IOWA STATE UNIVERSITY
Digital Repository

Retrospective Theses and Dissertations

Iowa State University Capstones, Theses and Dissertations

1994

The fate of fertilizers and pesticides when applied to turfgrass maintained under golf course fairway conditions

Steven Kent Starrett
Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/rtd

Part of the Civil Engineering Commons, and the Environmental Sciences Commons

Recommended Citation

Starrett, Steven Kent, "The fate of fertilizers and pesticides when applied to turfgrass maintained under golf course fairway conditions " (1994). *Retrospective Theses and Dissertations*. 10512.
https://lib.dr.iastate.edu/rtd/10512

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

المنارة للاستشارات

www.manaraa.com

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

University Microfilms International
A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
313/761-4700 800/521-0600

Order Number 9503597

The fate of fertilizers and pesticides when applied to turfgrass maintained under golf course fairway conditions

Starrett, Steven Kent, Ph.D.

Iowa State University, 1994

U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

The fate of fertilizers and pesticides when applied to turfgrass maintained under golf course fairway conditions

by

Steven Kent Starrett

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Department: Civil and Construction Engineering
Major: Civil Engineering (Environmental Engineering)

Approved:

Signature was redacted for privacy.

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1994

TABLE OF CONTENTS

PAGE

GENERAL INTRODUCTION 1

Explanation of Dissertation Format 4

PAPER 1: COMPARING DISPERSIVITIES AND SOIL CHLORIDE CONCENTRATIONS OF TURFGRASS COVERED UNDISTURBED AND DISTURBED SOIL COLUMNS 6

ABSTRACT 7

INTRODUCTION 8

METHODS 10

RESULTS 13

CONCLUSIONS 14

ACKNOWLEDGMENTS 16

REFERENCES 17

PAPER 2: FATE OF ^{15}N-LABELED UREA APPLIED TO TURFGRASS COVERED UNDISTURBED SOIL COLUMNS 24

ABSTRACT 25

INTRODUCTION 26

MATERIALS AND METHODS 28

RESULTS 32

DISCUSSION 34

REFERENCES 42

PAPER 3: FATE OF ISAZOFOS, CHLORPYRIFOS, METALAXYL, AND PENDIMETHALIN APPLIED TO TURFGRASS COVERED UNDISTURBED SOIL COLUMNS 44

ABSTRACT 45

INTRODUCTION 46

MATERIALS AND METHODS 48

RESULTS 53

DISCUSSION 55

REFERENCES 64

GENERAL SUMMARY 66

ADDITIONAL LITERATURE CITED 69

ACKNOWLEDGMENTS 71

GENERAL INTRODUCTION

Over 14,100 golf courses (1994) cover more than 533,000 ha in the United States, and new courses are opening every day. The research reported in this thesis was initiated because of environmental concerns related to golf course management techniques. Environmental concerns became more justified when Cohen et al. (1990) detected pesticides that were applied to golf courses on a sandy soil at Cape Cod, MA in water wells. The United States Golf Association (USGA) invested $3.2 million in 1991 to start a research program studying environmental related issues pertaining to the golf industry. Twenty-one research projects were funded across the United States to investigate: the fate of fertilizers and pesticides when applied to golf courses in different geographic regions, the implications of applying recycled water to golf courses, and alternative pest management techniques that are more environmentally friendly.

At Iowa State University, the fate of fertilizers and pesticides when applied to Kentucky bluegrass maintained in a golf course fairway condition was investigated as part of the USGA study. Paper 1 investigates the differences between undisturbed and disturbed soils in chemical transport through the soil profile. This issue is important because of the difficulties in applying results from research using protocols that do not represent actual field conditions. Much research has been conducted in the agricultural setting, but little has been performed to determine the fate of applied chemicals in the turfgrass setting. This research will provide valuable information specific to the turfgrass industry on how management techniques can be improved to prevent environmental degradation.

Macropores are pores formed by soil fauna (e.g., earthworms), plant roots, and cracks and fissures (Beven and Germann, 1982). The macropore structure found in an undisturbed soil can have a major impact on water and solute distribution in the profile (Thomas and Phillips, 1979). White (1985) concluded from studies on undisturbed soils that macropores can greatly decrease the time taken for surface-applied, dissolved, and suspended matter to reach subsurface drains or ground water. The influence of macropores is eliminated when experiments are done in a laboratory using dried, sieved, and repacked soil columns (Evert, 1989). Tindall et al. (1992) stated that while several methods exist for laboratory analysis of column experiments, they deal with disturbed, sieved soil samples and are not typically suitable for intact soil cores because of their basic design and the nature of their construction. Applying the results of studies performed using disturbed soils to situations where undisturbed soils exist may lead to inaccurate conclusions.

Nitrogen (N) is applied to grasses on golf courses, home lawns, sports complexes, industrial parks, and other areas to improve turf quality. Current public concern for the environment has focused attention on the environmental effects of chemical applications to turfgrass areas. Little research has been done concerning the environmental effects of N, P, and other materials applied to turfgrasses (Balogh and Walker, 1992). Petrovic (1990) reported that few studies have investigated the fate of N applied to turfgrasses using a mass balance approach. An understanding of the fate of these chemicals is needed to manage turfgrass maintenance better and to identify the chemicals that pose an environmental threat. Possible movement of N into ground water, thereby degrading water quality, is of greatest concern (Haynes, 1986). Also, excessive algae growth that decreases dissolved oxygen of surface waters (eutrophication) can occur if N and P are abundant (Mugaas et al., 1991; W. C. Huber, 1993).

Brown et al. (1977) studied the influence of management on the fate of N applied to golf greens. They reported that a change from 0.7-cm irrigation applications to 0.9-cm irrigation applications greatly increased nitrate leaching from surface applied NH_4NO_3 to a simulated golf green. Paper 2 investigates the fate of nitrogen when applied to undisturbed soil columns covered with turfgrass under a heavy and a light irrigation regime.

Pesticides are applied to grasses on golf courses, home lawns, sports complexes, industrial parks, and other areas to improve turf quality. Possible adverse environmental effects of pesticides are: they are potentially harmful to humans, may reduce certain bird populations, can destroy nontarget organisms, and may elevate nonpest species to pest status (Balogh and Walker, 1992).

Little research has been done concerning the fate of pesticides applied to turfgrasses. Volatilization of chlorpyrifos when applied to a no-till agricultural setting was estimated at 23% of applied over 4 days (Whang et al., 1993). Volatilization of pendimethalin when applied to Kentucky bluegrass was estimated at 13% of applied over 5 days when no supplemental irrigation was applied (Cooper et al., 1990). Maki (1993) reported that chlorpyrifos was detected in 32 out of 5155 samples that were collected from discharged tile water from golf courses in Japan. Pendimethalin was detected in 31 out of 5451 samples. Stahnke et al. (1991) reported that most of the pendimethalin applied to a Kentucky bluegrass was recovered in the plant tissue and the thatch layer. Paper 3 investigates the fate of isazofos, chlorpyrifos, metalaxyl, and pendimethalin when applied to undisturbed soil columns covered with turfgrass under a heavy and a light irrigation regime.

The objective of Paper 1 was to compare the solute movement characteristics of undisturbed soil columns with those columns containing dried, sieved, and repacked (disturbed) soil under turfgrass conditions. The dispersivities and soil chloride (Cl) concentrations of the undisturbed and disturbed soils were compared.

The objectives of Paper 2 were to investigate the hydrology of an undisturbed soil column with a Kentucky bluegrass cover and intact macropores under a heavy and light irrigation regime and to measure the fate of N (using ^{15}N as a tracer) when it is applied to an undisturbed soil column.

The objective of Paper 3 was to investigate the fate of pendimethalin, chlorpyrifos, isazofos, and metalaxyl when applied to Kentucky bluegrass turf established on undisturbed soil columns with intact macropores under a heavy and light irrigation regime.

Explanation of Dissertation Format

The papers included in this dissertation are suitable for publication. The paper entitled, "Comparing dispersivities and soil chloride concentration of undisturbed and disturbed soil columns covered with a turfgrass cover" follows the Journal of Hydrology format. The papers entitled, "Fate of ^{15}N-amended urea applied to undisturbed soil columns with a turfgrass cover" and "Fate of isazofos, chlorpyrifos, metalaxyl, and pendimethalin applied to undisturbed soil columns with a turfgrass cover" follow the Transactions of the American Society of Agricultural Engineers format. There is a General Summary following the papers, and the additional literature cited in the General Introduction and the General Summary follows the General Summary.

I was the senior author of the papers generated from this research, designed the experimental protocol, supervised and participated in all aspects of the project (with exception to analytical testing methods), and performed all calculations reported in this thesis. Drs. Nick Christians and Al Austin provided guidance during the project.

The soil columns were collected from the turf section of the Horticulture Research Station north of Ames, Iowa. Work for Paper 1 was performed in a laboratory in the Horticulture Building at Iowa State University. Work for Papers 2 and 3 was performed in the Horticulture Department greenhouses.

PAPER 1: COMPARING DISPERSIVITIES AND SOIL CHLORIDE CONCENTRATIONS OF TURFGRASS COVERED UNDISTURBED AND DISTURBED SOIL COLUMNS

ABSTRACT

Research relating to soil leaching properties under turfgrass conditions has often been conducted on disturbed soils where macropore structure has been destroyed. The objective of this study was to compare the solute movement characteristics of undisturbed and disturbed soil columns covered with turfgrass. We studied the dispersivities and chloride (Cl) breakthrough curves of undisturbed and disturbed soils. Chloride was used as a conservative tracer to obtain breakthrough curves. Soil columns were excavated into 3 sections after testing and bulk density was measured. The mean bulk density was 1.33 Mg m^{-3} for the undisturbed columns and 1.16 Mg m^{-3} for the disturbed columns. The dispersivity was over 3 times higher for the undisturbed columns than for the disturbed columns. Chloride concentration found in; layer #1 (0 to 6.7 cm), layer #2 (6.7 to 13.4 cm), and in layer #3 (13.4 to 20.0 cm) were 2.8, 5.3, 4.8 times higher, respectively, for the disturbed soils than for the undisturbed. Applying conclusions from solute movement studies using repacked columns covered with turfgrass to actual undisturbed field conditions could lead to errors in interpretation because of the effect of the macropore structures.

INTRODUCTION

Macropores are pores formed by soil fauna (e.g., earthworms), plant roots, and cracks and fissures (Beven and Germann, 1982). The macropore structure found in an undisturbed soil can have a major impact on water and solute distribution in the profile (Thomas and Phillips, 1979). White (1985) concluded from studies on undisturbed soils that macropores can greatly decrease the time taken for surface-applied, dissolved, and suspended matter to reach subsurface drains or ground water.

Solute movement through soil profiles covered with turfgrass has been studied using disturbed soils where the macropore structure has been destroyed (Hardt et al., 1993; Brown et al., 1977; Mitchell et al., 1978; Mancino and Troll, 1990; Yates, 1991; Smith and Bridges, 1991). The influence of macropores is eliminated when experiments are done in a laboratory using dried, sieved, and repacked soil columns (Evert, 1989). Tindall et al. (1992) stated that while several methods exist for laboratory analysis of column experiments, they deal with disturbed, sieved soil samples and are not typically suitable for intact soil cores because of their basic design and the nature of their construction. Applying the results of studies performed using disturbed soils to situations where undisturbed soils exist may lead to inaccurate conclusions. Kladivko et al. (1991) concluded pesticides appeared in tile drains, from an agricultural area in Indiana, much sooner than predicted by simple convective-dispersive transport theory.

The objective of this study was to compare the solute movement characteristics of undisturbed soil columns with those columns containing dried, sieved, and repacked (disturbed) soil with a turfgrass cover. We compared dispersivities and soil chloride (Cl) concentrations of the undisturbed and disturbed soils.

METHODS

The soil for four undisturbed soil columns and four disturbed soil columns of Nicollet (fine-loamy, mixed, mesic-Aquic Hapludolls) soil were collected in summer, 1992, from a 400-m^2 area with 'Glade' Kentucky bluegrass established in 1991 and maintained at a 2.54-cm mowing height at the Iowa State University Horticulture Research Station, Gilbert, Iowa. The area had been graded in 1968. The undisturbed soil columns were collected by modifying the mortar encasement method of Priebe and Blackmer (1989). Soil was excavated from around a 10-cm diameter by 20-cm deep free standing cylindrical soil column. When the columns had been properly shaped, a 15-cm diameter polyvinyl chloride (PVC) pipe was placed around the soil columns, and mortar was placed in the space between the soil and the PVC. The mortar was allowed to set for approximately one week. These encased soil columns were then brought to the lab for testing.

