapludoll). Soil for each of 16 lysimeters (12 were used in this study), was excavated and an impermeable liner was placed in each excavated volume. A 10-cm diameter perforated PVC drainage tube was placed horizontally in the bottom on the plastic liner, and a 1.25-cm PVC vertical water access tube was attached to the drainage tube. Soil was returned to the excavated volume in respective horizons and at previous bulk densities. Seasonal use of the lysimeters with repeated freeze-thaw cycles and vegetation growth since their construction in 1982 should have restored much of the original unexcavated soil structure (Ressler et al, 1998; Stamm, 2001).

Treatments

The experiment was designed as a two-by-two-factorial study. The twelve lysimeters to be used in this study were laid out in a randomized block design with three replications, using two tillage practices (no-till and tillage) and two methods of N-fertilizer applications (local soil compaction and no compaction as a line source). The treatments (Figure 2) are denoted as tillage/local compaction (TC), tillage/no compaction (TNC), no-till/local compaction (NTC), and no-till/no compaction (NTNC). Before $\text{NO}_3\text{-N}$ addition and rainfall

simulation, background soil samples were taken to determine the initial moisture contents and $\text{NO}_3\text{-N}$ concentrations in the soil profile of each lysimeter.

One month prior to rainfall simulation in the fall of 2003, all vegetation (grass and weeds; no crops were grown in 2003) was cut and removed from the lysimeters. In order to monitor water table changes during and after rainfall simulation, the lysimeters were pre-drained to decrease the water table. They were pumped twice each week, using a small electric impeller pump, until the water table was located around the same depth as the top of perforated drain tube (10 cm). Before $\text{NO}_3\text{-N}$ addition, the soil surface of six lysimeters for the tillage treatment were “tilled” with a Four-Cycle Cultivator/Edger (Craftsman, Model 316.29270, Sears, Roebuck and Co.) to a 13-cm depth, followed by hand raking to level the plots. This probably reduced the number and continuity of macropores due to shearing the upper 13 cm (although judging from the “loosening” of the soil, total porosity was increased). The six other lysimeters were kept in no-till. Three small parallel “trenches” were made in each lysimeter, with a 76-cm spacing (simulating the row-crop spacing for much of Iowa), in the direction perpendicular to the long dimension of the lysimeters and to the subsurface drainage tube, and to be used for placing the compacted soil bars containing $\text{NO}_3\text{-N}$ or applying the $\text{NO}_3\text{-N}$ solution as a line source. Background concentrations of nutrients in drainage water are displayed as individual points 1.5 days before rainfall simulations.

Compacted soil bars

Aluminum channels were used as “forms” in the laboratory to hold the soil in a rectangular cross section as it was being compressed to create the compacted soil bars. The dimensions of aluminum channel were 38.10 cm long by 2.67 cm wide by 2.29 cm high,

resulting in 101.61 cm^2 surface area and 232.29 cm^3 volume. Each aluminum channel was packed with 255.5 g (dry weight) of soil, with 30 mL of $\text{Ca}(\text{NO}_3)_2$ (concentration of 0.844 g/mL) added to it, which gave an initial bulk density of 1.1 g/cm^3 . A “Sintech” computer-integrated testing machine (MTC Corporation) was used to compress the soil bars to the desired bulk density ranging from 1.1 (no additional compaction) to 1.8 g/cm^3 . Compression was done by using a grid cell and iron press bar attached to it with dimensions fitting inside the aluminum channel. By fixing the speed and varying the time-of-travel for the iron press bar, the desired distance of travel was reached, which was related to bulk density. Plastic wrap was placed inside the aluminum channel to reduce the friction between the soil and the aluminum channel for easier removal of soil bar after compaction (Nasritdinov, 2003). After compression to the desired density was complete, the aluminum channel was put in a bench clamp, and the open edge of channel was expanded a little, which allowed removal of the soil bar from the channel without breaking it.

TDR setup

The TDR assembly used in this study included a Tektronix 1502 cable tester (model 1502B, Tektronix Corp., Redmond, OR), SDM50 multiplexer, SDM1502 interface, and TACQ program (Evelt, 1998; Lee, 2000). Equations 4-2 and 4-4 were used to determine volumetric water content and EC_b , respectively. This was done as a function of time during the rainfall simulation experiments. In addition, the calibration curves for EC_b and volumetric water content were made prior to rainfall simulation. Three-rod, 2-mm diameter, 15-cm long TDR probes were used during the rainfall simulation experiments. Four probes were installed in each lysimeter. Two of them were placed horizontally in one of the three parallel lines 1

cm below the line source; the other two probes were vertically placed between one side line and the middle line. It was assumed that the two vertical TDR probes measure the average values of EC_b and moisture content for the top 15-cm layer of soil.

Tracers

Two “tracers”, Br and phosphate-phosphorus ($PO_4\text{-P}$) were dissolved in the rainwater (deionized water at a 4000-L tank) at 50 and 10 mg/L, respectively, and were used to evaluate the movement of water and solute through the soil to subsurface drains.

Nitrogen-nitrogen addition

Nitrate-nitrogen at the rate of 100 kg/ha (as $Ca(NO_3)_2$) was added to the soil as a line source shortly before rainfall simulation, either as compacted soil bars or applied in solution to small trenches. Three parallel trenches per lysimeter, with a 76.2-cm spacing and approximately 12.7 cm deep, were dug in the soil with a small hoe for line source placement. Two and one-half lengths (38.1 cm) of the compacted bars were placed end to end in each row 1 cm above previously positioned TDR probes. Thus the soil bars were located 10 cm below the surface of soil. For the no compaction treatment, soil was removed from a trench until the depth was 10 cm, and 74 mL of $NO_3\text{-N}$ solution (concentration of 0.844 g/mL) per row was uniformly applied with a hand sprayer to the bottom of the trench. The trench was then back-filled with soil.

Simulation and Sample Collection

A three-nozzle sweep rainfall simulator was used to produce simulated rainfall over the lysimeters. The simulator was positioned 3.05 m above the lysimeters and the combination of nozzle height, 0.42 kg/cm^2 operating pressure, and flow rate created droplet sizes and velocities similar to natural rainfall. An electronic timer that could be adjusted to attain the desired rainfall intensity controlled the sweep period of nozzles (Stamm, 2001). One by one, after chemical application, each lysimeter immediately received 5 cm of simulated rain at 5 cm/h. Although the probability of such a storm occurring so soon after chemical application is small, it is not impossible (Ressler et al. 1998). Despite this high intensity, water infiltration and soil permeabilities were sufficient to allow most of rainfall to infiltrate for the no-till treatment for the duration of the rain. However, water that did not immediately infiltrate collected in small surface depressions that existed naturally for the tillage treatment by the end of the rainfall simulation, and most of soil surface was ponded possibly due to surface crusting/sealing. After the simulation, all lysimeters were covered by tarps to protect them from natural rainfall and minimize evaporation of water from the soil surface.

Subsurface drainage samples from each lysimeter drain tube were pumped to sample pails using a small electric impeller pump. Cross-contamination of samples between lysimeters was prevented by allowing the sampling pump to run for approximate 1 min prior to taking a sample. Eight samples were taken from each lysimeter at 3.5, 3.8, 4.9, 7.8, 22.9, 96.8, and 242.5 h after rainfall simulation ended. The amount of subsurface drainage

associated with each sample was determined by weighing the water that was pumped. The water samples were stored in plastic bottles at 4°C immediately after collection.

Bubbler/pressure sensors (ISCO 3230) were installed in the outlet access tube of each lysimeter for water table measurement before, during, and after rainfall simulation. Measurement was stopped at the time of the first subsurface drainage sampling (3.5 h after rainfall beginning).

Soil samples were taken before and after rainfall simulation (see Figure 4-1; soil core 1 and 2 represent samples taken before and after rainfall simulation, respectively). Soil cores 1 and 2 were collected with a tractor soil core sampler one-fourth the lysimeter width from the side to minimize any effect of plot edges and the subsurface drainage line. Soil core 2 was taken from the area of a line source. Soil samples were taken and analyzed by depth to 120 cm in 15-cm increments.

Sample analysis

Soil extraction was performed using a 2:1 ratio by weight of distilled water and soil. Approximately 50 g of wet soil and 80 g of distilled water were transferred to 250 mL flasks, and thoroughly mixed for 1 h using an Orbit Shaker (Model 3250, Lab-Line International Inc.). After mixing, samples were allowed to set overnight. Sediment and water were separated using a high-speed centrifugation (Model HR-1 International Equipment CO.) at 10,000 rpm for 20 min in 40-mL PVC centrifuge cups. After centrifuging, samples were then filtered through a syringe filter (Coster 8112) having a pore size of 0.45 μm .

$\text{NO}_3\text{-N}$ in drainage samples and soil extracts was analyzed by the automated flow injection cadmium reduction method using a Lachat Quickchem 2000 Automated Ion Analyzer system. In this method, $\text{NO}_3\text{-N}$ is reduced to nitrite ($\text{NO}_2\text{-N}$) by a cadmium/copper column. Nitrite is diazotized with sulfanilamide and then reacted with N-(1-naphthyl)-ethylenediamine dihydrochloride at a pH of 8.5 to form a colored (pink to red) azo compound, whose intensity is proportional to the amount of $\text{NO}_3\text{-N}$ plus $\text{NO}_2\text{-N}$ in the sample. Measurements were made with a colorimeter at a wavelength of 520 nm, and $\text{NO}_3\text{-N}+\text{NO}_2\text{-N}$ concentrations in samples were determined by comparing sample absorbance with those obtained a calibration curve comprised of standards containing $\text{NO}_3\text{-N}$ concentrations from 0.25 to 30.0 mg $\text{NO}_3\text{-N/L}$. Bromide analyses were performed by the automated flow injection phenol red method using the same Lachat 2000 Automated Ion Analyzer system. Chloramine-T reagent oxidizes bromide to bromine which is then brominated with phenol red (buffered at pH of 4.5-4.7) to form a reddish to brown colored compound whose intensity is proportional to the concentration of Br in the sample. Measurements were made with a colorimeter at 590 nm. Bromide concentrations in the sample were determined by comparing absorbance of the sample with a calibration curve based on absorbances of standards containing Br concentration from 1 to 60 mg Br/L. $\text{PO}_4\text{-P}$ was determined by using the ascorbic acid method (Owen, 1992). In this method, ammonium molybdate and potassium antimonyl tartrate react in acid medium with orthophosphate to form a heteropoly acid (phosphomolybdic acid) that is intensely colored molybdenum blue by ascorbic acid. Measurements were made with a colorimeter at a wavelength of 880 nm, and $\text{PO}_4\text{-P}$ concentrations in samples were determined by comparing sample absorbance with those

obtained a calibration curve comprised of standards. P range from this method is from < 5 ug/L to 2000 ug/L.

Statistical analyses were performed using SAS for developing the relationships among the drainage and solute concentration data; a 5% level of significance was used.

Results and Discussion

Calibration results of volumetric water content and bulk electrical conductivity

Prior to rainfall simulation, calibration curves were made for volumetric water content measured by TDR versus the values determined gravimetrically, using two equations, Topp et al. (1980) and Malicki et al. (1996) The results showed that Malicki equation was better than Topp equation. Therefore, the Malicki (equation 4-2) was used with TDR measurement in this study. The relationship of water content determined by Malicki equation to that measured gravimetrically is given by the calibration equation:

$$\theta_{v1} = 0.9127\theta_{v2} + 0.0517 \quad [4-5]$$

Where θ_{v1} is volumetric water content determined by TDR, and θ_{v2} is volumetric water content determined gravimetrically. An EC calibration was also made by measuring $1/Z$ when immersing the TDR probe in five different salt solutions of known conductivity ranging from 0 to 1.2 S/m. Solutions of 0, 0.02, 0.04, 0.06, and 0.08% of KCl were used in this experiment, and the eight probes used were immersed in these five solutions, with two duplications, one by one. A conductivity meter (Accumet, Model 30, Fisher Scientific) was

used for determination of solution EC. A linear relationship was determined between solution EC and TDR measured EC and is given by the calibration equation:

$$EC_1 = 41.263EC_2 - 0.0159 \quad [4-6]$$

Where EC_1 is value from EC meter, and EC_2 is from TDR. Statistical analysis of measured data for each individual probe, indicated that there were no significant differences among the eight probes used in this study.

Water results

Tables 4-1 and 4-2 present hydrological data related to inflow and outflow during and after the rainfall simulations. Neither tillage nor compaction treatments significantly affected overall hydrology, but there were differences with time (Table 4-3). The volumetric water contents measured by the two horizontally placed TDR probes (beneath the NO_3 -N line source) and the two vertically placed probes (between line sources) are shown in Figure 4-3 as a function of time during rainfall simulation. A gradual increase in moisture content with time is observed for compaction treatments, and a more abrupt rise was observed for the no compaction treatments for the TDR probes beneath the line sources. A relatively constant water content beneath the line sources of 0.50 to 0.55 was reached at about 20 min for all treatments. Corresponding values of moisture content determined for 15 cm of top soil between line sources in all treatment lysimeters showed less and more gradual change with time. But the figure shows that water content of the no till treatment was greater than that of till treatment in the first 20 min of rainfall simulation.

An overview of the water table and drainage hydrology of the lysimeters as a function of time is given in Figure 4-4. This graph shows the impact of tillage and local soil compaction on subsurface drainage rates (a), volumes (b), and water table depth (c). At 3.5 h after the beginning of rainfall, the first subsurface drainage sample was pumped from the vertical withdrawal tube of each lysimeter. The greatest volume of subsurface drainage occurred within 24 h of rainfall simulation. Clearly, macropore or bypass flow occurred during the simulated rain (Ressler et al. 1998). The subsurface drainage rate decreased significantly after the first day after rainfall simulation.

In this study, the water table depth was continuously monitored during rainfall simulation. The water table began to raise (implying that water arrived at the depth of the top of the drainage tube or air pressure from entrapped air resulted in the water table to raise) in about 50 min after rainfall begin. Within about 3.5 h after the beginning of simulated rainfall (the time the first drainage sample was taken), the water table had become stable. The decreases in depth to lysimeter water tables following the simulated rainfall were 0.8 to 0.9 m. However, the rates of water table elevation increase were different among lysimeters. As mentioned in introduction, water table levels and water table change rates could reflect an air entrapment situation during rainfall and infiltration. Figure 4-4 shows that the slope of the curves for NTC and NTNC were higher than those for TC and TNC, indicating tillage may have had an effect, where it was observed the tilled treatment may have had a higher degree of surface sealing than no-till. Cook et al. (2001) developed the concept of pressuring the drainage tube and thus connected macropores with air, in an attempt to prevent immediate contaminate transport to the subsurface drain depth via preferential flow during the time of manure application. They found that the “pressurization” treatment retained more water

earlier in the study. This could be explained by the possible elimination or at least reduction of macropore flow. Another past study (Wang et al, 1998) indicated that the hydraulic conductivity during the air-confining condition is reduced by 60% as compared to the air-draining condition. In another study, it was found from field experiments with air entrapment effects that the hydraulic conductivity of the transmission zone remained less than 20% of saturated conditions. Many studies showed preferential flow may lead to the accelerated transport of water and solutes toward the groundwater, although further study is needed to quantify the size and rates of preferential flow. However, results of this study reflected here indicate that the effects of the soil air phase cannot be neglected when modeling the infiltration process, which can cause an uneven distribution of water and fertilizers in the crop root zone and influence their degree of leaching to the water table.

Nitrate leaching

Figure 4-5 shows anion concentrations for subsurface drainage samples collected over time after rainfall simulation. Nitrate-nitrogen concentrations peaked almost immediately after rainfall simulation, then declined rapidly. During the drainage period, the compaction treatments produced lower $\text{NO}_3\text{-N}$ concentrations than the no compaction treatment possibly due to macroflow bypassing the local compacted zone containing the added $\text{NO}_3\text{-N}$. This is consistent with $\text{NO}_3\text{-N}$ losses measured for these for treatments (Table 4-2). Ressler et al. (1998) also indicated that by their direct measurement of leaching loss, the LCD method of application can reduce the leaching of injected anionic chemicals through the soil profile when intense rain occur soon after application. From the data in Table 4-2, the compaction treatment was found to reduce $\text{NO}_3\text{-N}$ leaching by a factor of over four, but the absolute

difference of losses was only 1.81 kg/ha during the drainage period. This value may be not “significant” compared with 100 kg/ha of $\text{NO}_3\text{-N}$ input. Further discussion follows in the soil profile section. Tables 4-1 and 4-2 show that tillage did not significantly impact $\text{NO}_3\text{-N}$ concentrations and losses, but soil compaction and sampling time factors did (Table 4-3).

