This is to certify that the

thesis entitled

THE FATE OF NITROGEN APPLIED TO A MATURE, 10-YEAR OLD, KENTUCKY BLUEGRASS TURFSTAND

presented by

Kevin Matthew O'Reilly

has been accepted towards fulfillment
of the requirements for

Master of Science degree in Crop and Soil Sciences

Major professor

Date 5/21/03

# THE FATE OF NITROGEN APPLIED TO A MATURE, 10-YEAR OLD, KENTUCKY BLUEGRASS TURFSTAND

By

Kevin Matthew O'Reilly

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Crop and Soil Science

2003

**ABSTRACT**

THE FATE OF NITROGEN APPLIED TO A MATURE, 10-YEAR OLD, KENTUCKY BLUEGRASS TURFSTAND

By

Kevin Matthew O'Reilly

Extensive research on nitrate-nitrogen ($NO_3$-N) leaching in turfgrass systems indicates that in most cases leaching poses little risk to the environment. Most of the research, however, was conducted on research sites that were either recently disturbed or established, and the potential exists for $NO_3$-N concentrations in leachate to increase on mature turf sites. The fate of nitrogen (N) was examined for a 10-year old Kentucky bluegrass (*Poa pratensis* L.) turfstand using intact monolith lysimeters and microplots. From October 2000 through 2002, half of the lysimeters and microplots were treated annually with urea at a high N rate of 245 kg N $ha^{-1}$ (49 kg N $ha^{-1}$ $application^{-1}$). The remaining lysimeters and microplots were treated annually with urea at a low N rate of 98 kg N $ha^{-1}$ (24.5 kg N $ha^{-1}$ $application^{-1}$). The October 2000 urea application was made with $^{15}N$ double-labeled urea to facilitate fertilizer identification among clippings, verdure, thatch, soil, roots, and leachate. The average total N recovery for the low and high N rates was 78 and 74%, respectively. $NO_3$-N concentrations in leachate for the low N rate were typically below 5 mg $L^{-1}$. For the high N rate, $NO_3$-N concentrations in leachate were typically greater than 20 mg $L^{-1}$. Over approximately two years, 1.3 and 10.9% of labeled fertilizer-N was recovered in leachate for the low and high N rates, respectively. These results indicate that total yearly applications of 245 kg N $ha^{-1}$ in the form of urea to a 10-year old Kentucky bluegrass stand with monolith lysimeters in place, resulted in elevated levels of $NO_3$-N in leachate.

To my parents for their many sacrifices, love, and support

## ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Kevin Frank, for his time, support, and guidance throughout my graduate program. I thank my committee members, Dr. James Crum and Dr. James Flore, for their insight and guidance throughout both my graduate and undergraduate studies. I would like to thank Dr. Sasha Kravachenko for her invaluable assistance with the statistical portion of this research. I thank Jon Bristol and Chad Cates for their attention to detail and hard work preparing samples for analysis in the laboratory. I would like to thank Mark Collins, Frank Roggenbuck, and the rest of the staff at the Hancock Turfgrass Research Center for all their assistance. I thank Dr. Paul Rieke and The Friends of Dr. Paul Rieke Committee for honoring me as the first recipient of the Dr. Paul Rieke graduate fellowship. I would like to thank the United States Golf Association, The Michigan Agricultural Experiment Station, and The Michigan Turfgrass Foundation for their support of this research. And a special thank you to Debi Warnock and Brian Leach for your friendship and assistance with so many of the "smaller" details in life and graduate school.

I would like to thank my parents, Daniel and Eleanor O'Reilly, for their many sacrifices, love, and unending support throughout my studies and life. I thank my brothers Darren and Brian for their friendship, encouragement, and stress relief.

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

## INTRODUCTION

Nitrogen (N) is the nutrient most commonly applied to a turfgrass system (Beard, 1973). The potential for N to leach is increased by high N rates, type of N carrier, over watering, and sandy soils. Turf managers reduce the potential for N leaching by using slow release fertilizers, applying N at low rates over multiple applications, reducing N rates on sandy soils, promoting deep root systems, and adjusting irrigation practices so that excessive water is not applied.

Extensive research on nitrate-nitrogen ($NO_3$-N) leaching in turfgrass systems indicates that in most cases leaching poses little risk to the environment. Previous research (Starr and DeRoo, 1981; Miltner et al., 1996; Frank, 2000; and Horgan et al. 2002) using $^{15}N$ labeled fertilizers applied to cool season turf stands lead to the following estimates: 26% of applied fertilizer N is recovered in clippings; 3-13% is recovered in the verdure; 21-40% is recovered in the thatch; 14-41% is recovered in the soil; 2% is recovered in roots; 5% is lost through denitrification; and trace amounts are leached. Total recovery of applied fertilizer N ranged from 64 to 90%. These studies, however, were conducted on younger sites that ranged in age from 1 to 7 years old.

The potential exists for $NO_3$-N concentrations in leachate to increase on mature turf sites. Porter et al. (1980) examined total N content in soil to a depth of 40 cm within 105 turf systems ranging in age from 1 to 125 years old. The data suggests that soil organic N accumulation is rapid in the first 10 years after establishment, and slowly builds to an equilibrium at 25 years where no further net N immobilization occurs. Porter et al. (1980) concluded that there is a rather limited capacity of the soil to store organic N and that after 10 years the potential for overfertilization is "greatly enhanced." Valiela et al. (1997), based on the data of Porter et al. (1980), modeled the flux of N through a coastal watershed, and predicted that 61% of N applied to a 10 year or older turf stand leaches to groundwater. Conclusions such as these show the need to examine the fate of N applied to a mature turf stand. The objectives of this research were to quantify $NO_3$-N and ammonium-nitrogen ($NH_4$-N) concentrations in leachate, and the fate of $^{15}$N double-labeled urea fertilizer among clippings, verdure, thatch, soil, roots, and leachate for a Kentucky bluegrass turfstand 10 years after establishment.

## LITERATURE REVIEW

Groundwater quality is likely to decline as a result of human activities altering the global N cycle (Vitousek et al., 1997). The United States Environmental Protection Agency (EPA) has set a safe drinking water standard of 10 mg $NO_3$-N $L^{-1}$. Violation of the EPA nitrate standard for drinking water has closed more public water supplies in the United States than any other contaminant (Bhumbla, 2002). Drinking water in excess of the nitrate standard may cause: acute health effects including blue-baby syndrome (methemoglobinemia) and sometimes death; chronic health effects including diuresis, increased starchy deposits and hemorrhaging of the spleen (EPA, 2002). The misuse of fertilizers applied to home lawns may potentially have a significant impact on water quality. These concerns have prompted several studies examining the fate of N applied to turf systems. Four of the major fates of N in a turf system are leaching, gaseous loss, plant uptake, and soil storage.

### Leaching

A nutrient is considered leached once it has moved past the turfgrass root zone (Carrow et al., 2001). Factors that influence N leaching losses from a turfgrass system are N rate and carrier, amount of water that moves through the root zone, soil texture, and N uptake by the grass (Carrow et al., 2001). Cultural practices that reduce N leaching include: using slow release fertilizers; applying N at low rates over multiple applications (spoon feeding); enhancing the cation exchange capacity of sands; promoting deep root development and root viability; and adjusting irrigation practices so that excessive water is not applied (Carrow et al., 2001).

Morton et al. (1988) studied three N fertilization rates (0, 97, and 244 kg N $ha^{-1}$ as urea and methylene urea) and two irrigation practices (scheduled by a tensiometer to prevent drainage from the root zone and overwatering consisting of 3.75 cm $wk^{-1}$ regardless of rainfall) on a 90% Kentucky bluegrass and 10% red fescue (*Festuca rubra* L.) turfstand established 4 years earlier. Suction plate lysimeters, to a depth of 70 cm, were used to sample leachate from the turf system. When irrigation was scheduled using a tensiometer, the average $NO_3$-N concentration in leachate for the 0, 97, and 244 kg N $ha^{-1}$ rates was 0.51, 0.87, and 1.24 mg $L^{-1}$, respectively. In the overwatering treatments $NO_3$-N concentrations in leachate averaged 0.36, 1.77, and 4.02 mg $L^{-1}$, for the 0, 97, and 244 kg N $ha^{-1}$ rates, respectively. The authors concluded that leaching losses from home lawns did not pose a threat to drinking water aquifers.

Gold and Groffman (1993) compared the leaching of $NO_3$-N from four different land uses over a 2 year period. The four land uses consisted of a home lawn turf (established 6 years earlier), corn grown for silage (plowed each spring), a mature mixed oak-pine forest (80-120 years old), and a septic system. Nitrogen was applied to the turf system in the form of urea and UREAFORM at an annual rate of 344 kg N $ha^{-1}$ divided into five applications. Nitrogen applied to the corn was in the form of urea at an annual rate of 202 kg N $ha^{-1}$ (34 kg N $ha^{-1}$ in June and 168 kg N $ha^{-1}$ in July). Nitrogen entered the septic system through household wastewater, and the forest system through natural deposition. $NO_3$-N leaching was highest for the septic system, with an average concentration of 59 mg $L^{-1}$. Concentrations in the silage corn leachate ranged from 3-50 mg $NO_3$-N $L^{-1}$, and home lawns contained concentrations in the range of 0.2-5.0 mg $NO_3$-N $L^{-1}$. $NO_3$-N concentration from the mature forest was consistently near 0.2 mg $L^{-1}$.

The authors concluded that septic systems are major contributors of N leaching to groundwater, while the extended growing period and small, frequent applications of fertilizer maximized the ability of the home lawn turf to absorb the fertilizer, reducing the potential of $NO_3$-N leaching.

## $^{15}N$ Research

To gain a greater understanding of N applied to a turf system, the naturally occurring isotope $^{15}N$ can be applied as fertilizer. Fertilizers enriched with $^{15}N$ enable a researcher to distinguish fertilizer N from N that is already in the system. $^{15}N$ is a powerful tool to study the fate of applied N because it can be followed in the plant-soil system as it enters, is transported within, or leaves the system (Hauck and Bremmer, 1976).

Starr and DeRoo (1981) applied $^{15}N$ labeled ammonium nitrate at a rate of 180 kg N $ha^{-1}$, divided into two applications, to a mixture of Kentucky bluegrass and creeping red fescue established the previous spring. They measured the concentration of labeled fertilizer N in clippings, thatch, soil (to a depth of 30 cm), and leachate. One year after $^{15}N$ application, 64 and 73% of the labeled fertilizer N was recovered within the system when clippings were either removed or returned, respectively. Suction lysimeters used to sample soil water to depths ranging from 180 to 240 cm showed $NO_3$-N concentrations in leachate averaging 1.9 and 2.0 mg $L^{-1}$ when clippings were either removed or returned, respectively. The authors concluded that little, if any, leaching losses of N from the turf plots occurred.

Frank (2000) applied $^{15}N$ labeled ammonium nitrate to 7 year old stands of Kentucky bluegrass (cv. 'Adelphi,' 'Baron,' 'Merit,' and 'Touchdown') and tall fescue (*Festuca arundinacea* Schreb., cv. 'Arid,' 'Mustang,' and 'Olympic') at two rates, 24.4 and 48.8 kg N $ha^{-1}$. Mass N balance was determined for each N treatment among top growth, thatch, roots, and soil to a depth of 64 cm. The average percent N recovered from fertilizer (%NRFF) for the thatch and soil was 37 and 42%, respectively. The total %NRFF at the 24.4 and 48.8 kg N $ha^{-1}$ rates was 95 and 73%, respectively. Based on these data, Frank (2000) concluded that the majority of applied N is either retained in the soil or taken up by the turf.

Over a period of 3 years, Miltner et al. (1996) studied the fate of $^{15}N$ labeled urea applied to a 1 year old polystand of Kentucky bluegrass (cv. 'Adelphi,' 'Nassau,' and 'Nugget'). Nitrogen was applied at an annual rate of 196 kg N $ha^{-1}$ divided into five applications of urea over 38 day intervals, defined by either a spring or fall application schedule. The first application of the spring schedule was in April and the last was in September, while the fall application schedule began in June and ended in November. Using intact monolith lysimeters (1.2 m deep), $NO_3$-N concentrations in leachate were generally below 1 mg $L^{-1}$ throughout the study. Only 0.23% of the labeled $^{15}N$ was collected in leachate. The majority of the labeled $^{15}N$ was collected in clippings, thatch, and soil. Total recovery of the labeled $^{15}N$ was 64 and 81% for the spring and fall application schedules, respectively. Miltner et al. (1996) concluded that $NO_3$-N leaching for both the spring and fall application schedules was negligible.

## Gaseous Losses

In many studies using $^{15}N$ labeled fertilizers, the authors have suggested that denitrification and $NH_3$ volatilization losses were responsible for incomplete recovery of applied $^{15}N$ (Starr and DeRoo, 1981; Miltner et al., 1996). Similar to leaching losses, denitrification and volatilization losses have received increased attention in recent years.

### *Denitrification*

Denitrification results in the gaseous loss of N in the form of nitric oxide (NO), nitrous oxide ($N_2O^-$), or $N_2$ gas. The reaction for denitrification involves the following sequence:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Factors that influence denitrification include: the presence of a thatch layer and/or readily decomposable organic matter; soil moisture and oxygen content; soil temperature; soil pH; plant growth and root activity; and $NO_3^-$ level (Carrow et al., 2001).

Mancino et al. (1988) studied the effects of soil texture, percent soil saturation, and ambient temperature on denitrification losses from 'Baron' Kentucky bluegrass fertilized with potassium nitrate ($KNO_3$) at a rate of 45 kg N $ha^{-1}$. Over a 10 day period, maximum denitrification losses occurred when soils were saturated and accounted for 2.2 and 5.4% of applied N for the silt loam and silt soils, respectively. Below 80% saturation, little to no denitrification losses were observed when soil temperature was maintained at 22° C. When high soil temperatures (30 and 35° C) were combined with saturated soil conditions, denitrification losses were 44.6 and 92.6% of applied N for the silt loam and silt soils, respectively. The authors concluded that saturated soil conditions in combination with high soil temperatures could result in large denitrification losses in a fertilized turfstand.

Horgan et al. (2002) examined denitrification rates from Kentucky bluegrass after a 49 kg N $ha^{-1}$ application of $^{15}N$ labeled $KNO_3^-$ in solution. Over a 6 week period in the spring, recovery of $N_2$ and $N_2O$ averaged 4.3 and 0.6% of applied N, respectively. Over a 4 week period in the summer, $N_2$ and $N_2O$ concentrations averaged 15 and 5.6% of applied N, respectively. The authors concluded that the higher $N_2O$ and $N_2$ levels observed in the summer were due to ideal conditions for denitrification, including elevated soil temperatures and anaerobic conditions caused by 8.9 cm of rainfall 4 days after fertilization.

### *Volatilization*

Volatilization is the gaseous loss of N in the form of ammonia ($NH_3$). Volatilization losses are common to fertilizers that contain urea (Carrow et al., 2001). The enzyme urease is responsible for the following hydrolysis reaction:

$$\underset{\text{(urea)}}{CO(NH_2)} + H_2O \xrightarrow{\text{urease}} 2NH_3 + CO_2$$

Factors that influence $NH_3$ volatilization include: level of urea and ammonium ($NH_4^+$) present; temperature; soil pH; soil moisture; cation exchange capacity; N carrier, form (liquid versus dry), and rate; and the presence of a thatch layer (Carrow et al., 2001; Petrovic, 1990).

Nelson et al. (1980) compared the influence of a thatch layer and N carrier on volatilization rates from Kentucky bluegrass. When a 5 cm thatch layer was present, 39 and 4% of applied N volatilized after 8 days from urea and isobutyldine diurea (IBDU) applications, respectively. When no thatch layer was present, 5 and 2% of applied N volatilized from urea and IBDU applications, respectively. Although the N application rate was extremely high (253 kg N $ha^{-1}$ in a single application), the authors concluded that in turf stands with high thatch accumulations, the use of slow release N carriers and reduction of the thatch layer would decrease $NH_3$ volatilization losses.