Disturbed soil columns were made from the soil excavated from around the undisturbed columns. This soil was air dried and ground to pass through a #10 sieve (2.5 mm). When the test period was completed on the undisturbed soil columns, the soil was excavated and the mortar and PVC encasements were cleaned by using distilled water and a wire brush. The sieved soil was then placed into the encasement and water-settled for compaction. 'Glade' Kentucky bluegrass sod, which was obtained from the same location was placed on top of the soil to form the disturbed soil column. The study was conducted 2 days after the sod was placed to maintain the disturbed characteristics of the column.

A PVC adapter (smooth female end to threaded female end) was glued onto the outside of the PVC encasement (Fig. 1). Before the PVC adapter was glued to the PVC encasement a permeable membrane was placed on the bottom of the soil column for support. A PVC plug was threaded into the adapter and Tygon® was connected to the nipple. The Tygon® was used to control the depth of the solution (on the surface of the soil) during the experiment. The columns were supported by ring stands so that the polyethylene collection bottles could be placed underneath the columns.

The soil columns were submerged in distilled H_2O for over 24 hr to ensure a saturated condition. Two reservoirs were connected to a Varistalic® pump, Manostat, New York, NY (Fig. 1). A saturated steady-state flow condition was achieved by running distilled H_2O from one reservoir through the soil columns for about 4 hours. A constant, saturated-flow rate of 44 mL min^{-1} (0.56 cm min^{-1}) was maintained for the duration of the experiment. Chloride was used as the conservative tracer. A second reservoir that contained a solution of $CaCl_2$ (Cl = 47 mg L^{-1}) was introduced to the soil columns at time = 0. Flow samples were collected at approximately 6 min intervals (≈ 0.33 pore volume). At the end of the 180 min test period, the columns were excavated into three sections: layer #1 = 0 to 6.7 cm, layer #2 = 6.7 to 13.4 cm, and layer #3 = 13.4 to 20.0 cm. The soil was placed on wax paper and allowed to dry at room temperature (19-25° C).

The Cl concentration of the flow samples and the soil layers was determined by using a Cl-specific-ion electrode (Hach© (Ames, Iowa) 1989, model 44510). Soil Cl concentrations were determined by extracting a liquid sample. The liquid sample was collected by placing soil in distilled water, mixing, and separating the liquid from the sediment particles.

The advection-dispersion equation for nonreactive dissolved constituents in saturated, homogeneous, isotropic, materials under steady-state, uniform flow is (Freeze and Cherry, 1979)

$$D_l \frac{\partial^2 C}{\partial x^2} - \bar{v}\frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} \qquad (1)$$

where D_l is the longitudinal coefficient of dispersion, and $\bar{v}$ the average linear velocity along the flowline. The initial and boundary equations for equation 1 are:

$$C(x,0) = 0 \quad x \geq 0$$

$$C(0,t) = C_o \quad t \geq 0$$

$$C(\infty,t) = 0 \quad t \geq 0$$

where C is the concentration, C_o is the input concentration (Cl = 47 mg L^{-1}), x is the distance along the flow path, and t is time starting when the tracer was introduced. The solution to the one-dimensional form of the advection-dispersion equation for the listed initial and boundary conditions (Ogata, 1970) is

$$\frac{C}{C_o} = \frac{1}{2}\left[erfc\left(\frac{x - \bar{v}t}{2\sqrt{D_l t}}\right) + exp\left(\frac{\bar{v}x}{D_l}\right) erfc\left(\frac{x + \bar{v}t}{2\sqrt{D_l t}}\right)\right]$$

where erfc represents the complementary error function. The dispersion coefficients were determined by using a computer program (L.C. Jones, 1992). Since $\bar{v}$ and D_l were not known, they were varied to minimize the sum of the squares of the differences between the theoretical solution (obtained from computer program) and the observed breakthrough curves.

Neglecting molecular dispersion, longitudinal dispersivity (α) can be determined by the following equation (Freeze and Cherry, 1979).

$$\alpha = \frac{D_l}{\bar{v}}$$

RESULTS

The mean bulk density for the undisturbed columns was 1.33 Mg m^{-3} (SD = 0.03 Mg m^{-3}), which was different ($p < 0.001$) from the disturbed columns that had a mean bulk density of 1.16 Mg m^{-3} (SD = 0.02 Mg m^{-3}). Average porosity estimated from bulk density for the undisturbed and disturbed columns were 0.50 and 0.56, respectively.

Individual breakthrough curves for each soil column show the observed data collected and the curve for the theoretical solution (Fig. 2, Fig. 3). A relative concentration of 0.5 is reached at 28 min for the undisturbed soil and 47 min for the disturbed soil (Fig. 4). Mean dispersivities of 20.50 cm (SD = 7.43 cm) for the undisturbed soil columns and 6.46 cm (SD = 1.05 cm) for the disturbed soil columns were different ($p = 0.0096$). A difference does exist in Cl concentration for each soil layer between the undisturbed and the disturbed soils (Table 1).

CONCLUSIONS

We conclude that undisturbed soil columns covered with turfgrass greatly differ in solute transport characteristics compared to disturbed soil columns covered with turfgrass.

The flow rate used probably encouraged macropore flow. It is unlikely that flow between the soil and mortar interface occurred. Upon excavation of the undisturbed soil columns it was observed that the cement particles had moved into the soil column about 1 to 2 mm. Upon excavation of the disturbed soil columns, no channels were observed between the mortar and soil interface. Some sediment was collected in the flow samples from the undisturbed and disturbed soil columns.

The disturbed soil columns retained 3 to 5 times as much Cl compared to the undisturbed soil columns due to the destruction of the macropore structure. The maximum Cl concentration possible in the undisturbed and disturbed soil was about 18, and 23 mg kg^{-1}, respectively, based on solute concentration, bulk density, assuming no Cl being adsorbed to soil particles, and all pore water being replaced with incoming solute. After about 10 pore volumes had flowed through the soil columns, the Cl concentration in the disturbed soil columns was within 8% of the maximum which implies flow was occurring throughout the entire column (Table 1). The vast majority of the initial water present in the pores was displaced with the incoming Cl solution. In the undisturbed soil columns the Cl concentration was less than 0.25 times the maximum Cl concentration and is evidence of preferential flow. Since the Cl concentrations were a small portion of the maximum concentration, we conclude that a small portion of the initial water present in the pores was displaced with the incoming Cl solution. Kung (1990) determined that water flow through soils could occur in less than 1% of the total area due to preferential flow.

Applying conclusions from solute movement studies on turfgrass areas using repacked, disturbed columns to actual undisturbed field conditions could lead to errors in interpretation because of the effect of the macropore structures. Tyler and Thomas (1981) concluded that laboratory studies using repacked soil columns may not represent soils with distinct macropore structures.

The results of this study should be taken into consideration when designing future studies where field conditions need to be more closely simulated.

ACKNOWLEDGMENTS

The authors would like to thank the United States Golf Association (USGA) Green Section for financial support of this research.

REFERENCES

Beven, K. and P. Germann. 1982. Macropores and water flow in soils. Water Resour. Res. 18:1311-1325.

Brown, K. W., R. L. Duble, and J. C. Thomas. 1977. Influence of management and season of fate of N applied to golf greens. Agron. J. 69:667-671.

Evert, C. A. 1989. Role of preferential flow on water and chemical transport in a glacial till soil. Ph. D. thesis. Iowa Sate University. Ames, Iowa.

Freeze, R. A. and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Hardt, G., B. Leinauer, and H. Schulz. 1993. Nitrogen leaching losses of different N-sources and N-levels from golf greens. International Turfgrass Society Research J. 7:950-956.

Jones, L. C. 1992. Personal communication. Dispersion coefficient analysis computer program. Civil and Const. Eng. Dep. Iowa State University. Ames, Iowa. (515) 294-6848.

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

Kung, K-J. S. 1990. Preferential flow in a sandy vadose zone: 1. Field observations. Geoderma. 46:51-8.

Mancino C. F., and J. Troll. 1990. Nitrate and ammonium leaching losses from N fertilizers applied to 'Penncross' creeping bentgrass. HortScience. 25:194-196.

Mitchell, W. H., A. L. Morehart, L. J. Cotnoir, B. B. Hesseltine, and D. N. Langston, III. 1978. Effect of soil mixtures and irrigation methods on leaching of N in golf greens. Agron. J. 70:29-35.

Ogata, A. 1970. Theory of dispersion in a granular medium. U. S. Geol. Surv. Prof. Paper 411-I.

Priebe, D. L. and A. M. Blackmer. 1989. Preferential movement of Oxygen-18-labeled water and nitrogen-15-labeled urea through macropores in a Nicollet soil. J. Environ. Qual. 18:66-72.

Smith A. and D. C. Bridges. 1991. Evaluation of the potential movement of pesticides following application to a golf course. 1991 Environmental Research Summary. United States Golf Association. pp. 9-10.

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

Tindall, J. A., K. Hemmen, and J. F. Dowd. 1992. An improved method for field extraction and laboratory analysis of large, intact soil cores. J. Environ. Qual. 21:259-263.

Tyler, D. D., and G. W. Thomas. 1981. Chloride movement in undisturbed soil columns. J. Soil Sci. 45:459-461.

White, R. E. 1985. The influence of macropores on the transport of dissolved and suspended matter through soil. Advances in Soil Science, vol. 3. Springer-Verlag, New York.

Yates, M. 1991. The fate of pesticides and fertilizers in a turfgrass environment. 1991 Environmental Research Summary. United States Golf Association. pp. 5-6.

Table 1. Mean Chloride concentrations (mg kg-1) for undisturbed and disturbed soil columns covered with turfgrass.†

	Undisturbed Soil			Disturbed Soil	
Soil Layer	Mean	Std. Dev.	p-value ‡	Mean	Std. Dev.
1 (0 - 6.7 cm)	8.4	6.6	0.0046	23.4	1.9
2 (6.7 - 13.4 cm)	4.0	3.2	0.0002	21.3	3.0
3 (13.4 - 20.0 cm)	4.5	4.5	0.0062	21.5	6.9

† Values from four replications.

‡ *t* - test, based on the null hypothesis that undisturbed and disturbed are the same.

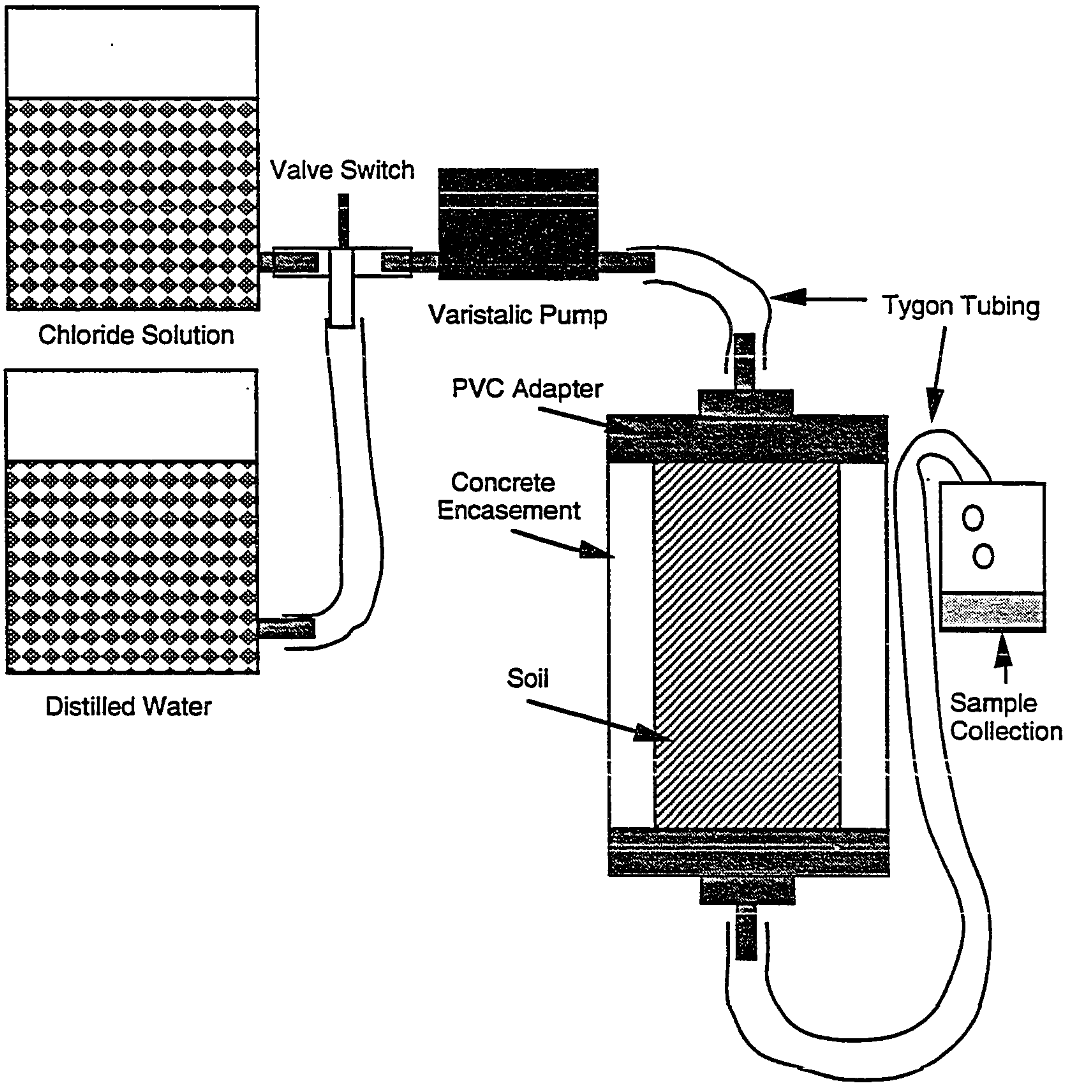


Figure 1. Breakthrough Curve Experimental Apparatus.