The application of rainfall containing the tracer Br anion on the day of $\text{NO}_3\text{-N}$ application produced subsurface drainage in which Br concentrations peaked soon after drainage was withdrawn. Tracer Br concentrations versus time are also shown in Figure 4-5. Following the peak concentration, concentrations decreased rapidly with time. Data in Tables 4-1, 4-2, and 4-3 show that tillage, soil compaction, and sampling time factors did not significantly impact tracer Br and $\text{PO}_4\text{-P}$ concentrations for the entire drainage event. Figure 4-6 shows concentration ratios by sample number, indicating relative concentrations of $\text{NO}_3\text{-N}$ for the no compaction treatments were higher throughout the study period than Br and $\text{PO}_4\text{-P}$. Corresponding ratios of $\text{PO}_4\text{-P}$ to Br for all treatment lysimeters were not significantly different for the entire drainage period. $\text{NO}_3\text{-N}$ is very soluble and susceptible to leaching, resulting in higher concentrations and greater transport for the no compaction treatment. Br was present at a concentration of 50 mg/L in rainfall, and concentrations in background drainage water before rainfall simulation were less than 1 mg/L. Although Br in rainfall contributed a limited amount to subsurface concentrations, it did indicate the role of preferential flow in moving the Br lower in the soil profile compared with the Br background concentration in drainage. Lower relative concentrations of $\text{PO}_4\text{-P}$ to Br were observed (the ratio in rainfall was 0.2) because this nutrient has a tendency to be precipitated and/or adsorbed to soil particles.

In this study, in addition to volumetric water content, EC_b beneath the compacted and no compacted line sources, and also in the 15-cm layer of top soil were measured by TDR during rainfall simulation. Figure 4-7 shows that EC_b for no compaction treatments beneath the NO_3-N line source changed rapidly with time. Following the peak in about 15-20 min, EC_b decreased rapidly with time, was still changing when rainfall ended after 60 min, and reached a stable value in about 90-100 min. However, EC_b for compaction treatments remained stable at the end and after rainfall following only a slight increase early in the rain. The rise in EC_b for the vertically installed TDR probes is also shown in Figure 4-7. The corresponding EC_b values for 15 cm of top soil between the line sources in all treatment lysimeters were almost constant due to the fact that the TDR probes were measuring the average concentration over the entire 15 cm length of the probe, with a contrast input of Br and PO_4-P in rain and probably little or no lateral transport of applied NO_3-N in the top soil layer during rainfall simulation. These results also indicate localized soil compaction can reduce NO_3-N leaching relative to no compaction. In order to determine solute concentration by TDR, EC_b or EC_w measured by TDR can be related to the solute concentration via calibration. Many researchers perform a calibration prior to experiments under laboratory conditions, but the calibration environment may be different in a field experiment. In order to have a simple and practical method, a “in situ” calibration between EC_b and NO_3-N was used in this study. EC_b values in the beginning and the end of rainfall simulation event were determined by TDR in top 15 cm of soil (the layer with compacted/no compacted line sources). Corresponding NO_3-N concentrations can be determined by chemical analyses via the soil sample in the same layer. The relationship between EC_b and NO_3-N in the top 15 cm of soil is shown in Figure 4-10. The results indicated that NO_3-N in 15 cm of top soil is

curvilinear related to EC_b beneath line sources. A power function can fit the observed data with R^2 , 0.9006. However many previous studies indicated a linear relationship exists between resident concentration and EC_b (Nadler et al., 1991; Ward et al., 1994; Heimovaara et al. 1995; Mallants et al., 1996). The discrepancy is probably due to a change of volumetric water content (Mallants et al., 1996), or mobile water fraction (Rhoades et al., 1989). Vogeler et al. (1996) indicated that a linear relationship exists between EC_b and EC_w in a range of 0.1 to about 0.5 S/m at each θ , and at low concentrations, EC_w is linearly related to the concentration of a particular salt solution.

Figure 4-8 shows volumetric water content profiles before and after (11 days, when drainage had stopped) rainfall simulation. The water contents of all treatments are similar in shape. For the 5.36-cm rainfall, the average water recovery was 77.3%. Figure 4-9 shows the concentrations of Br and NO_3-N with soil depth before and after rainfall simulation. Both NO_3-N and Br are very soluble and susceptible to leaching. Br was present at a concentration of 50 mg/L in rainfall. At 11 days after rainfall, the top 30 cm of soil contained the greater concentrations of Br, and the tillage treatments retained more Br than the no till treatment in this top 30 cm layer of soil. Surface sealing with the tillage treatments during the rain could delay Br movement downward. However, NO_3-N in the soil profile exhibited an opposite pattern; the no till treatments retained more NO_3-N in the top 30 cm layer of soil than the tillage treatments. It is believed that more macropore flow bypassed the NO_3-N in line sources, and more NO_3-N remained in this layer. Table 4-4 shows the estimated mass balances for NO_3-N and Br, also indicating that the no till treatments retained greater amounts of NO_3-N in the soil profile than the tillage treatments. The concentration peaks and declines of both NO_3-N and Br are quite similar during the drainage period possibly as a

result of water flow conditions. Lysimeter drainage was distributed between flow through the soil matrix and macropores. Shortly after the rainfall simulation, nutrients were flushed from the top 15 cm of soil and were possibly transported through soil macroporosity to the subsurface drainage depth with drainage water. As the rates of drainage decreased, the fraction of the total drainage water flowing in macropores may have decreased due to decreasing soil water potential.

Summary and conclusions

Field lysimeters were used with rainfall simulation to study the effect of tillage and localized compaction in the zone of $\text{NO}_3\text{-N}$ addition on $\text{NO}_3\text{-N}$ leaching. Line sources with compaction/no compaction were imposed in the soil 5 cm below the soil surface. Compacted soil bars represented only 3.5% of the soil surface area and at most 0.035% of the soil volume in the lysimeters. Rainfall with Br and $\text{PO}_4\text{-P}$ dissolved in it at 50 and 10 mg/L respectively, was applied to the lysimeters.

Tillage treatments did not significantly affect overall drainage volumes. Due to the small percentage of soil surface area and soil volume occupied by the line sources, compaction treatments also showed no significant effect on subsurface hydrology. Different water table depth patterns measured with time in this study could reflect an air entrapment situation during rain fall and infiltration.

Localized compaction caused significantly lower concentrations and losses of NO_3N in subsurface drainage. Tillage treatments did not show significant difference in $\text{NO}_3\text{-N}$ concentration or losses. For 5.4 cm of rainfall, averaged overall all treatments, only 1.44% of the applied $\text{NO}_3\text{-N}$ leached with subsurface drainage. A majority of the $\text{NO}_3\text{-N}$ remained in

the upper 30 cm of soil profile. This study indicated that no till treatments held greater amounts of $\text{NO}_3\text{-N}$ in the soil profile than did the tillage treatments. It is believed that more macropore flow bypassed the $\text{NO}_3\text{-N}$ in line sources, allowing more $\text{NO}_3\text{-N}$ to be retained in the layer of application.

Br and $\text{PO}_4\text{-P}$ in rainwater was used to help in understanding the effect of difference solute source/location on leaching. Neither tillage, nor soil compaction did significantly impacted tracer Br and $\text{PO}_4\text{-P}$ concentrations in subsurface drainage for the entire drainage period. Tillage treatments retained more Br in the soil profile than no till treatments. Surface sealing with the tillage treatment during the rain could have delayed Br movement downward. In total, 4.9% of applied Br leached with subsurface drainage. This leaching percentage is greater than for $\text{NO}_3\text{-N}$ leaching percentage, indicating that preferential flow occurred during rainfall simulation and drainage.

Soil EC_b and volumetric water content were measured using TDR. Volumetric water content data provided a “time-to-saturation”, for the top 15 cm of soil of about 20 min in this study. Before that time, water contents were different for the different treatments. However, after that, there were no significant differences in water content for all treatments. Soil EC_b results indicate localized soil compaction can reduce $\text{NO}_3\text{-N}$ leaching relative to no compaction. Moreover, the relationship between $\text{NO}_3\text{-N}$ and EC_b was tested in this study, indicating $\text{NO}_3\text{-N}$ in 15 cm of top soil is curvilinear related to EC_b beneath line sources.

Resident solute concentration related EC_b can be determined by TDR technique, and soil local compaction can reduce $\text{NO}_3\text{-N}$ leaching. Combined use of these two techniques has the potential to simultaneously quantify solute leaching and water infiltrating, and provide information for model development and testing.

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Table 4-1 Flow-weighted concentrations and losses of anions with subsurface drainage and EC_b in top soil with different tillage treatments.

Tillage	Rainfall	Subsurface Drainage	Soil Water	EC in drainage	EC beneath line	EC between rows	NO ₃ -N		PO ₄ -P		Br	
		cm	cm	μS/cm	mS/cm	mS/cm	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
Till	5.53a	4.19a	45.05a	299.30a	1.178a	0.221b	3.28a	1.46a	0.100a	0.040a	3.15a	1.33a
No-till	5.20a	4.10a	44.00a	353.88a	1.113a	0.269a	3.47a	1.42a	0.148a	0.062a	3.31a	1.35a

Values with the same letter in each column are not significantly different at 0.05 level

Table 4-2 Flow-weighted concentrations and losses of anions of subsurface drainage and EC_b in top soil with different soil compaction treatments.

Compaction	Rainfall	Subsurface Drainage	Soil Water	EC in drainage	EC beneath line	EC between rows	NO ₃ -N		PO ₄ -P		Br	
	cm	cm	cm	μS/cm	mS/cm	mS/cm	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
Soil compaction	5.24a	4.24a	44.70a	286.57a	0.689b	0.246a	1.28b	0.54b	0.145a	0.060a	3.76a	1.54a
soil no compaction	5.49a	4.04a	44.08a	366.62a	1.602a	0.242a	5.47a	2.35a	0.103a	0.042a	2.70a	1.14a

Values with the same letter in each column are not significant differently at 0.05 level

Table 4-3 Subsurface drainage rates, flow weighted concentrations, and losses of tracers versus time

Sampling time	Subsurface Drainage rate	NO ₃ -N		PO ₄ -P		Br	
		mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
h	cm/h						
3.5	0.374b	2.588bc	0.354a	0.228a	0.028a	3.632ab	0.462a
3.8	0.905a	8.097a	0.299ab	0.140ab	0.004b	6.233a	0.206b
4.9	0.373b	5.758ab	0.238abc	0.095ab	0.004b	4.113ab	0.175b
7.8	0.138c	4.495bc	0.141abc	0.129ab	0.004b	5.004ab	0.165b
22.9	0.046c	2.365c	0.179abc	0.054ab	0.004b	1.927b	0.142b
96.8	0.009c	1.867c	1.115bc	0.048b	0.003b	1.408b	0.089b
169.6	0.004c	2.288c	0.061c	0.059ab	0.002b	1.759b	0.052b
242.5	0.004c	2.516bc	0.059c	0.068ab	0.002b	2.054ab	0.055b

Values with the same letter in each column are not significant different at 0.05 level

Table 4-4 NO₃-N, Br, and PO₄-P mass balance

		NO ₃ -N				
		Water	input	drainage	Storage*	recovered
		-----kg/ha-----				
Till	comp.	0.11	100	0.70	78.42	79.12
	no-comp.	0.41	100	2.19	78.80	80.99
notill	comp.	0.09	100	0.38	115.31	115.69
	no-comp.	0.37	100	2.38	99.42	101.80

		Br			
		Water	input	drainage	storage
		-----kg/ha-----			
Till	comp.	----	26.55	1.59	23.28
	no-comp.	----	28.9	1.04	17.69
notill	comp.	----	25.8	1.47	9.49
	no-comp.	----	26.15	1.20	6.31

		PO ₄ -P			
		Water	input	drainage	storage
		-----kg/ha-----			
Till	comp.	----	10.62	0.05	----
	no-comp.	----	11.56	0.03	----
notill	comp.	----	10.32	0.07	----
	no-comp.	----	10.46	0.06	----

* Assumed that the affecting width of each line source containing NO₃-N is 10 cm.

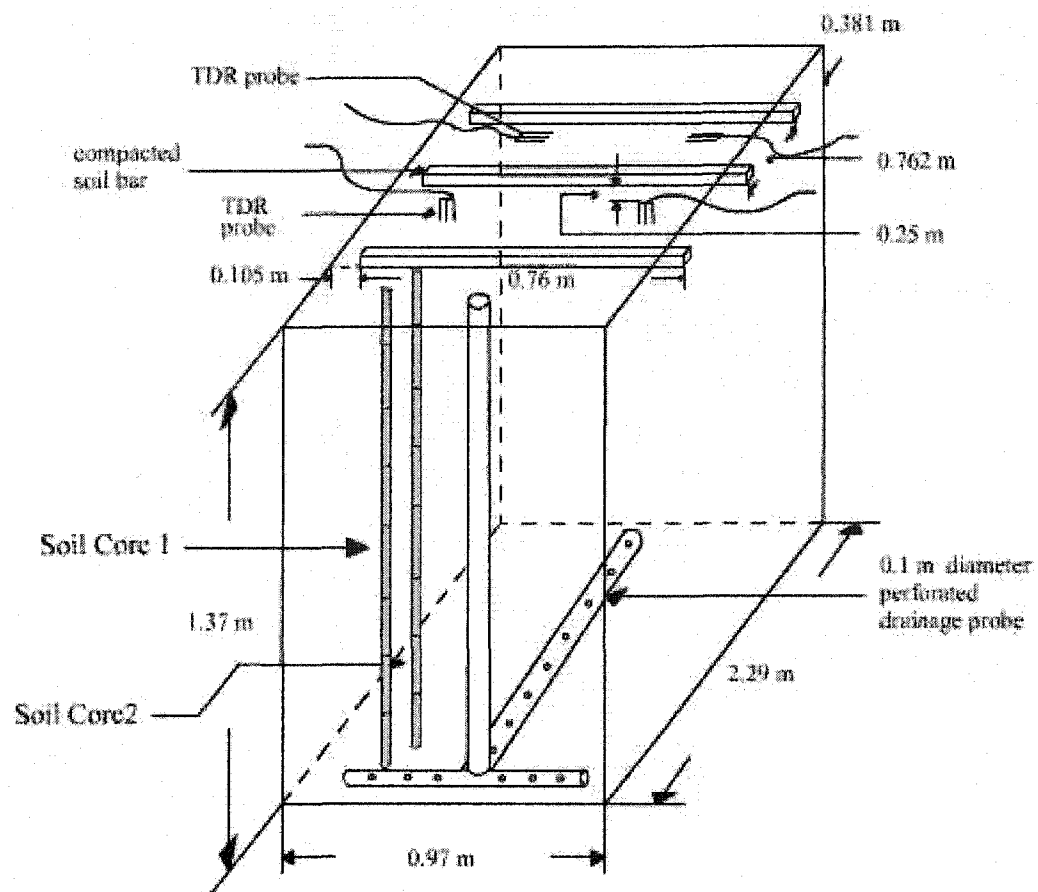
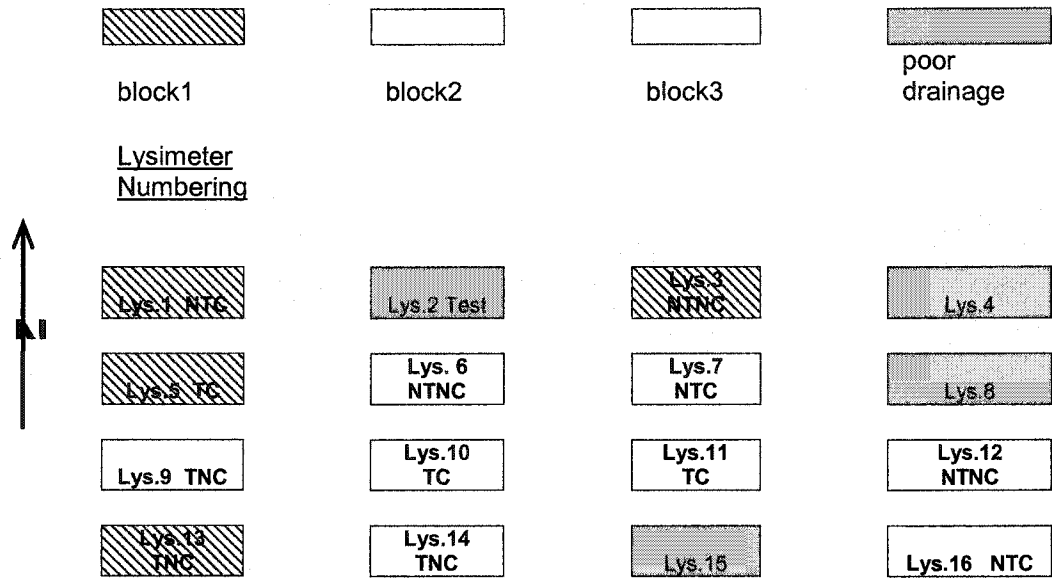


Figure 1 A schematic drawing of a drainage lysimeter.