Bowman et al. (1987) studied the influence of supplemental irrigation on $NH_3$ volatilization rates after urea application (50 kg N $ha^{-1}$) to Kentucky bluegrass. Immediately after urea application, irrigation at the rate of 0, 0.5, 1, 2, or 4 cm was applied. Without supplemental irrigation, losses of up to 36% were observed. With 1 cm of supplemental irrigation, losses were reduced to 3 to 8%; with 4 cm of irrigation, 1% of applied N was lost. In a second experiment the authors determined that in the irrigated plots $NH_3$ losses returned to control levels 11 hours following urea application. In the unirrigated plots, $NH_3$ losses continued for up to 24 hours after urea application. The authors concluded that irrigation should be applied as soon as possible after fertilizer application to reduce volatilization losses.

Urease inhibitors have been suggested as a means to reduce volatilization losses. Urease inhibitors slow the conversion of urea-N to $NH_3$-N. The thatch layer contains large quantities of urease, increasing volatilization losses. Joo et al. (1991) investigated the effectiveness of using a urease inhibitor to reduce volatile N losses. $^{15}N$ labeled urea was applied at 49 kg N $ha^{-1}$ to a 6 year old blend of cv. 'Adelphi,' 'Glade,' 'Parade,' and 'Rugby' Kentucky bluegrass. After 5 weeks, 28.8% of applied N was retained in clippings, shoots, thatch, and the top 15 cm of soil. When 0.25 and 0.5 % of the urease inhibitor N-(*n*-butyl) thiophosphoric triamide (NBPT) was added, 45.0 and 36.1% of applied $^{15}N$ was recovered, respectively. Although leachate was not collected, the authors speculated that a large portion of the $^{15}N$ leached through the soil profile due to 13 cm of rainfall on the fifth day after treatment. The authors concluded that NBPT, in combination with proper water management to move the urea into the soil profile, would reduce $NH_4$ volatilization losses.

**Mature sites**

The majority of N fate research has been conducted on relatively young turf stands, ranging in age from 1 to 7 years; however, the age of a turf stand has been proposed as an important factor in determining the fate of N. Bouldin and Lathwell (1968) suggested that the ability of a soil to store organic N under relatively constant management and climatic conditions, which are typical of turf systems, would decrease with time and eventually an equilibrium level of soil organic N would be obtained. Porter et al. (1980) examined total N content in soil to a depth of 40 cm in 105 turf systems ranging in age from 1 to 125 years old. The data suggest that soil organic matter accumulation is rapid in the first 10 years after establishment, and slowly builds to an equilibrium at 25 years, when no further net N immobilization occurs. Porter et al. (1980) concluded that there is a rather limited capacity of the soil to store organic N, and that after 10 years the potential for overfertilization is greatly increased.

In a 1990 review article entitled 'The Fate of Nitrogenous Fertilizers Applied to Turfgrass,' Petrovic hypothesized, based on the data of Porter et al. (1980), that older turf sites, or sites with high organic matter contents, should be fertilized at a reduced N rate to minimize the potential for $NO_3$-N leaching. Petrovic theorized that the rate of N applied to younger turf stands (less than 10 years of age) should equal the rate at which N is used by the plants, lost to the atmosphere, and stored in the soil. Older turf sites (greater than 25 years of age) lose the ability to store additional N in the soil, and therefore should be fertilized at a rate equal to the rate N is used by the turf and lost to the atmosphere (Petrovic, 1990).

Valiela et al. (1997) modeled the flux of N through a coastal watershed. The model assumed, based on the data of Porter et al. (1980), that "...net N storage in plants and soil does not increase after the first decade following establishment." The model also assumed that on average all turf parcels within the watershed were greater than 10 years old. Based on these assumptions and combined data from numerous studies, the authors estimated that 39% of applied fertilizer N is lost through gaseous means (volatilization and denitrification), and the remaining 61% leaches to the subsoil below the turf parcel.

One study has examined leaching losses of N applied to a mature Kentucky bluegrass stand. Duff et al. (1997) applied four N fertilization rates, (0, 104, 180, and 257 kg N $ha^{-1}$) in the form of urea divided into five equal applications, on a mature Kentucky bluegrass turf stand. Prior to this study, the soil had been in turf for at least 25 years and although soil organic matter contents were not measured, the soil was assumed to have a high organic N content. It is unclear, however, what the age of the turfstand was at the initiation of this study. Suction plate lysimeters, to a depth of 60 cm, were installed in the seventh year of the study to sample leachate from the turf system. Over a 19-month period (June 1992 through December 1993), $NO_3$-N concentrations in leachate were below 10 mg $L^{-1}$ for all N fertilization rates, except for two sampling dates in the autumn of the second year for the 257 kg N $ha^{-1}$ rate. After 8 years of intensive management, $NO_3$-N concentrations in leachate were not appreciably greater than those reported for younger sites.

## MATERIALS AND METHODS

Between 1989 and 1991, four monolith lysimeters were constructed according to the specifications of Miltner et al. (1996) at the Hancock Turfgrass Research Center, Michigan State University. The lysimeters, 1.14 m in diameter and 1.20 m deep, were constructed with grade 304 stainless steel (0.05 cm thick). The bottom of each lysimeter was constructed with a 3% slope to facilitate collection into a 19 L jug.

In September 1990 the lysimeters and surrounding area were treated with glyphosate and then sodded with a polystand of Kentucky bluegrass (cv. 'Adelphi', 'Nassau', and 'Nugget'). Prior to the glyphosate application, the area had been a turfgrass stand for six years. Between 1991 and 1993, the lysimeters were used for a mass N balance study conducted by Eric D. Miltner and associates. The soil type was a Marlette fine sandy loam (Fine-loamy, mixed mesic Glossoboric Hapludalfs) with a pH of 7.2. For complete soil physical and chemical characteristics see Appendix Table 2A. The lysimeters and surrounding plot area received fertilizer applications, mowing, and irrigation to maintain optimum growing conditions. The turfgrass was mowed twice a week at 7.6 cm with the clippings returned. Irrigation replaced 80% of potential evapotranspiration, estimated by a WS-200 Rainbird Maxi weather station (Rainbird, Glendora, CA). For complete weather and irrigation data see Appendix Table 3A.

In the fall of 2000, 90 microplots were installed in the area adjacent to the lysimeters. Of the 90 microplots, 56 were for this study and 34 were reserved for future research. The microplots were constructed of 20 cm diameter polyvinyl chloride (PVC) piping 45 cm in length. To preserve the soil structure within the microplots, the leading edge of the PVC piping was beveled and driven into the ground using a hydraulic press until it was flush with the soil surface.

On October 17, 2000, $^{15}N$ double-labeled urea with 10% enrichment was applied in solution to the microplots and lysimeters, followed by 0.50 cm of irrigation. Two of the lysimeters and half of the microplots were treated at a low N rate of 24.5 kg N $ha^{-1}$, and the remaining lysimeters and microplots were treated at a high N rate of 49 kg N $ha^{-1}$.

In 2001 and 2002, the lysimeters and microplots received unlabeled N in the form of urea in solution, followed by 0.50 cm of irrigation. The low N treatment lysimeters and microplots were treated annually with 98 kg N $ha^{-1}$, divided into four applications of 24.5 kg N $ha^{-1}$. The high N treatment lysimeters and microplots were treated annually with 245 kg N $ha^{-1}$, divided into five applications of 49 kg N $ha^{-1}$. The application dates were May 7, June 4, July 3, and October 8, 2001, and May 8, June 6, July 3, and October 15, 2002. The high N treatment lysimeters and microplots received additional applications on September 13, 2001 and September 13, 2002.

Clipping samples were collected weekly from each microplot throughout the growing season. Eight microplots, four from each N treatment, were excavated and collected intact on seven sampling dates: November 1, 2000 (15 Days After $^{15}N$ Treatment); December 1, 2000 (45 DAT); April 19, 2001 (184 DAT); July 18, 2001 (274 DAT); October 9, 2001 (357 DAT); April 20, 2002 (549 DAT); and July 17, 2002 (637 DAT). The PVC pipe containing the microplot was cut away, and the remaining core was partitioned into verdure, thatch, and soil samples, all of which were dried in a 60°C convection oven for 72 hr.

Verdure samples included the crown and leaf portions of the plants. Thatch samples consisted of all plant material above the soil surface after verdure was removed. Soil within the thatch samples was removed by hand massaging, and then ground to a fine powder using a mortar and pestle. Clipping, verdure, and thatch samples were weighed and then ground to pass a 0.5 mm screen using a UdyMill Cyclone Sample Mill (Udy Corporation, Fort Collins, CO).

The soil portion was partitioned into depths of 0-5, 5-10, 10-20, and 20-40 cm. At each soil depth two subsamples were taken. The first subsample (250 g oven dry weight) was placed in a 500 ml Fleaker (Corning Glass Works, Corning, NY) with approximately 10 ml of a 5% sodium hexametaphosphate dispersion agent and filled with water to reach a 450 ml volume. The Fleaker was capped and placed on a horizontal shaker for 24 hr to displace the soil from the roots. The Fleaker cap was removed and the Fleaker was placed on a US Standard Sieve (0.05 mm) under running water, to float the roots and fine soil particles out of the Fleaker with the water, leaving the heavier soil particles in the Fleaker. The smaller soil particles passed through the sieve, while the roots were retained. Root samples were collected and dried in a 60°C convection oven for 72 hr, weighed, and then ground to pass a 0.5 mm screen using a UdyMill Cyclone Sample Mill. The second subsample, 320 $cm^3$ in volume, was ground to a fine powder using a mortar and pestle after all visible root material was removed. The ground samples of clippings, verdure, thatch, roots, and soil were dried for an additional 24 hr in a 60°C convection oven.

Leachate collected from the monolith lysimeters was collected continuously throughout the experiment. The final leachate sampling date occurred on December 23, 2002, 796 DAT. The volume of leachate was measured when the jugs were approximately 75% full, and two subsamples were taken. One subsample was sent to the Soil and Plant Nutrient Testing Lab, Michigan State University, to determine $NO_3$-N and $NH_4$-N concentrations by flow injection analysis (QuikChem 10-107-04-1-A) using a LaChat rapid flow injection unit (LaChat Instruments, Milwaukee, WI). The second subsample was used to determine $^{15}N$ enrichment by the N diffusion technique of Moran et al. (2002). Due to the low $^{15}N$ concentration in the leachate an analysis was performed for $NO_3$-N and $NH_4$-N species combined.

Total N concentration and $^{15}N$ enrichment in clipping, verdure, thatch, root, soil, and leachate samples were determined using a Europa 20-20 mass spectrometer (Europa Scientific, Crewe UK). Mass of N and percent of $^{15}N$ recovered calculations were from Kessavalou (1994), the calculations are listed below. Soil bulk densities were as follows: 0-10 cm, 1.14 g $cm^{-3}$; 10-20 cm, 1.54 g $cm^{-3}$; 20-40 cm, 1.58 g $cm^{-3}$. Background atom % $^{15}N$ values are presented in Table 1. The background atom % $^{15}N$ value for leachate was taken from Miltner et al. (1996). It was assumed that after nine years $^{15}N$ enrichment in the leachate samples returned to background levels.

1. Percent nitrogen derived from fertilizer (%NDFF)

$$\%NDFF = \frac{(A-B)}{(C-D)}$$

A = Atom % $^{15}N$ of the plant, soil, or leachate sample

B = Background atom % $^{15}N$ of the unfertilized plant, soil, or leachate sample

C = Atom % $^{15}N$ of the nitrogen fertilizer

D = Background % $^{15}N$ of the atmosphere

2. Nitrogen derived from fertilizer (NDFF, kg N $ha^{-1}$)

NDFF = %NDFF * TN

%NDFF = Percent N derived from fertilizer

TN = Total nitrogen in the plant or soil, kg N $ha^{-1}$

3. Percent nitrogen recovered from fertilizer (%NRFF)

$$\%NRFF = \frac{(NDFF,\ kg\ N\ ha^{-1})}{(Total\ fertilizer\ nitrogen\ applied,\ kg\ N\ ha^{-1})}$$

The experimental design was a completely randomized design. $NH_4$-N concentration, $NO_3$-N concentration, NDFF, and the %NRFF were determined for each sampling date for the leachate from lysimeters. Leachate data were analyzed as a two-factor experiment, with N rate and sampling date as the two factors. Soil and root NDFF and %NRFF data were analyzed as a three-factor experiment with N rate, DAT, and depth as the three factors. Potential correlation between the measurements taken on the same core at different depths was accounted for by analyzing the measurements taken at different depths as repeated measures. All depths for the soil and root samples were then totaled to determine the cumulative amount of NDFF and the %NRFF at each sampling date. Weekly clipping data was summed to determine the cumulative amount of NDFF and %NRFF from all weekly sampling dates prior to the corresponding microplot sampling date. Leachate data was summed to determine the cumulative amount of NDFF and %NRFF from all sampling dates prior to the corresponding microplot sampling date. Kentucky bluegrass clipping, verdure, thatch, soil, root, and leachate components were combined to determine the total amount of NDFF and the %NRFF at each sampling date. The clipping, verdure, thatch, soil, root, leachate, and total recovery data were analyzed as a two-factor experiment with N rate and DAT as the two factors. Treatment differences were analyzed using the Proc Mixed procedure of SAS (SAS Institute Inc., 2001). Means were separated using Fischer's LSD procedure at the 0.05 level of probability.

Table 1. Background atom % $^{15}N$ values for Kentucky bluegrass plant, soil, and leachate components.

| Component | | Atom % $^{15}N$ |
|---|---|---|
| Clippings | | 0.3680 |
| Verdure | | 0.3676 |
| Thatch | | 0.3706 |
| Root | (cm) | |
| | 0-5 | 0.3705 |
| | 5-10 | 0.3699 |
| | 10-20 | 0.3695 |
| | 20-40 | 0.3697 |
| Soil | (cm) | |
| | Thatch Soil | 0.3675 |
| | 0-5 | 0.3681 |
| | 5-10 | 0.3672 |
| | 10-20 | 0.3677 |
| | 20-40 | 0.3680 |
| Leachate | | 0.3712 |

## RESULTS AND DISCUSSION

### Clippings

There was a significant N rate X DAT interaction for the total amount of NDFF in clippings (Table 2). The high N rate had a greater total amount of NDFF in clippings than the low N rate on all sampling dates (Table 3). For the low N rate the total amount of NDFF in clippings increased from 0.29 kg N $ha^{-1}$ at 45 DAT to 1.73 kg N $ha^{-1}$ at 637 DAT. For the high N rate, the total amount of NDFF in clippings increased from 0.77 kg N $ha^{-1}$ at 45 DAT to 4.76 kg N $ha^{-1}$ at 637 DAT. Kentucky bluegrass treated at the high N rate had a greater %NRFF than the low N rate on all sampling dates (Table 4). The amount of NDFF and %NRFF in Kentucky bluegrass clippings were the summed amount of all weekly sampling dates prior to microplot sampling date. The increase in the amount of NDFF and %NRFF in Kentucky bluegrass clippings from 45 to 637 DAT, regardless of N rate, would be expected due the accumulation of weekly sampling dates. Only one weekly sampling date occurred prior to the 45 DAT sampling date, thus resulting in a low amount of NDFF and %NRFF in the clippings, regardless of N rate. By 637 DAT, 35 weekly sampling dates had occurred resulting in a greater amount of NDFF and %NRFF in clippings than at 45 DAT, regardless of N rate.

There was a significant linear effect for the N rate X DAT interaction (Figure 1). The high N rate had a steeper positive slope, indicating a more rapid increase of NDFF in clippings over time than at the low N rate.