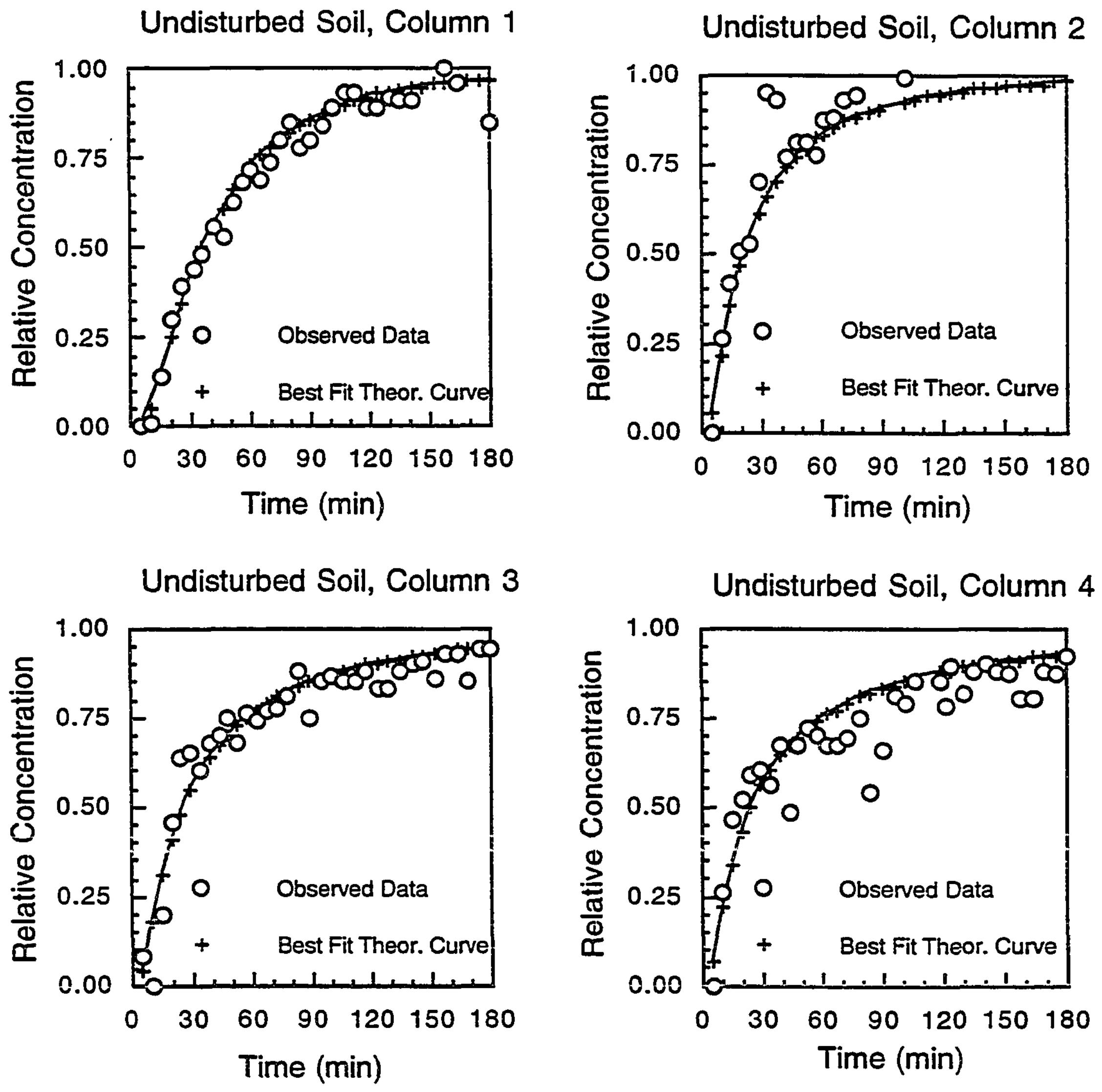
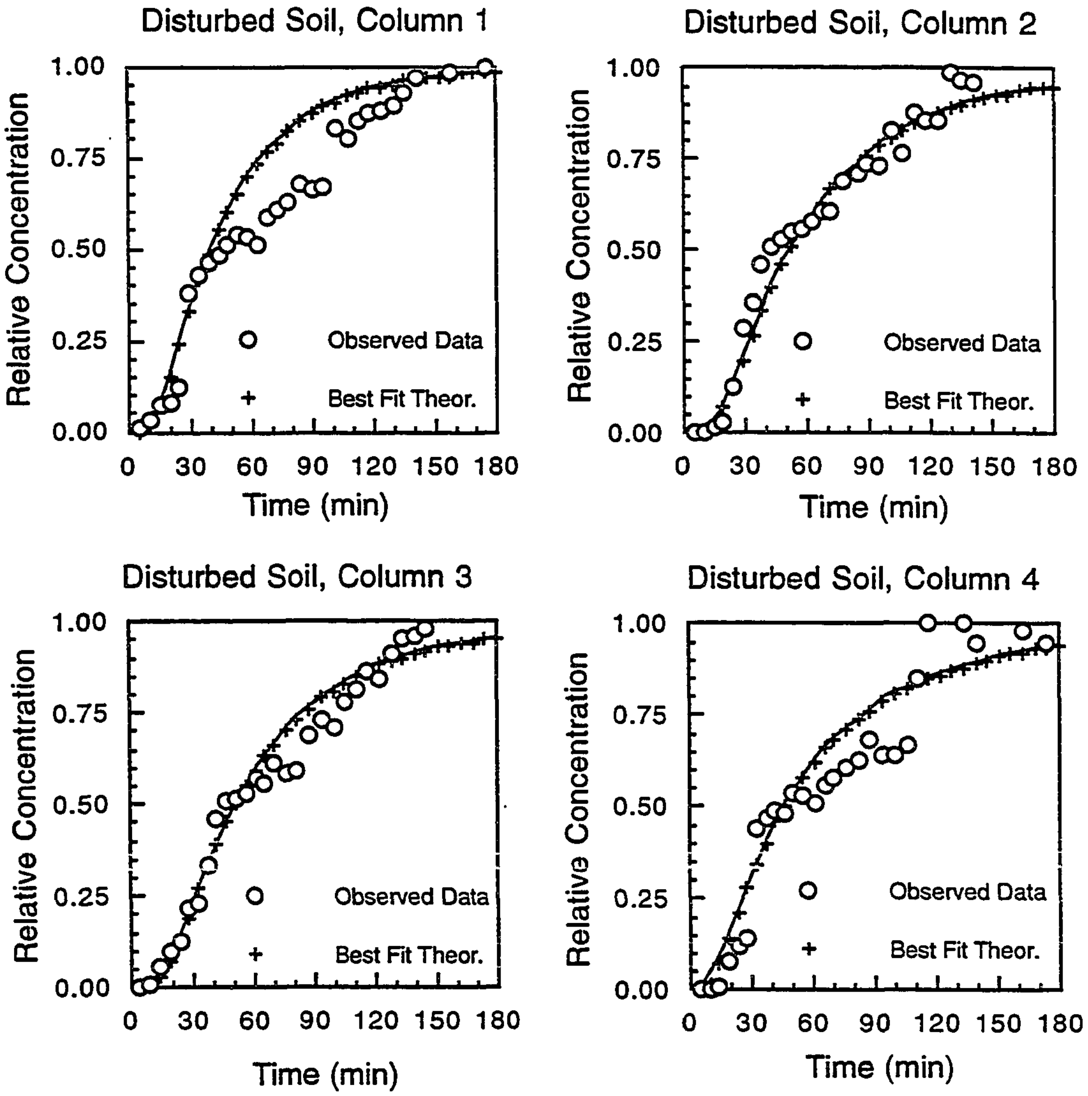


Figure 2. Breakthrough Curves for Undisturbed Soil Columns Covered with Turfgrass.



Disturbed Soil, Column 1

Disturbed Soil, Column 2

Disturbed Soil, Column 3

Disturbed Soil, Column 4

Figure 3. Breakthrough Curves for Disturbed Soil Columns Covered with Turfgrass.

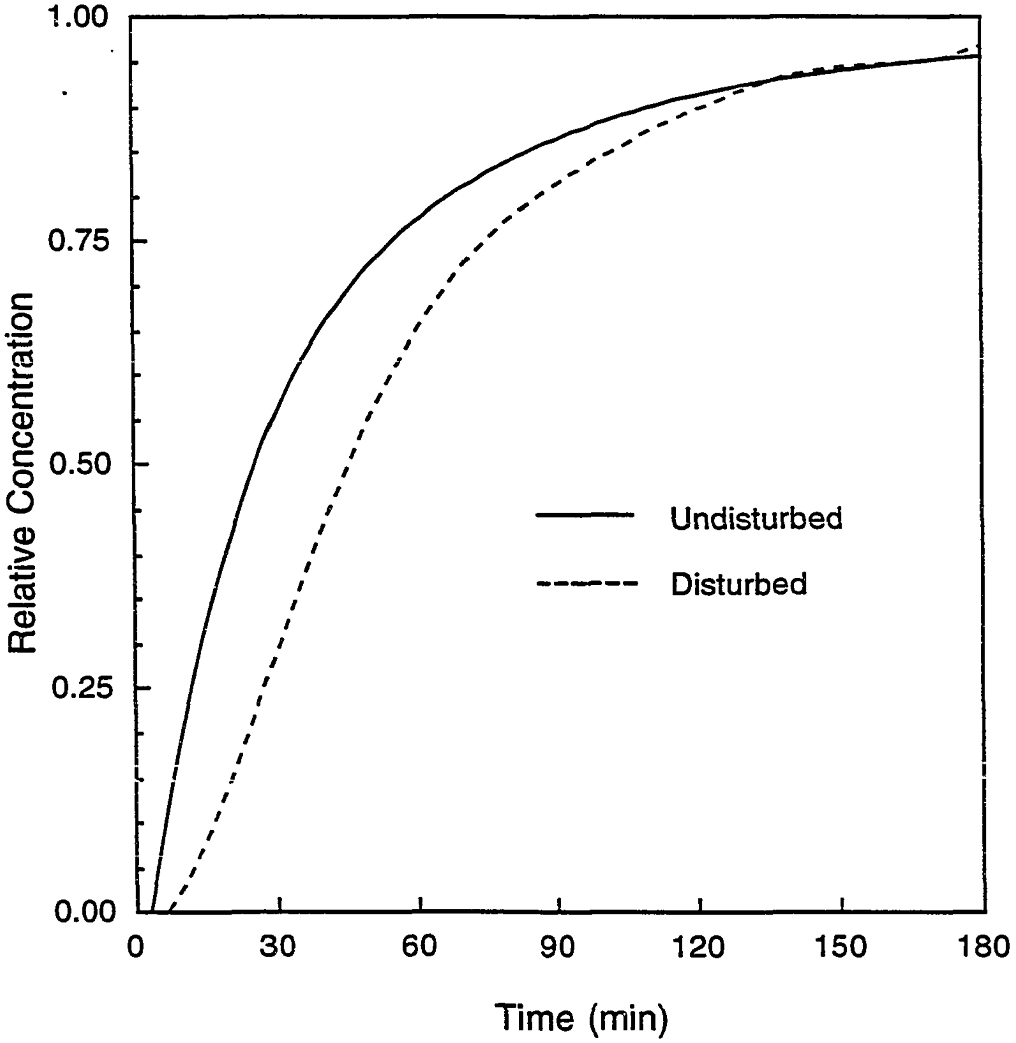


Figure 4. Theoretical Breakthrough Curves for Undisturbed and Disturbed Soil Columns Covered with Turfgrass.