NTNC: no till-line source; NTC: no till-compacted;
 TNC: till-line source; TC: till-compacted

Figure 4-2 Field experiment layout

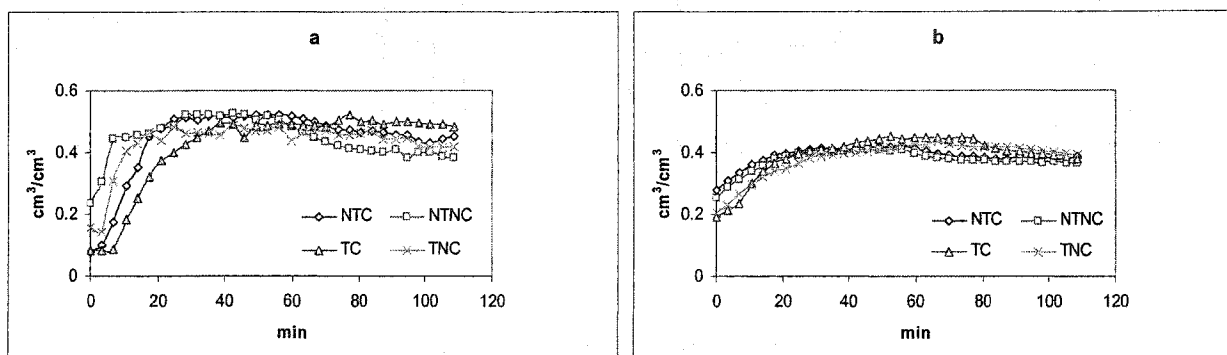


Figure 4-3 Soil volumetric water content with time of rainfall, (a) beneath compacted/no compacted soil line sources and (b) between two line sources.

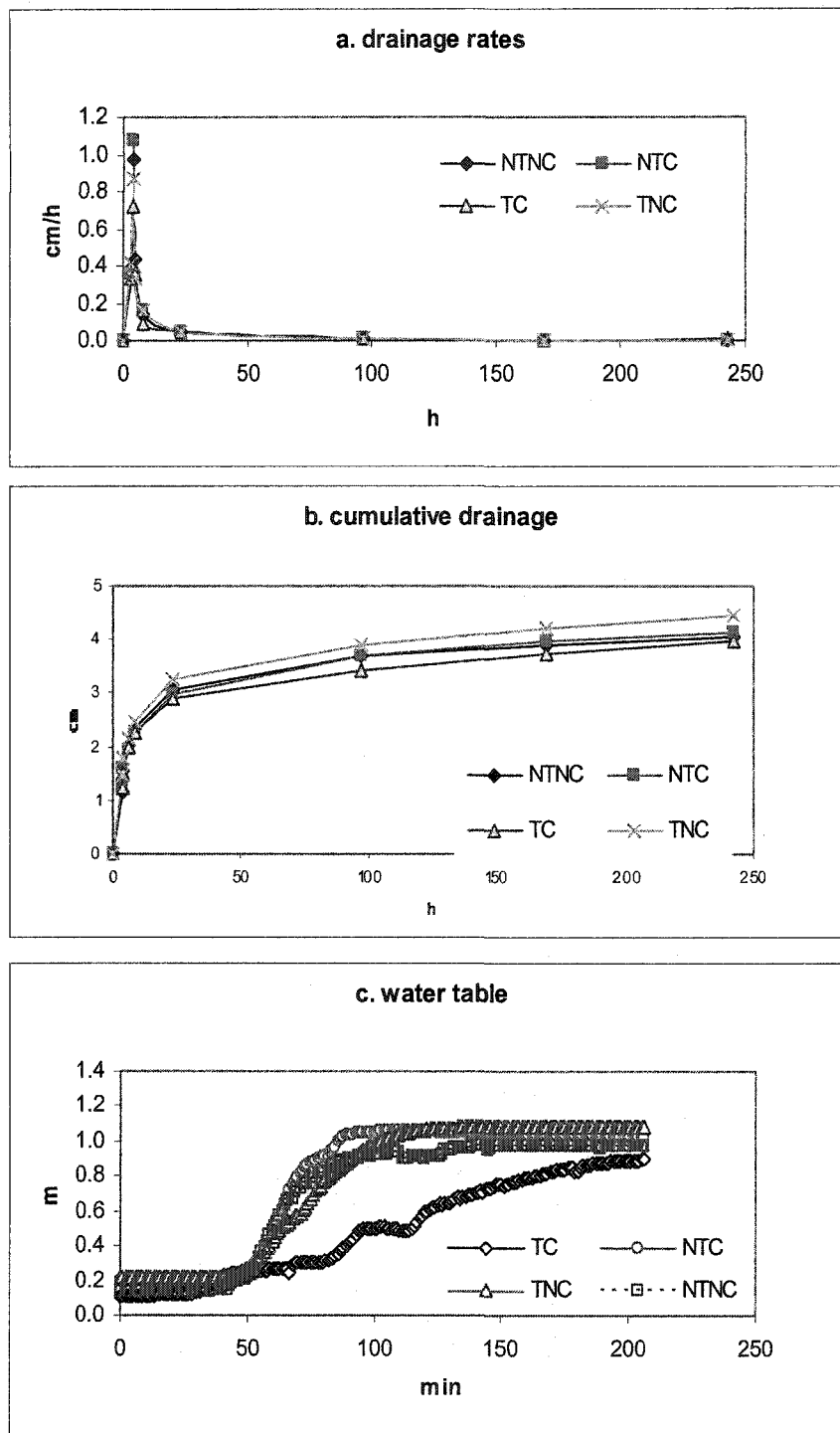


Figure 4-4 Subsurface drainage rates (a), cumulative subsurface drainage (b) during the drainage period, and water table change (c) within 3.5 hours from rainfall beginning.

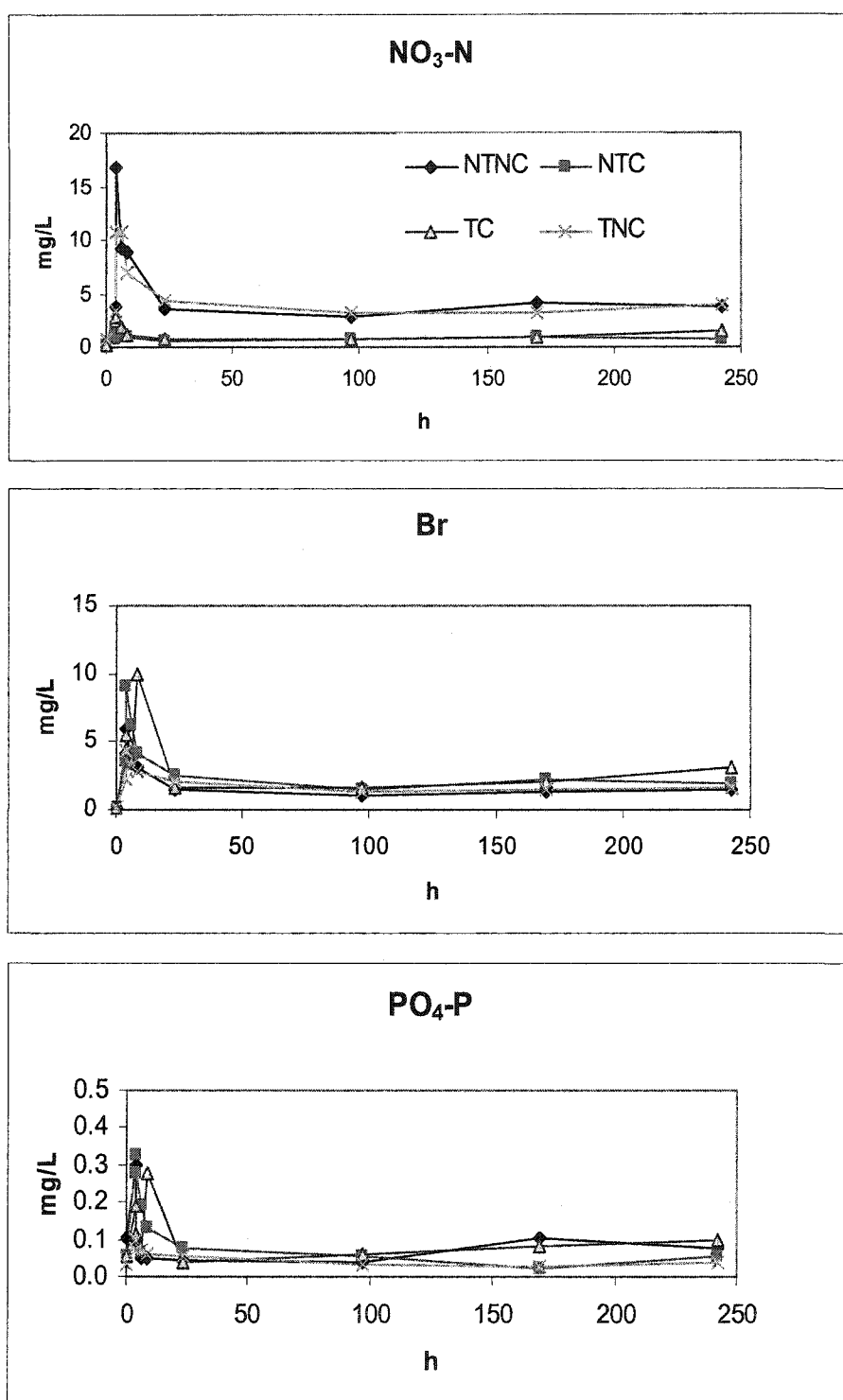


Figure 4-5 Anion concentrations in subsurface drainage with time

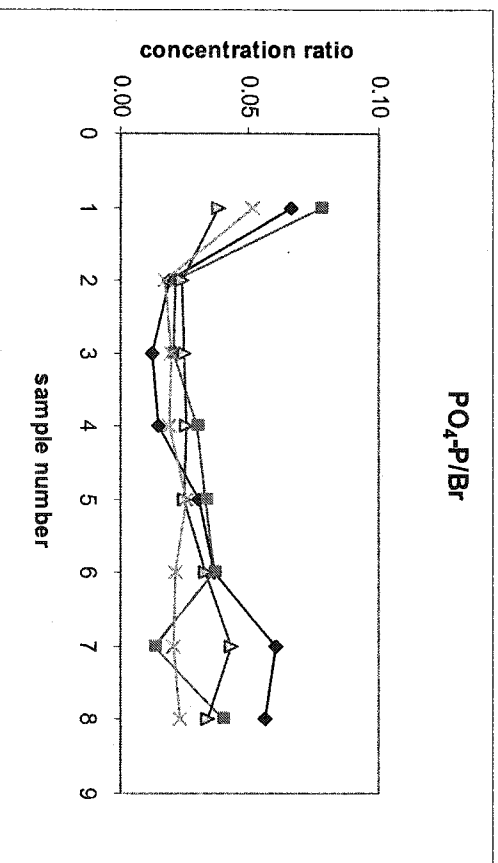
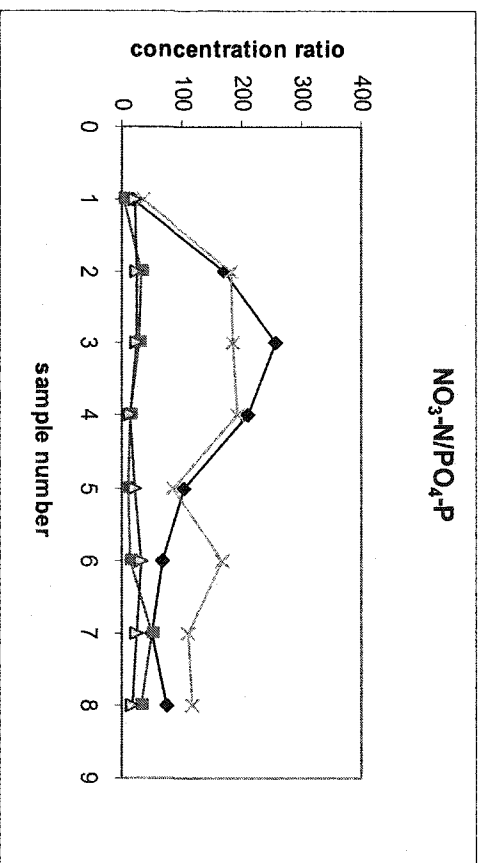
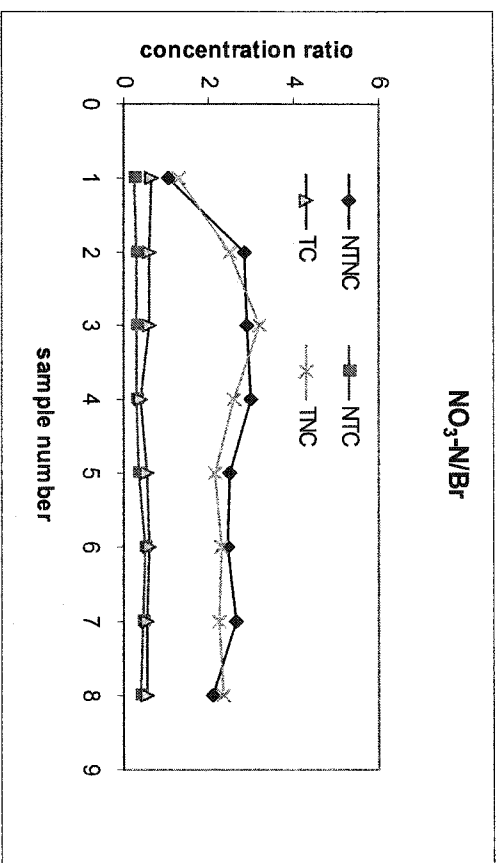


Figure 4-6 Anion Concentration ratio

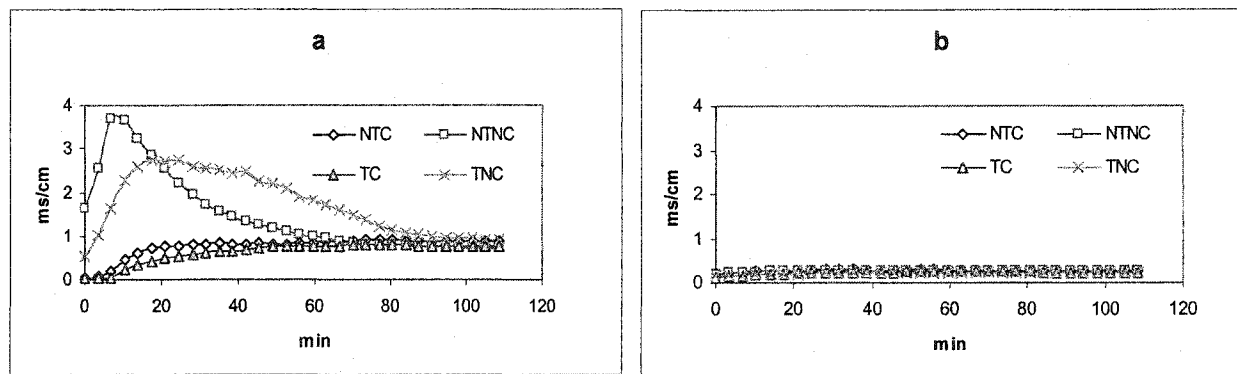


Figure 4-7 Soil EC_b with time of rainfall; (a) beneath compacted/no compacted soil line sources and (b) between line sources.

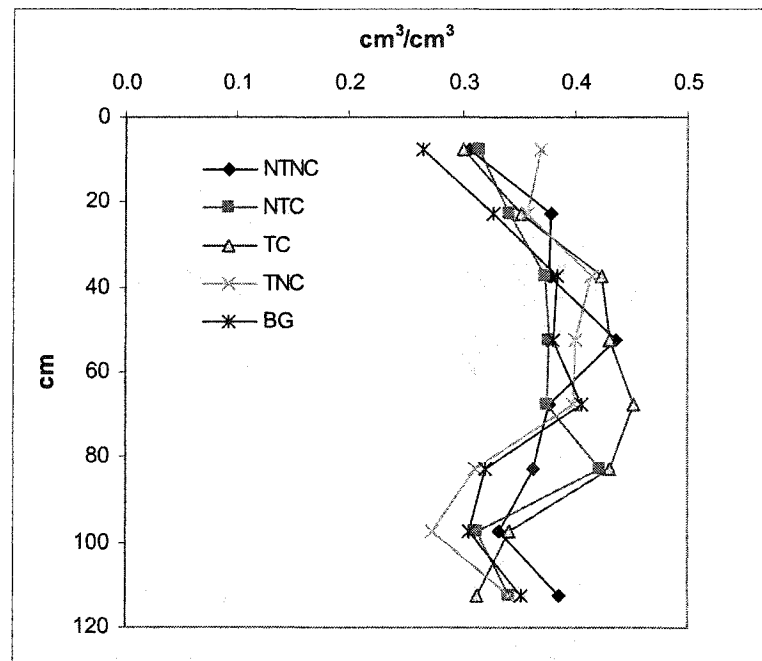


Figure 4-8 Average volumetric water content in the soil profile before and after simulated rainfall.