Table 2. Analysis of variance table for nitrogen derived from fertilizer (NDFF) and percent N recovered from fertilizer (%NRFF) in Kentucky bluegrass clippings.

| Source | df | Clippings | |
|---|---|---|---|
| | | NDFF | %NRFF |
| | | Pr > F | |
| N rate | 1 | <.0001 | <.0001 |
| DAT† | 5 | <.0001 | <.0001 |
| N rate X DAT | 5 | <.0001 | 0.002 |

† Days after treatment

Table 3. Total amount of nitrogen derived from fertilizer (NDFF) in the clippings of Kentucky bluegrass for the N rate X days after treatment (DAT) interaction.

| DAT | N Rate | |
|---|---|---|
| | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | ---------- kg N $ha^{-1}$ ---------- | |
| 45 | 0.29B†d‡ | 0.77Ad |
| 184 | 0.29Bd | 0.77Ad |
| 274 | 1.23Bc | 3.35Ac |
| 357 | 1.45Bb | 4.34Ab |
| 549 | 1.47Bb | 4.14Abc |
| 637 | 1.73Ba | 4.76Aa |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

Table 4. Total percent of nitrogen recovered from fertilizer (%NRFF) in the clippings of Kentucky bluegrass for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | ------------- % ------------- | |
| 45 | 1.17B[†]d[‡] | 1.57Ac |
| 184 | 1.17Bd | 1.57Ac |
| 274 | 5.02Bc | 6.84Ab |
| 357 | 5.93Bb | 8.86Aa |
| 549 | 5.98Bb | 8.45Aab |
| 637 | 7.04Ba | 9.71Aa |

[†] Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)
[‡] Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

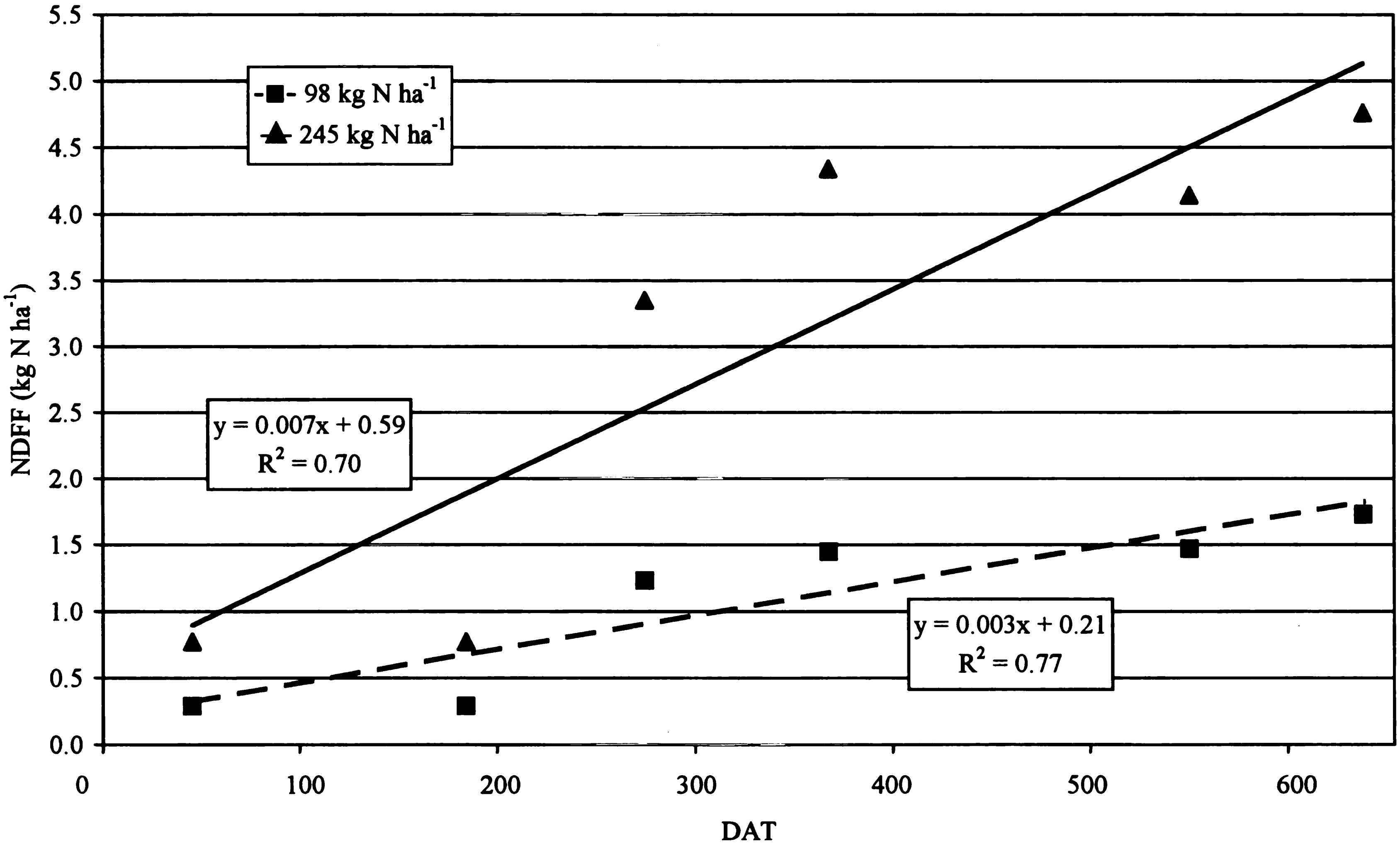


Figure 1. Total amount of nitrogen derived from fertilizer (NDFF) in clippings for the N rate X days after treatment (DAT) interaction and regression of NDFF on DAT for each N rate.

**Verdure**

There was a significant N rate X DAT interaction for the amount of NDFF in verdure (Table 5). The high N rate had a greater amount of NDFF in verdure than the low N rate at the 15, 45, and 184 DAT sampling dates (Table 6). Following 184 DAT, the amount of NDFF in verdure, regardless of N rate, declined significantly and was not statistically different between the two N rates. The largest amount of NDFF in verdure was 10.22 kg N $ha^{-1}$ (20.85 %NRFF) at 184 DAT at the high N rate. At 274 DAT at the high N rate, the amount of NDFF in verdure declined to 1.66 kg N $ha^{-1}$ (3.39 %NRFF), a decline of 17% from 184 DAT. The amount of NDFF in verdure, for the 15, 45, and 184 DAT sampling dates at the low N rate were not statistically different, averaging 3.7 kg N $ha^{-1}$ (15.11 %NRFF). At 274 DAT at the low N rate, the amount of NDFF declined to 1.02 kg N $ha^{-1}$ (4.15 %NRFF), a decline of 11% from the mean of the 15, 45, and 184 DAT sampling dates. With respect to %NRFF, the two N rates were not statistically different on 6 of 7 sampling dates (Table 7).

The amount of NDFF reported was similar to the values reported by Miltner et al. (1996) and greater than the values reported by Frank (2000), for similar N rates applied to Kentucky bluegrass turf. Miltner et al. (1996) reported %NRFF in verdure declining from 22.7% at 199 DAT to 0.69 % at 752 DAT for a fall application of 39.2 kg N $ha^{-1}$. These values were similar to the decline from 20.85% at 184 DAT to 1.06% at 637 DAT for the current research. Frank (2000) reported %NRFF in verdure declining from 7.1 to 2.1 % for a 24.4 kg N $ha^{-1}$ rate. The difference in the %NRFF in verdure between the current research and the Frank (2000) study is most likely related to mowing height. Plots for the current research were maintained at 7.6 cm, whereas the plots in the Frank

Table 5. Analysis of variance table for nitrogen derived from fertilizer (NDFF) and percent N recovered from fertilizer (%NRFF) in the verdure and thatch layers of Kentucky bluegrass.

| Source | df | Verdure NDFF | Verdure %NRFF | Thatch NDFF | Thatch %NRFF |
|---|---|---|---|---|---|
| | | Pr > F | | | |
| N rate | 1 | <.0001 | 0.0336 | <.0001 | 0.3338 |
| DAT† | 6 | <.0001 | <.0001 | <.0001 | <.0001 |
| N rate X DAT | 6 | <.0001 | 0.0236 | <.0001 | <.0001 |

† Days after treatment

Table 6. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass verdure for the N rate X days after treatment (DAT) interaction.

| DAT | N Rate: 98 kg N $ha^{-1}$ | N Rate: 245 kg N $ha^{-1}$ |
|---|---|---|
| | ---------- kg N $ha^{-1}$ | ----------- |
| 15 | 3.65B†a‡ | 7.95Ab |
| 45 | 3.79Ba | 8.34Ab |
| 184 | 3.66Ba | 10.22Aa |
| 274 | 1.02Ab | 1.66Ac |
| 357 | 0.91Ab | 1.70Ac |
| 549 | 0.47Ab | 1.19Ac |
| 637 | 0.30Ab | 0.52Ac |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

Table 7. Percent nitrogen recovered from fertilizer (%NRFF) in Kentucky bluegrass verdure for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | -------------- % -------------- | |
| 15 | 14.91A[†]a[‡] | 16.22Ab |
| 45 | 15.49Aa | 17.02Ab |
| 184 | 14.93Ba | 20.85Aa |
| 274 | 4.15Ab | 3.39Ac |
| 357 | 3.71Ab | 3.48Ac |
| 549 | 1.93Ab | 2.43Ac |
| 637 | 1.21Ab | 1.06Ac |

[†] Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

[‡] Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

study were maintained at 5 cm. Since mass is used to determine the amount of NDFF in a particular component, an increased mowing height would have a greater mass of verdure and therefore a greater amount of NDFF in verdure. Similar to the current research, Miltner et al. (1996) and Frank (2000) reported a decline over time in the amount of NDFF recovered in verdure.

**Thatch**

There was a significant N rate X DAT interaction for the amount of NDFF in thatch (Table 5). The high N rate had a greater amount of NDFF in thatch than the low N rate for all sampling dates, except at 637 DAT where they were not statistically different (Table 8). Similar to verdure, the amount of NDFF in thatch, regardless of N rate, declined significantly after the 184 DAT sampling date. Within each N rate the largest amount of NDFF in thatch was observed at 184 DAT. At 184 DAT for the low and high N rates, the amount of NDFF in thatch was 4.55 and 6.81 kg N $ha^{-1}$, respectively. At 274 DAT for the low and high N rates, the amount of NDFF in thatch declined to 1.07 and 1.93 kg N $ha^{-1}$, respectively. From 184 DAT to 274 DAT, a decline of 14 and 10% was observed for the low and high N rates, respectively. With respect to %NRFF the high N rate had a greater %NRFF at the 15 and 45 DAT sampling dates, while the low N rate was greater at 184 DAT (Table 9). For all sampling dates after 184 DAT the %NRFF was not statistically different between the two N rates.

For the current research, regardless of N rate, a smaller amount of NDFF and %NRFF were recovered in thatch than reported by Starr and DeRoo (1981), Miltner et al. (1996), and Frank (2000). The manner in which thatch layer was defined may be

Table 8. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass thatch for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | ---------- kg N $ha^{-1}$ ---------- | |
| 15 | 2.17B†b‡ | 5.14Ab |
| 45 | 2.06Bb | 6.59Aa |
| 184 | 4.55Ba | 6.81Aa |
| 274 | 1.07Bc | 1.93Acd |
| 357 | 0.86Bc | 2.39Ac |
| 549 | 0.82Bc | 1.50Ad |
| 637 | 0.45Ac | 0.56Ae |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)
‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

Table 9. Percent nitrogen recovered from fertilizer (%NRFF) in Kentucky bluegrass thatch for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | -------------- % -------------- | |
| 15 | 8.84B†b‡ | 10.48Ab |
| 45 | 8.4Bb | 13.46Aa |
| 184 | 18.55Aa | 13.91Ba |
| 274 | 4.35Ac | 3.93Acd |
| 357 | 3.53Ac | 4.88Ac |
| 549 | 3.34Acd | 3.06Ad |
| 637 | 1.82Ad | 1.13Ae |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)
‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

responsible for the differences in the amount of NDFF reported in this study compared to Miltner et al. (1996) and Frank (2000). Miltner et al. (1996) defined thatch as the material between the green tissue and the point below the soil surface where a layer of rhizomes was reached. The soil in the thatch layer was returned to the soil component. Frank (2000) included the soil within the thatch layer in the thatch component. It is unclear, however, what depth into the soil was included in the thatch layer. For the current research the thatch layer was defined as the plant material above the soil surface after verdure was removed. Any soil in the thatch layer was removed and defined as the thatch soil component. The different definitions for the thatch component of Kentucky bluegrass between each study would lead to differences in the amount of NDFF recovered in the thatch layer.

### Roots

There was a significant N rate X DAT X depth interaction for the amount of NDFF in roots (Table 10). The 0-5 cm depth, regardless of N rate, contained a greater amount of NDFF in roots than the 5-10, 10-20, and 20-40 cm depths (Figures 2 and 3). This result would be expected due to the majority of roots being in the 0-5 cm depth. The 0-5 cm depth, regardless of N rate, averaged 13,451 kg roots $ha^{-1}$. The 5-10, 10-20, and 20-40 cm depths combined, regardless of N rate, averaged 2,910 kg roots $ha^{-1}$. Although statistical differences were observed between the 5-10, 10-20, and 20-40 cm depths, the amount of NDFF recovered in these depths was typically less than 0.15 kg N $ha^{-1}$, regardless of N rate or DAT, and are of little practical significance (Table 11).

Table 10. Analysis of variance table for nitrogen derived from fertilizer (NDFF) and percent N recovered from fertilizer (%NRFF) for Kentucky bluegrass roots.

| Source | df | Roots NDFF | Roots %NRFF |
|---|---|---|---|
| | | Pr > F | |
| N rate | 1 | <.0001 | <.0001 |
| DAT[†] | 4 | <.0001 | <.0001 |
| N rate X DAT | 4 | 0.1537 | 0.1541 |
| Depth | 3 | <.0001 | <.0001 |
| N rate X Depth | 3 | <.0001 | <.0001 |
| DAT X Depth | 12 | <.0001 | <.0001 |
| N rate X DAT X Depth | 12 | 0.0027 | 0.0027 |

[†] Days after treatment

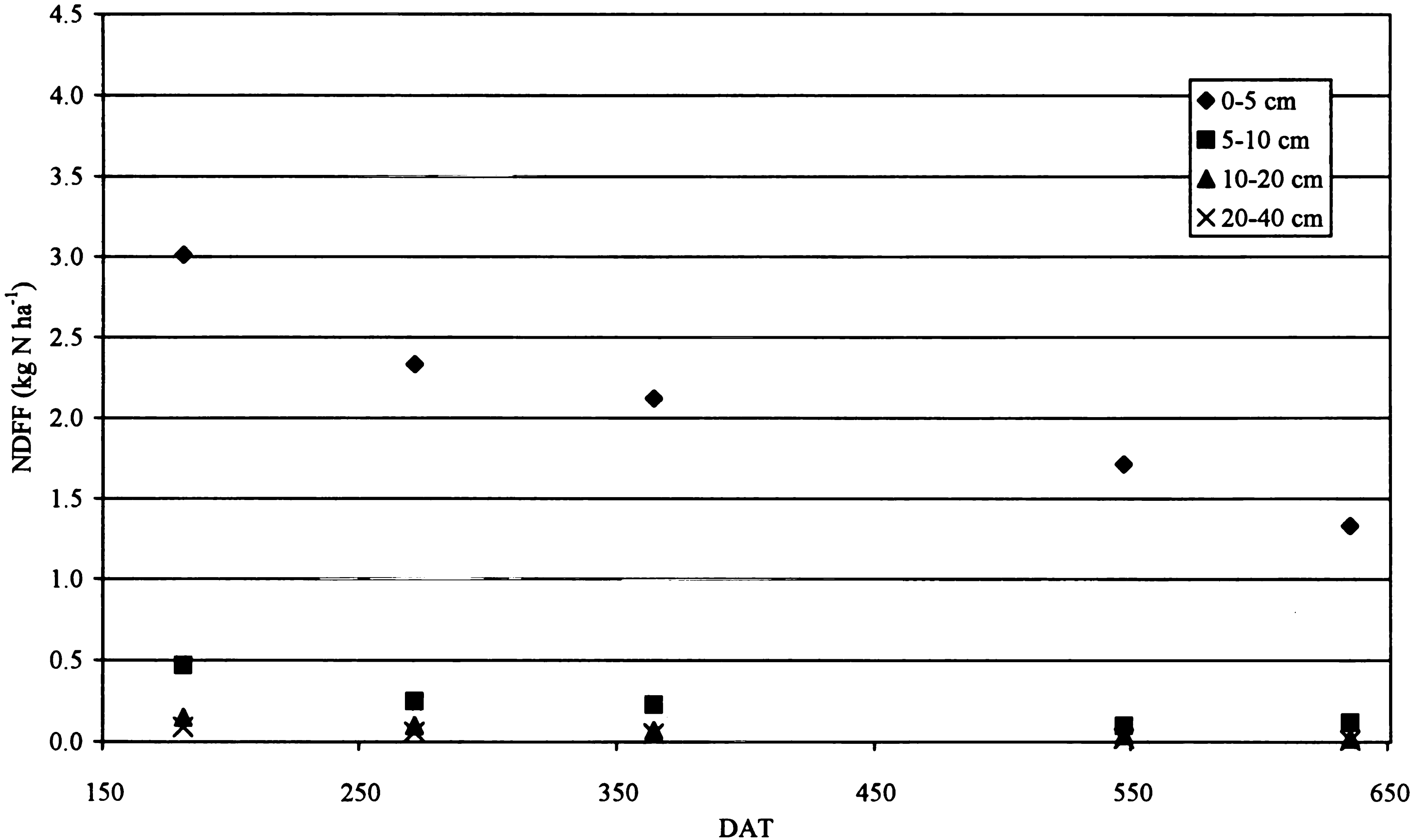


Figure 2. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass roots for the N rate X days after treatment (DAT) X depth interaction for the low N rate (98 kg N $ha^{-1}$).