PAPER 2: FATE OF ^{15}N-LABELED UREA APPLIED TO TURFGRASS COVERED UNDISTURBED SOIL COLUMNS

ABSTRACT

Current public concern for the environment has focused attention on the environmental effects of chemical applications to turfgrass areas. Little research has been done concerning the environmental effects of nitrogen (N) and pesticides applied to turfgrasses. The objectives of this study were to investigate the hydrology of 50-cm undisturbed soil columns with a Kentucky bluegrass turf and intact macropores under a heavy and light irrigation regime, and to measure the fate of N (using ^{15}N as a tracer) when applied to an undisturbed soil column. We found that a heavy irrigation increased N that leached through the 50-cm undisturbed soil columns by 40 times compared with light irrigation, and decreased volatilization of liquid urea compared with a light irrigation.

Keywords. Nitrogen, Leaching, Nutrients, Golf Courses.

INTRODUCTION

Nitrogen (N) is applied to grasses on golf courses, home lawns, sports complexes, industrial parks, and other areas to improve turf quality. Current public concern for the environment has focused attention on the environmental effects of chemical applications to turfgrass areas. Little research has been done concerning the environmental effects of N and other materials applied to turfgrasses (Balogh and Walker, 1992). Petrovic (1990) reported that few studies have investigated the fate of N applied to turfgrasses using a mass balance approach. An understanding of the fate of these chemicals is needed to manage turfgrass maintenance better and to identify the chemicals that pose an environmental threat. Possible movement of N into ground water, thereby degrading water quality, is of greatest concern (Haynes, 1986). Also, excessive algae growth that decreases dissolved oxygen of surface waters (eutrophication) can occur if N and P are abundant (Mugaas et al., 1991; W. C. Huber, 1993).

Nitrate (NO_3^-) is the most mobile form of N in soil. Nitrate in ground water near urban areas has been attributed to surface-applied fertilizers (Flipse et al., 1984). Brown et al. (1982) showed that NO_3^- leached from ureaformaldehyde was negligible, but 9 to 22% of applied NH_4NO_3 leached. In a 3-year study where N was applied at 245 kg ha^{-1} yr^{-1} in various forms, Hummel and Waddington (1981) found N recovered in clippings ranged from 46 to 59%. Joo et al. (1991) accounted for less than 29% of applied N in the turf tissue, and the top 17 cm of the soil profile during a 5-week test.

Macropore flow may dominate transport of surface-applied irrigation (Beven and Germann, 1982). After reviewing macropore flow research, Evert (1989) concluded macropores may increase water and solute flux through soils and that the influence of macropores was negated when experiments were done in a laboratory using dried, sieved, and repacked soil columns.

Brown et al. (1977) studied the influence of management on the fate of N applied to golf greens. They reported that a change from 0.7-cm irrigation applications to 0.9-cm irrigation applications greatly increased nitrate leaching from surface applied NH_4NO_3 to a simulated golf green.

The objectives of this study were to investigate the hydrology of an undisturbed soil column with a Kentucky bluegrass cover and intact macropores under a heavy and light irrigation regime and to measure the fate of N (using ^{15}N as a tracer) when it is applied to an undisturbed soil column.

MATERIALS AND METHODS

Twelve undisturbed columns of Nicollet (fine-loamy, mixed, mesic-Aquic Hapludolls) soil were collected in summer, 1992, from a 400-m^2 area that had been graded in 1968 at the Iowa State University Horticulture Research Station, Gilbert, Iowa. Available P was 6 mg kg^{-1} (s.d. = 1 mg kg^{-1}), available K was 306 mg kg^{-1} (s.d. = 20 mg kg^{-1}), and pH was 7.4. The area had been established in 1991 with 'Glade' Kentucky bluegrass (*Poa pratensis* L.) and mowed to 2.54 cm. The annual application of sulfur-coated urea and P to the turf was applied 12 months before excavation at a level of 196 kg N ha^{-1} and 49 kg P ha^{-1}. Columns were 20 cm in diam. and were excavated to a 50-cm depth (Priebe and Blackmer, 1989). A 30-cm-diam. heating duct pipe was placed around the free-standing column, leaving 5 cm between the soil column and the pipe. Mortar was poured between the pipe and soil column. The mortar-soil columns were allowed to set for 10 days and then were moved to the greenhouse 4 weeks before testing.

About 1.3 cm of distilled water was applied to each column twice a week. Natural irradiation was supplemented with high-pressure sodium lamps with an average irradiation of 870 µmol s^{-1} m^{-2} 90 cm from the top of the columns. Fourteen-h photoperiods were used for supplemental irradiation from October to April. The greenhouse was maintained at 19 ± 2 °C at night and at 27 ± 2 °C during the day.

The columns were lowered (8.33 cm h^{-1}) into distilled water over a 6-h period and left submerged for 24 h to obtain a moisture content at water holding capacity. The columns were raised out of the water and drained for 24 h (Priebe and Blackmer, 1989).

A collection system similar to that described by Joo et al. (1987) was used to collect volatilized N in the form of ammonia (NH_3) for the first 7 days of the 28-day test period. The chamber was a glass hemisphere of 21.5-cm diam. Two holes, 3.2 cm and 1.9 cm in diam., were drilled in the glass to provide holes for stoppers. Small glass tubes were placed in the stoppers to allow air intake and exhaust. A hole was made directly on top of the column for the exhaust, and the intake hole was on the side. The intake air tube was connected to a 15-cm ring made from perforated copper tubing to disperse the incoming air. Mortite® rope caulk (Mortell Co., Kankakee, IL) was used to seal the concrete and the glass chamber, and a rubber sealant (Big Stretch®, Sashco Co., Commerce City, CO) was applied to the outside of the chamber for added protection against leakage. The sealant was not in contact with the air in the chamber.

Compressed air was filtered through DX (93% efficient for removal of 0.1 micron particles) and BX (99.99% efficient) Balston® (Balston, Inc., Lexington, MA) paper filters in series, and passed through a 19-L glass jar that contained 5 L of 0.25-N sulfuric acid to remove NH_3. Next, the air was bubbled through distilled water for humidification and to remove acid. Perforated stainless steel tubing was used to disperse the air in the sulfuric acid and in the distilled water. The air supply was branched to four different collection chambers connected in parallel. Air-flow meters with flow valves were placed on both the intake and the exhaust of each collection chamber to insure proper flow. Tygon® connected the various devices.

Filtered air was drawn through the collection chambers by using a vacuum pump. A pumping rate of 1.9 chamber volumes min^{-1} (5 L min^{-1}) was used. The collected gas was bubbled through a trap solution of 0.25-N H_2SO_4. The trap solution was replaced at 24 h, 48 h, and 7 days. The acid was tested for NH_3 by steam distillation.

Urea N (46%) labeled with 5.4 atom % ^{15}N and monobasic calcium phosphate [$Ca(H_2PO_4)_2$] were dissolved in distilled water and applied to the surface of the turf at 49 kg N ha^{-1} and 33 kg P ha^{-1}, respectively, using a DeVilbiss (Jackson, TN) spray-mist atomizer attached to an air pressure pump. The pesticides pendimethalin, MCPP, 2,4-D, dicamba, isazofos, chlorpyrifos, and metalaxyl were applied by a spray mist atomizer at the same time as the N and P. Due to the large quantity of data, the fate of the applied pesticides will be reported on in other manuscripts.

Two irrigation regimes were used. A heavy regime consisted of irrigating the column with 2.54 cm of distilled water immediately after the urea was applied, with three additional 2.54-cm applications made at 1-week intervals. Ponding occurred on most of the soil columns under the heavy irrigation regime. A light irrigation regime included a 0.64-cm application immediately after fertilizing, with 15 additional 0.64-cm applications at 42-h intervals. The two treatments were replicated six times. The initial applications were applied over 4 min with a Teejet® (Spraying System Co., Wheaton, IL) Conejet-TXVS-4 nozzle before the volatilization chamber was placed over the column. For the first week applications of the light irrigation regime, the top stopper was removed and the spray nozzle was inserted into the hole. All soil columns under both irrigation regimes were considered to be in an unsaturated condition.

A glass funnel was used to collect leachate. A plastic bag was placed around the bottom of the column to prevent drying. Leachate was collected at about 100 mL intervals and frozen. Leachate was not allowed to stand in the collection device more than 24 h.

Clipping, verdure, and thatch/mat samples were taken from each column, and the soil was excavated in 10-cm layers at the end of the 28-day period. The soil was spread into a thin layer and dried at room temperature (19 to 25 °C) for 3 days (Priebe and Blackmer, 1989). The soil then was placed in plastic bags, thoroughly mixed, and sampled for analysis.

The soil layers were tested for Kjeldahl N (Bremner and Mulvaney, 1982), ammonium (NH_4^+), and NO_3^- (steam distillation). The plant material and leachate were tested for Kjeldahl N. Each fraction was tested for atom % ^{15}N present by using a Finnigan MAT 250 mass spectrometer, Finnigan MAT, San Jose, CA, (Sanchez and Blackmer, 1988). All N calculations were based on the atom % ^{15}N found in each sample (Sanchez and Blackmer, 1988).

RESULTS

Mean bulk density of the undisturbed soil was 1.42 Mg m^{-3} (s.d. = 0.13 Mg m^{-3}). Porosity estimated from bulk density averaged 0.46 m^3 m^{-3}. Organic matter content averaged 5.5 (s.d. = 1.9), 3.3 (s.d. = 0.3), 2.9 (s.d. = 0.4), 2.5 (s.d. = 0.5), 2.2 (s.d. = 0.5), and 1.8 (s.d. = 0.4)% for the thatch mat, 0 to 10, 10 to 20, 20 to 30, 30 to 40, and the 40 to 50 cm soil-layer fractions, respectively.

We applied a total of 3192 mL of distilled water to each column for both the heavy and light irrigation regime. Mean total leachate volumes for the heavy and light irrigation regimes were 1350 mL (s.d. = 329 mL) and 401 mL (s.d. = 427 mL), respectively (fig. 1). Total leachate quantities collected for the two treatments differed ($p = 0.0015$). Over two times the leachate from replication 1, 2, 3, 5, and 6 was collected for replication 4 under light irrigation (fig. 1).

Average total N (Kjeldahl N + NH_4^+-N + NO_3^--N) recovery did not vary between the heavy and light irrigation regimes (table 1). Volatilized N was three times higher from columns under the light irrigation compared to columns under the heavy irrigation. There were no differences in N recovery between the heavy and light irrigation regimes for the clippings, verdure, thatch mat, 0 to 10, 10 to 20, 20 to 30, 30 to 40, and the 40 to 50 cm layer fractions.

Mean N collected in leachate from the soil columns under the heavy irrigation regime was 40 times greater than from columns under the light irrigation regime. Over 95% of the total N that leached from replications 4, 5, and 6 under the heavy irrigation regime occurred within 10 h (fig. 2). Only 25%, however, of the total N leached from replications 1, 2, and 3 occurred within 10 h. Twenty-four of the 154 mg N that was applied was leached through the 50-cm soil profile in a few hours for replication 6 under the heavy irrigation regime (fig. 2). One-hundred percent of the total N leached from replication 4 under the light irrigation regime occurred after 100 h.

Mean N recovered from the soil columns under both irrigation regimes as NO_3^- averaged 3.4% (table 2). No differences existed in NO_3^- recovery between irrigation rates. Nitrogen recovered as NH_4^+ was less than 0.1% of applied for both irrigation regimes (table 3).

DISCUSSION

We conclude that a heavy irrigation to undisturbed soil columns that are covered with turfgrass increases N transport compared with a light irrigation, and decreased volatilization of liquid urea compared with a light irrigation.

The macropore structure found in undisturbed soil columns can have a major impact on water and solute distribution in the profile (Thomas and Phillips, 1979). It is unlikely that preferential flow occurred between the soil and masonry interface due to cement occupying soil pores at the boundary (Priebe and Blackmer, 1989). We observed that leaching occurred for some of the soil columns under the heavy irrigation within 30 s after the beginning of the irrigation. The leachate was observed coming from macropores near the center of the soil column. Replication 4 under the light irrigation appeared to have a more extensive macropore structure compared to the other replications. Since less leachate was collected from columns under the light irrigation, more of the applied irrigation was available for evapotranspiration. Also, since about 4 times the average leachate recovered from the other soil columns under the light irrigation was collected from replication 4, the potential for N leaching was increased.