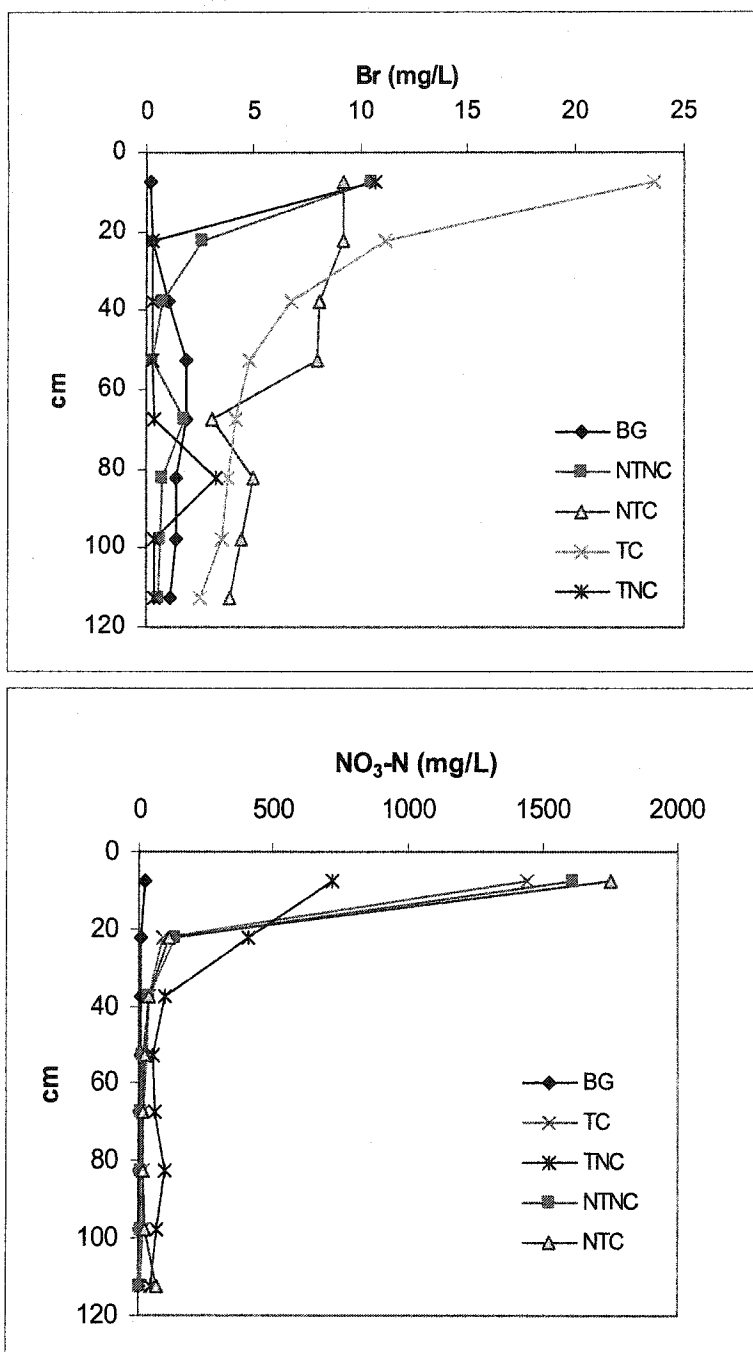


Figure 4-9 Br and NO₃-N in soil profile before and after simulated rainfall

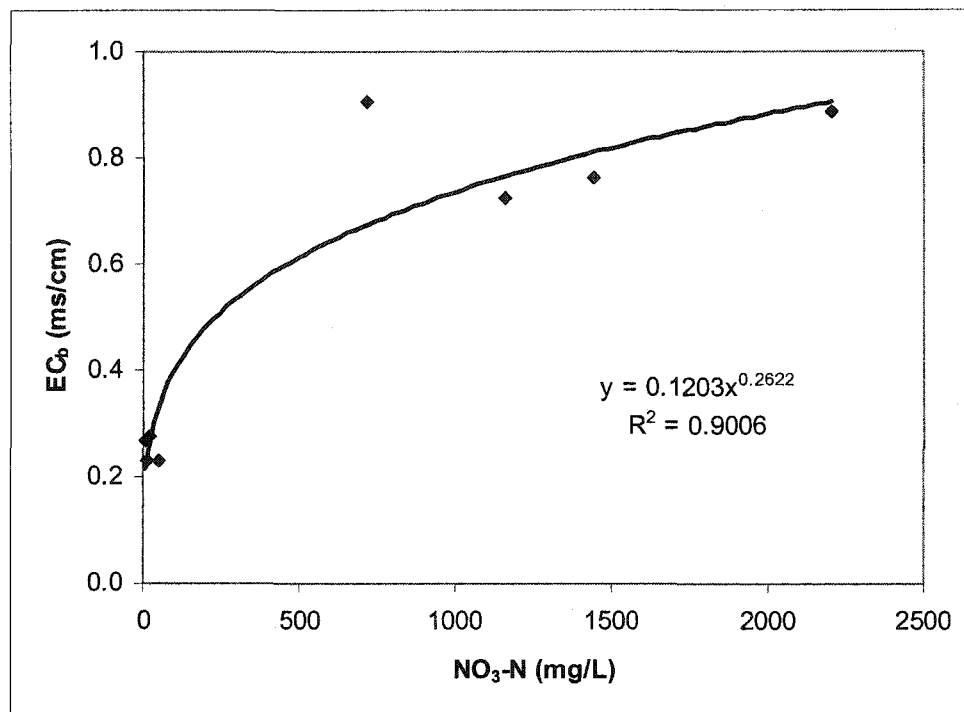


Figure 4-10 Relationship between TDR measured EC_b and NO_3-N concentrations beneath line sources

CHAPTER 5. GENERAL CONCLUSIONS

Conclusions

$\text{NO}_3\text{-N}$ is the form of N which, because of its specific physical and chemical properties, is not adsorbed to soil. It usually is the most abundant form of N in the soil water; that, combined with hydrological factors and lack of adsorption will determine how much leaches. Because subsurface tile drainage is a common agricultural practice to remove excess moisture in the shallow soil profiles in many parts of the United States, management practices/systems for the nearly flat, tile-drained areas, such as those within Iowa, need to be more focused on N because of $\text{NO}_3\text{-N}$ leaching losses. Substantially reducing $\text{NO}_3\text{-N}$ losses from these agricultural systems will require a combination of in-field best management practices and off-site landscape modifications. Soil property management in the zone of N application is one of the more promising in-field strategies for reducing subsurface water contamination, and some studies have demonstrated that localized compaction has the potential to reduce $\text{NO}_3\text{-N}$ leaching losses with tile drainage.

The overall purpose of this research was to estimate the effects of soil properties, including local compaction, antecedent soil moisture content, and tillage on $\text{NO}_3\text{-N}$ leaching from runoff/drainage pans in laboratory and in field lysimeters during rainfall simulation with the help of tracer anions and TDR measurements, and to use this information to help in the development/improvement of N application methods/equipment. For indoor rainfall simulation, rainfall containing Br was applied to soil in runoff/drainage pans with two different antecedent soil moisture contents. The soil in the runoff/drainage pans had been

treated with $\text{NO}_3\text{-N}$ (in a localized line source with different degrees of compaction) and Cl (uniformly mixed in the soil). Furthermore, field lysimeters were used for outdoor rainfall simulation, using two tillage practices (no-till and tillage) and two methods of N-fertilizer applications (local soil compaction and no compaction as a line source). Two “tracers”, Br and phosphate-phosphorus ($\text{PO}_4\text{-P}$) were added in rainwater.

Indoor rainfall simulation

The antecedent soil moisture treatment affected water infiltration, subsurface drainage, and storage. Soil pans with the 10% moisture treatment had more infiltration and subsurface drainage than those with 15%. These results go beyond just the effect of a difference in moisture content, and indicate evidence of a difference in soil structure between the treatments, i.e. the mixing and packing processes likely caused some soil structure differences.

Higher compaction caused lower concentrations and losses of NO_3N in subsurface drainage, resulting in a significant difference between bulk densities for both 10 and 15% moisture treatments. The 10% moisture treatment produced greater $\text{NO}_3\text{-N}$ losses due to greater volume of drainage at that moisture. Higher bulk densities and moisture retained greater amounts of $\text{NO}_3\text{-N}$ in soil..

Cl and Br leaching results help us to understand effect of difference solute source/location to leaching pattern. The amounts of their leaching were all greater in low moisture treatments. Br from surface application only leached a little because of soil surface condition effect (sealing caused from rainfall). However, Cl as incorporated source in soil had a greater leaching level than that of $\text{NO}_3\text{-N}$ and Br for both antecedent soil moisture and

local compaction treatments, which was attributed to macroflow and possible “anion exclusion” function.

TDR measured soil volumetric water content indicated the different change pattern in top soil and subsurface soil and the “time-to-saturation”, and confirmed higher final soil moisture for 10% moisture treatment than 15%, suggesting higher water holding capacity for the former. Significant effect of EC_b with NO_3-N by both antecedent moisture and compaction treatments, combined with modeling provides a potential to estimate solute concentration in subsurface drainage by TDR techniques.

Outdoor rainfall simulation

Tillage treatments didn’t significantly affect overall drainage volumes. Different water table depth patterns measured with time in this study could reflect an air entrapment situation during rain fall and infiltration. Due to the small percentage of soil surface area and soil volume occupied by the line sources, compaction treatments also showed no significant effect on subsurface hydrology.

Localized compaction caused lower concentrations and losses of NO_3-N in subsurface drainage. Tillage treatment did not show a significant difference in NO_3-N losses. For 5.4 cm average rainfall, only 1.44% of applied NO_3-N leached with subsurface drainage. A majority of the NO_3-N still remained in the upper 30 cm of soil profile. This study indicates that no-till treatment held greater amount of NO_3-N in the soil profile than tillage treatment. It is believed that more macropore flow bypassed the NO_3-N in line sources, allowing more NO_3-N to be retained in the layer of application.

Neither tillage, nor soil compaction did significantly impacted tracer Br and $\text{PO}_4\text{-P}$ concentrations in subsurface drainage for the entire drainage period. Tillage treatments retained more Br in the soil profile than no-till treatments. Surface sealing with the tillage treatment during the rain could have delayed Br movement downward. In total, 4.9% of applied Br leached with subsurface drainage. This leaching percentage is greater than for $\text{NO}_3\text{-N}$ leaching percentage, indicating that preferential flow occurred during rainfall simulation and drainage.

The relationship between $\text{NO}_3\text{-N}$ and EC_b was tested in this study, indicating $\text{NO}_3\text{-N}$ in 15 cm of top soil is curvilinear related to EC_b beneath line sources.

Overall conclusions

In this study, higher antecedent soil moisture helped to reduce $\text{NO}_3\text{-N}$ leaching because of some unique effects on the hydrology of the packed soil in runoff/drainage pans. No-till treatment can increase solute retention in the soil profile. Localized soil compaction can reduce $\text{NO}_3\text{-N}$ leaching. EC_b in top soil can be a realistic estimation of solute transport from soil matrix to subsurface drainage. These findings suggest that N fertilizer placement in local compacted zone can offer desired results to reduce $\text{NO}_3\text{-N}$ leaching. TDR techniques have potential for in situ monitoring solute transport. This information is useful to help in the development/improvement of N application methods/equipment.

Prospects for Further Research

This study provides an opportunity to quickly estimate the agricultural chemical concentrations in runoff and resident concentration in soil profile by measuring EC_b by the

TDR method instead of chemical analyses of solutes. In addition, volumetric water contents in top layer of soil can be determined by TDR simultaneously, which could be an indicator of the soil hydrology conditions. Use of TDR method, combined with study of soil properties, could help in the development of improved management practices to reduce soluble chemical runoff losses. On the basis of this study, two factors should be considered in further research:

Soil compaction to desired bulk density could be adjusted by adding or removing weights to the fertilizer applicator, such as LCD applicator. Although greater antecedent soil moisture helped to reduce $\text{NO}_3\text{-N}$ leaching, the factor that beyond just the effect of a differences in moisture content (the evidences of a difference in soil structure between the treatments, i.e. the mixing and packing processes likely caused some soil structure differences in this study) need to be confirmed in more field studies.

The TDR data obtained from shallow soil layers have shown the potential to estimate solute concentration, such as $\text{NO}_3\text{-N}$ in the soil profile; however, further studies are needed to quantify the relationship between EC_b and solute concentrations under different conditions, such as combining TDR techniques and transient-state modeling to predict soluble solute leaching.

**APPENDIX: INDOOR AND OUT DOOR RAINFALL
SIMULATION DATA**

Table A-1 Volumetric water content determined by TDR with side probes and low probes, gravimetrically by oven

	side probe	Antecedent moisture	Bulk density g/cm ³	Side probe -----cm ³ /cm ³ -----	Low probe -----cm ³ /cm ³ -----	Oven value
1	initial	10%	1.1	0.0390	0.117	0.101
2	initial	10%	1.1	0.0434	0.119	0.101
3	initial	10%	1.1	0.0352	0.116	0.110
4	initial	10%	1.1	0.0568	0.108	0.110
5	initial	10%	1.1	0.0314	0.114	0.105
6	initial	10%	1.1	0.0478	0.122	0.105
7	initial	10%	1.33	0.0628	0.106	0.108
8	initial	10%	1.33	0.0874	0.111	0.108
9	initial	10%	1.33	0.0683	0.122	0.110
10	initial	10%	1.33	0.0670	0.121	0.110
11	initial	10%	1.33	0.0494	0.114	0.107
12	initial	10%	1.33	0.0492	0.120	0.107
13	initial	10%	1.57	0.0563	0.124	0.108
14	initial	10%	1.57	0.1256	0.129	0.108
15	initial	10%	1.57	0.0919	0.125	0.101
16	initial	10%	1.57	0.1264	0.120	0.101
17	initial	10%	1.57	0.0494	0.113	0.107
18	initial	10%	1.57	0.0601	0.129	0.107
19	initial	10%	1.81	0.0459	0.113	0.101
20	initial	10%	1.81	0.0444	0.115	0.101
21	initial	10%	1.81	0.0805	0.108	0.101
22	initial	10%	1.81	0.0865	0.122	0.101
23	initial	10%	1.81	0.0517	0.102	0.105
24	initial	10%	1.81	0.0481	0.108	0.105
25	initial	15%	1.1	0.0452	0.141	0.173
26	initial	15%	1.1	0.0667	0.137	0.173
27	initial	15%	1.1	0.0596	0.139	0.166
28	initial	15%	1.1	0.0709	0.137	0.166
29	initial	15%	1.1	0.0581	0.140	0.160
30	initial	15%	1.1	0.0734	0.131	0.160
31	initial	15%	1.33	0.0603	0.146	0.163
32	initial	15%	1.33	0.0744	0.141	0.163
33	initial	15%	1.33	0.0689	0.133	0.166
34	initial	15%	1.33	0.0707	0.129	0.166
35	initial	15%	1.33	0.0723	0.136	0.160
36	initial	15%	1.33	0.0924	0.144	0.160
37	initial	15%	1.57	0.0709	0.141	0.173
38	initial	15%	1.57	0.0678	0.142	0.173
39	initial	15%	1.57	0.0718	0.140	0.172
40	initial	15%	1.57	0.0588	0.138	0.172