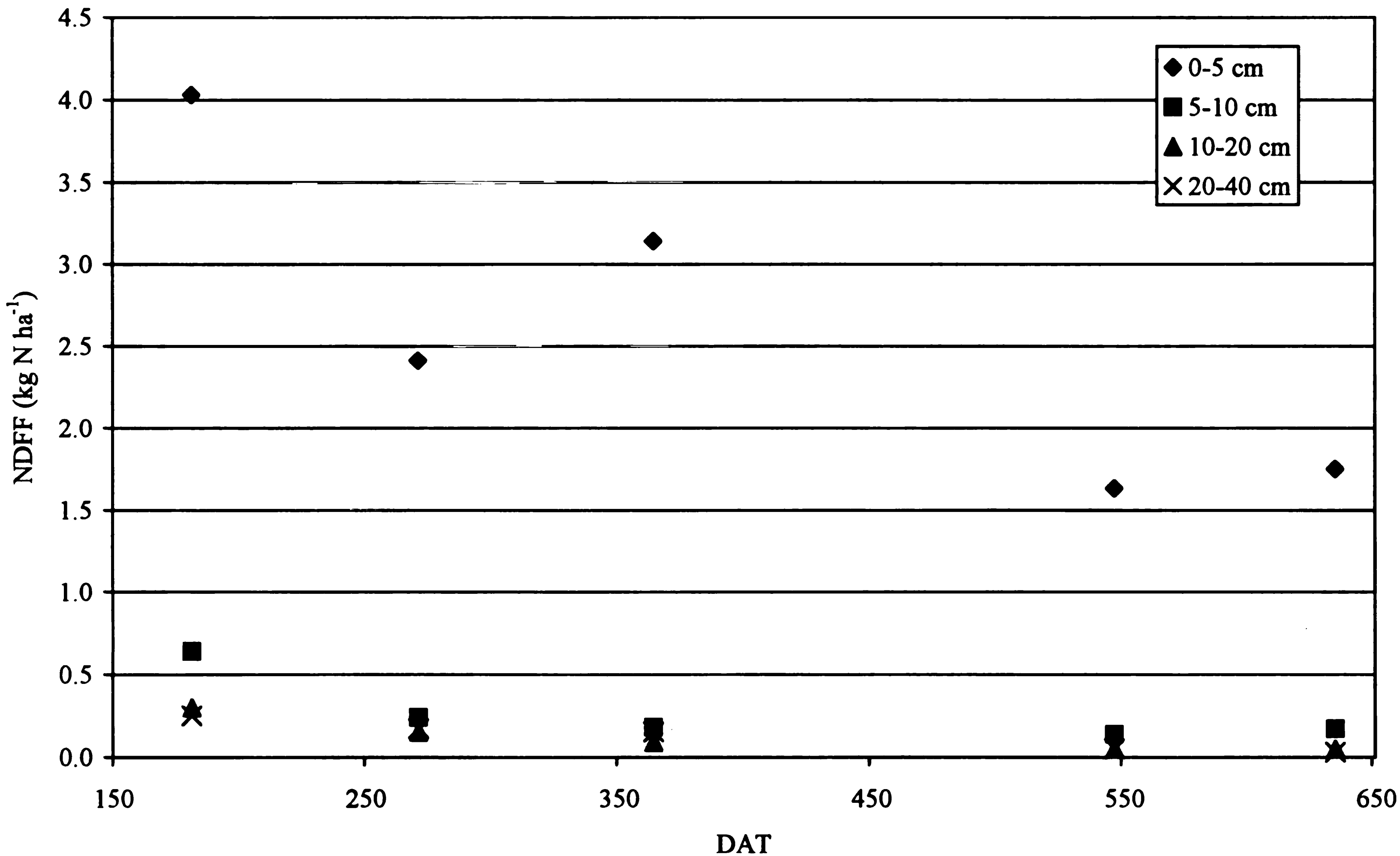


Figure 3. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass roots for the N rate X days after treatment (DAT) X depth interaction for the high N rate (245 kg N $ha^{-1}$).

Table 11. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass roots for the N rate X days after treatment (DAT) X depth interatction separated by N rate.

| | Low N Treatment (98 kg N $ha^{-1}$) | | | | |
|---|---|---|---|---|---|
| | DAT | | | | |
| Depth | 184 | 274 | 357 | 549 | 637 |
| 0-5 cm | 3.01A†a‡ | 2.33Ba | 2.12Ba | 1.71Ca | 1.33Da |
| 5-10 cm | 0.47Ab | 0.25Bb | 0.23Bb | 0.10Cb | 0.12Cb |
| 10-20 cm | 0.15Ac | 0.10Bc | 0.07Bc | 0.04Cc | 0.02Dc |
| 20-40 cm | 0.09Ad | 0.06Bd | 0.05Bd | 0.02Cd | 0.01Dd |

| | High N Treatment (245 kg N $ha^{-1}$) | | | | |
|---|---|---|---|---|---|
| | DAT | | | | |
| Depth | 184 | 274 | 357 | 549 | 637 |
| 0-5 cm | 4.03A†a‡ | 2.41Ca | 3.14Ba | 1.63Da | 1.75Da |
| 5-10 cm | 0.64Ab | 0.24Bb | 0.18Cb | 0.14Cb | 0.17Cb |
| 10-20 cm | 0.30Ac | 0.15Bc | 0.09Cc | 0.05Dc | 0.05Dc |
| 20-40 cm | 0.25Ac | 0.17Bc | 0.15Bc | 0.05Cc | 0.03Dd |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05).

‡ Means in a column followed by the lower case letter are not significantly different according to Fischer's protected LSD (p=0.05).

When the amount of NDFF for all root depths was summed, there was a significant N rate X DAT interaction for the total amount of NDFF in roots (Table 12). The high N rate had a greater total amount of NDFF in roots than the low N rate on 2 of 5 sampling dates (Table 13). The N rate X DAT interaction showed that Kentucky bluegrass treated at the high N rate had a greater decline in NDFF in roots than at the low N rate. At 184 DAT, the amount of NDFF in roots for the low and high N rates was 3.66 and 5.14 kg N $ha^{-1}$, respectively. By 637 DAT, the amount of NDFF declined to 1.47 and 2.03 kg N $ha^{-1}$ for the low and high N rates, respectively. From 184 to 637 DAT, a decrease of 9 and 13% was observed for the low and high N rates, respectively.

Kentucky bluegrass treated at the high N rate had a greater %NRFF in roots than the low N rate on 3 of 5 sampling dates (Table 14). Regardless of N rate, the %NRFF declined significantly from 184 DAT to 637 DAT. At the low N rate the %NRFF decreased from 14.94% at 184 DAT to 5.99% at 637 DAT. At the high N rate the %NRFF decreased from 20.99% to 8.28% from 184 to 637 DAT, respectively. These results were similar to the values reported by Power and Legg (1984), who reported that the %NRFF in roots in a crested wheatgrass (*Agropyron desertorum* (Fisch. Ex Link) Schult.) grassland decreased from 15 to 5% from 1 to 3 years after application, respectively. The authors concluded that some of the applied labeled fertilizer-N initially immobilized in the roots was mineralized and would account for a portion of the cumulative increase of $^{15}N$ recovered in the "tops" of the plant.

There was not a significant linear effect for the N rate X DAT interaction for the total amount of NDFF in roots (Figure 4). The negative slope of the regression lines for

Table 12. Analysis of variance table for the total amount of nitrogen derived from fertilizer (NDFF) and percent N recovered from fertilizer (%NRFF) in Kentucky bluegrass roots.

| | | Roots | |
|---|---|---|---|
| Source | df | NDFF | %NRFF |
| | | Pr > F | |
| N rate | 1 | <.0001 | <.0001 |
| DAT† | 4 | <.0001 | <.0001 |
| N rate X DAT | 4 | 0.0061 | 0.0061 |

† Days after treatment

Table 13. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass roots when all depths were totaled for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | ---------- kg N $ha^{-1}$ ----------- | |
| 184 | 3.66B†a‡ | 5.14Aa |
| 274 | 2.76Ab | 3.00Ac |
| 357 | 2.49Bbc | 3.60Ab |
| 549 | 1.95Acd | 1.93Ad |
| 637 | 1.47Ad | 2.03Ad |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

Table 14. Percent nitrogen recovered from fertilizer (NDFF) in Kentucky bluegrass roots when all depths were totaled for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | ------------- % ------------- | |
| 184 | 14.94B[†]a[‡] | 20.99Aa |
| 274 | 11.25Ab | 12.25Ac |
| 357 | 10.15Bbc | 14.69Ab |
| 549 | 7.95Acd | 7.88Ad |
| 637 | 5.99Bd | 8.28Ad |

[†] Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

[‡] Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

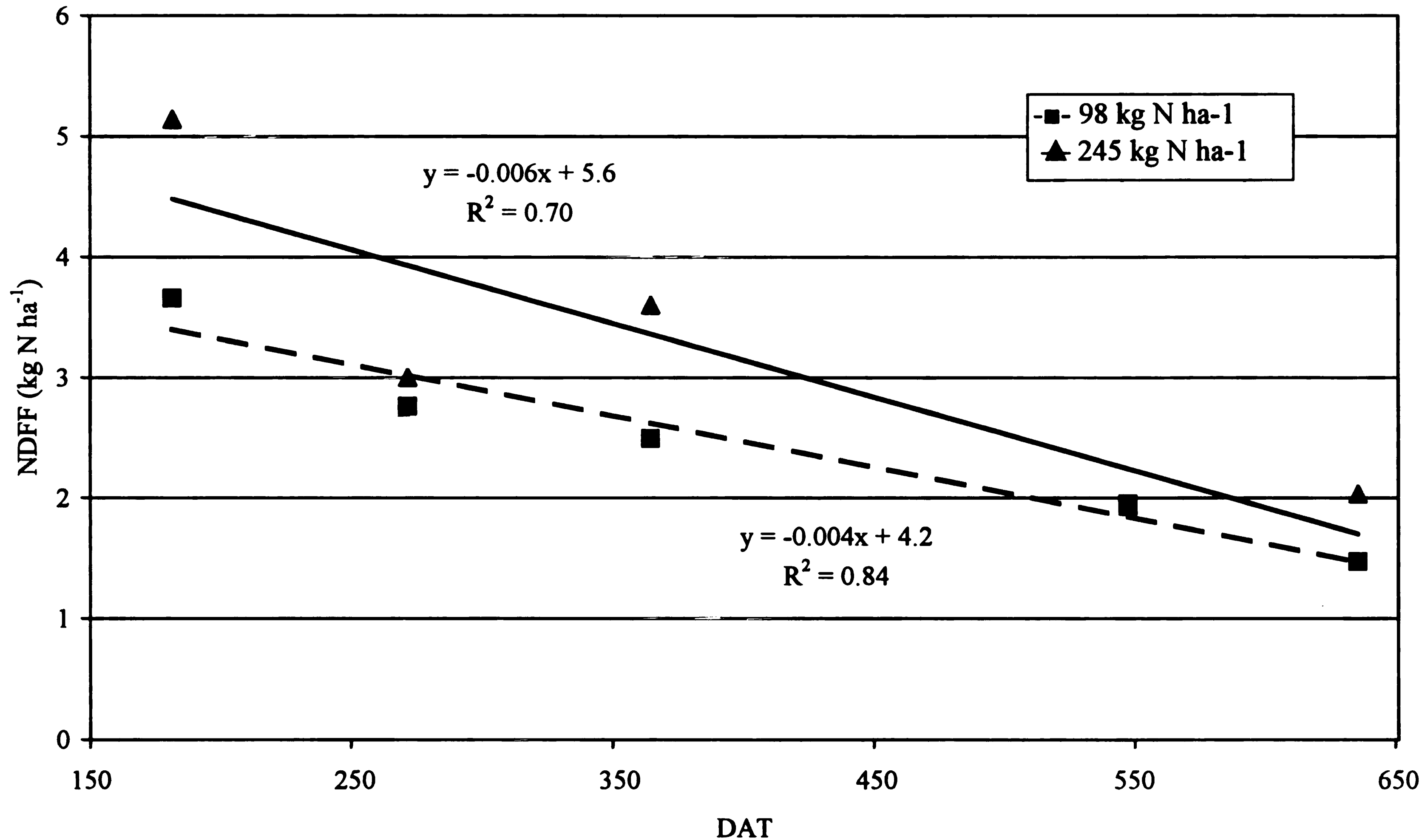


Figure 4. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass roots when all depths were totaled for the N rate X days after treatment (DAT) interaction.

the amount of NDFF in the roots of Kentucky bluegrass, regardless of N rate, indicates that the amount of NDFF in roots decreases over time.

For the current research, regardless of N rate, a greater amount of NDFF was recovered in Kentucky bluegrass roots than reported by Frank (2000). Frank (2000) reported high $^{15}N$ enrichments in roots, but the amount NDFF ranged between 0.4 and 1.6 kg N $ha^{-1}$ (0.8 and 4.1 %NRFF). Frank (2000) attributed the low percent recoveries to the low mass of roots on a per hectare basis when compared to soil or thatch. Since mass is used to determine the amount NDFF in a particular component, a substantially smaller mass would yield a smaller amount of NDFF, even if $^{15}N$ enrichments were high. To a depth of 64 cm, Frank (2000) averaged 6,354 kg roots $ha^{-1}$, whereas the current research to a depth of 40 cm, regardless of N rate, averaged 16,361 kg roots $ha^{-1}$. The large difference in root mass on a per hectare basis is the most likely reason higher percent N recoveries were observed for the current research as compared to the Frank (2000) study.

**Soil**

There was a significant N rate X DAT X depth interaction for the amount of NDFF in soil (Table 15). The 0-5 cm depth, regardless of N rate, had the greatest amount of NDFF (Table 16). The remaining depths, regardless of N rate, revealed no trends (Figures 5 and 6). The total amount of NDFF in soil fluctuated among sampling depths and dates. Miltner et al. (1996) and Frank (2000) noted similar fluctuations and attributed them to mixing procedures and sample variability.

When the amount of NDFF for all soil depths was summed, there was a significant N rate X DAT interaction for the total amount of NDFF in soil (Table 17).