Calculations based on a field-capacity volumetric soil water content = 0.33 m^3 m^{-3}, show that surface applied irrigation should move 7.7 cm per 2.54 cm irrigation into the soil profile by water displacement only (Priebe and Blackmer, 1989). Collecting applied N in the leachate from 50 cm soil columns after the first irrigation, therefore, was evidence of preferential flow occurring.

About 10% of the applied N under heavy irrigation was collected in the leachate within a few h of application, which was likely due to macropore flow. The heavy irrigation seeped into the matrix of the soil near the surface, ponded, and then filled the macropores, which allowed rapid flow through the soil profile to occur. Because the light irrigation was 0.25 times the heavy irrigation and little ponding occurred, the majority of irrigation probably infiltrated into the soil matrix. Similar effects of macropore flow of surface-applied chemicals were reported by Thomas and Phillips (1979).

Morton et al. (1988) concluded that irrigation rate affected N leaching. The data described here also shows N leaching was affected initially by irrigation rate, and for several weeks after N application. Replication 1 and 3 are examples of how the heavy irrigation transported N through the soil profile weeks after application (fig. 3). Differences among replications probably can be attributed to macropore structure variations. Nitrogen was rapidly transported through a portion in the soil column for columns where the macropore structure was truncated by the mortar boundary or dead ended before reaching 50 cm where the N entered the soil matrix. Additional heavy irrigations transported the N through the remaining soil until it leached from the bottom of the soil columns.

Volatilized N was less than 3% of the applied N under either irrigation regime. This agrees with the work of Bowman et al. (1987). Irrigation applied immediately after N application reduced volatilization by transporting the applied N slightly below the soil surface where N is more likely to be adsorbed than volatilized (Haynes, 1986). The heavy irrigation transported more of the surface applied N below the soil surface compared to the light irrigation, therefore, further reducing N volatilization.

The practical implication of this research is that N losses by volatilization or leaching can be reduced by irrigation management procedures. Volatilization is reduced by lightly watering in N after application. By applying light, frequent irrigations instead of heavy, infrequent irrigations for several weeks after N application, the likelihood of N leaching is reduced. Timing of N application is also important with regard to reducing leaching losses. It is a common practice for fertilizer to be applied to turfgrass areas before a forecasted rainfall to move the fertilizer into the soil profile. Applying N before heavy rainfall events would cause greater losses of N due to leaching than a light irrigation after N application.

Table 1. Percentage of applied N recovered as Kjeldahl N or NH_4^+-N or NO_3^--N that volatilized from the surface, was taken up by the plant, adsorbed to soil layers, or that leached from undisturbed soil columns with a turfgrass cover.

	Heavy Irrigation*		Light Irrigation†		
Category	Mean‡	s.d.	Mean‡	s.d.	p-value**
	% of labeled N applied				
Volatilization	0.9	0.6	2.8	1.7	0.029
Clippings, Verdure	14.3	5.5	32.2	29.4	0.173
Thatch Mat	11.3	4.2	15.0	11.1	0.460
0 to 10 cm	13.4	7.6	14.2	6.5	0.859
10 to 20 cm	7.7	5.2	8.5	6.5	0.822
20 to 30 cm	7.2	7.3	7.0	5.4	0.965
30 to 40 cm	7.8	8.0	7.6	7.2	0.955
40 to 50 cm	7.6	8.1	3.1	2.5	0.217
Leachate	12.2	5.0	0.3	0.6	<0.001
Cumulative Totals	82.4	28.9	90.7	36.1	0.670

* Heavy irrigation, four 2.54-cm irrigation applications.

† Light irrigation, sixteen 0.64-cm irrigation applications.

‡ Each treatment had six replications.

** *t* - test, based on the hypothesis that heavy and light irrigation are same.

Table 2. Percentage of applied N recovered as NO_3^--N that adsorbed to soil layers from undisturbed soil columns with a turfgrass cover.

	Heavy Irrigation*		Light Irrigation†		
Category	Mean‡	s.d.	Mean‡	s.d.	p-value**
	% of labeled N applied				
10 to 20 cm	0.5	0.4	0.7	0.6	0.602
20 to 30 cm	0.7	0.4	0.5	0.4	0.431
30 to 40 cm	0.7	0.4	0.6	0.7	0.747
40 to 50 cm	0.9	0.7	0.5	0.6	0.325
Totals	3.7	2.4	3.1	2.7	0.684

* Heavy irrigation, four 2.54-cm irrigation applications.

† Light irrigation, sixteen 0.64-cm irrigation applications.

‡ Each treatment had six replications.

** *t* - test, based on the hypothesis that heavy and light irrigation are same.

Table 3. Percentage of applied N recovered as NH_4^+-N that adsorbed to soil layers from undisturbed soil columns with a turfgrass cover.

	Heavy Irrigation*		Light Irrigation†		
Category	Mean‡	s.d.	Mean‡	s.d.	p-value**
	% of labeled N applied				
0 to 10 cm	0.019	0.010	0.010	0.005	0.065
10 to 20 cm	0.003	0.004	0.002	0.003	0.650
20 to 30 cm	0.003	0.004	0.001	0.001	0.401
30 to 40 cm	0.004	0.005	0.001	0.001	0.111
40 to 50 cm	0.003	0.004	0.001	0.001	0.117
Totals	0.032	0.015	0.015	0.006	0.022

* Heavy irrigation, four 2.54-cm irrigation applications.

† Light irrigation, sixteen 0.64-cm irrigation applications.

‡ Each treatment had six replications.

** *t* - test, based on the hypothesis that heavy and light irrigation are same.

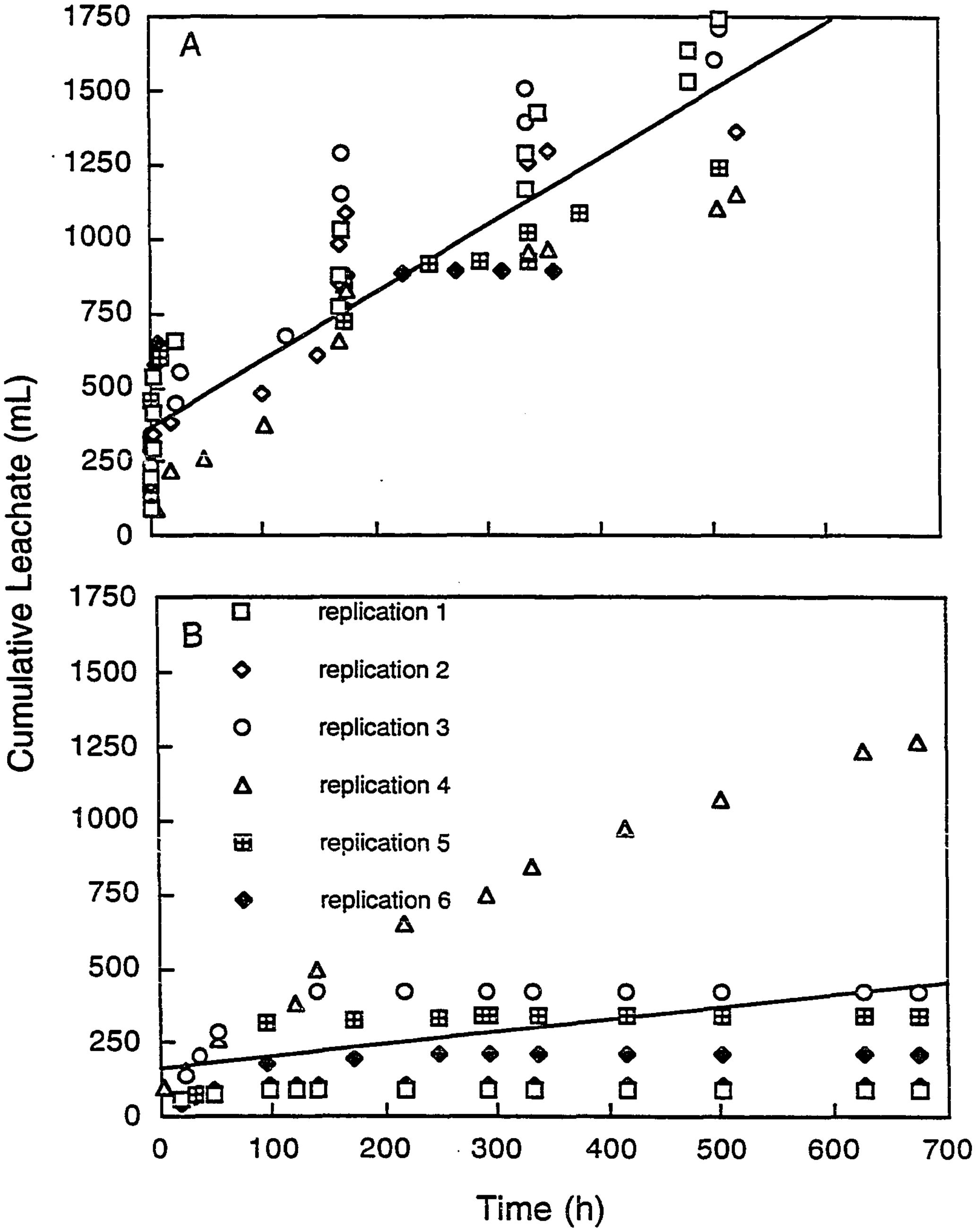


Figure 1. Cumulative leachate collected from undisturbed soil columns with a turfgrass cover under a heavy (A) and a light (B) irrigation regime.

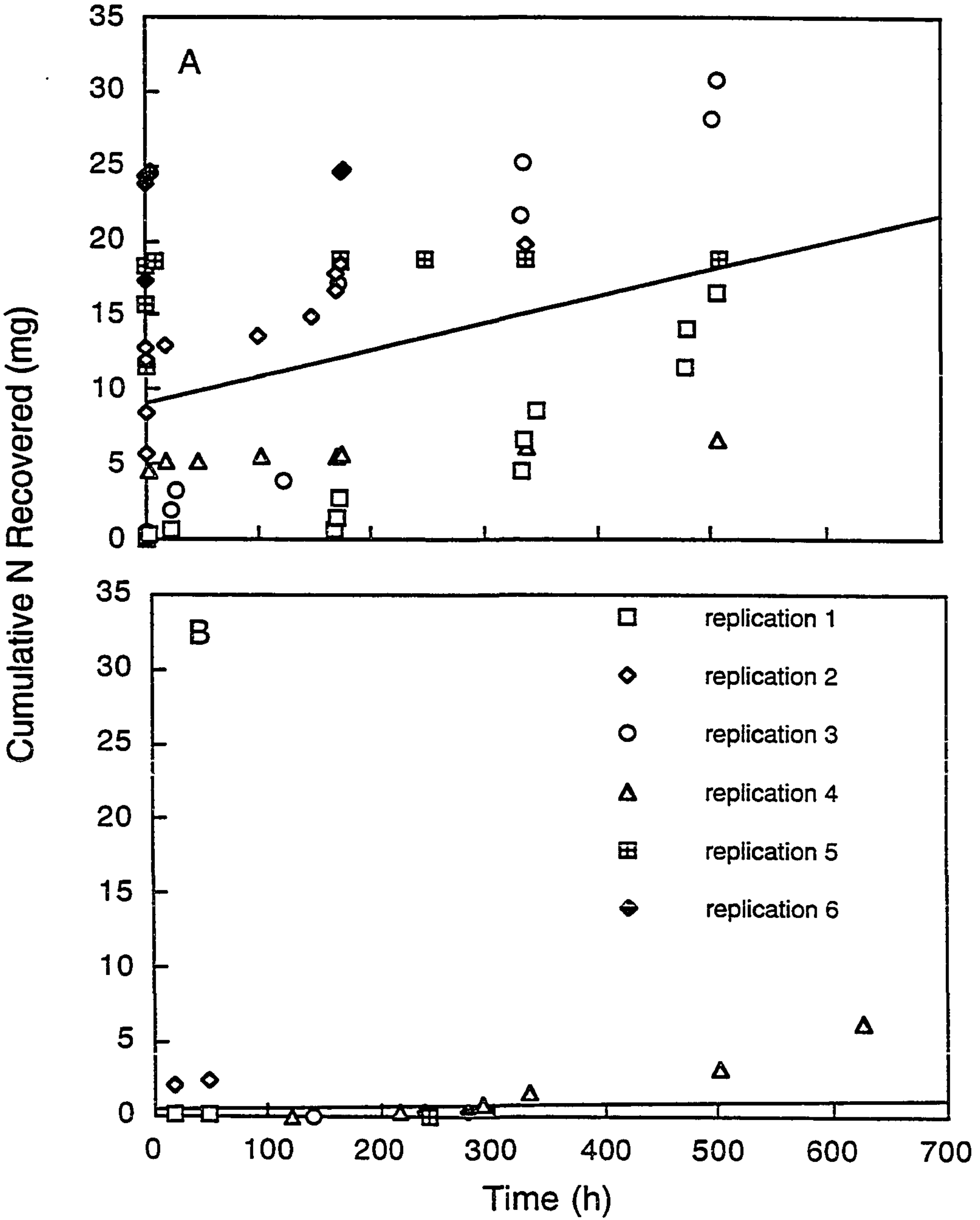


Figure 2. Cumulative N recovered in leachate from undisturbed soil columns with a turfgrass cover heavy (A) and a light (B) irrigation regime.