41	initial	15%	1.57	0.0543	0.131	0.176
42	initial	15%	1.57	0.0593	0.129	0.176
43	initial	15%	1.81	0.0521	0.140	0.163
44	initial	15%	1.81	0.0748	0.144	0.163
45	initial	15%	1.81	0.0686	0.136	0.172
46	initial	15%	1.81	0.0676	0.135	0.172
47	initial	15%	1.81	0.0693	0.126	0.176
48	initial	15%	1.81	0.0699	0.128	0.176
49	final	15%	1.1	0.2493	0.453	0.375
50	final	15%	1.1	0.3018	0.399	0.375
51	final	15%	1.1	0.2764	0.452	0.369
52	final	15%	1.1	0.3107	0.419	0.369
53	final	15%	1.1	0.2660	0.730	0.375
54	final	15%	1.1	0.2957	0.399	0.375
55	final	15%	1.33	0.2687	0.473	0.375
56	final	15%	1.33	0.3005	0.851	0.375
57	final	15%	1.33	0.3060	0.566	0.378
58	final	15%	1.33	0.3045	0.411	0.378
59	final	15%	1.33	0.3171	0.444	0.367
60	final	15%	1.33	0.2886	0.752	0.367
61	final	15%	1.57	0.3297	0.417	0.379
62	final	15%	1.57	0.2894	0.388	0.379
63	final	15%	1.57	0.3095	0.499	0.379
64	final	15%	1.57	0.2763	0.424	0.379
65	final	15%	1.57	0.2801	0.634	0.380
66	final	15%	1.57	0.3191	0.482	0.380
67	final	15%	1.81	0.2694	0.381	0.372
68	final	15%	1.81	0.3169	0.482	0.372
69	final	15%	1.81	0.3180	0.419	0.378
70	final	15%	1.81	0.2955	0.461	0.378
71	final	15%	1.81	0.2822	0.386	0.352
72	final	15%	1.81	0.2813	0.385	0.352
73	final	10%	1.1	0.3406	0.520	0.423
74	final	10%	1.1	0.3603	0.507	0.423
75	final	10%	1.1	0.3206	0.492	0.414
76	final	10%	1.1	0.3217	0.465	0.414
77	final	10%	1.1	0.3081	0.510	0.420
78	final	10%	1.1	0.3448	0.521	0.420
79	final	10%	1.33	0.3298	0.479	0.409
80	final	10%	1.33	0.3398	0.530	0.409
81	final	10%	1.33	0.3313	0.486	0.407
82	final	10%	1.33	0.3277	0.604	0.407
83	final	10%	1.33	0.3575	0.505	0.408
84	final	10%	1.33	0.3241	0.473	0.408
85	final	10%	1.57	0.3413	0.511	0.402
86	final	10%	1.57	0.3272	0.768	0.402
87	final	10%	1.57	0.3223	0.721	0.404
88	final	10%	1.57	0.3359	0.537	0.404

89	final	10%	1.57	0.3317	0.524	0.413
90	final	10%	1.57	0.3609	0.508	0.413
91	final	10%	1.81	0.3570	0.474	0.423
92	final	10%	1.81	0.3471	0.507	0.423
93	final	10%	1.81	0.3475	0.424	0.405
94	final	10%	1.81	0.3266	0.502	0.405
95	final	10%	1.81	0.3689	0.433	0.413
96	final	10%	1.81	0.3387	0.469	0.413

Table A-2 Volumetric water content determined by TDR with two equations, and gravimetrically by oven

soil	K	-----cm ³ /cm ³ -----		
		Malicki	Topp	Oven
Nicollet	2.659	0.051	0.021	0.096
	5.945	0.147	0.102	0.187
	12.703	0.280	0.238	0.286
	19.389	0.379	0.338	0.378
	2.930	0.061	0.028	0.116
	9.990	0.232	0.188	0.266
	20.700	0.396	0.354	0.444

Table A-3 Calibration EC between TDR and EC meter

	Conc.1	Conc.2	Conc.3	Conc.4	Conc.5
	-----1/ohms-----				
Probe 1	0.0004	0.0110	0.0193	0.0280	0.0367
Probe 2	0.0004	0.0112	0.0193	0.0279	0.0369
Probe 3	0.0004	0.0111	0.0193	0.0278	0.0335
Probe 4	0.0005	0.0111	0.0193	0.0278	0.0361
Probe 5	0.0004	0.0110	0.0191	0.0276	0.0363
Probe 6	0.0004	0.0111	0.0194	0.0279	0.0367
Probe 7	0.0005	0.0111	0.0193	0.0278	0.0361
Probe 8	0.0005	0.0111	0.0192	0.0278	0.0373
	-----mS/cm-----				
EC meter	0.0011	0.4430	0.7815	1.1450	1.4950

Table A-4 Water mass balance

Moisture Content (%)	Bulk Density (g cm ⁻³)	Rainfall Quantity (cm)	Subsurface Drainage (cm)	Runoff Quantity (cm)	Stored in Soil (cm)	Stored in Sand (cm)	Collected Quantity ♣ (cm)	Difference ♣ (cm)
10	1.10	7.62	1.70	3.53	2.38	0.39	8.28	0.65
10	1.33	7.64	1.82	3.24	2.25	0.37	7.92	0.28
10	1.57	7.57	1.65	3.24	2.27	0.34	7.76	0.19
10	1.81	7.56	1.60	3.38	2.37	0.40	7.91	0.35
15	1.10	7.80	0.69	5.18	1.57	0.42	8.07	0.27
15	1.33	7.82	0.57	4.98	1.60	0.41	7.75	-0.07
15	1.57	7.92	0.68	4.90	1.55	0.41	7.88	-0.03
15	1.81	7.94	0.56	5.31	1.49	0.41	8.01	0.07

† Soil surface area = 3281 cm²

♣ The sum of drainage, runoff, and stored quantities.

♣ Numbers with negative sign in this column indicate shortage of water

Table A-5 Average rainfall, runoff, drainage, and storage of water

		Bulk Density (g/cm ³)				
	Moisture Content	1.10	1.33	1.57	1.81	Mean
	%	-----cm-----				
Rainfall	10	7.56	7.57	7.64	7.62	7.60a
	15	7.94	7.92	7.82	7.80	7.90a
Mean		7.71a	7.73a	7.74a	7.75a	
Surface	10	3.38	3.24	3.24	3.53	3.35b
Runoff	15	5.31	4.90	4.98	5.18	5.10a
Mean		4.35a	4.11a	4.10a	4.34a	
Subsurface drainage	10	1.60	1.65	1.82	1.70	1.69a
	15	0.56	0.68	0.57	0.69	0.62b
Mean		1.19a	1.20a	1.17a	1.10a	
Storage in soil	10	2.38	2.25	2.27	2.37	2.32a
	15	1.57	1.60	1.55	1.49	1.55b
Mean		1.97a	1.92a	1.91a	1.93a	
Storage in sand	10	0.67	0.61	0.60	0.57	0.61a
	15	0.64	0.60	0.75	0.66	0.66a
Mean		0.40a	0.39a	0.38a	0.40a	

† Means with the same letter in each column are not significantly different at the $\alpha=0.05$ level.

Table A-6 NO₃-N mass balance

Moisture Content %	Bulk Density g cm ⁻³	Surface Runoff	Retained by Soil	Retained by Sand	Sub- Surface Drainage kg ha ⁻¹	Initial soil total ±	Total recovered	Difference
10	1.10	0.04	2.96	4.41	125.87	116.87	133.29	-14.13
	1.33	0.03	22.66	6.59	82.75	117.18	112.04	4.06
	1.57	0.02	77.81	3.94	31.58	117.75	113.35	3.75
	1.81	0.02	82.55	1.09	14.70	117.44	98.37	16.37
15	1.10	0.06	50.68	24.50	38.38	125.36	113.63	9.24
	1.33	0.05	61.84	25.80	24.52	125.40	112.20	10.40
	1.57	0.06	97.44	4.63	10.58	125.56	112.71	10.14
	1.81	0.04	98.15	4.35	9.43	125.60	111.97	10.72

± 112 kg ha⁻¹ added in compacted soil bar; remainder from that in soil originally.

Table A-7 Br mass balance

Moisture Content %	Bulk Density g cm ⁻³	Surface Runoff	Retained by Soil	Retained by Sand	Sub- Surface Drainage kg ha ⁻¹	Initial total ±	Total recovered	Difference
10	1.10	17.56	10.07	2.76	8.38	35.83	38.77	-8.52
	1.33	16.40	9.95	2.39	8.93	38.53	37.67	2.12
	1.57	16.22	10.65	2.35	8.28	38.56	37.50	2.62
	1.81	16.31	10.30	2.51	7.67	38.91	36.80	4.88
15	1.10	25.86	9.32	2.19	1.58	38.91	38.95	-0.22
	1.33	25.44	10.30	2.23	1.26	39.93	39.23	1.79
	1.57	24.80	9.55	2.56	1.91	39.26	38.82	1.05
	1.81	26.77	8.72	2.14	1.20	39.88	38.83	2.71

± With rainwater (amount in soil <2.0 kg ha⁻¹)

Table A-8 Cl mass balance

Moisture Content %	Bulk Density g cm ⁻³	Surface Runoff	Retained by Soil	Retained by Sand	Sub- Surface Drainage kg ha ⁻¹	Initial soil total ±	Total recovered	Difference
10	1.10	--	2.42	3.78	115.56	121.04	121.76	-0.55
	1.33	--	2.64	2.82	108.16	122.22	113.62	6.93
	1.57	--	4.80	3.35	111.00	122.86	119.14	2.91
	1.81	--	4.49	3.16	115.48	121.72	123.13	-1.34
	1.10	--	11.83	29.62	78.49	121.18	119.94	1.01
15	1.33	--	9.33	30.16	82.84	120.45	122.33	-1.57
	1.57	--	10.52	26.27	80.25	119.65	117.04	2.18
	1.81	--	12.83	28.71	73.93	118.16	115.47	2.17

± 112 kg ha⁻¹ added before soil pans were packed; remainder from that in soil originally.

Table A-9 Volumetric water content beneath compacted soil bar (low probe) in runoff/drainage pans for 10% moisture treatment

Time min	Bulk density (g/cm ³)											
	1.1			1.33			1.57			1.81		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	cm ³ /cm ³											
0	0.144	0.148	0.148	0.142	0.150	0.147	0.153	0.150	0.150	0.146	0.140	0.145
3.5	0.145	0.149	0.149	0.143	0.150	0.144	0.152	0.151	0.150	0.147	0.139	0.142
7	0.145	0.150	0.150	0.166	0.151	0.147	0.158	0.149	0.147	0.152	0.142	0.143
10.5	0.199	0.181	0.147	0.265	0.164	0.182	0.183	0.162	0.169	0.218	0.161	0.146
14	0.437	0.436	0.154	0.327	0.334	0.338	0.294	0.233	0.254	0.277	0.233	0.156
17.5	0.447	0.457	0.155	0.396	0.499	0.453	0.334	0.332	0.316	0.322	0.290	0.203
21	0.442	0.476	0.231	0.429	0.527	0.453	0.375	0.364	0.369	0.342	0.320	0.287
24.5	0.449	0.478	0.491	0.435	0.502	0.466	0.392	0.419	0.368	0.354	0.333	0.333
28	0.441	0.477	0.524	0.430	0.498	0.398	0.416	0.417	0.379	0.352	0.337	0.346
31.5	0.433	0.473	0.529	0.428	0.528	0.375	0.407	0.437	0.374	0.349	0.340	0.361
35	0.379	0.418	0.521	0.418	0.489	0.415	0.448	0.428	0.385	0.352	0.337	0.357
38.5	0.370	0.400	0.491	0.413	0.473	0.413	0.426	0.457	0.393	0.351	0.339	0.351
42	0.360	0.392	0.505	0.403	0.468	0.392	0.424	0.446	0.365	0.354	0.339	0.358
45.5	0.366	0.379	0.493	0.393	0.452	0.397	0.423	0.425	0.388	0.352	0.340	0.356
49	0.363	0.387	0.466	0.387	0.468	0.379	0.426	0.438	0.387	0.354	0.338	0.361
52.5	0.359	0.384	0.385	0.383	0.459	0.377	0.432	0.449	0.378	0.354	0.338	0.366
56	0.364	0.382	0.396	0.407	0.459	0.380	0.419	0.441	0.381	0.361	0.341	0.365
59.5	0.366	0.384	0.388	0.389	0.377	0.380	0.423	0.439	0.403	0.356	0.341	0.360
63	0.363	0.384	0.382	0.381	0.387	0.364	0.415	0.428	0.385	0.354	0.341	0.363
66.5	0.359	0.383	0.376	0.378	0.379	0.391	0.424	0.420	0.381	0.358	0.344	0.365
70	0.364	0.384	0.378	0.377	0.394	0.368	0.457	0.451	0.384	0.352	0.345	0.369

Table A-10 Volumetric water content beneath compacted soil bar (low probe) in runoff/drainage pans for 15% moisture treatment

Time min	Bulk density (g/cm ³)											
	1.1			1.33			1.57			1.81		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	cm ³ /cm ³											
0	0.160	0.159	0.158	0.163	0.155	0.160	0.163	0.160	0.155	0.162	0.158	0.153
3.5	0.159	0.158	0.159	0.162	0.156	0.160	0.162	0.159	0.156	0.162	0.158	0.157
7	0.163	0.163	0.170	0.163	0.166	0.164	0.170	0.163	0.158	0.168	0.158	0.165
10.5	0.220	0.287	0.227	0.228	0.423	0.276	0.206	0.190	0.170	0.224	0.175	0.195
14	0.312	0.446	0.464	0.483	0.440	0.460	0.265	0.235	0.267	0.258	0.255	0.235
17.5	0.346	0.454	0.433	0.546	0.464	0.518	0.294	0.265	0.321	0.277	0.292	0.247
21	0.360	0.452	0.429	0.549	0.468	0.517	0.300	0.301	0.340	0.296	0.314	0.262
24.5	0.380	0.455	0.538	0.548	0.466	0.516	0.306	0.308	0.450	0.310	0.312	0.271
28	0.375	0.467	0.485	0.548	0.506	0.514	0.309	0.317	0.451	0.306	0.311	0.275
31.5	0.379	0.489	0.503	0.551	0.506	0.527	0.314	0.319	0.357	0.318	0.317	0.282
35	0.382	0.469	0.539	0.548	0.504	0.510	0.320	0.326	0.375	0.330	0.319	0.285
38.5	0.379	0.458	0.453	0.545	0.506	0.513	0.314	0.337	0.397	0.351	0.325	0.290
42	0.379	0.450	0.512	0.547	0.466	0.513	0.316	0.343	0.469	0.330	0.324	0.298
45.5	0.364	0.392	0.504	0.550	0.467	0.513	0.321	0.341	0.420	0.328	0.327	0.300
49	0.380	0.399	0.498	0.548	0.402	0.472	0.316	0.351	0.386	0.330	0.325	0.300
52.5	0.353	0.376	0.466	0.549	0.398	0.449	0.320	0.352	0.371	0.317	0.334	0.297
56	0.346	0.372	0.420	0.546	0.374	0.455	0.321	0.352	0.426	0.336	0.334	0.300
59.5	0.350	0.365	0.442	0.548	0.381	0.433	0.323	0.350	0.424	0.332	0.338	0.301
63	0.342	0.357	0.420	0.510	0.369	0.456	0.323	0.351	0.411	0.329	0.336	0.297
66.5	0.335	0.353	0.412	0.481	0.343	0.432	0.329	0.345	0.421	0.326	0.325	0.294
70	0.331	0.336	0.412	0.470	0.367	0.432	0.317	0.352	0.409	0.334	0.338	0.306

Table A-11 Volumetric water content 1 cm below soil surface (side probe) in runoff/drainage pans for 10% moisture treatment

Time min	Bulk density (g/cm ³)											
	1.1			1.33			1.57			1.81		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----cm ³ /cm ³ -----											
0	0.096	0.089	0.091	0.124	0.117	0.099	0.140	0.157	0.104	0.132	0.099	0.095
3.5	0.238	0.222	0.091	0.277	0.230	0.203	0.278	0.298	0.246	0.240	0.127	0.095
7	0.317	0.319	0.148	0.355	0.329	0.319	0.349	0.351	0.330	0.339	0.278	0.119
10.5	0.354	0.348	0.302	0.378	0.355	0.357	0.377	0.371	0.358	0.371	0.342	0.303
14	0.366	0.362	0.353	0.386	0.371	0.373	0.387	0.382	0.372	0.384	0.373	0.353
17.5	0.375	0.368	0.372	0.387	0.382	0.382	0.388	0.386	0.382	0.388	0.389	0.377
21	0.379	0.370	0.385	0.387	0.391	0.387	0.388	0.388	0.392	0.389	0.397	0.390
24.5	0.380	0.369	0.392	0.390	0.394	0.387	0.389	0.388	0.393	0.390	0.402	0.397
28	0.379	0.369	0.395	0.390	0.393	0.387	0.389	0.385	0.391	0.390	0.401	0.400
31.5	0.380	0.369	0.393	0.389	0.391	0.384	0.392	0.386	0.391	0.389	0.400	0.399
35	0.379	0.369	0.394	0.389	0.389	0.384	0.390	0.386	0.390	0.388	0.401	0.398
38.5	0.375	0.369	0.394	0.390	0.387	0.383	0.389	0.386	0.389	0.389	0.400	0.398
42	0.375	0.368	0.394	0.391	0.385	0.381	0.390	0.386	0.390	0.389	0.400	0.395
45.5	0.375	0.369	0.395	0.389	0.386	0.382	0.390	0.385	0.390	0.389	0.400	0.395
49	0.376	0.369	0.394	0.392	0.384	0.382	0.391	0.387	0.389	0.389	0.400	0.394
52.5	0.377	0.370	0.394	0.392	0.385	0.384	0.391	0.386	0.394	0.389	0.400	0.394
56	0.375	0.370	0.396	0.392	0.384	0.384	0.390	0.386	0.394	0.389	0.399	0.394
59.5	0.375	0.370	0.396	0.392	0.385	0.384	0.391	0.386	0.395	0.388	0.399	0.399
63	0.375	0.370	0.397	0.392	0.387	0.385	0.390	0.386	0.394	0.388	0.399	0.397
66.5	0.376	0.370	0.398	0.391	0.387	0.386	0.390	0.386	0.394	0.387	0.399	0.397
70	0.369	0.370	0.398	0.378	0.378	0.384	0.378	0.373	0.389	0.380	0.397	0.398