Table 15. Analysis of variance table for nitrogen derived from fertilizer (NDFF) and percent N recovered from fertilizer (%NRFF) for Kentucky bluegrass soil.

| | | Soil | |
|---|---|---|---|
| Source | df | NDFF | %NRFF |
| | | Pr > F | |
| N rate | 1 | <.0001 | <.0001 |
| DAT† | 6 | <.0001 | <.0001 |
| N rate X DAT | 6 | <.0001 | <.0001 |
| Depth | 4 | <.0001 | <.0001 |
| N rate X Depth | 4 | <.0001 | 0.0057 |
| DAT X Depth | 24 | <.0001 | <.0001 |
| N rate X DAT X Depth | 24 | <.0001 | <.0001 |

† Days after treatment

Table 16. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass soil for the N rate X days after treatment (DAT) X depth interaction separated by N rate.

| | Low N Treatment (98 kg N ha$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | DAT | | | | | | |
| Depth | 15 | 45 | 184 | 274 | 357 | 549 | 637 |
| thatch soil[†] | 1.09A[‡]cd[§] | 1.27Aa | 1.02Ac | 1.34Ac | 1.37Ad | 1.02Ad | 1.17Ac |
| 0-5 cm | 2.38Cab | 1.81Ca | 4.41Ba | 6.25Aa | 7.27Aa | 5.73Aa | 6.95Aa |
| 5-10 cm | 0.84Dd | 0.89Da | 1.94Cb | 2.35BCb | 2.83Bc | 2.64BCb | 4.70Ab |
| 10-20 cm | 1.88Abc | 1.23Aa | 1.48Abc | 1.85Abc | 2.37Ac | 1.88Ac | 1.77Ac |
| 20-40 cm | 3.40Aa | 2.13Ba | 1.71Bbc | 2.20Bb | 3.89Ab | 1.50Bcd | 0.30Cd |

| | High N Treatment (245 kg N ha$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | DAT | | | | | | |
| Depth | 15 | 45 | 184 | 274 | 357 | 549 | 637 |
| thatch soil | 1.66Bd | 2.60Aa | 1.87Bc | 1.73Bc | 1.39BCd | 1.02CDd | 0.84Dd |
| 0-5 cm | 7.52Ca | 3.16Da | 6.73Ca | 7.38Ca | 10.06Ba | 10.63Ba | 12.70Aa |
| 5-10 cm | 4.27Ac | 1.34Db | 2.53BCb | 1.86CDc | 3.15Bb | 3.29Bb | 4.77Ab |
| 10-20 cm | 6.28Ab | 1.79Cb | 1.87Cc | 1.89Cc | 3.10Bc | 2.03Cc | 2.02Cc |
| 20-40 cm | 6.58Ab | 3.44BCa | 1.88DEbc | 2.75CDb | 4.09Bb | 0.94EFd | 0.73Fd |

[†] Soil removed from thatch layer

[‡] Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

[§] Means in a column followed by the lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

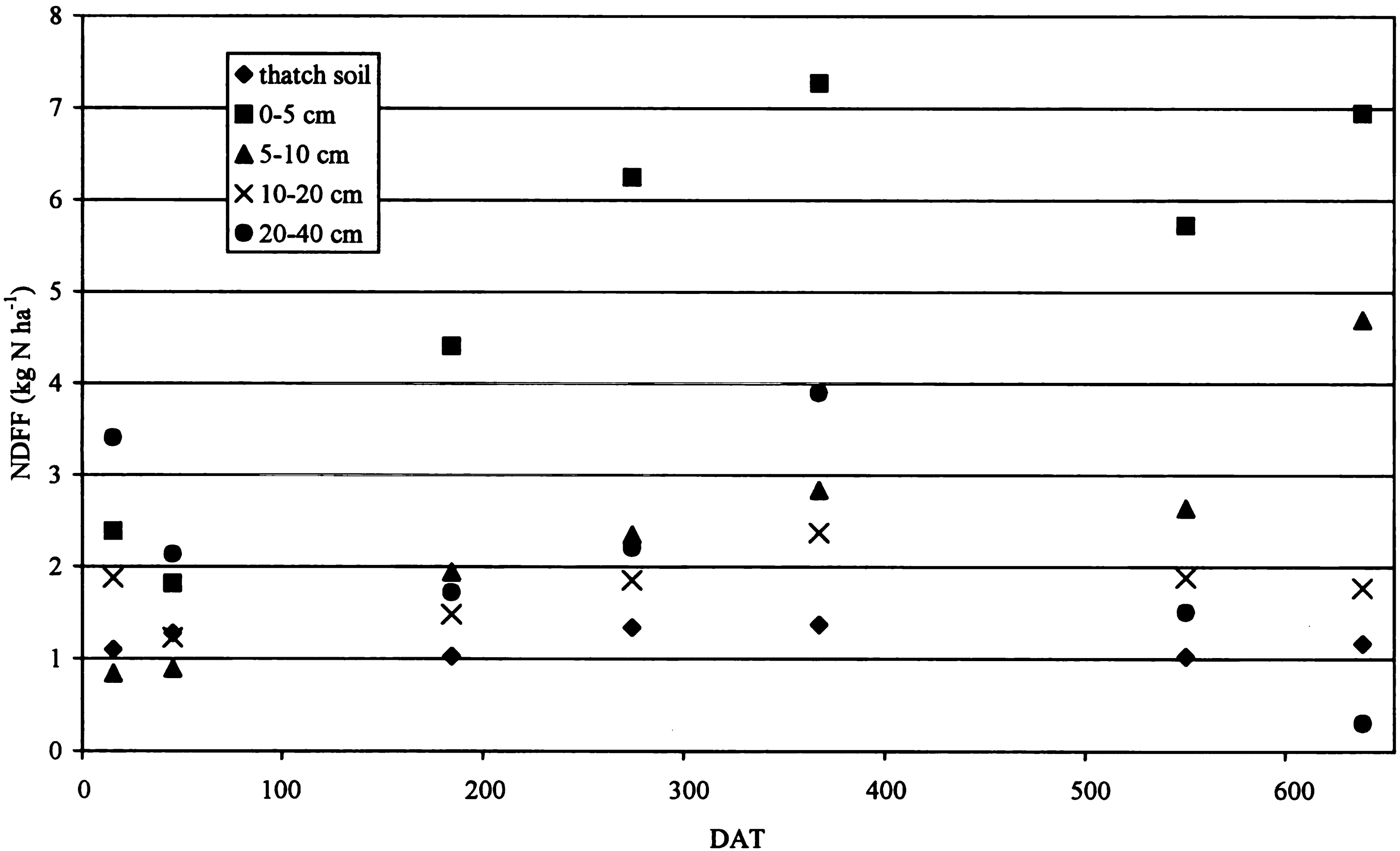


Figure 5. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass soil for the N rate X days after treatment (DAT) X depth interaction for the low N rate (98 kg N $ha^{-1}$).

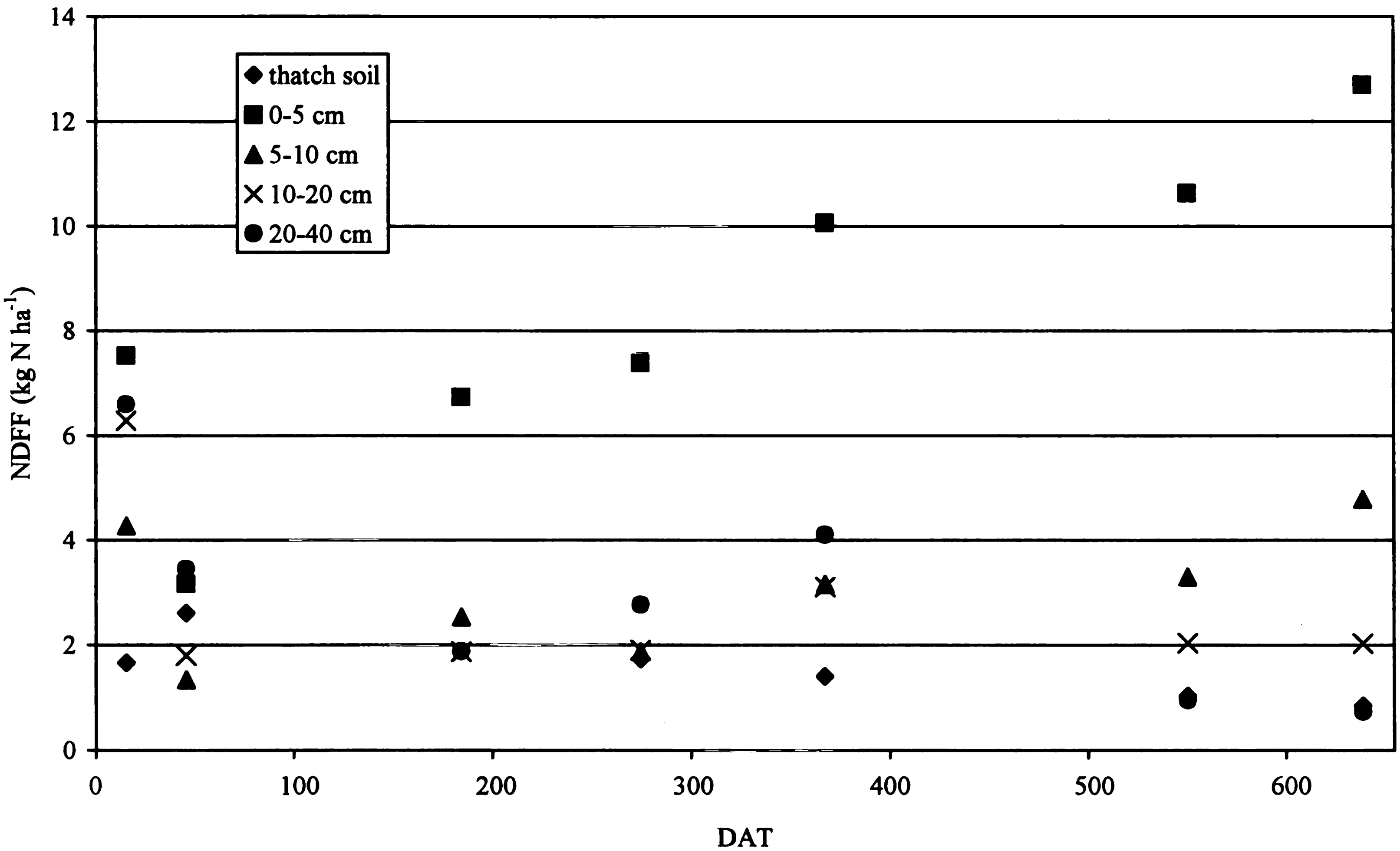


Figure 6. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass soil for the N rate X days after treatment (DAT) X depth interaction for the high N rate (245 kg N $ha^{-1}$).

Table 17. Analysis of variance table for nitrogen derived from fertilizer (NDFF) and percent N recovered from fertilizer (%NRFF) in Kentucky bluegrass soil.

| Source | df | Soil NDFF | Soil %NRFF |
|---|---|---|---|
| | | Pr > F | |
| N rate | 1 | <.0001 | <.0001 |
| DAT† | 6 | <.0001 | <.0001 |
| N rate X DAT | 6 | <.0001 | <.0001 |

†Days after treatment

The high N rate had a greater total amount of NDFF than the low N rate for all sampling dates, except at 274 DAT where they were not different. The highest observed value was 26.63 kg N $ha^{-1}$ at 15 DAT for the high N rate (Table 18). With respect to %NRFF, the low N rate usually contained a greater percent of N recovered than the high N rate (Table 19).

The amount of NDFF reported were similar to the values reported by Frank (2000) and greater than the values reported by Miltner et al. (1996), for similar N rates applied to Kentucky bluegrass turf. Miltner et al. (1996) reported %NRFF averaging 15.5% for a fall application of 39.2 kg N $ha^{-1}$. This value was smaller than the 50.6 and 37.9% averages for the current research at the low and high N rate, respectively. Frank (2000) reported %NRFF in soil averaging 45.4 and 30.2 % for applications of 24.4 and 48.8 kg N $ha^{-1}$, respectively.

## Leachate

### *Nitrogen Derived From Fertilizer*

There was a significant N rate X sampling date interaction for the amount of NDFF in leachate (Table 20). The high N rate had a greater amount of NDFF in leachate than the low N rate on 10 of 39 sampling dates (Table 21). The amount of NDFF in leachate for the low N rate ranged from 0.0003 to 0.0788 kg N $ha^{-1}$ (0.0014 to 0.3215 %NRFF, Table 22). The amount of NDFF in leachate for the high N rate ranged from 0.0131 to 0.7281 kg N $ha^{-1}$ (0.0268 to 1.486 %NRFF).

When the amount of NDFF from all sampling dates prior to the corresponding microplot excavation date were summed, there was a significant N rate X DAT

Table 18. Nitrogen derived from fertilizer (NDFF) in Kentucky bluegrass soil when all depths were totaled for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | ---------- kg N $ha^{-1}$ ----------- | |
| 15 | 9.65B†de‡ | 26.63Aa |
| 45 | 7.36Be | 12.28Ae |
| 184 | 10.57Bcd | 14.91Ade |
| 274 | 13.99Aab | 15.62Acd |
| 357 | 16.30Ba | 21.77Ab |
| 549 | 12.58Bbc | 17.69Ac |
| 637 | 16.35Ba | 21.05Ab |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

Table 19. Percent nitrogen recovered from fertilizer (NDFF) in Kentucky bluegrass soil when all depths were totaled for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | -------------- % -------------- | |
| 15 | 39.38B†c‡ | 54.35Aa |
| 45 | 30.03Ad | 25.07Ad |
| 184 | 43.13Ac | 30.42Bcd |
| 274 | 57.08Ab | 31.88Bcd |
| 357 | 66.53Aa | 44.42Bb |
| 549 | 51.35Ab | 36.11Bc |
| 637 | 66.75Aa | 42.97Bb |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

Table 20. Analysis of variance table for nitrate-nitrogen ($NO_3$-N) concentration, ammonium-nitrogen ($NH_4$-N) concentration, nitrogen derived from fertilizer (NDFF), and percent N recovered from fertilizer (%NRFF) in leachate collected from lysimeters.

| Source | df | $NO_3$-N | $NH_4$-N | NDFF | %NRFF |
|---|---|---|---|---|---|
| | | Pr > F | | | |
| N rate | 1 | 0.0030 | 0.3072 | 0.0071 | 0.0085 |
| Date | 38 | <.0001 | <.0001 | <.0001 | <.0001 |
| N rate X Date | 38 | <.0001 | <.0001 | <.0001 | <.0001 |

Table 21. Nitrogen derived from fertilizer (NDFF) in leachate from lysimeters for the N rate X sampling date interaction.

| Date | N Treatment 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
|---|---|---|
| | ---------- kg N $ha^{-1}$ | ---------- |
| 11/20/00 | 0.0018A† | 0.0131A |
| 1/10/01 | 0.0038A | 0.0586A |
| 2/9/01 | 0.0117B | 0.7281A |
| 2/13/01 | 0.0061B | 0.3675A |
| 3/19/01 | 0.0049A | 0.1111A |
| 3/23/01 | 0.0007A | 0.1366A |
| 4/8/01 | 0.0788A | 0.0519A |
| 4/17/01 | 0.0012A | 0.0463A |
| 4/24/01 | 0.0027A | 0.1138A |
| 5/2/01 | 0.0012A | 0.0812A |
| 5/16/01 | 0.0131B | 0.4128A |
| 5/25/01 | 0.0015A | 0.0378A |
| 5/31/01 | 0.0026A | 0.0863A |
| 6/8/01 | 0.0030B | 0.0909A |
| 6/25/01 | 0.0003A | 0.0640A |
| 8/13/01 | 0.0008A | 0.0304A |
| 10/3/01 | 0.0034A | 0.0329A |
| 10/17/01 | 0.0274B | 0.6341A |
| 10/24/01 | 0.0074A | 0.0918A |
| 10/30/01 | 0.0125A | 0.1264A |
| 11/20/01 | 0.0022A | 0.0276A |
| 12/3/01 | 0.0066B | 0.1977A |
| 12/21/01 | 0.0102B | 0.1908A |
| 1/11/02 | 0.0094A | 0.0896A |
| 2/12/02 | 0.0088B | 0.1536A |
| 3/1/02 | 0.0148B | 0.2786A |
| 3/10/02 | 0.0107B | 0.1751A |
| 3/22/02 | 0.0072A | 0.0808A |
| 4/10/02 | 0.0060A | 0.1140A |
| 5/2/02 | 0.0056A | 0.0770A |
| 5/14/02 | 0.0053A | 0.0655A |
| 5/20/02 | 0.0035A | 0.0772A |
| 6/3/02 | 0.0045A | 0.0920A |
| 6/10/02 | 0.0058A | 0.0678A |
| 7/16/02 | 0.0131A | 0.0826A |
| 7/19/02 | 0.0040A | 0.0602A |
| 7/30/02 | 0.0049A | 0.0804A |
| 8/15/02 | 0.0054A | 0.0452A |
| 12/23/02 | 0.0044A | 0.0210A |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD ($p=0.05$).