REFERENCES

Balogh, J. C. and W. J. Walker. 1992. *Golf Course Management & Construction Environmental Issues.* Chelsea, Michigan: Lewis Pub.

Beven, K. and P. Germann. 1982. Macropores and water flow in soils. *Water Res. Res.* 18:1311-1325.

Bowman, D. C., J. L. Paul, W. B. Davis and S. H. Nelson. 1987. Reducing ammonia volatilization from Kentucky bluegrass turf by irrigation. *HortScience* 22:84-87.

Bremner, J. M. and C. S. Mulvaney. 1982. Nitrogen-total. In *Methods of Soil Analysis. Part 2.* ed. A. L. Page. Agronomy 9:595-624.

Brown, K. W., J. C. Thomas and R. L. Duble. 1982. Nitrogen source effect on nitrate and ammonium leaching and runoff losses from greens. *J. Agron.* 74:947-950.

Brown, K. W., R. L. Duble and J. C. Thomas. 1977. Influence of management and season of fate of N applied to golf greens. *J. Agron.* 69:667-671.

Evert, C. A. 1989. Role of preferential flow on water and chemical transport in a glacial till soil. Ph. D. thesis. Iowa State University. Ames, Iowa.

Flipse, W. J., Jr., B. G. Katz, J. B. Linder and R. Markel. 1984. Sources of nitrate in ground water in a sewered housing development, central Long Island, New York. *Ground Water.* 32:418-426.

Haynes, R. J. 1986. *Mineral Nitrogen in the Plant-Soil System.* Orlando, Florida: Academic Press, Inc.

Huber, W. C. 1993. Contaminant transport in surface water. in D. R. Maidment (Ed.). *Handbook of hydrology.* McGraw-Hill, New York. p. 14.43.

Hummel, N. W., Jr. and D. V. Waddington. 1981. Evaluation of slow-release nitrogen sources on 'Baron' Kentucky bluegrass. *J. Soil Sci.* 45:966-970.

Joo, Y. K., N. E. Christians and A. M. Blackmer, 1991. Kentucky bluegrass recovery of urea-derived nitrogen-15 amended with urease inhibitor. *J. Soil Sci.* 55:528-530.

Joo, Y. K., N. E. Christians and J. M. Bremner, 1987. Effect of N-(n-butyl) thiophosphoric triamide (NBPT) on growth response and ammonia volatilization following fertilization of Kentucky bluegrass (Poa pratensis L.) with urea. *J. Fert. Issues.* 4:98-102.

Morton, T. G., A. J. Gold and W. M. Sullivan. 1988. Influence of overwatering and fertilization on nitrogen losses from home lawns. *J. Environ. Qual.* 17:124-130.

Mugaas, B. J., M. L. Agnew, N. E. Christians and E. Edwards. 1991. Turfgrass management for protecting surface water quality. Iowa State University Extension. File: Horticulture 4-1.

Petrovic, A. M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. *J. Environ. Qual.* 19:1-14.

Priebe, D. L. and A. M. Blackmer. 1989. Preferential movement of Oxygen-18-labeled water and nitrogen-15-labeled urea through macropores in a Nicollet soil. *J. Environ. Qual.* 18:66-72.

Sanchez, C. A. and A. M. Blackmer. 1988. Recovery of anhydrous ammonia-derived nitrogen-15 during three years of corn production in Iowa. *Agron. J.* 80:102-108.

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

PAPER 3: FATE OF ISAZOFOS, CHLORPYRIFOS, METALAXYL, AND PENDIMETHALIN APPLIED TO TURFGRASS COVERED UNDISTURBED SOIL COLUMNS

ABSTRACT

Pesticides are applied to grasses on golf courses, home lawns, sports complexes, industrial parks, and other areas to improve turf quality. Current public concern has focused attention on the environmental effects of chemical applications to turfgrass areas. The objective of this study was to investigate the fate of pendimethalin, chlorpyrifos, isazofos, and metalaxyl when applied to Kentucky bluegrass turf established on 50-cm undisturbed soil columns with intact macropores under a heavy and light irrigation regime. On average 6.3, 0.5, 7.7, and 0.2% of the applied isazofos, chlorpyrifos, metalaxyl, and pendimethalin, respectively, was found in leachate from undisturbed soil columns under a heavy irrigation compared to 0.4, 0.0, 0.2, and 0.0% from undisturbed soil columns under a light irrigation. From this research, we conclude that irrigation practices can have an impact on the movement of pesticides through soil profiles.

INTRODUCTION

Pesticides are applied to grasses on golf courses, home lawns, sports complexes, industrial parks, and other areas to improve turf quality. Current public concern for the environment has focused attention on the environmental effects of chemical applications to turfgrass areas. Possible adverse environmental effects of pesticides are: they are potentially harmful to humans, may reduce certain bird populations, can destroy nontarget organisms, and may elevate of nonpest species to pest status (Balogh and Walker, 1992).

Little research has been done concerning the fate of pesticides applied to turfgrasses. Volatilization of chlorpyrifos when applied to a no-till agricultural setting was estimated at 23% of applied over 4 days (Whang et al., 1993). Volatilization of pendimethalin when applied to Kentucky bluegrass was estimated at 13% of applied over 5 days when no supplemental irrigation was applied (Cooper et al., 1990). Maki (1993) reported that chlorpyrifos was detected in 32 out of 5155 samples that were collected from discharged tile water from golf courses in Japan. Pendimethalin was detected in 31 out of 5451 samples. Stahnke et al. (1991) reported that most of the pendimethalin applied to a Kentucky bluegrass was recovered in the plant tissue and the thatch layer.

Macropore flow may dominate transport of surface-applied irrigation (Beven and Germann, 1982). After reviewing macropore flow research Evert (1989) concluded macropores may increase water and solute flux through soils, and that the influence of macropores was negated when experiments were done in a laboratory using dried, sieved, and repacked soil columns. Kladivko et al. (1991) studied the movement of pesticides into subsurface tiles in an agricultural setting and determined that pesticides appeared in drains much sooner than predicted by models that assume convective-dispersive transport.

Brown et al. (1977) studied the influence of management of the fate of N applied to golf greens. They reported that a change from 0.7-cm irrigation applications to 0.9-cm irrigation applications greatly increased nitrate leaching from surface applied NH_4NO_3 to a simulated golf green.

The objective of this study was to investigate the fate of pendimethalin, chlorpyrifos, isazofos, and metalaxyl when applied to Kentucky bluegrass turf established on undisturbed soil columns with intact macropores under a heavy and light irrigation regime.

MATERIALS AND METHODS

Twelve undisturbed columns of a Nicollet (fine-loamy, mixed, mesic-Aquic Hapludolls) soil were collected in summer, 1992, from a 400-m^2 area that had been graded in 1968 at the Iowa State University Horticulture Research Station, Gilbert, Iowa. Available P was 6 mg kg^{-1} (s.d. = 1 mg kg^{-1}), available K was 306 mg kg^{-1} (s.d. = 20 mg kg^{-1}), and pH was 7.4 from the collection site. The area had been established in 1991 with 'Glade' Kentucky bluegrass (*Poa pratensis* L.) and maintained at golf course fairway mowing height of 2.54 cm. The columns were 20 cm in diameter and were excavated to a 50-cm depth (Priebe and Blackmer, 1989). A free-standing column of soil was excavated by removing the surrounding material. A 30-cm-diam. heating duct pipe was placed around the column, leaving 5 cm between the soil column and the pipe. Mortar was poured between the pipe and soil column. The mortar was allowed to set for 10 days in the field and then was moved to the greenhouse 4 weeks before testing.

About 1.3 cm of distilled water was applied to each column twice a week. Natural radiation was supplemented with high-pressure sodium lamps with an average intensity of 870 μmol s^{-1} m^{-2} measured at 90 cm from top of columns. A 14-h photoperiod was used for supplemental irradiation from October to April. The greenhouse was maintained at 19 ± 2 °C at night and at 27 ± 2 °C during the day.

The annual application of sulfur-coated urea and P to the turf 12 months before excavation at a level of 196 kg N ha^{-1} and 49 kg P ha^{-1}. No pesticides were applied to the plot within 18 months of soil column collection.

The columns were slowly lowered into distilled water over a 6-h period (8.33 cm h^{-1}) and left submerged for 24 h to obtain saturation to obtain a moisture content at water holding capacity. The columns were slowly raised out of the water and drained for 24 h (Priebe and Blackmer, 1989).

Pendimethalin (N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine) 60 DG (dispersible granule) was applied at 2.22 kg ai ha^{-1}, chlorpyrifos ([0, 0-diethyl-0-(3,5,6-trichloro-2-pyridinyl) phosphorothioate]) 4EC (emulsified concentrate) at 1.12 kg ai ha^{-1}, isazofos ({O-[5-chloro-1-(1-methylethyl)-1H-1,2,4-triazol-3-yl]O,O-diethyl phosphorothioate}) 4EC at 2.24 kg ai ha^{-1}, and metalaxyl (N-(2,6-dimethylphenyl)-N-(methoxyacetyl) alanine methyl ester) 2EC at 2.24 kg ai ha^{-1} (Table 1). Trimec® (dicamba {dimethylamine salt of 3,6-dichloro-o-anisic acid}, 2,4-D {dimethylamine salt of 2,4-dichlorophenoxyacetic acid}, MCPP {dimethylamine salt of 2-(2-methyl-4-chlorophenoxy)}) was applied at 1.86 kg ai ha^{-1} and will be reported on in a later paper. The pesticides used are commercially available and were not labeled in any way. Urea N (46%) labeled with a 5.4 atom % ^{15}N and monobasic calcium phosphate [$Ca(H_2PO_4)_2$] (Starrett, et al. 1994) were also applied. The N, P and pesticides were applied in solution with a DeVilbiss (Jackson, TN) spray-mist atomizer that was attached to an air pressure pump. Due to the large quantity of data, the fate of the applied N and other pesticides will be reported on in other manuscripts.

A collection system similar to that described by Joo et al. (1987) was used to collect volatilized N in the form of ammonia (NH_3) for the first 7 days of the 28-day test period. The chamber was a glass hemisphere of 21.5-cm diam. Two holes, 3.2 cm and 1.9 cm in diam., were drilled in the glass to provide holes for stoppers. Small glass tubes were placed in the stoppers to allow air intake and exhaust. The intake air tube was connected to a 15-cm ring made from perforated-copper tubing to disperse the incoming air. Mortite® rope caulk (Mortell Co., Kankakee, IL) was used to seal the concrete and the glass chamber, and a rubber sealant (Big Stretch®, Sashco Co., Commerce City, CO) was applied to the outside of the chamber for added protection against leakage. The sealant was not in contact with the air in the chamber. Filtered air was drawn through the collection chambers by using a vacuum pump. A pumping rate of 1.9 chamber volumes min^{-1} (5 L min^{-1}) was used. The collected gas was bubbled through a trap solution and replaced at 24 h, 48 h, and at 7 days.

Two irrigation regimes were used. A heavy regime consisted of irrigating the column with 2.54 cm of distilled water immediately after the pesticides were applied, followed by three additional 2.54-cm applications at 1-week intervals. A light irrigation regime included a 0.64-cm application immediately after fertilizing, with 15 additional 0.64-cm applications at 42-h intervals. A total of 2.54 cm of irrigation was distributed evenly over a 7-day period. The two treatments were replicated six times. The initial applications were applied over 4 min with a Teejet® (Spraying System Co., Wheaton, IL) Conejet-TXVS-4 nozzle before the volatilization chamber was placed over the column. For the later applications of the light irrigation regime for the first week, the top stopper was removed and the spray nozzle inserted into the hole. All soil columns under both irrigation regimes were considered to be in an unsaturated condition. All soil columns under both irrigation regimes were considered to be in an unsaturated condition.

A glass funnel was used as the leachate collection device. A plastic bag was placed around the bottom of the column to prevent drying. Leachate was collected at about 100-mL intervals and frozen. Leachate was not allowed to stand in the collection device more than 24 h.