Table A-12 Volumetric water content 1 cm below soil surface (side probe) in runoff/drainage pans for 15% moisture treatment

Time min	Bulk density (g/cm ³)											
	1.1 rep 1	rep 2	rep 3	1.33 rep 1	rep 2	rep 3	1.57 rep 1	rep 2	rep 3	1.81 rep 1	rep 2	rep 3
	cm ³ /cm ³											
0	0.105	0.114	0.115	0.116	0.119	0.131	0.118	0.115	0.106	0.113	0.117	0.119
3.5	0.272	0.250	0.253	0.273	0.168	0.268	0.194	0.244	0.219	0.236	0.161	0.182
7	0.322	0.325	0.317	0.323	0.322	0.332	0.293	0.326	0.319	0.325	0.301	0.282
10.5	0.332	0.348	0.325	0.337	0.344	0.347	0.343	0.336	0.349	0.342	0.345	0.304
14	0.331	0.354	0.327	0.336	0.348	0.349	0.352	0.337	0.362	0.342	0.354	0.310
17.5	0.329	0.352	0.326	0.335	0.347	0.349	0.353	0.335	0.363	0.339	0.357	0.314
21	0.329	0.353	0.327	0.334	0.349	0.349	0.354	0.336	0.361	0.339	0.358	0.316
24.5	0.327	0.350	0.326	0.333	0.350	0.348	0.353	0.335	0.359	0.337	0.358	0.319
28	0.326	0.348	0.326	0.333	0.349	0.348	0.355	0.335	0.359	0.337	0.357	0.322
31.5	0.325	0.347	0.326	0.332	0.349	0.348	0.355	0.337	0.355	0.336	0.358	0.322
35	0.323	0.347	0.326	0.332	0.350	0.346	0.354	0.337	0.354	0.336	0.356	0.325
38.5	0.323	0.347	0.325	0.332	0.349	0.346	0.354	0.340	0.354	0.337	0.357	0.325
42	0.322	0.342	0.325	0.332	0.349	0.346	0.355	0.340	0.355	0.337	0.358	0.326
45.5	0.320	0.344	0.326	0.332	0.349	0.347	0.355	0.340	0.355	0.338	0.358	0.327
49	0.321	0.344	0.325	0.331	0.348	0.347	0.354	0.339	0.355	0.338	0.355	0.328
52.5	0.320	0.341	0.326	0.330	0.349	0.345	0.355	0.340	0.354	0.337	0.354	0.328
56	0.322	0.340	0.325	0.331	0.349	0.346	0.355	0.339	0.347	0.337	0.355	0.327
59.5	0.322	0.342	0.326	0.332	0.349	0.347	0.356	0.340	0.347	0.338	0.354	0.327
63	0.323	0.341	0.327	0.332	0.349	0.346	0.356	0.340	0.347	0.338	0.352	0.328
66.5	0.324	0.342	0.325	0.332	0.350	0.347	0.356	0.340	0.346	0.339	0.353	0.326
70	0.320	0.338	0.325	0.329	0.349	0.347	0.353	0.337	0.344	0.337	0.351	0.326

Table A-13 EC in surface runoff for 10% moisture treatment

sampling time	Bulk density (g/cm ³)											
	1.1			1.33			1.57			1.81		
min	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----ms/cm-----											
31.8	5.581	7.164	7.771	7.097	7.316	7.567	4.229	5.386	5.229	7.051	6.667	6.378
37.0	8.571	10.78	10.11	5.149	7.742	6.464	5.244	5.171	5.919	5.252	4.819	4.728
41.0	9.304	10.46	10.84	3.983	7.319	6.191	4.551	3.807	4.203	3.705	3.308	3.641
45.0	10.029	8.968	10.25	3.091	6.657	5.977	4.221	2.811	2.959	2.652	2.392	2.752
49.0	9.767	6.957	8.509	2.537	5.984	5.514	4.361	2.109	2.125	1.976	1.759	2.038
53.0	9.952	5.126	6.505	2.175	5.25	5.107	4.627	1.701	1.605	1.606	1.337	1.505
57.0	8.001	3.657	4.691	2.021	4.501	4.522	5.055	1.478	1.263	1.283	1.054	1.138
61.0	6.313	2.776	3.271	1.977	4.272	4.093	5.343	1.406	1.062	1.061	0.883	0.905
65.0	5.201	2.024	2.338	2.024	3.749	3.633	5.272	1.321	0.959	0.917	0.777	0.746
69.0	4.142	1.415	1.583		3.082	3.221		1.334	0.887	0.808	0.714	0.633

Table A-14 EC in subsurface drainage for 10% moisture treatment

sampling time	Bulk density (g/cm ³)											
	1.1			1.33			1.57			1.81		
min	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----ms/cm-----											
45.9	4.996	6.476	3.861	4.442	5.304	6.468	5.162	1.486	6.221	5.578	5.716	4.545
50.2	4.693	9.123	5.239	5.895	5.715	6.521	5.412	3.918	6.802	5.519	5.941	5.354
54.2	4.617	9.699	5.392	5.657	5.915	6.783	5.055	4.772	6.245	5.242	5.244	5.468
58.2	4.536	10.56	5.606	5.895	6.118	6.911	4.684	4.802	5.359	4.994	4.865	5.274
62.2	4.771	11.43	5.745	5.968	6.197	7.424	4.353	4.682	4.671	4.716	3.921	5.138
66.2	5.026	12.03	6.234	6.222	6.341	8.221	4.041	3.973	3.937	4.398	3.751	
70.2	5.532	12.27		6.786	7.381		3.676	2.839	3.079	3.811	3.133	

Table A-15 EC_b beneath compacted soil bar (low probe) in runoff/drainage pans for 10% moisture treatment

Time min	Bulk density (g/cm ³)											
	1.1			1.33			1.57			1.81		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----ms/cm-----											
0	0.030	0.027	0.035	0.034	0.029	0.031	0.031	0.026	0.028	0.031	0.030	0.039
3.5	0.030	0.028	0.036	0.036	0.029	0.033	0.032	0.028	0.028	0.032	0.031	0.043
7	0.130	0.028	0.121	0.258	0.030	0.102	0.033	0.028	0.039	0.033	0.070	0.172
10.5	1.496	0.085	0.183	0.862	0.739	0.671	0.070	0.029	0.157	0.182	0.221	0.315
14	2.232	0.705	0.215	1.484	1.669	1.265	0.376	0.189	0.330	0.339	0.292	0.402
17.5	1.916	2.147	0.401	1.753	1.913	1.253	0.420	0.372	0.293	0.337	0.257	0.535
21	1.380	2.118	0.656	1.850	1.523	0.970	0.406	0.378	0.246	0.308	0.223	0.565
24.5	1.059	1.668	0.795	1.754	1.128	0.755	0.389	0.368	0.218	0.286	0.207	0.540
28	0.826	1.208	0.820	1.577	0.847	0.602	0.379	0.358	0.204	0.273	0.198	0.515
31.5	0.657	0.900	0.710	1.385	0.680	0.505	0.369	0.350	0.197	0.264	0.194	0.485
35	0.536	0.705	0.582	1.215	0.568	0.437	0.361	0.341	0.193	0.260	0.194	0.453
38.5	0.446	0.571	0.506	1.067	0.489	0.387	0.357	0.335	0.191	0.259	0.196	0.418
42	0.381	0.478	0.452	0.933	0.435	0.347	0.355	0.332	0.189	0.258	0.199	0.384
45.5	0.331	0.409	0.412	0.819	0.394	0.315	0.355	0.329	0.188	0.260	0.204	0.349
49	0.292	0.359	0.385	0.722	0.361	0.290	0.355	0.328	0.189	0.263	0.209	0.318
52.5	0.261	0.322	0.366	0.641	0.336	0.271	0.355	0.326	0.187	0.265	0.215	0.289
56	0.236	0.290	0.349	0.572	0.317	0.255	0.357	0.324	0.187	0.269	0.220	0.265
59.5	0.215	0.266	0.334	0.516	0.300	0.242	0.358	0.324	0.187	0.273	0.225	0.246
63	0.199	0.247	0.322	0.475	0.284	0.231	0.359	0.323	0.188	0.276	0.230	0.230
66.5	0.195	0.234	0.311	0.470	0.271	0.225	0.359	0.321	0.187	0.278	0.233	0.224
70	0.197	0.224	0.311	0.470	0.273	0.225	0.362	0.323	0.187	0.283	0.233	0.225

Table A-16 EC_b beneath compacted soil bar (low probe) in runoff/drainage pans for 15% moisture treatment

Time min	Bulk density (g/cm ³)											
	1.1 rep 1	1.1 rep 2	1.1 rep 3	1.33 rep 1	1.33 rep 2	1.33 rep 3	1.57 rep 1	1.57 rep 2	1.57 rep 3	1.81 rep 1	1.81 rep 2	1.81 rep 3
	-----ms/cm-----											
0	0.048	0.036	0.049	0.045	0.045	0.039	0.039	0.051	0.037	0.049	0.038	0.043
3.5	0.049	0.038	0.050	0.048	0.049	0.041	0.041	0.053	0.039	0.051	0.040	0.045
7	0.054	0.039	0.055	0.051	0.074	0.044	0.044	0.057	0.040	0.073	0.042	0.050
10.5	0.198	0.269	0.199	0.213	0.926	0.412	0.184	0.114	0.127	0.224	0.087	0.211
14	0.614	1.576	0.429	1.052	1.676	0.995	0.313	0.261	0.392	0.339	0.282	0.375
17.5	0.787	2.150	0.605	1.946	2.077	1.353	0.377	0.380	0.457	0.409	0.372	0.468
21	0.890	2.169	0.809	2.610	2.319	1.497	0.397	0.466	0.449	0.447	0.381	0.527
24.5	0.957	2.004	1.068	3.047	2.441	1.510	0.405	0.528	0.438	0.470	0.376	0.558
28	1.005	1.777	1.343	3.307	2.544	1.466	0.409	0.575	0.426	0.484	0.366	0.565
31.5	1.045	1.518	1.605	3.416	2.480	1.376	0.413	0.608	0.415	0.492	0.356	0.563
35	1.053	1.291	1.814	3.395	2.287	1.261	0.418	0.634	0.409	0.501	0.349	0.543
38.5	1.016	1.108	1.941	3.293	2.006	1.147	0.421	0.657	0.403	0.507	0.345	0.517
42	0.941	0.936	1.994	3.101	1.681	1.036	0.418	0.665	0.397	0.501	0.345	0.484
45.5	0.857	0.798	1.973	2.864	1.437	0.925	0.415	0.662	0.391	0.498	0.343	0.451
49	0.759	0.684	1.886	2.603	1.233	0.785	0.413	0.656	0.384	0.495	0.330	0.415
52.5	0.659	0.588	1.770	2.336	1.080	0.671	0.410	0.650	0.376	0.491	0.328	0.380
56	0.564	0.510	1.634	2.057	0.924	0.585	0.406	0.644	0.367	0.488	0.325	0.349
59.5	0.481	0.444	1.478	1.784	0.796	0.517	0.401	0.636	0.363	0.484	0.323	0.322
63	0.411	0.388	1.323	1.535	0.684	0.464	0.395	0.627	0.359	0.480	0.323	0.300
66.5	0.353	0.342	1.173	1.305	0.576	0.420	0.390	0.616	0.356	0.475	0.323	0.281
70	0.324	0.309	1.173	1.128	0.515	0.420	0.386	0.607	0.354	0.472	0.324	0.271

Table A-17 EC_b 1 cm below soil surface (side probe) in runoff/drainage pans for 10% moisture treatment

Time min	Bulk density (g/cm ³)											
	rep 1	1.1 rep 2	rep 3	rep 1	1.33 rep 2	rep 3	rep 1	1.57 rep 2	rep 3	rep 1	1.81 rep 2	rep 3
	-----ms/cm-----											
0	0.011	0.006	0.004	0.040	0.026	0.008	0.066	0.088	0.005	0.043	0.007	0.008
3.5	0.144	0.184	0.003	0.290	0.185	0.148	0.269	0.203	0.200	0.203	0.048	0.007
7	0.176	0.180	0.067	0.234	0.233	0.252	0.241	0.151	0.198	0.254	0.326	0.025
10.5	0.152	0.135	0.212	0.171	0.170	0.186	0.176	0.129	0.145	0.184	0.269	0.243
14	0.136	0.120	0.152	0.147	0.146	0.151	0.152	0.128	0.126	0.155	0.189	0.168
17.5	0.130	0.121	0.129	0.139	0.138	0.142	0.144	0.128	0.125	0.146	0.156	0.136
21	0.128	0.120	0.124	0.135	0.136	0.138	0.139	0.127	0.126	0.142	0.143	0.132
24.5	0.127	0.118	0.124	0.133	0.134	0.135	0.136	0.126	0.124	0.140	0.137	0.130
28	0.126	0.117	0.123	0.132	0.133	0.134	0.133	0.126	0.124	0.138	0.134	0.128
31.5	0.125	0.117	0.122	0.131	0.131	0.132	0.133	0.125	0.123	0.138	0.132	0.127
35	0.125	0.116	0.122	0.130	0.130	0.131	0.131	0.125	0.123	0.136	0.131	0.128
38.5	0.124	0.116	0.121	0.130	0.129	0.130	0.131	0.125	0.122	0.137	0.129	0.126
42	0.124	0.115	0.121	0.129	0.128	0.129	0.129	0.125	0.122	0.136	0.129	0.125
45.5	0.124	0.114	0.120	0.128	0.127	0.129	0.130	0.125	0.122	0.136	0.128	0.125
49	0.123	0.114	0.120	0.127	0.127	0.128	0.129	0.125	0.122	0.136	0.127	0.125
52.5	0.123	0.113	0.120	0.127	0.126	0.126	0.128	0.126	0.120	0.137	0.127	0.124
56	0.123	0.113	0.120	0.126	0.126	0.126	0.128	0.126	0.119	0.136	0.127	0.125
59.5	0.122	0.114	0.120	0.126	0.126	0.125	0.128	0.126	0.119	0.137	0.127	0.125
63	0.122	0.114	0.120	0.126	0.126	0.124	0.127	0.126	0.119	0.136	0.127	0.125
66.5	0.122	0.114	0.120	0.125	0.126	0.124	0.127	0.126	0.119	0.137	0.127	0.125
70	0.121	0.113	0.121	0.124	0.124	0.124	0.124	0.124	0.118	0.134	0.125	0.127

Table A-18 EC_b 1 cm below soil surface (side probe) in runoff/drainage pans for 15% moisture treatment

Time min	Bulk density (g/cm ³)											
	rep 1	1.1 rep 2	rep 3	rep 1	1.33 rep 2	rep 3	rep 1	1.57 rep 2	rep 3	rep 1	1.81 rep 2	rep 3
	-----ms/cm-----											
0	0.020	0.019	0.026	0.024	0.031	0.055	0.026	0.029	0.014	0.028	0.024	0.031
3.5	0.020	0.268	0.277	0.279	0.141	0.244	0.158	0.212	0.202	0.249	0.094	0.153
7	0.246	0.227	0.242	0.201	0.379	0.229	0.311	0.239	0.238	0.243	0.367	0.312
10.5	0.165	0.160	0.182	0.150	0.272	0.176	0.285	0.195	0.164	0.175	0.256	0.291
14	0.132	0.140	0.157	0.137	0.219	0.157	0.226	0.171	0.134	0.156	0.186	0.259
17.5	0.125	0.130	0.143	0.130	0.191	0.145	0.190	0.154	0.125	0.144	0.158	0.230
21	0.119	0.125	0.136	0.125	0.174	0.137	0.169	0.143	0.119	0.136	0.144	0.208
24.5	0.116	0.121	0.128	0.122	0.163	0.132	0.156	0.136	0.115	0.131	0.137	0.188
28	0.113	0.117	0.125	0.120	0.155	0.128	0.146	0.130	0.113	0.126	0.132	0.174
31.5	0.111	0.115	0.122	0.118	0.148	0.125	0.140	0.126	0.111	0.124	0.128	0.162
35	0.109	0.113	0.117	0.116	0.147	0.123	0.134	0.124	0.109	0.121	0.125	0.152
38.5	0.108	0.112	0.116	0.115	0.141	0.121	0.131	0.123	0.109	0.120	0.123	0.144
42	0.107	0.111	0.112	0.114	0.136	0.119	0.128	0.122	0.108	0.119	0.122	0.138
45.5	0.106	0.110	0.112	0.113	0.135	0.118	0.125	0.118	0.108	0.117	0.121	0.132
49	0.104	0.109	0.110	0.112	0.130	0.117	0.123	0.118	0.108	0.116	0.119	0.128
52.5	0.105	0.108	0.110	0.110	0.128	0.116	0.121	0.116	0.107	0.119	0.119	0.124
56	0.103	0.107	0.107	0.110	0.129	0.115	0.120	0.115	0.106	0.115	0.118	0.122
59.5	0.103	0.107	0.110	0.110	0.135	0.114	0.118	0.115	0.105	0.115	0.116	0.119
63	0.102	0.106	0.106	0.109	0.126	0.113	0.117	0.113	0.105	0.113	0.116	0.119
66.5	0.103	0.105	0.108	0.108	0.126	0.113	0.117	0.113	0.105	0.113	0.115	0.117
70	0.103	0.105	0.108	0.108	0.126	0.113	0.117	0.113	0.105	0.113	0.115	0.117