Table 22. Percent nitrogen recovered from fertilizer (%NRFF) in leachate from lysimeters for the N rate X sampling date interaction.

| | N Treatment | |
|---|---|---|
| Date | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | ------------ % ------------ | |
| 11/20/00 | 0.0075A† | 0.0268A |
| 1/10/01 | 0.0153A | 0.1196A |
| 2/9/01 | 0.0477B | 1.4860A |
| 2/13/01 | 0.0250B | 0.7500A |
| 3/19/01 | 0.0201A | 0.2267A |
| 3/23/01 | 0.0027A | 0.2788A |
| 4/8/01 | 0.3215A | 0.1059A |
| 4/17/01 | 0.0050A | 0.0945A |
| 4/24/01 | 0.0111A | 0.2323A |
| 5/2/01 | 0.0048A | 0.1656A |
| 5/16/01 | 0.0533B | 0.8424A |
| 5/25/01 | 0.0060A | 0.0771A |
| 5/31/01 | 0.0108A | 0.1761A |
| 6/8/01 | 0.0121A | 0.1855A |
| 6/25/01 | 0.0014A | 0.1307A |
| 8/13/01 | 0.0034A | 0.0621A |
| 10/3/01 | 0.0137A | 0.0671A |
| 10/17/01 | 0.1120B | 1.2941A |
| 10/24/01 | 0.0303A | 0.1873A |
| 10/30/01 | 0.0511A | 0.2580A |
| 11/20/01 | 0.0089A | 0.0563A |
| 12/3/01 | 0.0270B | 0.4036A |
| 12/21/01 | 0.0415B | 0.3893A |
| 1/11/02 | 0.0383A | 0.1829A |
| 2/12/02 | 0.0358B | 0.3134A |
| 3/1/02 | 0.0602B | 0.5686A |
| 3/10/02 | 0.0435B | 0.3574A |
| 3/22/02 | 0.0295A | 0.1649A |
| 4/10/02 | 0.0247A | 0.2327A |
| 5/2/02 | 0.0228A | 0.1570A |
| 5/14/02 | 0.0215A | 0.1336A |
| 5/20/02 | 0.0141A | 0.1575A |
| 6/3/02 | 0.0184A | 0.1877A |
| 6/10/02 | 0.0235A | 0.1384A |
| 7/16/02 | 0.0535A | 0.1686A |
| 7/19/02 | 0.0162A | 0.1229A |
| 7/30/02 | 0.0200A | 0.1640A |
| 8/15/02 | 0.0219A | 0.0923A |
| 12/23/02 | 0.0180A | 0.0429A |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05).

interaction for the total amount of NDFF in leachate (Table 23). The high N rate had a greater total amount of NDFF in leachate than the low N rate for all sampling dates except the 15 and 45 DAT sampling dates (Table 24). The 15 DAT sampling date occurred on November 1, 2000, whereas the first lysimeter sampling date occurred on November 20, 2000, therefore the total amount of NDFF in leachate was zero for both N rates at 15 DAT due to no sampling dates occurring prior to 15 DAT. At 45 DAT, the total amount of NDFF in leachate was 0.002 and 0.013 kg N $ha^{-1}$ for the low and high N rates, respectively. The low values observed at 45 DAT can be attributed to only one lysimeter sampling date occurring prior to 45 DAT. At 796 DAT the total amount of NDFF in leachate for the low N rate was 0.32 kg N $ha^{-1}$. This value was not statistically different from zero and accounted for only 1.3% of N recovered from fertilizer (Table 25). The total amount of NDFF in leachate for the high N rate at 796 DAT was 5.33 kg N $ha^{-1}$, or 10.9% of N recovered from fertilizer. This illustrates that time is an important factor in moving fertilizer-N into leachate.

There was a significant linear effect for the total amount of NDFF in leachate for the N rate X DAT interaction (Figure 7). The high N rate had a steep positive slope, indicative of a rapid increase in the total amount of NDFF in leachate, over time. The low N rate had a flat slope indicative of little fertilizer-N leaching at this rate.

On the same site as the current research, from 1991 through 1993, Miltner et al. (1996) applied N as urea at 39.2 kg N $ha^{-1}$ defined by either a spring or fall application schedule. Miltner et al. (1996) reported 0.18% of applied labeled fertilizer-N from a fall application was recovered in leachate. For the current research, the low N rate showed a

Table 23. Analysis of variance table for nitrogen derived from fertilizer (NDFF) and percent N recovered from fertilizer (%NRFF) in leachate from lysimeters.

| Source | df | Leachate NDFF | Leachate %NRFF |
|---|---|---|---|
| | | Pr > F | |
| N rate | 1 | 0.0320 | 0.0362 |
| DAT† | 7 | <.0001 | <.0001 |
| N rate X DAT | 7 | <.0001 | <.0001 |

†Days after treatment

Table 24. Nitrogen derived from fertilizer (NDFF) in leachate from lysimeters for the N rate X days after treatment (DAT) interaction.

| DAT | N Rate 98 kg N ha$^{-1}$ | N Rate 245 kg N ha$^{-1}$ |
|---|---|---|
| | ---------- kg N ha$^{-1}$ | ----------- |
| 15 | 0.000A†a‡ | 0.000Ae |
| 45 | 0.002Aa | 0.013Ae |
| 184 | 0.110Ba | 1.445Ad |
| 274 | 0.134Ba | 2.268Ac |
| 357 | 0.139Ba | 2.477Ac |
| 549 | 0.262Ba | 4.637Ab |
| 637 | 0.286Ba | 5.016Aab |
| 796 | 0.316Ba | 5.332Aa |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

Table 25. Percent nitrogen recovered from fertilizer (%NRFF) in leachate from lysimeters for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | -------------- % -------------- | |
| 15 | 0.000A†a‡ | 0.000Ae |
| 45 | 0.007Aa | 0.027Ae |
| 184 | 0.449Ba | 2.949Ad |
| 274 | 0.548Ba | 4.628Ac |
| 357 | 0.566Ba | 5.054Ac |
| 549 | 1.069Ba | 9.463Ab |
| 637 | 1.169Ba | 10.237Aab |
| 796 | 1.291Ba | 10.882Aa |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

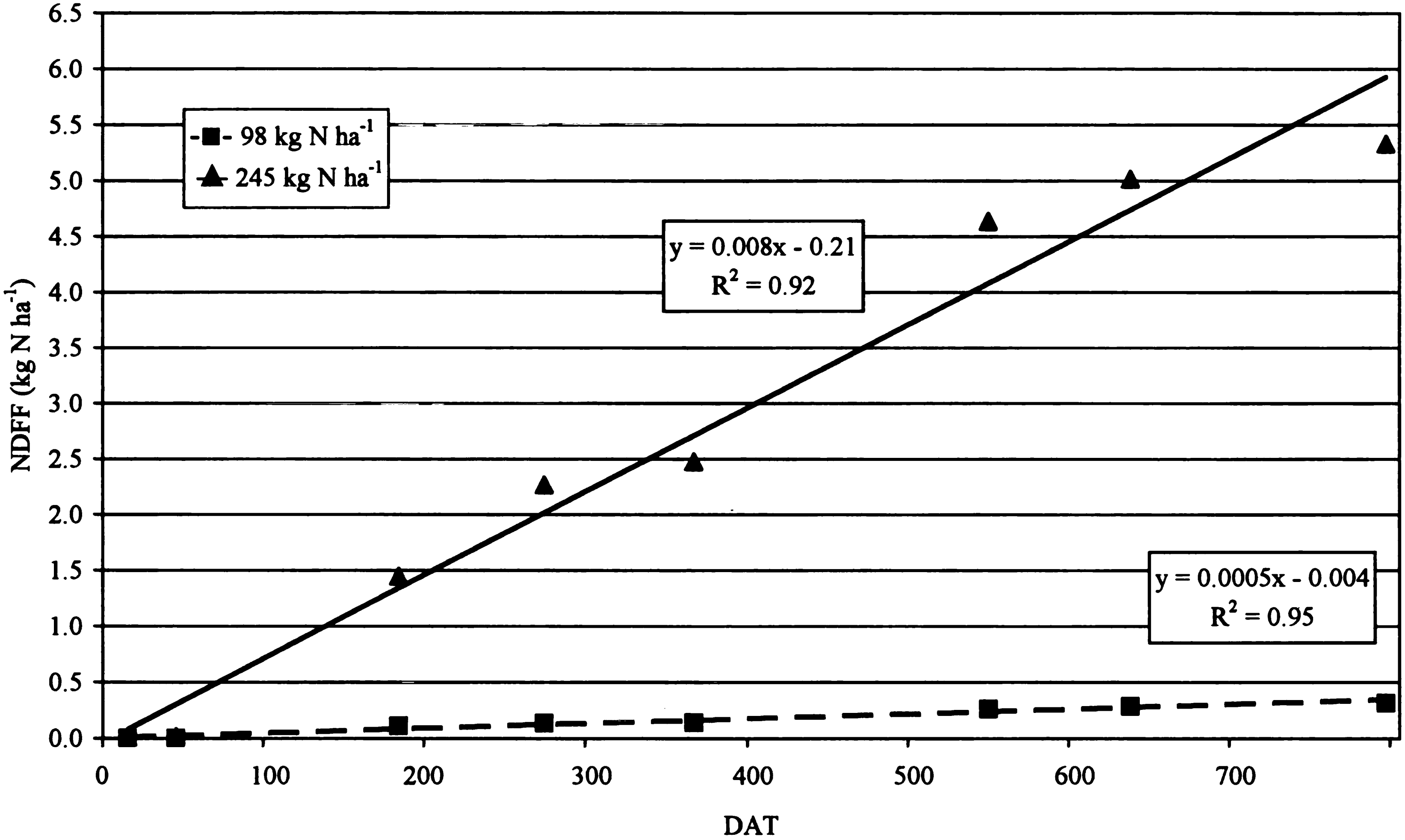


Figure 7. Nitrogen derived from fertilizer (NDFF) in leachate from lysimeters by days after treatment (DAT) for the N rate X DAT interaction and regression of NDFF on DAT for each N rate.

similar low amount of NDFF in leachate as reported in the Miltner et al. (1996) study. The high N rate, however, showed different results than the Miltner et al. (1996) study. For the duration of the current research, with a similar N rate, 10.9% of labeled fertilizer-N was recovered in leachate for the high N rate (49 kg N $ha^{-1}$ rate).

***$NH_4$-N concentration (mg $L^{-1}$)***

There was a significant N rate X sampling date interaction for the concentration of $NH_4$-N recovered in leachate (Table 20). The high N rate had a greater concentration of $NH_4$-N than the low N rate on 1 of 39 sampling dates (Table 26). For the remaining 38 sampling dates, the concentration of $NH_4$-N in leachate was not statistically different between N rates. The largest concentration of $NH_4$-N was 0.87 mg $L^{-1}$ at the high N rate, a value 5.5 times greater than the next largest observed value. The remaining concentrations were typically below 0.07 mg $NH_4$-N $L^{-1}$, regardless of N rate. Flow-weighted means for the low and high N rates were 0.04 and 0.13 mg $NH_4$-N $L^{-1}$, respectively (Table 27). These values were similar to the values reported by Miltner et al. (1996), who reported values for flow-weighted means averaging 0.13 mg $L^{-1}$. Brown et al. (1982) reported that $NH_4$-N losses contributed very little of total N losses from putting greens and only occasionally exceeded 1 mg $L^{-1}$.

***$NO_3$-N concentration (mg $L^{-1}$)***

There was a significant N rate X sampling date interaction for the concentration of $NO_3$-N recovered in leachate (Table 20). The high N rate had a greater concentration of $NO_3$-N in leachate than the low N rate on 32 of 39 sampling dates (Table 28). The

Table 26. Ammonium-nitrogen ($NH_4$-N) concentration (mg $L^{-1}$) in leachate from lysimeters for the N rate X sampling date interaction.

| Date | N Treatment 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
|---|---|---|
| | ------------ mg $L^{-1}$ | ------------ |
| 11/20/00 | 0.07A† | 0.07A |
| 1/10/01 | 0.02A | 0.02A |
| 2/9/01 | 0.10B | 0.87A |
| 2/13/01 | 0.02A | 0.02A |
| 3/19/01 | 0.17A | 0.18A |
| 3/23/01 | 0.10A | 0.00A |
| 4/8/01 | 0.02A | 0.02A |
| 4/17/01 | 0.02A | 0.02A |
| 4/24/01 | 0.03A | 0.05A |
| 5/2/01 | 0.00A | 0.01A |
| 5/16/01 | 0.06A | 0.03A |
| 5/25/01 | 0.02A | 0.01A |
| 5/31/01 | 0.08A | 0.04A |
| 6/8/01 | 0.04A | 0.05A |
| 6/25/01 | 0.00A | 0.00A |
| 8/13/01 | 0.08A | 0.00A |
| 10/3/01 | 0.10A | 0.00A |
| 10/17/01 | 0.00A | 0.00A |
| 10/24/01 | 0.00A | 0.00A |
| 10/30/01 | 0.00A | 0.00A |
| 11/20/01 | 0.04A | 0.04A |
| 12/3/01 | 0.08A | 0.09A |
| 12/21/01 | 0.04A | 0.07A |
| 1/11/02 | 0.06A | 0.05A |
| 2/12/02 | 0.06A | 0.05A |
| 3/1/02 | 0.00A | 0.01A |
| 3/10/02 | 0.09A | 0.03A |
| 3/22/02 | 0.02A | 0.06A |
| 4/10/02 | 0.03A | 0.05A |
| 5/2/02 | 0.10A | 0.11A |
| 5/14/02 | 0.08A | 0.14A |
| 5/20/02 | 0.00A | 0.00A |
| 6/3/02 | 0.02A | 0.04A |
| 6/10/02 | 0.04A | 0.02A |
| 7/16/02 | 0.02A | 0.03A |
| 7/19/02 | 0.03A | 0.04A |
| 7/30/02 | 0.02A | 0.03A |
| 8/15/02 | 0.03A | 0.03A |
| 12/23/02 | 0.06A | 0.07A |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD ($p=0.05$).