Clipping, verdure, and thatch/mat samples were taken from each column, and the soil was excavated in 10-cm layers at the end of the 28-day-test period. The soil was spread into a thin layer and air dried at room temperature for 3 days. It was then placed in plastic bags, thoroughly mixed, and sampled for analysis. Mean bulk density for the entire column and organic matter content for each layer was determined.

Pesticide concentrations in the soil layers were determined by collecting a representative sample of wet soil weighing 50 to 51 g into a 250 mL Nalgene^{tm} bottle. One hundred mL of acetone was added and the sample was placed on a Burrell wrist action shaker, #10 intensity, for 45 min. After shaking, the soil samples were individually filtered into a round bottom 250 mL flask using a plastic buchner funnel and #1 (7 cm) Whatman filter paper. Soil samples were rinsed twice with 25 mL acetone, and dried in a vacuum apparatus, and the dry weight was recorded.

When 20 to 24 soil extracts were accumulated, 0.5 mL of 1-octanol was added to each flask. Samples were then concentrated on a rotary evaporator at 45° C until the acetone was removed, and water was removed by additional rotary evaporation at 50° C and 760 mm vacuum. After samples were cooled to room temperature, 2.5 mL of toluene was added. Each sample was then sonicated for 20 to 30 sec and transferred to a gas chromatograph autosample vial.

Quantitative analysis was by gas chromatograph (Perkins-Elmer Sigma, model 2000/2100) using a 25 m wide-bore (0.53 mm) capillary column with a bonded SPB-5 stationary phase for the separation and thermonic N-P detection. Typical operating temperature for the column oven was 185° C, for the injector block was 265 ° C, and for the detector 300° C. Carrier gas was helium at 4 mL min^{-1}. Detector gases were air (160 mL min^{-1}) and hydrogen (2 mL min^{-1}). Only parent compounds were determined.

RESULTS

Mean bulk density of the 12 undisturbed soil columns was 1.42 Mg m^{-3} (s.d. = 0.13 Mg m^{-3}). Porosity estimated from bulk density averaged 0.46 m^3 m^{-3}. Organic matter content averaged 5.5 (s.d. = 1.9), 3.3 (s.d. = 0.3), 2.9 (s.d. = 0.4), 2.5 (s.d. = 0.5), 2.2 (s.d. = 0.5), and 1.8 (s.d. = 0.4) % for the thatch mat, 0 to 10, 10 to 20, 20 to 30, 30 to 40, and the 40 to 50 cm soil-layer fractions, respectively.

We applied 3192 mL of distilled water to each column. Mean total leachate volumes that varied significantly ($p = 0.0015$) for the heavy and light irrigation regimes were 1350 mL (s.d. = 329 mL) and 401 mL (s.d. = 427 mL), respectively.

Isazofos total recovery averaged 6.1% of the applied (table 2). Isazofos recovered in the leachate from soil columns under the heavy irrigation regime was 15 times more than from soil columns under the light irrigation regime. Over 4 times more isazofos was recovered in the thatch mat from soil columns under the heavy irrigation regime compared to the light irrigation regime.

Chlorpyrifos total recovery averaged 9.0% of the applied (table 3). Chlorpyrifos recovered in the leachate from soil columns under the heavy irrigation regime was 53 times more than from soil columns under the light irrigation regime.

Metalaxyl total recovery averaged 18.9% of the applied (table 4). Metalaxyl recovered in the leachate from soil columns under the heavy irrigation regime was 35 times more than from soil columns under the light irrigation regime. Over 3 times the amount of metalaxyl was recovered in the 0-10 cm soil layer from columns under the light irrigation regime compared to the heavy irrigation regime.

Pendimethalin total recovery averaged 6.24% of the applied (table 5). Pendimethalin recovered in the leachate from soil columns under the heavy irrigation regime was 20 times more than from soil columns under the light irrigation regime.

Isazofos, chlorpyrifos, metalaxyl, and pendimethalin recovered in the thatch mat averaged 19, 79, 24, and 71%, respectively, of total amount recovered (table 2-5). More than 10 times the applied metalaxyl was recovered in the soil from 20 to 50 cm compared to applied isazofos, chlorpyrifos, and pendimethalin recovered.

DISCUSSION

From this research, we conclude that irrigation practices can have an impact on the movement of pesticides through the soil. The heavy irrigation compared to the light irrigation significantly increased isazofos, chlorpyrifos, metalaxyl, and pendimethalin found in leachate from 50-cm undisturbed soil columns covered with turfgrass.

Wauchope et al. (1992) state that half-lives of chemicals are difficult to determine because they are greatly affected by site- soil- and climate characteristics. Isazofos, chlorpyrifos, metalaxyl, and pendimethalin degraded more rapidly under the conditions of this study than would be expected (table 1). Branham and Wehner (1985) determined following an application of diazinon to a turfgrass area with irrigation reduced volatilization to less than 4% of applied by moving applied pesticide below volatilization sites on the soil surface. Since irrigation was applied immediately after pesticide application we suspect that volatilization was negligible, therefore, applied chemical that was not accounted for was assumed to have degraded.

Although metabolites were not studied in this project, the movement of metabolites and their implications to environmental quality is of interest. Snyder and Cisar (1993) studied the mobility of fenamiphos and fonofos using lysimeters covered with bermudagrass to collect leachate samples at a depth of approximately 40 cm. They determined that the metabolites of the applied fenamiphos that leached through the profile totaled 17.7% of the parent compound.

Calculations based on a field-capacity volumetric soil water content = 0.33 $m^3\ m^{-3}$, show that surface applied irrigation should move 7.7 cm per 2.54 cm irrigation into the soil profile by water displacement only (Priebe and Blackmer, 1989). Evidence of preferential flow occurring was collecting applied pesticides in the leachate from 50 cm soil columns.

Isazofos recovered was similar between all soil layers from columns under the light irrigation due to isazofos having a relatively low K_{OC} value, and a relatively high water solubility. With each light irrigation a portion of the isazofos present was transported into the lower soil layers. Bowman (1992) reported that no applied isazofos leached through 70-cm repacked field lysimeters. We determined that on average 6.3% of the applied isazofos did leach through 50-cm undisturbed soil columns covered with turfgrass under the heavy irrigation regime in this study (table 2). This leaching was likely due to the macropore system that existed in the undisturbed soil columns, isazofos' properties, and the heavy irrigation regime.

Over 4% of the applied chlorpyrifos was found in the thatch/mat layer (table 3), and less than 0.8% was recovered from the 10 to 50 cm soil in the undisturbed soil columns due to chlorpyrifos having a low water solubility and having a relatively high K_{OC} value. Racke (1993) reported an unpublished study by McCall (1985, DowElanco, Indianapolis, IN) where no chlorpyrifos was recovered in leachate from 30-cm disturbed soil columns after applying 50.8-cm of irrigation. We report, however, 0.53% of the applied chlorpyrifos leached through undisturbed soil columns in this study due to the heavy irrigation regime and the macropore structure.

Metalaxyl has a relatively high water solubility and relatively low K_{OC} value making it susceptible to leaching. About 8% of the applied metalaxyl leached through the undisturbed soil columns under the heavy irrigation due to metalaxyl's properties and the macropore structure. Three times the metalaxyl was recovered in the 0-10 cm soil layer from columns under the light irrigation compared to the heavy irrigation (table 4). It seems likely that metalaxyl was transported to the 0 to 10 cm soil layer for soil columns under the light irrigation by soil water displacement.

Pendimethalin has a relatively low water solubility and relatively high K_{OC} value making it more susceptible to adsorption. On average, 5.6% of the applied pendimethalin was recovered in the thatch/mat due to its properties. Our research showed, however, that irrigation practices still effected pendimethalin leaching. Undetectable amounts were reported in the 20-30, 30-40, and 40-50 cm soil layers from columns under the heavy irrigation and yet 0.19% was found in the leachate (table 5).

On average, 10% of the applied material remained in the parent material form. The thatch/mat retained a large portion of the applied pesticides. Chlorpyrifos and pendimethalin were highly retained in the thatch/mat due to adsorbing to the organic matter present. A mature thatch/mat is useful in reducing movement of pesticides into the soil profile due to a relatively high organic matter content. Shea et al. (1993) showed the importance of thatch/mat in reducing pesticide movement through the soil profile.

Comparing the four applied pesticides, metalaxyl is most likely to be leached due to a low soil sorption, followed by isazofos, pendimethalin, and chlorpyrifos (table 1). Metalaxyl was found in the highest percentage in the leachate followed by isazofos, pendimethalin, and chlorpyrifos. Soil sorption coefficients appear to be good indicators of leaching potential.

The practical implication of this research is that pesticide losses by leaching can be reduced by irrigation management procedures. By applying light, more-frequent irrigations instead of heavy less-frequent irrigations after pesticide application, the possibility of pesticide leaching is greatly reduced. Timing of pesticide application is also important with regard to reducing leaching losses. It is a common practice for some pesticides to be applied to turfgrass areas before a forecasted rainfall to move the pesticide into the soil profile. Applying pesticides before heavy rainfall events would cause greater losses due to leaching than a light irrigation after pesticide application.

Table 1. Properties of metalaxyl, isazofos, chlorpyrifos, and pendimethalin.

Pesticide	Water Solubility (mg L^{-1})	K_{OW}	K_{OC}	Field Half-Life (days)	Vapor Pressure (mPa)	SCS Rating Leaching	 Runoff
metalaxyl	8400.0	50	50	70	0.63	Large	Large
isazofos	69.0	1000	100	34	11.40	Large	Large
chlorpyrifos	2.0	100000	6070	30	2.50	Small	Small
pendimethalin	0.3	150000	5000	90	3.90	Small	Medium

(Wauchope, et al., 1992)

Table 2. Percentage of isazofos recovered when applied to undisturbed soil columns covered with turfgrass.

	Heavy Irrigation*		Light Irrigation†		
Category	Mean‡	s.d.	Mean‡	s.d.	p-value**
Thatch/Mat	2.14	1.74	0.48	0.57	0.051
0 to 10 cm	0.21	0.19	0.63	1.02	0.340
10 to 20 cm	0.06	0.03	0.75	1.23	0.202
20 to 30 cm	0.02	0.03	0.50	1.21	0.362
30 to 40 cm	0.07	0.11	0.40	0.97	0.426
40 to 50 cm	0.01	0.01	0.27	0.65	0.342
Leachate	6.30	6.08	0.40	0.64	0.039
Cumulative Total	8.80	7.38	3.43	4.62	0.161

* Heavy irrigation, four 2.54-cm irrigation applications.

† Light irrigation, sixteen 0.64-cm irrigation applications.

‡ Each treatment had six replications.

** *t* - test, based on the hypothesis that heavy and light irrigation are same.

Table 3. Percentage of chlorpyrifos recovered when applied to undisturbed soil columns covered with turfgrass.

	Heavy Irrigation*		Light Irrigation†		
Category	Mean‡	s.d.	Mean‡	s.d.	p-value**
Thatch/Mat	9.29	6.60	5.01	3.56	0.193
0 to 10 cm	1.34	1.53	0.94	0.44	0.554
10 to 20 cm	0.18	0.13	0.51	1.02	0.444
20 to 30 cm	0.03	0..06	<0.01	<0.01	0.244
30 to 40 cm	0.09	0.21	0.03	0.05	0.543
40 to 50 cm	0.06	0.07	0.05	0.05	0.814
Leachate	0.53	0.51	0.01	0.02	0.032
Cumulative Total	11.50	6.93	6.55	3.38	0.147

* Heavy irrigation, four 2.54-cm irrigation applications.

† Light irrigation, sixteen 0.64-cm irrigation applications.

‡ Each treatment had six replications.

** *t* - test, based on the hypothesis that heavy and light irrigation are same.

Table 4. Percentage of metalaxyl recovered when applied to undisturbed soil columns covered with turfgrass.

	Heavy Irrigation*		Light Irrigation†		
Category	Mean‡	s.d.	Mean‡	s.d.	p-value**
Thatch/Mat	5.04	3.14	3.82	2.40	0.467
0 to 10 cm	1.63	1.71	5.15	3.01	0.032
10 to 20 cm	0.28	0.45	1.65	2.41	0.203
20 to 30 cm	1.43	3.20	1.97	3.28	0.779
30 to 40 cm	5.05	6.57	0.93	1.50	0.166
40 to 50 cm	2.67	5.65	0.18	0.44	0.307
Leachate	7.74	5.45	0.22	0.53	0.007
Cumulative Total	23.83	13.09	13.91	8.65	0.152

* Heavy irrigation, four 2.54-cm irrigation applications.

† Light irrigation, sixteen 0.64-cm irrigation applications.