Table A-19 Anion tracer concentration in subsurface drainage for 10% moisture treatment

Time min	Bulk density (cm3/cm3)											
	1.1	1.33	1.57	1.81	1.1	1.33	1.57	1.81	1.1	1.33	1.57	1.81
	NO3-N				Br				Cl			
	-----mg/L-----											
31.8	410.07	326.69	150.36	205.71	34.45	28.46	38.18	30.16	1554.39	1614.29	1839.22	2045.24
37.0	885.17	412.46	180.02	156.67	39.36	42.73	40.68	42.98	1701.00	1367.42	1559.32	1436.26
41.0	1187.32	490.30	149.50	110.51	48.09	51.41	48.96	50.77	1189.81	966.04	1012.44	969.31
45.0	1196.94	539.15	151.93	86.50	53.50	54.95	53.65	52.93	755.79	630.65	665.83	629.29
49.0	1068.50	506.66	171.74	63.71	54.73	55.96	56.10	54.21	488.28	443.21	461.17	416.62
53.0	928.25	507.73	207.27	49.06	54.55	55.43	58.89	53.20	366.39	285.30	281.41	289.22
57.0	716.08	454.14	246.48	46.49	54.16	54.16	54.72	52.52	254.71	199.70	187.67	181.47
61.0	491.96	435.77	276.18	40.98	54.60	52.23	53.14	51.52	164.72	121.93	126.51	146.67
65.0	384.73	403.33	288.42	37.19	52.45	50.75	51.36	50.43	114.74	75.64	90.11	103.12
69.0	281.15	417.26	101.71	38.76	51.63	49.29	50.52	49.47	72.92	34.76	51.69	60.52

Table A-20 Anion tracer concentration in subsurface drainage for 15% moisture treatment

Time	Bulk density (cm3/cm3)											
	1.1	1.33	1.57	1.81	1.1	1.33	1.57	1.81	1.1	1.33	1.57	1.81
min	NO3-N				Br				Cl			
	-----mg/L-----											
45.9	248.80	299.94	145.09	179.06	15.24	18.66	20.90	13.20	1247.51	1266.75	1160.46	1488.13
50.2	362.68	311.47	174.95	188.85	14.30	11.82	19.72	10.68	1388.73	1453.11	1406.44	1599.15
54.2	431.10	351.70	184.88	179.36	16.71	14.11	20.08	14.30	1321.94	1398.81	1468.10	1442.56
58.2	517.23	427.11	170.06	168.01	19.52	18.16	24.68	18.13	1215.82	1273.18	1379.48	1430.09
62.2	661.14	437.53	161.13	169.61	22.77	18.18	28.93	22.78	1213.41	1332.21	1217.91	1294.83
66.2	753.84	549.19	142.56	147.94	26.32	22.76	34.77	33.51	1102.96	1210.51	977.94	702.40
70.2	1024.53	579.89	118.41	133.66	34.13	26.66	41.01	39.96	567.65	730.85	783.46	594.15
70.2	1106.75	736.51	107.35		38.52	22.99	28.85		509.21	356.94	446.60	

Table B-1 Subsurface drainage from lysimeters for four treatments

Time min	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----cm-----											
0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.50	1.07	1.18	1.25	1.06	1.26	1.40	1.19	1.24	1.32	1.13	1.84	1.49
3.84	0.21	0.30	0.62	0.21	0.31	0.55	0.11	0.27	0.34	0.17	0.33	0.42
5.93	0.42	0.49	0.57	0.36	0.31	0.37	0.17	0.83	0.55	0.26	0.41	0.38
8.18	0.32	0.26	0.31	0.42	0.27	0.29	0.08	0.33	0.35	0.51	0.22	0.24
22.95	0.80	0.65	0.70	0.80	0.66	0.66	0.56		0.67	0.99	0.74	0.68
96.84	0.67	0.51	0.70	0.79	0.73	0.65	0.39	0.61	0.57	0.56	0.66	0.65
169.58	0.21	0.18	0.25	0.34	0.26	0.27	0.30	0.21	0.45	0.20	0.35	0.42
242.49	0.13	0.21	0.17	0.16	0.18	0.14	0.84	0.15	0.31	0.14	0.24	0.29

Table B-2 NO₃-N concentrations in subsurface drainage for four treatments

Time min	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----mg/L-----											
0.00												
3.50	1.76	6.51	3.03	0.42	0.63	0.98	1.20	4.49	1.77	0.60	5.99	3.67
3.84	6.41	22.42	21.64	0.61	1.02	3.89	2.01	2.93	3.74	11.20	15.77	5.52
5.93	6.22	16.19	5.29	1.05	0.82	2.07	1.36	1.83	2.22	15.66	10.87	5.51
8.18	4.53	9.83	12.21	0.99	0.68	1.19	1.58	1.03	0.97	9.57	7.60	3.76
22.95	2.23	5.38	3.28	0.47	0.55	0.92	0.89	--	0.77	5.13	4.68	3.25
96.84	1.21	4.04	3.12	0.24	0.53	1.35	0.98	0.85	0.64	3.61	3.01	2.82
169.58	0.80	3.44	8.18	0.13	1.46	1.29	0.87	0.71	1.11	4.57	2.41	2.48
242.49	0.64	3.12	7.39	0.11	1.09	1.20	1.68	0.68	2.15	6.26	3.49	2.38

Table B-3 Br concentrations in subsurface drainage for four treatments

Time min	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----mg/L-----											
0.00												
3.50	2.23	8.42	1.85	5.73	1.85	3.20	1.33	5.65	6.50	0.99	2.89	2.94
3.84	2.14	8.29	7.40	16.19	3.80	7.36	2.27	5.08	9.30	3.49	5.60	3.88
5.93	1.61	6.20	2.38	11.70	2.78	4.22	1.81	2.50	6.42	3.78	2.95	3.01
8.18	1.25	3.63	4.60	7.86	2.06	2.52	1.97	25.05	2.82	3.85	2.04	2.40
22.95	0.91	1.93	1.45	4.25	1.44	1.86	1.30	--	1.96	2.91	1.51	2.00
96.84	0.80	1.32	1.14	2.09	1.06	1.52	1.05	2.12	1.56	1.67	1.08	1.48
169.58	0.61	1.20	2.18	1.40	3.83	1.61	1.05	1.65	3.33	1.50	1.65	1.10
242.49	0.57	1.47	2.40	1.20	3.10	1.70	2.20	1.45	5.55	1.86	1.86	1.29

Table B-4 PO₄-P concentrations in subsurface drainage for four treatments

Time min	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----mg/L-----											
0.00												
3.50	0.109	0.664	0.131	0.619	0.067	0.286	0.039	0.195	0.329	0.075	0.165	0.060
3.84	0.056	0.161	0.084	0.704	0.016	0.116	0.068	0.134	0.138	0.113	0.064	0.027
5.93	0.016	0.109	0.022	0.487	0.017	0.061	0.058	0.070	0.089	0.124	0.034	0.048
8.18	0.018	0.072	0.049	0.258	0.082	0.044	0.060	0.728	0.047	0.140	0.025	0.019
22.95	0.016	0.044	0.075	0.110	0.076	0.037	0.042		0.034	0.090	0.039	0.041
96.84	0.023	0.050	0.048	0.075	0.044	0.050	0.016	0.149	0.022	0.071	0.015	0.011
169.58	0.013	0.065	0.230	0.018	0.014	0.039	0.015	0.150	0.081	0.030	0.029	0.026
242.49	0.021	0.170	0.042	0.105	0.015	0.045	0.047	0.069	0.179	0.036	0.066	0.019

Table B-5 EC measured by EC meter in subsurface drainage for four treatments

Time Hr.	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----us/cm-----											
0.00												
3.50	428.8	220.7	197.2	519.8	464.4	305.2	146.1	219.1	188.4	158.1	566	522.7
3.84	418.8	312.5	326.8	399.2	368.1	235.6	146.5	157.4	178.3	227.2	572.9	483.9
5.93	429.7	261.1	208.5	408.5	391.2	266.1	145.2	170.1	166.7	264.3	587.9	512.2
8.18	438.1	233.6	250.1	419.4	412.2	299.9	152.8	186.4	180.3	212.7	586.9	531.5
22.95	446.3	218	198.4	484.9	444.6	334.9	166.4		184.3	177.8	592.3	540.7
96.84	465.6	218.4	221.3	557.7	469.4	327.7	143.3	182.3	184.9	162.1	601.6	549.2
169.58	482.8	218.1	177.3	570.7	381.9	316.6	137.8	190.9	166.9	166.1	547.2	548.9
242.49	501.8	198	200.4	604.1	416.2	315.7	133.9	198.1	129.2	180.2	505.5	526.6

Table B-6 Volumetric water content in soil profile before rainfall simulation for four treatments

depth cm	NTL			NTC			TC			TL		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----cm ³ /cm ³ -----											
0--15	0.253	0.285	0.292	0.220	0.302	0.237	0.271	0.214	0.305	0.259	0.279	0.259
15--30	0.298	0.296	0.393	0.296	0.327	0.298	0.349	0.304	0.378	0.379	0.317	0.299
30--46	0.349	0.368	0.451	0.325	0.435	0.356	0.406	0.426	0.432	0.359	0.299	0.398
46--61	0.306	0.347	0.406	0.261	0.388	0.277	0.431	0.451	0.461	0.411	0.442	0.397
61--76	0.337	0.440	0.431	0.356	0.498	0.327	0.404	0.443	0.444	0.446	0.332	0.412
76--91	0.289	0.320	0.334	0.360	0.333	0.269	0.286	0.401	0.310	0.292	0.372	0.274
91--107	0.290	0.260	0.378	0.323	0.331	0.317	0.307	0.287	0.292	0.308	0.299	0.280
107--122	0.340	0.411	0.424	0.358	0.380	0.350	0.366	0.344	0.355	0.284	0.279	0.337

Table B-7 NO₃-N concentrations in soil profile before rainfall simulation for four treatments

depth cm	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----mg/L-----											
0--15	0.11	7.87	20.24	6.40	7.03	49.22	14.15	18.66	7.85	71.75	72.27	1.75
15--30	0.10	7.35	14.04	0.69	4.94	2.31	7.96	17.18	11.76	13.41	8.50	11.29
30--46	0.10	4.34	8.65	0.09	4.98	8.24	3.06	9.00	8.03	7.10	7.16	4.95
46--61	0.11	2.52	6.63	0.56	4.39	5.94	4.42	8.14	3.05	2.17	5.59	1.55
61--76	0.52	2.77	5.06	0.22	2.40	1.60	0.61	2.29	4.05	1.19	0.77	2.47
76--91	0.35	0.09	3.73	0.10	2.71	1.39	3.41	1.63	2.16	0.49	0.10	2.66
91--107	0.12	0.81	0.66	0.11	0.14	0.54	2.57	3.85	1.24	0.27	1.43	0.53
107--122	0.12	0.10	0.65	2.58	0.20	0.11	0.16	0.55	0.67	0.36	1.13	0.34

Table B-8 Br concentrations in soil profile before rainfall simulation for four treatments

depth cm	NTL			NTC			TC			TL		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----mg/L-----											
0--15	0.21	0.18	0.19	0.48	0.18	0.22	0.18	0.21	0.20	0.20	0.18	0.21
15--30	0.20	0.19	0.17	0.21	1.78	0.21	0.19	0.19	0.17	0.17	0.20	0.20
30--46	0.20	0.18	0.33	0.19	0.33	0.20	2.29	0.25	3.14	3.18	0.22	1.90
46--61	0.21	2.29	1.76	0.23	1.70	0.93	2.18	2.44	4.03	5.43	1.40	0.25
61--76	0.25	1.45	1.98	0.21	3.29	0.18	2.37	4.21	4.42	2.98	0.93	0.18
76--91	0.25	1.22	0.04	0.21	1.38	0.26	2.15	2.85	5.13	3.34	0.21	0.24
91--107	0.25	1.41	0.24	5.04	0.22	0.23	2.76	2.66	2.40	1.22	0.24	0.20
107--122	0.24	0.21	1.77	4.47	0.20	0.23	1.49	1.77	1.01	1.27	0.25	0.21

Table B-9 Volumetric water content in soil profile after rainfall simulation for four treatments

depth cm	NTL			NTC			TC			TL		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----cm ³ /cm ³ -----											
0--15	0.322	0.288	0.306	0.307	0.336	0.304	0.273	0.312	0.319	0.343	0.373	0.393
15--30	0.326	0.309	0.506	0.345	0.348	0.330	0.353	0.344	0.361	0.367	0.345	0.360
30--46	0.357	0.360	0.415	0.348	0.401	0.373	0.385	0.435	0.448	0.406	0.423	0.413
46--61	0.381	0.497	0.432	0.354	0.406	0.372	0.391	0.455	0.444	0.418	0.372	0.413
61--76	0.347	0.384	0.402	0.371	0.408	0.347	0.440	0.457	0.457	0.429	0.387	0.378
76--91	0.356	0.376	0.357	0.367	0.402	0.495	0.389	0.464	0.437	0.430	0.288	0.215
91--107	0.294	0.332	0.372	0.302	0.347	0.291	0.430	0.299	0.295	0.283	0.292	0.248
107--122	0.314	0.453	0.389	0.344	0.400	0.278	0.339	0.297	0.303	0.290	0.292	0.444

Table B-10 NO₃-N concentrations in soil profile after rainfall simulation for four treatments

depth cm	NTL			NTC			TC			TL		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----mg/L-----											
0--15	1869.07	964.94	2010.32	509.63	2509.00	2241.64	1460.55	882.32	1977.69	723.62	798.58	630.97
15--30	106.70	239.81	60.56	191.34	117.39	33.62	109.73	76.44	78.63	339.31	314.10	567.24
30--46	8.04	84.79	15.97	78.57	14.75	12.62	49.26	27.13	34.71	111.01	11.91	171.62
46--61	0.00	25.32	8.25	54.15	4.87	5.93	31.47	20.03	30.86	29.63	9.07	116.02
61--76	0.00	16.28	8.63	32.86	2.48	10.08	13.98	13.61	12.27	6.79	4.58	166.28
76--91	0.00	16.22	3.61	11.66	0.40	33.60	35.66	6.69	1.83	6.54	2.44	270.49
91--107	0.85	12.96	0.20	33.24	3.42	35.02	41.40	5.42	2.02	2.61	0.78	200.57
107--122	0.00	4.89	2.15	138.84	0.78	59.88	17.19	2.39	2.09	0.76	2.26	127.81

Table B-11 Br concentrations in soil profile after rainfall simulation for four treatments

depth cm	NTL			NTC			TC			TL		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----mg/L-----											
0--15	5.88	18.34	7.22	8.48	8.35	10.71	22.98	19.88	27.94	18.78	11.22	11.29
15--30	0.27	7.43	0.20	4.32	2.05	0.29	12.15	16.99	4.40	6.42	4.96	7.20
30--46	0.30	1.76	0.24	2.95	0.26	0.29	7.40	10.96	1.90	5.79	0.26	5.07
46--61	0.27	0.33	0.23	1.63	1.14	0.27	5.50	7.26	1.62	0.78	0.29	5.53
61--76	0.32	4.80	0.26	0.30	3.45	0.33	4.61	5.23	2.72	3.33	0.29	5.88
76--91	0.32	1.01	0.96	6.05	5.62	3.24	4.11	4.75	2.53	4.31	0.36	10.90
91--107	0.36	1.59	0.06	7.30	0.63	0.41	3.50	5.93	1.05	4.02	0.34	8.06
107--122	0.35	0.95	0.27	5.85	0.98	0.37	2.07	5.05	0.31	1.29	0.35	5.96