Table 27. Flow-weighted means of nitrate-nitrogen ($NO_3$-N) and ammonium-nitrogen ($NH_4$-N) concentrations in leachate from lysimeters.

| N Rate | Nitrate-N | Ammonium-N |
|---|---|---|
| | ---------------mg $L^{-1}$--------------- | |
| 98 kg N $ha^{-1}$ | 4.12 | 0.04 |
| 245 kg N $ha^{-1}$ | 20.92 | 0.13 |

Table 28. Nitrate-nitrogen ($NO_3$-N) concentration (mg $L^{-1}$) in leachate from lysimeters for the N rate X sampling date interaction.

| | N Treatment | |
|---|---|---|
| Date | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | ---------- mg $L^{-1}$ ---------- | |
| 11/20/00 | 3.01B† | 12.75A |
| 1/10/01 | 12.61A | 15.88A |
| 2/9/01 | 3.29B | 20.52A |
| 2/13/01 | 3.76B | 21.35A |
| 3/19/01 | 4.17B | 15.57A |
| 3/23/01 | 4.18B | 17.45A |
| 4/8/01 | 10.28A | 11.67A |
| 4/17/01 | 2.42A | 10.73A |
| 4/24/01 | 4.21B | 18.38A |
| 5/2/01 | 4.23B | 18.26A |
| 5/16/01 | 2.57A | 9.66A |
| 5/25/01 | 2.84A | 9.96A |
| 5/31/01 | 3.09B | 12.29A |
| 6/8/01 | 2.81B | 11.99A |
| 6/25/01 | 2.57B | 12.47A |
| 8/13/01 | 2.53A | 8.11A |
| 10/3/01 | 2.77B | 15.07A |
| 10/17/01 | 4.37B | 20.90A |
| 10/24/01 | 6.88B | 28.10A |
| 10/30/01 | 7.90B | 31.08A |
| 11/20/01 | 3.05A | 8.60A |
| 12/3/01 | 7.64B | 25.83A |
| 12/21/01 | 6.16B | 35.37A |
| 1/11/02 | 7.27B | 34.65A |
| 2/12/02 | 7.34B | 38.48A |
| 3/1/02 | 6.25B | 39.51A |
| 3/10/02 | 5.68B | 35.94A |
| 3/22/02 | 5.40B | 29.54A |
| 4/10/02 | 4.23B | 33.14A |
| 5/2/02 | 3.21B | 27.73A |
| 5/14/02 | 2.95B | 26.66A |
| 5/20/02 | 2.91B | 24.43A |
| 6/3/02 | 3.01B | 31.08A |
| 6/10/02 | 2.97B | 23.37A |
| 7/16/02 | 2.78B | 21.88A |
| 7/19/02 | 3.04B | 19.22A |
| 7/30/02 | 2.20B | 19.44A |
| 8/15/02 | 2.67B | 20.25A |
| 12/23/02 | 3.31B | 19.29A |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05).

$NO_3$-N concentration for the low N rate was less than 5 mg $L^{-1}$ on 28 of 39 sampling dates, and exceeded the EPA safe drinking water standard of 10 mg $L^{-1}$ on only two sampling dates. The flow-weighted mean for the low N rate was 4.12 mg $NO_3$-N $L^{-1}$ (Table 27). The high N rate exceeded the EPA standard on 35 of 39 sampling dates, and was greater than 20 mg $NO_3$-N $L^{-1}$ on 20 sampling dates. On eight sampling dates, the $NO_3$-N concentration ranged between 30-40 mg $L^{-1}$. The flow-weighted mean for the high N rate was 20.92 mg $NO_3$-N $L^{-1}$, which is double the EPA safe drinking water standard (Table 27).

The findings for the low N rate agree with those of Starr and DeRoo (1981), Morton et al. (1988), and Miltner et al. (1996), who stated the leaching of $NO_3$-N from turfgrass systems posed little risk to groundwater sources. Duff et al. (1997) reported that $NO_3$-N concentrations in leachate were not appreciably greater for older turf sites than those reported for younger sites. The findings for the high N rate, however, disagree with the hypothesis that leaching from older turfgrass systems is not a risk to groundwater sources. From 1991 through 1993, on the same site as the current research, Miltner et al. (1996) reported that $NO_3$-N concentrations in leachate were generally well below 1 mg $L^{-1}$. For the duration of the current study, with a similar N rate, the concentration of $NO_3$-N rarely dropped below 20 mg $L^{-1}$ for the high N rate. These results would support the hypothesis of Porter et al. (1980) that older turf sites should be fertilized at a reduced N rate to minimize the potential for $NO_3$-N leaching.

**Total Nitrogen Recovery**

There was a significant N rate X DAT interaction for the total amount of NDFF recovered in Kentucky bluegrass (Table 29). Kentucky bluegrass treated at the high N rate contained a greater total amount of NDFF than at the low N rate on all sampling dates (Table 30). The highest observed value was 39.72 kg N $ha^{-1}$ at 15 DAT for the high N rate. Soil accounted for the greatest amount of NDFF among the turfgrass, soil, and leachate components, regardless of N rate or sampling date (Table 31). With respect to %NRFF, the two N rates were similar on four of seven sampling dates (Table 32). The high N rate was greater on the 45 and 184 DAT sampling dates, while the low N rate was greater on the 274 DAT sampling date.

The total %NRFF averaged 77.65 and 73.43% for the low and high N rates, respectively. The highest observed percent recovery was 95.53% at 357 DAT for the low N rate. The lowest recoveries were at the 45 DAT sampling date, regardless of N rate. These low recoveries are most likely attributed to missing root data. The average total percent recoveries for the current research were similar to the values reported by Starr and DeRoo (1981), Miltner (1996), and Frank (2000). Total recovery of applied fertilizer-N for these studies ranged from 64 to 90%. These researchers suggested that denitrification and $NH_3$ volatilization losses were responsible for incomplete recovery of applied $^{15}N$. Substantial losses of N can occur through denitrification. In a greenhouse study, Horgan et al. (2002) compared denitrification losses from bare soil and Kentucky bluegrass. Denitrification losses ($N_2$ and $N_2O$) accounted for 7 and 19% of applied labeled fertilizer-N for bare soil and Kentucky bluegrass systems, respectively. Rolston

Table 29. Analysis of variance table nitrogen derived from fertilizer (NDFF) and percent nitrogen recovered from fertilizer (%NRFF) in all components of Kentucky bluegrass.

| Source | df | Total Recovery NDFF | Total Recovery %NRFF |
|---|---|---|---|
| | | Pr > F | |
| N rate | 1 | <.0001 | 0.0501 |
| DAT† | 6 | <.0001 | <.0001 |
| N rate X DAT | 6 | <.0001 | 0.0006 |

†Days after treatment

Table 30. Nitrogen derived from fertilizer (NDFF) in all components of Kentucky bluegrass for the N rate X days after treatment (DAT) interaction.

| DAT | N Rate: 98 kg N $ha^{-1}$ | N Rate: 245 kg N $ha^{-1}$ |
|---|---|---|
| | ---------- kg N $ha^{-1}$ | ---------- |
| 15 | 15.47B†cd‡ | 39.72Aa |
| 45 | 13.54Bd | 28.00Ad |
| 184 | 22.83Ba | 39.30Aa |
| 274 | 20.19Babc | 27.83Ad |
| 357 | 23.41Ba | 36.28Aab |
| 549 | 17.36Bbc | 31.09Acd |
| 637 | 20.37Bab | 33.93Abc |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)
‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

Table 31. Nitrogen derived from fertilizer (NDFF) and percent nitrogen recovered from fertilizer (%NRFF) in Kentucky bluegrass components treated at the low and high N rates at all sampling dates.

| N Treatment | DAT | Clippings | Verdure | Thatch | Soil† | Roots† | Leachate | Total‡ |
|---|---|---|---|---|---|---|---|---|
| | | kg N ha$^{-1}$ (%) | | | | | | |
| Low | 15 | . | 3.65 (14.91) | 2.17 (8.84) | 9.65 (39.38) | . | 0.00 (0.00) | 15.47 (63.13) |
| (98 kg N ha$^{-1}$) | 45 | 0.29 (1.17) | 3.79 (15.49) | 2.06 (8.40) | 7.36 (30.03) | . | 0.002 (0.01) | 13.54 (55.28) |
| | 184 | 0.29 (1.17) | 3.66 (14.93) | 4.55 (18.55) | 10.57 (43.13) | 3.66 (14.94) | 0.11 (0.45) | 22.83 (93.17) |
| | 274 | 1.23 (5.02) | 1.02 (4.15) | 1.07 (4.35) | 13.99 (57.08) | 2.76 (11.25) | 0.13 (0.55) | 20.19 (82.40) |
| | 357 | 1.45 (5.93) | 0.91 (3.71) | 0.86 (3.53) | 16.30 (66.53) | 2.49 (10.15) | 0.14 (0.57) | 23.41 (95.53) |
| | 549 | 1.47 (5.98) | 0.47 (1.93) | 0.82 (3.34) | 12.58 (51.35) | 1.95 (7.95) | 0.26 (1.07) | 17.36 (70.88) |
| | 637 | 1.73 (7.04) | 0.30 (1.21) | 0.45 (1.82) | 16.35 (66.75) | 1.47 (5.99) | 0.29 (1.17) | 20.37 (83.14) |
| High | 15 | . | 7.95 (16.22) | 5.14 (10.48) | 26.63 (54.35) | . | 0.00 (0.00) | 39.72 (81.06) |
| (245 kg N ha$^{-1}$) | 45 | 0.77 (1.57) | 8.34 (17.02) | 6.59 (13.46) | 12.28 (25.07) | . | 0.01 (0.03) | 28.00 (57.14) |
| | 184 | 0.77 (1.57) | 10.22 (20.85) | 6.81 (13.91) | 14.91 (30.42) | 5.14 (20.99) | 1.45 (2.95) | 39.30 (90.96) |
| | 274 | 3.35 (6.84) | 1.66 (3.39) | 1.93 (3.93) | 15.62 (31.88) | 3.00 (12.25) | 2.27 (4.63) | 27.83 (62.92) |
| | 357 | 4.34 (8.86) | 1.70 (3.48) | 2.39 (4.88) | 21.77 (44.42) | 3.60 (14.69) | 2.48 (5.05) | 36.28 (81.39) |
| | 549 | 4.14 (8.45) | 1.19 (2.43) | 1.50 (3.06) | 17.69 (36.11) | 1.93 (7.88) | 4.64 (9.46) | 31.09 (67.39) |
| | 637 | 4.76 (9.71) | 0.52 (1.06) | 0.56 (1.13) | 21.05 (42.96) | 2.03 (8.28) | 5.02 (10.24) | 33.93 (73.39) |

† Apparent $^{15}N$ values are not equal to the sum of the apparent $^{15}N$ recovery values for the depths due to differences in the statistical calculations performed on missing data points.

‡ Total apparent $^{15}N$ values are not equal to the sum of the apparent $^{15}N$ recovery values for the components due to differences in the statistical calculations performed on missing data points.

Table 32. Percent nitrogen recovered from fertilizer (%NRFF) in all components of Kentucky bluegrass for the N rate X days after treatment (DAT) interaction.

| | N Rate | |
|---|---|---|
| DAT | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | -------------- % -------------- | |
| 15 | 63.13B†cd‡ | 81.06Aabc |
| 45 | 55.28Ad | 57.14Ae |
| 184 | 93.17Aab | 90.69Aa |
| 274 | 82.40Ab | 62.92Bde |
| 357 | 95.53Aa | 81.39Bab |
| 549 | 70.88Ac | 67.39Ade |
| 637 | 83.14Ab | 73.39Abcd |

† Means in a row followed by the same capital letter are not significantly different according to Fischer's protected LSD (p=0.05)

‡ Means in a column followed by the same lower case letter are not significantly different according to Fischer's protected LSD (p=0.05)

et al. (1982) found denitrification losses to be greatest following irrigation and from frequently irrigated plots. Mancino et al. (1988) reported little to no denitrification losses when the soil was below 80% saturation in combination with low soil temperatures, however, when saturated soil conditions were combined with high soil temperatures denitrification losses were high. The current research returned 80% evapotranspiration twice a week, which at least temporarily may have created favorable conditions for denitrification losses.

Volatilization losses may also have accounted for incomplete recovery of applied $^{15}N$. The thatch layer contains large quantities of urease, increasing volatilization losses. Nelson et al. (1980) reported 5 and 39% of applied N volatilized from Kentucky bluegrass following urea applications when a thatch layer was not present or was present, respectively. Bowman et al. (1987) reported that volatilization losses declined dramatically from Kentucky bluegrass when as little as 1 cm of supplemental irrigation was applied immediately following urea application. Torello et al. (1983) reported that approximately three times as much N was lost from Kentucky bluegrass following an application of solubilized urea as compared to a prilled urea application. The large thatch layer present at the current research site combined with a solubilized urea application may have created a favorable environment for volatilization losses.

## CONCLUSIONS

The total %NRFF in Kentucky bluegrass averaged 77.65 and 73.43% for the low and high N rates, respectively. These values are similar to the values reported by Starr and DeRoo (1981), Miltner et al. (1996), and Frank (2000), who reported total %NRFF ranging between 64 to 90%. The majority of applied labeled fertilizer-N was recovered in the soil, averaging 50.61 and 37.89% for the low and high N rates, respectively. Porter et al. (1980) hypothesized that the capacity of the soil to store fertilizer N is a function of the age of the turfgrass and that older turf sites lose the ability to store additional N in the soil. In the current research, however, the %NRFF in the soil was much greater than the values reported by Miltner et al. (1996) from a previous study on the same site 9 years earlier.

The amount of labeled fertilizer-N recovered in leachate from lysimeters treated at the high N rate was greater than expected. From October 17, 2000 through December 23, 2002, a period of 796 days, 1.3 and 10.9% of applied labeled fertilizer-N was recovered in leachate for the low and high N rates, respectively. Flow weighted means for the low and high N rates were 4.12 and 20.92 mg $NO_3$-N $L^{-1}$, respectively. The results for the low N rate were similar to the results reported by Miltner et al. (1996) at the same site from 1991-1993, and indicate that at the low N rate the potential for groundwater contamination is minimal. At the high N rate, however, the amount of NDFF and concentration of $NO_3$-N in leachate were substantially greater than the values reported by Miltner et al. (1996). At the high N rate the $NO_3$-N concentration in leachate was typically two or more times greater than the EPA safe drinking water standard of 10 mg $NO_3$-N $L^{-1}$. These results indicate that urea applied at the low N rate (98 kg N $ha^{-1}$;

24.5 kg N $ha^{-1}$ $application^{-1}$) to Kentucky bluegrass is a more appropriate than the high N rate (245 kg N $ha^{-1}$; 49 kg N $ha^{-1}$ $application^{-1}$). This research indicates that single dose, high rate N applications using a water-soluble N source, such as urea, should be avoided to help minimize the potential for $NO_3$-N leaching. Future research into the fate of N applied to mature turf stands should determine if:

1) $NO_3$-N concentrations in leachate continue to increase as the age of the turfstand increases
2) the soil does lose the ability to store additional fertilizer-N as it increases in age
3) reducing the N rate would lower the $NO_3$-N concentrations in leachate.

# APPENDIX

Table 1A. Mean organic matter concentration (%) of experimental soil.

| | N Treatment | |
|---|---|---|
| Depth (cm) | 98 kg N $ha^{-1}$ | 245 kg N $ha^{-1}$ |
| | ------------- % ------------- | |
| 0-5 | 5.7 | 5.3 |
| 5-10 | 3.0 | 2.5 |

Table 2A. Chemical and physical characteristics of experimental soil.

| Characteristics | Marlette |
|---|---|
| Textural Class | fine sandy loam |
| Taxanomy | Fine-loamy, mixed mesic Glossoboric Hapludalfs |
| Soil Partical Size | |
| Sand (%) | 65.9 |
| Silt (%) | 22.7 |
| Clay (%) | 11.4 |
| Bulk Densities (g $cm^{-3}$) | |
| 0-10 cm | 1.14 |
| 10-20 cm | 1.54 |
| 20-40 cm | 1.58 |
| pH | 7.4 |
| Phosphorus (ppm) | 17 |
| Potassium (ppm) | 78 |
| Calcium (ppm) | 1320 |
| Magnesium (ppm) | 330 |
| Cation Exchange Capacity (me/ 100 g) | 9.5 |

Table 3A. Weather and irrigation data for the lysimeter plot area, Hancock Turfgrass Research Center, East Lansing, MI (October 17, 2000 - 2002). Continued on pages 67-87.