‡ Each treatment had six replications.

** *t* - test, based on the hypothesis that heavy and light irrigation are same.

Table 5. Percentage of pendimethalin recovered when applied to undisturbed soil columns covered with turfgrass.

	Heavy Irrigation*		Light Irrigation†		
Category	Mean‡	s.d.	Mean‡	s.d.	p-value**
Thatch/Mat	5.89	4.58	3.09	2.50	0.218
0 to 10 cm	1.57	2.31	0.70	1.01	0.421
10 to 20 cm	0.21	0.51	0.76	1.04	0.271
20 to 30 cm	<0.01	<0.01	0.07	0.17	0.341
30 to 40 cm	<0.01	<0.01	<0.01	<0.01	N.A.
40 to 50 cm	<0.01	<0.01	<0.01	<0.01	N.A.
Leachate	0.19	0.19	<0.01	<0.01	0.032
Cumulative Total	7.86	6.75	4.62	2.96	0.307

* Heavy irrigation, four 2.54-cm irrigation applications.

† Light irrigation, sixteen 0.64-cm irrigation applications.

‡ Each treatment had six replications.

** *t* - test, based on the hypothesis that heavy and light irrigation are same.

REFERENCES

Balogh, J. C. and W. J. Walker. 1992. *Golf Course Management & Construction Environmental Issues.* Chelsea, Michigan: Lewis Pub.

Beven, K. and P. Germann. 1982. Macropores and water flow in soils. *Water Res. Res.* 18:1311-1325.

Bowman, B. T. 1992. Mobility and persistence of isazofos in granular and microencapsulated formulations in two soils, using field lysimeters. Pestic. Sci. 36:181-188.

Branham, B. E. and D. J. Wehner. 1985. The fate of diazinon applied to thatched turf. J. Agron. 77:101-104.

Brown, K. W., R. L. Duble and J. C. Thomas. 1977. Influence of management and season of fate of N applied to golf greens. J. Agron. 69:667-671.

Cooper, R. J., J. J. Jenkins and A. S. Curates. 1990. Pendimethalin volatility following application to turfgrass. J. Environ. Qual. 19:508-513.

Evert, C. A. 1989. Role of preferential flow on water and chemical transport in a glacial till soil. Ph. D. thesis. Iowa State University. Ames, Iowa.

Joo, Y. K., N. E. Christians and J. M. Bremner, 1987. Effect of N-(n-butyl) thiophosphoric triamide (NBPT) on growth response and ammonia volatilization following fertilization of Kentucky bluegrass (Poa pratensis L.) with urea. *J. Fert. Issues.* 4:98-102.

Kladivko, E. J., G. E. Van Scoyoc, E. J. Monke, K. M. Oates, W. Pask. 1991. Pesticide and nutrient movement into subsurface tile drains on a silt loam soil in Indiana. J. Environ. Qual. 20(1):264-270.

Maki, Y. 1993. Pesticide regulation in Japan. International Turfgrass Research J. 7:152-161.

Priebe, D. L. and A. M. Blackmer. 1989. Preferential movement of Oxygen-18-labeled water and nitrogen-15-labeled urea through macropores in a Nicollet soil. *J. Environ. Qual.* 18:66-72.

Racke, K. D. 1993. Environmental fate of chlorpyrifos. *In.* G. W. Ware, (ed.) *Reviews of environmental contamination and toxicology.* Springer-Verlag, New York. 131:1-154.

Shea, P J., G. L. Horst, N. E. Christians, D. R. Miller, S. K. Starrett, and C. L. Stuefer-Powell. 1993. Two years of monitoring pesticide fate in established turfgrass. Amer. Soc. of Agron. Ann. Meet. Abstracts.

Snyder, G. H., and J. L. Cisar. 1993. Mobility and persistence of pesticides in a USGA-type green II. Fenamiphos and fonofos. International Turfgrass Research J. 7978-983.

Stahnke, G. K., P. J. Shea, D. R. Tupy, R. N. Stougaard, and R. C. Shearman. 1991. Pendimethalin dissipation in Kentucky bluegrass turf. J. Weed Sci. 39:97-103.

Whang, J. M., C. J. Schomburg, D. E. Glotfelty, and A. W. Taylor. 1993. Volatilization of fonofos, chlorpyrifos, and atrazine from conventional and no-till surface soils in the field. J. Environ. Qual. 22:173-180.

Wauchope, R. D., T. M. Buttler, A. G. Hornsby, P. W. M. Augustijn-Beckers, and J. P. Burt. 1992. The SCS/ARS/CES pesticide properties database for environmental decision-making. *In* G. W. Ware, (ed.) Reviews of environmental contamination and toxicology. Springer-Verlag, New York. 123:1-35.

GENERAL SUMMARY

In Paper 1 we concluded that undisturbed soil columns covered with turfgrass greatly differ in solute transport characteristics compared to disturbed soil columns covered with turfgrass. The disturbed soil columns retained 3 to 5 times as much Cl compared to the undisturbed soil columns due to the destruction of the macropore structure.

The maximum Cl concentration possible in the undisturbed and disturbed soil based on solute concentration and bulk density was about 18, and 23 mg kg^{-1}, respectively. After about 10 pore volumes had flowed through the disturbed soil columns, the Cl concentration was within 8% of the maximum, which implies flow was occurring throughout the entire column. The vast majority of the initial water was displaced with the incoming Cl solution.

In the undisturbed soil columns, the Cl concentration was less than 0.25 times the maximum Cl concentration and is evidence of preferential flow. Since the Cl concentrations were a small portion of the maximum concentration, we conclude that a small portion of the initial water was displaced with the incoming Cl solution.

The data from Paper 1 implies that applying conclusions from solute movement studies on turfgrass areas using repacked, disturbed columns to actual undisturbed field conditions could lead to errors in interpretation because of the effect of the macropore structures.

In Paper 2 we concluded that heavy irrigation increases N transport compared with a light irrigation, and that volatilization of liquid urea was <3% when it is irrigated into the turf surface. The macropore structure found in undisturbed soil columns can have a major impact on water and solute distribution in the profile

(Thomas and Phillips, 1979). We observed that leaching occurred for some of the soil columns under the heavy irrigation within 30 seconds after the beginning of the irrigation. The leachate was observed coming from macropores near the center of the soil column. The heavy irrigation seeped into the matrix of the soil near the surface, ponded, and then filled the macropores, which allowed rapid flow through the soil profile to occur. Because the light irrigation application rate was 0.25 of the heavy irrigation and little ponding occurred, the majority of irrigation probably infiltrated into the soil matrix. The heavy irrigation regime transported more of the surface applied N into the soil profile compared to the light irrigation, therefore, reducing N volatilization.

In Paper 3 we concluded that irrigation practices can have an impact on the movement of pesticides through the soil. The heavier irrigation significantly increased isazofos, chlorpyrifos, metalaxyl, and pendimethalin found in leachate from 50-cm undisturbed soil columns covered with turfgrass.

Comparing the four applied pesticides, metalaxyl is most likely to be leached (due to relatively high water solubility and low soil sorption) followed by isazofos, chlorpyrifos, and pendimethalin. Metalaxyl was collected in the highest percentage of applied in the leachate followed by isazofos, chlorpyrifos, and pendimethalin.

Bowman (1992) reported no applied isazofos leached through 70-cm repacked field lysimeters. We determined in this study that on average 6.3% of the applied isazofos did leach through 50-cm undisturbed soil columns covered with turfgrass under a heavy irrigation regime. This leaching was caused by the macropore system that existed in the undisturbed soil columns and the heavy irrigation regime. The higher isazofos adsorbed in the thatch/mat from columns under the heavy irrigation is believed to have been caused by the longer time period before next watering.

Our findings are consistent with Racke (1993), 75% of the recovered chlorpyrifos was found in the thatch/mat layer. Racke (1993) reported an unpublished study by McCall (1985, DowElanco, Indianapolis, IN) where no chlorpyrifos was recovered in leachate from 30 cm disturbed soil columns after applying 50.8-cm of irrigation. We report, however, 0.53% of the applied chlorpyrifos leached through undisturbed soil columns in this study due to the heavy irrigation regime and the macropore structure.

Three times the metalaxyl was recovered in the 0-10 cm soil layer from columns under the light irrigation compared to the heavy irrigation. It seems likely that metalaxyl was transported to the 0 to 10 cm soil layer for soil columns under the light irrigation by soil water displacement.

Due to pendimethalin's properties, it is not likely to leach. Our research showed, however, that irrigation practices still effected pendimethalin leaching. Undetectable amounts were reported in the 20-30, 30-40, and 40-50 cm soil layers from columns under the heavy irrigation and yet 0.19% was found in the leachate.

The practical implication of the research reported in this thesis is that: there is a significant difference in solute transport characteristics between undisturbed and disturbed soil columns covered with turfgrass, and fertilizer and pesticide losses by leaching can be reduced by irrigation management procedures. By applying light, more-frequent irrigations instead of heavy, less-frequent irrigations for several weeks after fertilizer and pesticide application, the possibility of leaching is greatly reduced.

ADDITIONAL LITERATURE CITED

Balogh, J. C. and W. J. Walker. 1992. *Golf Course Management & Construction Environmental Issues*. Chelsea, Michigan: Lewis Pub.

Beven, K. and P. Germann. 1982. Macropores and water flow in soils. Water Resour. Res. 18:1311-1325.

Bowman, B. T. 1992. Mobility and persistence of isazofos in granular and microencapsulated formulations in two soils, using field lysimeters. Pestic. Sci. 36:181-188.

Brown, K. W., R. L. Duble, and J. C. Thomas. 1977. Influence of management and season of fate of N applied to golf greens. Agron. J. 69:667-671.

Cohen, S Z., S. Nickerson, R. Maxey, A. Dupuy Jr. and J. A. Senita. 1990. Ground water monitoring study for pesticides and nitrates associated with golf courses on Cape Cod. Ground Water Monit. Rev. 10:160-173.

Cooper, R. J., J. J. Jenkins and A. S. Curates. 1990. Pendimethalin volatility following application to turfgrass. J. Environ. Qual. 19:508-513.

Evert, C. A. 1989. Role of preferential flow on water and chemical transport in a glacial till soil. Ph. D. thesis. Iowa Sate University. Ames, Iowa.

Haynes, R. J. 1986. *Mineral Nitrogen in the Plant-Soil System*. Orlando, Florida: Academic Press, Inc.

Huber, W. C. 1993. Contaminant transport in surface water. in D. R. Maidment (Ed.). *Handbook of hydrology*. McGraw-Hill, New York. p. 14.43.

Maki, Y. 1993. Pesticide regulation in Japan. International Turfgrass Research J. 7:152-161.

Mugaas, B. J., M. L. Agnew, N. E. Christians and E. Edwards. 1991. Turfgrass management for protecting surface water quality. Iowa State University Extension. File: Horticulture 4-1.

Petrovic, A. M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. *J. Environ. Qual.* 19:1-14.

Racke, K. D. 1993. Environmental fate of chlorpyrifos. *In.* G. W. Ware, (ed.) *Reviews of environmental contamination and toxicology.* Springer-Verlag, New York. 131:1-154.

Stahnke, G. K., P. J. Shea, D. R. Tupy, R. N. Stougaard, and R. C. Shearman. 1991. Pendimethalin dissipation in Kentucky bluegrass turf. J. Weed Sci. 39:97-103.

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

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

Tindall, J. A., K. Hemmen, and J. F. Dowd. 1992. An improved method for field extraction and laboratory analysis of large, intact soil cores. J. Environ. Qual. 21:259-263.

Whang, J. M., C. J. Schomburg, D. E. Glotfelty, and A. W. Taylor. 1993. Volatilization of fonofos, chlorpyrifos, and atrazine from conventional and no-till surface soils in the field. J. Environ. Qual. 22:173-180.

White, R. E. 1985. The influence of macropores on the transport of dissolved and suspended matter through soil. Advances in Soil Science, vol. 3. Springer-Verlag, New York.

ACKNOWLEDGMENTS

I would like to thank the United States Golf Association (USGA) for providing financial support for this research. I would also like to thank the University of Nebraska - Lincoln for providing analytical services for pesticide concentration determination. Dr. Blackmer's lab at Iowa State University provided analytical services for nitrogen concentration determination.

I would like to thank my major advisors Dr. Al Austin and Dr. Nick Christians for the effort, advice, and friendship they provided to me during my education at Iowa State University. I am sure our friendships will last a lifetime. I appreciate Drs. Blackmer, Horton, Jones, and Gu's contributions as members of my committee.

I am very thankful for the support my family has given me. Most importantly, I would like to thank my wife Dr. Shelli Starrett for her endless support and help.