Table B-12 Volumetric water content beneath compacted soil bar (low probe) in lysimeters for four treatments

Time min	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----cm ³ /cm ³ -----											
0	0.278	0.262	0.159	0.084	0.074	0.074	0.092	0.063	0.093	0.144	0.203	0.266
3.5	0.289	0.438	0.186	0.156	0.074	0.074	0.092	0.064	0.093	0.136	0.160	0.215
7	0.466	0.430	0.437	0.295	0.155	0.075	0.097	0.072	0.100	0.419	0.259	0.353
10.5	0.468	0.436	0.439	0.359	0.358	0.158	0.162	0.272	0.153	0.408	0.353	0.456
14	0.493	0.427	0.452	0.374	0.381	0.302	0.269	0.328	0.228	0.424	0.428	0.431
17.5	0.458	0.440	0.489	0.452	0.397	0.506	0.329	0.372	0.312	0.428	0.503	0.447
21	0.538	0.448	0.454	0.441	0.423	0.572	0.356	0.365	0.397	0.424	0.445	0.450
24.5	0.537	0.476	0.448	0.480	0.457	0.589	0.375	0.379	0.440	0.435	0.433	0.510
28	0.590	0.502	0.471	0.484	0.476	0.581	0.412	0.379	0.467	0.448	0.431	0.457
31.5	0.567	0.501	0.495	0.481	0.456	0.574	0.440	0.428	0.463	0.449	0.433	0.478
35	0.568	0.502	0.498	0.499	0.478	0.577	0.459	0.461	0.460	0.447	0.456	0.464
38.5	0.524	0.499	0.532	0.495	0.483	0.579	0.498	0.474	0.499	0.427	0.501	0.459
42	0.581	0.503	0.497	0.486	0.478	0.581	0.472	0.472	0.482	0.438	0.496	0.508

45.5	0.553	0.503	0.503	0.495	0.503	0.555	0.476	0.409	0.486	0.439	0.486	0.496
49	0.510	0.500	0.500	0.513	0.505	0.542	0.470	0.469	0.523	0.438	0.487	0.485
52.5	0.544	0.505	0.507	0.488	0.493	0.584	0.478	0.457	0.519	0.443	0.498	0.466
56	0.508	0.476	0.530	0.502	0.493	0.574	0.490	0.473	0.516	0.444	0.487	0.496
59.5	0.494	0.457	0.502	0.516	0.473	0.562	0.507	0.483	0.486	0.415	0.505	0.419
63	0.473	0.443	0.486	0.499	0.471	0.559	0.501	0.492	0.465	0.444	0.491	0.458
66.5	0.454	0.418	0.476	0.485	0.476	0.539	0.496	0.485	0.470	0.440	0.497	0.461
70	0.458	0.411	0.434	0.449	0.463	0.549	0.500	0.486	0.459	0.469	0.469	0.474
73.5	0.432	0.407	0.432	0.437	0.449	0.534	0.501	0.490	0.517	0.442	0.490	0.436
77	0.424	0.393	0.419	0.459	0.442	0.517	0.513	0.495	0.542	0.431	0.512	0.435
80.5	0.423	0.388	0.414	0.470	0.428	0.501	0.512	0.495	0.525	0.428	0.494	0.455
84	0.415	0.384	0.410	0.448	0.451	0.505	0.512	0.499	0.516	0.443	0.480	0.460
87.5	0.419	0.374	0.406	0.458	0.444	0.492	0.521	0.489	0.500	0.415	0.473	0.432
91	0.419	0.404	0.402	0.420	0.442	0.511	0.510	0.432	0.543	0.423	0.472	0.432
94.5	0.398	0.353	0.397	0.449	0.394	0.531	0.517	0.466	0.540	0.414	0.480	0.431
98	0.407	0.396	0.392	0.429	0.406	0.467	0.522	0.469	0.499	0.410	0.473	0.393
101.5	0.409	0.395	0.394	0.422	0.385	0.484	0.520	0.457	0.491	0.399	0.481	0.384
105	0.397	0.380	0.387	0.411	0.425	0.491	0.514	0.470	0.492	0.399	0.454	0.394
108.5	0.387	0.371	0.383	0.443	0.407	0.504	0.512	0.425	0.521	0.403	0.462	0.381

Table B-13 Volumetric water content Between the N fertilizer line sources in lysimeters for four treatments

Time min	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----cm ³ /cm ³ -----											
0	0.281	0.252	0.220	0.310	0.267	0.263	0.202	0.184	0.192	0.198	0.189	0.226
3.5	0.319	0.268	0.273	0.355	0.298	0.270	0.224	0.205	0.205	0.218	0.208	0.272
7	0.338	0.294	0.304	0.384	0.323	0.303	0.269	0.231	0.207	0.258	0.246	0.284
10.5	0.364	0.325	0.322	0.417	0.343	0.322	0.325	0.346	0.227	0.285	0.320	0.282
14	0.379	0.358	0.337	0.412	0.354	0.353	0.377	0.403	0.237	0.302	0.377	0.291

17.5	0.390	0.374	0.368	0.412	0.382	0.380	0.398	0.455	0.244	0.311	0.410	0.294
21	0.394	0.384	0.384	0.418	0.389	0.386	0.398	0.472	0.267	0.319	0.431	0.297
24.5	0.405	0.386	0.392	0.424	0.391	0.398	0.395	0.472	0.314	0.342	0.451	0.299
28	0.404	0.396	0.391	0.419	0.400	0.404	0.397	0.480	0.335	0.360	0.484	0.305
31.5	0.404	0.409	0.388	0.426	0.406	0.406	0.399	0.487	0.344	0.377	0.480	0.304
35	0.405	0.409	0.394	0.420	0.402	0.411	0.403	0.483	0.356	0.387	0.483	0.305
38.5	0.405	0.411	0.392	0.424	0.412	0.395	0.412	0.475	0.361	0.396	0.481	0.304
42	0.406	0.413	0.393	0.419	0.411	0.410	0.416	0.497	0.379	0.402	0.484	0.309
45.5	0.409	0.415	0.396	0.430	0.411	0.405	0.423	0.487	0.395	0.410	0.487	0.312
49	0.408	0.419	0.399	0.431	0.408	0.412	0.410	0.493	0.426	0.419	0.490	0.314
52.5	0.403	0.410	0.399	0.429	0.422	0.406	0.419	0.500	0.432	0.433	0.492	0.313
56	0.407	0.412	0.403	0.428	0.424	0.411	0.420	0.477	0.429	0.435	0.495	0.320
59.5	0.397	0.398	0.393	0.411	0.409	0.424	0.430	0.488	0.431	0.448	0.499	0.322
63	0.391	0.394	0.380	0.408	0.392	0.412	0.423	0.484	0.432	0.462	0.485	0.327
66.5	0.387	0.391	0.371	0.400	0.382	0.405	0.421	0.491	0.427	0.467	0.505	0.327
70	0.381	0.384	0.365	0.396	0.374	0.399	0.410	0.493	0.424	0.449	0.481	0.343
73.5	0.377	0.383	0.363	0.394	0.371	0.399	0.420	0.495	0.426	0.442	0.484	0.338
77	0.380	0.377	0.361	0.392	0.369	0.398	0.407	0.491	0.427	0.433	0.481	0.341
80.5	0.379	0.384	0.360	0.387	0.365	0.393	0.406	0.438	0.422	0.430	0.479	0.349
84	0.377	0.377	0.356	0.391	0.361	0.385	0.404	0.423	0.418	0.424	0.486	0.343
87.5	0.372	0.378	0.356	0.391	0.367	0.382	0.391	0.407	0.409	0.427	0.477	0.344
91	0.375	0.378	0.356	0.387	0.364	0.409	0.397	0.405	0.406	0.420	0.470	0.345
94.5	0.374	0.384	0.354	0.385	0.361	0.395	0.403	0.384	0.397	0.415	0.467	0.345
98	0.370	0.365	0.355	0.385	0.361	0.395	0.403	0.390	0.393	0.410	0.453	0.349
101.5	0.376	0.374	0.353	0.389	0.357	0.388	0.395	0.382	0.396	0.404	0.448	0.350
105	0.371	0.373	0.352	0.390	0.349	0.392	0.393	0.376	0.389	0.402	0.437	0.349
108.5	0.365	0.376	0.354	0.394	0.356	0.406	0.384	0.377	0.380	0.398	0.427	0.346

Table B-14 EC_b beneath the N fertilizer line sources in lysimeters for four treatments

Time min	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----ms/cm-----											
0	3.806	0.599	0.486	0.027	0.019	0.038	0.033	0.014	0.024	0.334	0.556	0.720
3.5	4.148	2.863	0.674	0.192	0.020	0.039	0.034	0.013	0.027	0.354	0.585	2.158
7	3.396	4.941	2.735	0.412	0.155	0.039	0.035	0.017	0.028	1.451	1.204	2.265
10.5	2.811	4.397	3.796	0.693	0.441	0.247	0.147	0.371	0.128	1.757	2.919	2.213
14	2.355	3.502	3.836	0.779	0.433	0.596	0.292	0.491	0.230	2.048	3.185	2.575
17.5	2.093	2.755	3.733	0.800	0.450	0.876	0.319	0.586	0.354	2.128	2.992	3.051
21	1.888	2.288	3.447	0.820	0.494	0.955	0.387	0.634	0.417	2.354	2.848	2.871
24.5	1.670	1.949	3.017	0.803	0.535	0.963	0.459	0.659	0.458	2.435	2.702	3.147
28	1.534	1.682	2.574	0.788	0.565	0.998	0.530	0.693	0.494	2.310	2.629	2.851
31.5	1.420	1.500	2.173	0.760	0.585	1.102	0.583	0.701	0.517	2.607	2.509	2.522
35	1.356	1.386	1.922	0.763	0.609	1.102	0.612	0.745	0.540	2.521	2.508	2.525
38.5	1.316	1.259	1.762	0.789	0.586	1.051	0.671	0.740	0.575	2.542	2.541	2.269
42	1.249	1.134	1.647	0.779	0.609	1.029	0.705	0.839	0.564	2.724	2.486	2.222
45.5	1.205	1.046	1.540	0.816	0.632	1.036	0.727	0.847	0.614	2.531	2.383	1.818
49	1.148	0.953	1.444	0.795	0.647	1.008	0.759	0.859	0.612	2.489	2.297	1.803
52.5	1.101	0.899	1.354	0.800	0.637	1.020	0.775	0.871	0.644	2.288	2.232	1.745
56	0.987	0.849	1.261	0.838	0.651	1.045	0.804	0.839	0.680	2.087	2.111	1.571
59.5	0.925	0.807	1.216	0.831	0.641	1.095	0.810	0.815	0.675	2.025	1.991	1.487
63	0.873	0.790	1.153	0.831	0.637	1.133	0.823	0.810	0.676	1.892	1.901	1.382
66.5	0.832	0.772	1.079	0.825	0.650	1.181	0.842	0.811	0.678	1.813	1.673	1.277
70	0.812	0.727	0.992	0.804	0.639	1.230	0.873	0.800	0.684	1.772	1.549	1.155
73.5	0.797	0.706	0.953	0.802	0.630	1.276	0.862	0.794	0.744	1.758	1.307	1.068
77	0.773	0.715	0.926	0.774	0.627	1.290	0.882	0.763	0.730	1.598	1.097	1.011
80.5	0.762	0.681	0.904	0.763	0.627	1.318	0.863	0.765	0.735	1.550	0.933	0.975
84	0.757	0.675	0.883	0.754	0.602	1.300	0.871	0.770	0.711	1.516	0.803	0.903
87.5	0.740	0.681	0.869	0.753	0.606	1.308	0.871	0.743	0.696	1.443	0.746	0.901
91	0.739	0.672	0.856	0.752	0.603	1.292	0.883	0.726	0.704	1.438	0.689	0.856
94.5	0.721	0.673	0.846	0.744	0.614	1.302	0.874	0.731	0.695	1.433	0.647	0.829
98	0.724	0.662	0.833	0.759	0.621	1.290	0.870	0.707	0.697	1.374	0.633	0.823

101.5	0.718	0.642	0.824	0.747	0.623	1.298	0.903	0.724	0.689	1.407	0.615	0.793
105	0.721	0.638	0.819	0.754	0.615	1.309	0.890	0.714	0.692	1.394	0.607	0.786
108.5	0.711	0.648	0.815	0.745	0.604	1.316	0.860	0.732	0.695	1.376	0.582	0.763

Table B-15 EC_b between the N fertilizer line sources in lysimeters for four treatments

Time min	NTNC			NTC			TC			TNC		
	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3	rep 1	rep 2	rep 3
	-----ms/cm-----											
0	0.205	0.200	0.148	0.227	0.185	0.200	0.126	0.136	0.120	0.135	0.142	0.151
3.5	0.229	0.212	0.183	0.251	0.204	0.210	0.144	0.143	0.129	0.139	0.148	0.165
7	0.242	0.219	0.204	0.278	0.221	0.226	0.164	0.156	0.132	0.154	0.167	0.174
10.5	0.262	0.239	0.223	0.287	0.233	0.247	0.182	0.197	0.143	0.170	0.186	0.178
14	0.266	0.266	0.237	0.289	0.257	0.263	0.210	0.223	0.147	0.174	0.211	0.177
17.5	0.269	0.273	0.246	0.290	0.267	0.280	0.214	0.252	0.156	0.180	0.221	0.183
21	0.278	0.281	0.255	0.282	0.269	0.286	0.224	0.252	0.164	0.187	0.237	0.184
24.5	0.277	0.279	0.254	0.286	0.269	0.287	0.226	0.256	0.191	0.197	0.249	0.183
28	0.275	0.289	0.261	0.287	0.271	0.293	0.224	0.255	0.206	0.208	0.262	0.184
31.5	0.282	0.301	0.258	0.289	0.271	0.291	0.223	0.260	0.213	0.215	0.257	0.185
35	0.280	0.287	0.256	0.288	0.272	0.294	0.224	0.253	0.223	0.215	0.258	0.191
38.5	0.279	0.293	0.259	0.288	0.264	0.281	0.226	0.254	0.225	0.223	0.258	0.194
42	0.276	0.291	0.259	0.283	0.273	0.289	0.229	0.251	0.236	0.228	0.257	0.188
45.5	0.283	0.297	0.260	0.289	0.270	0.289	0.233	0.251	0.241	0.228	0.254	0.194
49	0.284	0.305	0.259	0.286	0.268	0.293	0.234	0.262	0.256	0.234	0.253	0.195
52.5	0.281	0.302	0.258	0.288	0.270	0.296	0.235	0.257	0.261	0.233	0.254	0.199
56	0.279	0.303	0.264	0.281	0.270	0.303	0.233	0.258	0.263	0.239	0.256	0.196
59.5	0.276	0.297	0.260	0.278	0.269	0.291	0.234	0.255	0.256	0.239	0.252	0.200
63	0.276	0.290	0.248	0.274	0.261	0.293	0.238	0.256	0.256	0.242	0.245	0.203
66.5	0.272	0.291	0.256	0.277	0.259	0.289	0.234	0.253	0.256	0.247	0.248	0.206
70	0.278	0.288	0.250	0.275	0.260	0.299	0.239	0.253	0.258	0.246	0.249	0.211
73.5	0.270	0.296	0.250	0.268	0.256	0.290	0.232	0.249	0.255	0.242	0.250	0.212
77	0.273	0.292	0.248	0.274	0.253	0.293	0.236	0.253	0.257	0.239	0.248	0.216
80.5	0.276	0.297	0.249	0.271	0.255	0.294	0.232	0.245	0.259	0.239	0.243	0.216

84	0.276	0.291	0.248	0.273	0.262	0.296	0.233	0.238	0.258	0.239	0.243	0.223
87.5	0.276	0.298	0.247	0.275	0.255	0.297	0.233	0.235	0.254	0.238	0.242	0.220
91	0.274	0.291	0.248	0.273	0.253	0.293	0.227	0.235	0.251	0.235	0.242	0.222
94.5	0.275	0.286	0.247	0.273	0.254	0.298	0.231	0.231	0.248	0.236	0.242	0.223
98	0.274	0.292	0.247	0.273	0.255	0.295	0.232	0.232	0.248	0.232	0.241	0.219
101.5	0.276	0.292	0.248	0.273	0.250	0.293	0.235	0.231	0.247	0.233	0.239	0.222
105	0.274	0.291	0.247	0.273	0.251	0.292	0.231	0.230	0.243	0.229	0.235	0.221
108.5	0.273	0.288	0.246	0.277	0.254	0.291	0.230	0.224	0.241	0.233	0.234	0.218

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