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 10/17/2000 | 17.3 | 7.6 | ---- | ---- | 0.50 |
| 10/18/2000 | 18.7 | 5.5 | ---- | ---- | ---- |
| 10/19/2000 | 21.3 | 3.4 | ---- | ---- | ---- |
| 10/20/2000 | 23.4 | 10.3 | ---- | ---- | ---- |
| 10/21/2000 | 20.5 | 8.2 | ---- | ---- | ---- |
| 10/22/2000 | 20.1 | 5.4 | ---- | ---- | ---- |
| 10/23/2000 | 18.9 | 8.7 | ---- | 4.57 | ---- |
| 10/24/2000 | 18.1 | 14.8 | ---- | 12.70 | ---- |
| 10/25/2000 | 19.2 | 13.0 | ---- | ---- | ---- |
| 10/26/2000 | 23.3 | 14.3 | ---- | ---- | ---- |
| 10/27/2000 | 22.5 | 9.2 | ---- | 6.86 | ---- |
| 10/28/2000 | 10.6 | 0.9 | ---- | ---- | ---- |
| 10/29/2000 | 13.3 | -2.7 | ---- | ---- | ---- |
| 10/30/2000 | 17.1 | -2.2 | ---- | ---- | ---- |
| 10/31/2000 | 18.1 | -1.3 | ---- | ---- | ---- |
| 11/1/2000 | 19.1 | 5.2 | ---- | ---- | ---- |
| 11/2/2000 | 20.5 | 8.9 | ---- | ---- | ---- |
| 11/3/2000 | 16.1 | 4.3 | ---- | ---- | ---- |
| 11/4/2000 | 11.2 | -0.6 | ---- | ---- | ---- |
| 11/5/2000 | 15.4 | -0.6 | ---- | ---- | ---- |
| 11/6/2000 | 12.8 | 0.4 | ---- | ---- | ---- |
| 11/7/2000 | 13.6 | 7.0 | ---- | 2.03 | ---- |
| 11/8/2000 | 14.0 | 5.2 | ---- | ---- | ---- |
| 11/9/2000 | 16.4 | 6.6 | ---- | 14.73 | ---- |
| 11/10/2000 | 9.3 | 3.4 | ---- | 1.02 | ---- |
| 11/11/2000 | 6.5 | 3.1 | ---- | ---- | ---- |
| 11/12/2000 | 5.4 | 3.1 | ---- | ---- | ---- |
| 11/13/2000 | 5.6 | -0.5 | ---- | 13.72 | ---- |
| 11/14/2000 | 2.6 | -1.6 | ---- | 1.27 | ---- |
| 11/15/2000 | 2.6 | -1.1 | ---- | 3.81 | ---- |
| 11/16/2000 | 5.6 | 0.2 | ---- | 0.51 | ---- |
| 11/17/2000 | 2.3 | -2.3 | ---- | ---- | ---- |
| 11/18/2000 | -0.5 | -3.2 | ---- | 0.25 | ---- |
| 11/19/2000 | 3.3 | -2.5 | ---- | ---- | ---- |

[†] Evapotranspiration

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 11/20/2000 | 1.6 | -4.4 | ---- | ---- | ---- |
| 11/21/2000 | -2.5 | -7.5 | ---- | ---- | ---- |
| 11/22/2000 | -2.4 | -11.2 | ---- | ---- | ---- |
| 11/23/2000 | -2.0 | -11.6 | ---- | ---- | ---- |
| 11/24/2000 | 3.4 | -8.7 | ---- | ---- | ---- |
| 11/25/2000 | 5.4 | -4.1 | ---- | 1.52 | ---- |
| 11/26/2000 | 7.4 | 3.7 | ---- | 7.62 | ---- |
| 11/27/2000 | 5.4 | 1.2 | ---- | 0.25 | ---- |
| 11/28/2000 | 2.5 | -1.5 | ---- | 0.76 | ---- |
| 11/29/2000 | 1.2 | -2.3 | ---- | 1.78 | ---- |
| 11/30/2000 | 2.1 | -0.4 | ---- | 3.30 | ---- |
| 12/1/2000 | 0.1 | -5.3 | ---- | ---- | ---- |
| 12/2/2000 | -0.1 | -9.2 | ---- | ---- | ---- |
| 12/3/2000 | 1.9 | -11.5 | ---- | ---- | ---- |
| 12/4/2000 | 1.1 | -6.6 | ---- | ---- | ---- |
| 12/5/2000 | 1.0 | -11.7 | ---- | ---- | ---- |
| 12/6/2000 | -6.5 | -12.6 | ---- | ---- | ---- |
| 12/7/2000 | -5.9 | -10.4 | ---- | ---- | ---- |
| 12/8/2000 | -3.5 | -13.6 | ---- | 0.25 | ---- |
| 12/9/2000 | -3.1 | -16.2 | ---- | ---- | ---- |
| 12/10/2000 | 0.4 | -5.7 | ---- | ---- | ---- |
| 12/11/2000 | -1.6 | -7.2 | ---- | ---- | ---- |
| 12/12/2000 | -5.1 | -11.9 | ---- | ---- | ---- |
| 12/13/2000 | -7.3 | -19.1 | ---- | ---- | ---- |
| 12/14/2000 | -4.7 | -10.8 | ---- | ---- | ---- |
| 12/15/2000 | -3.2 | -12.1 | ---- | ---- | ---- |
| 12/16/2000 | 3.6 | -3.3 | ---- | 11.43 | ---- |
| 12/17/2000 | 0.7 | -14.5 | ---- | ---- | ---- |
| 12/18/2000 | -11.4 | -17.4 | ---- | ---- | ---- |
| 12/19/2000 | -9.0 | -17.4 | ---- | ---- | ---- |
| 12/20/2000 | -5.8 | -17.6 | ---- | ---- | ---- |
| 12/21/2000 | -5.2 | -19.2 | ---- | ---- | ---- |
| 12/22/2000 | -13.7 | -21.9 | ---- | ---- | ---- |
| 12/23/2000 | -7.3 | -17.6 | ---- | ---- | ---- |
| 12/24/2000 | -5.7 | -15.9 | ---- | ---- | ---- |
| 12/25/2000 | -7.5 | -25.9 | ---- | ---- | ---- |
| 12/26/2000 | -6.4 | -12.2 | ---- | ---- | ---- |
| 12/27/2000 | -6.9 | -16.7 | ---- | ---- | ---- |
| 12/28/2000 | -8.3 | -21.0 | ---- | ---- | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 12/29/2000 | -4.6 | -13.7 | ---- | ---- | ---- |
| 12/30/2000 | -3.6 | -9.4 | ---- | ---- | ---- |
| 12/31/2000 | -1.4 | -11.1 | ---- | 0.25 | ---- |
| 1/1/2001 | -4.3 | -19.6 | ---- | ---- | ---- |
| 1/2/2001 | -3.3 | -22.8 | ---- | ---- | ---- |
| 1/3/2001 | -3.9 | -13.9 | ---- | ---- | ---- |
| 1/4/2001 | -2.7 | -6.5 | ---- | ---- | ---- |
| 1/5/2001 | 2.2 | -3.3 | ---- | 1.78 | ---- |
| 1/6/2001 | 0.2 | -3.1 | ---- | ---- | ---- |
| 1/7/2001 | 1.0 | -4.3 | ---- | ---- | ---- |
| 1/8/2001 | -4.0 | -17.8 | ---- | ---- | ---- |
| 1/9/2001 | -1.9 | -19.6 | ---- | ---- | ---- |
| 1/10/2001 | 2.4 | -6.7 | ---- | ---- | ---- |
| 1/11/2001 | 4.3 | -4.5 | ---- | ---- | ---- |
| 1/12/2001 | 3.6 | -1.5 | ---- | ---- | ---- |
| 1/13/2001 | 1.3 | -1.3 | ---- | ---- | ---- |
| 1/14/2001 | 2.3 | -2.4 | ---- | ---- | ---- |
| 1/15/2001 | 2.5 | 0.4 | ---- | 0.25 | ---- |
| 1/16/2001 | 1.4 | -1.4 | ---- | ---- | ---- |
| 1/17/2001 | -0.7 | -3.5 | ---- | ---- | ---- |
| 1/18/2001 | -1.6 | -5.1 | ---- | ---- | ---- |
| 1/19/2001 | -2.0 | -13.3 | ---- | ---- | ---- |
| 1/20/2001 | -3.9 | -17.8 | ---- | ---- | ---- |
| 1/21/2001 | -3.7 | -12.0 | ---- | ---- | ---- |
| 1/22/2001 | -0.2 | -9.5 | ---- | ---- | ---- |
| 1/23/2001 | 1.1 | -3.0 | ---- | ---- | ---- |
| 1/24/2001 | 1.0 | -6.4 | ---- | ---- | ---- |
| 1/25/2001 | -2.1 | -8.0 | ---- | ---- | ---- |
| 1/26/2001 | -1.7 | -9.5 | ---- | ---- | ---- |
| 1/27/2001 | -2.3 | -9.4 | ---- | ---- | ---- |
| 1/28/2001 | -3.7 | -9.5 | ---- | ---- | ---- |
| 1/29/2001 | 2.1 | -10.2 | ---- | 6.10 | ---- |
| 1/30/2001 | 6.0 | -0.1 | ---- | 6.35 | ---- |
| 1/31/2001 | 2.5 | -0.2 | ---- | 4.06 | ---- |
| 2/1/2001 | 0.8 | -3.3 | ---- | ---- | ---- |
| 2/2/2001 | -3.2 | -11.3 | ---- | ---- | ---- |
| 2/3/2001 | -3.9 | -13.1 | ---- | ---- | ---- |
| 2/4/2001 | 1.8 | -4.1 | ---- | 1.02 | ---- |
| 2/5/2001 | 1.3 | -2.9 | ---- | 1.27 | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 2/6/2001 | -0.4 | -3.1 | ---- | 0.25 | ---- |
| 2/7/2001 | 2.0 | -8.9 | ---- | ---- | ---- |
| 2/8/2001 | 6.6 | -1.9 | ---- | 5.33 | ---- |
| 2/9/2001 | 10.7 | -4.8 | ---- | 27.43 | ---- |
| 2/10/2001 | -4.2 | -9.8 | ---- | ---- | ---- |
| 2/11/2001 | -4.9 | -13.5 | ---- | ---- | ---- |
| 2/12/2001 | 2.5 | -7.8 | ---- | ---- | ---- |
| 2/13/2001 | 1.4 | 0.0 | ---- | ---- | ---- |
| 2/14/2001 | 2.2 | -3.3 | ---- | 3.56 | ---- |
| 2/15/2001 | -1.7 | -6.1 | ---- | ---- | ---- |
| 2/16/2001 | -0.4 | -7.2 | ---- | 0.51 | ---- |
| 2/17/2001 | -6.9 | -11.9 | ---- | ---- | ---- |
| 2/18/2001 | -3.3 | -12.1 | ---- | ---- | ---- |
| 2/19/2001 | 3.2 | -5.5 | ---- | ---- | ---- |
| 2/20/2001 | 2.3 | -5.7 | ---- | ---- | ---- |
| 2/21/2001 | -5.7 | -12.1 | ---- | ---- | ---- |
| 2/22/2001 | -2.1 | -12.8 | ---- | ---- | ---- |
| 2/23/2001 | -0.7 | -5.9 | ---- | ---- | ---- |
| 2/24/2001 | 2.4 | -5.3 | ---- | 24.64 | ---- |
| 2/25/2001 | 11.5 | -1.1 | ---- | 5.33 | ---- |
| 2/26/2001 | 3.4 | -1.4 | ---- | ---- | ---- |
| 2/27/2001 | 0.0 | -8.4 | ---- | ---- | ---- |
| 2/28/2001 | -2.0 | -10.0 | ---- | ---- | ---- |
| 3/1/2001 | 4.4 | -6.8 | ---- | ---- | ---- |
| 3/2/2001 | 3.6 | -1.6 | ---- | ---- | ---- |
| 3/3/2001 | 8.4 | -5.6 | ---- | ---- | ---- |
| 3/4/2001 | 1.5 | -5.3 | ---- | ---- | ---- |
| 3/5/2001 | -3.6 | -7.9 | ---- | ---- | ---- |
| 3/6/2001 | -0.3 | -6.9 | ---- | 0.25 | ---- |
| 3/7/2001 | 4.1 | -3.1 | ---- | ---- | ---- |
| 3/8/2001 | 1.6 | -3.5 | ---- | ---- | ---- |
| 3/9/2001 | -0.6 | -5.1 | ---- | 0.25 | ---- |
| 3/10/2001 | 6.0 | -8.5 | ---- | ---- | ---- |
| 3/11/2001 | 4.9 | -2.8 | ---- | 1.52 | ---- |
| 3/12/2001 | 4.5 | -4.6 | ---- | 0.51 | ---- |
| 3/13/2001 | 5.4 | -0.2 | ---- | 0.76 | ---- |
| 3/14/2001 | 9.3 | -0.0 | ---- | ---- | ---- |
| 3/15/2001 | 5.0 | -0.0 | ---- | 2.03 | ---- |
| 3/16/2001 | 2.8 | -2.1 | ---- | 0.25 | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 3/17/2001 | 3.0 | -4.1 | ---- | ---- | ---- |
| 3/18/2001 | 8.5 | -7.3 | ---- | ---- | ---- |
| 3/19/2001 | 9.5 | -6.1 | ---- | ---- | ---- |
| 3/20/2001 | 12.5 | -1.3 | ---- | ---- | ---- |
| 3/21/2001 | 13.2 | -3.9 | ---- | ---- | ---- |
| 3/22/2001 | 12.8 | -2.5 | ---- | ---- | ---- |
| 3/23/2001 | 10.8 | -1.0 | ---- | ---- | ---- |
| 3/24/2001 | 1.8 | -6.1 | ---- | 0.25 | ---- |
| 3/25/2001 | -4.3 | -12.2 | ---- | 0.25 | ---- |
| 3/26/2001 | -2.1 | -14.5 | ---- | ---- | ---- |
| 3/27/2001 | 1.2 | -9.2 | ---- | ---- | ---- |
| 3/28/2001 | 7.6 | -7.8 | ---- | ---- | ---- |
| 3/29/2001 | 7.8 | 0.9 | ---- | ---- | ---- |
| 3/30/2001 | 9.8 | 0.6 | ---- | ---- | ---- |
| 3/31/2001 | 11.4 | 0.8 | ---- | ---- | ---- |
| 4/1/2001 | 3.1 | -0.2 | 0.02 | 6.10 | ---- |
| 4/2/2001 | 12.0 | -3.1 | 0.09 | ---- | ---- |
| 4/3/2001 | 10.4 | 1.5 | 0.06 | 0.25 | ---- |
| 4/4/2001 | 13.5 | -3.2 | 0.08 | ---- | ---- |
| 4/5/2001 | 16.2 | -2.2 | 0.09 | ---- | ---- |
| 4/6/2001 | 18.4 | 7.0 | 0.03 | 12.19 | ---- |
| 4/7/2001 | 24.7 | 7.1 | 0.09 | 2.29 | ---- |
| 4/8/2001 | 21.9 | 11.3 | 0.21 | ---- | ---- |
| 4/9/2001 | 11.8 | 4.3 | 0.10 | 5.59 | ---- |
| 4/10/2001 | 11.2 | 4.1 | 0.04 | ---- | ---- |
| 4/11/2001 | 19.6 | 8.1 | 0.05 | ---- | ---- |
| 4/12/2001 | 21.5 | 8.6 | 0.10 | ---- | ---- |
| 4/13/2001 | 15.7 | 4.4 | 0.14 | ---- | ---- |
| 4/14/2001 | 16.7 | -1.0 | 0.06 | ---- | ---- |
| 4/15/2001 | 10.2 | 2.2 | 0.07 | ---- | ---- |
| 4/16/2001 | 5.9 | -1.7 | 0.06 | ---- | ---- |
| 4/17/2001 | 8.1 | -3.0 | 0.09 | 0.51 | ---- |
| 4/18/2001 | 11.0 | -1.5 | 0.12 | ---- | ---- |
| 4/19/2001 | 15.4 | -3.3 | 0.10 | ---- | ---- |
| 4/20/2001 | 12.7 | 7.9 | 0.07 | 10.41 | ---- |
| 4/21/2001 | 23.2 | 12.5 | 0.08 | 12.45 | ---- |
| 4/22/2001 | 19.8 | 8.9 | 0.08 | 10.67 | ---- |
| 4/23/2001 | 24.5 | 8.8 | 0.14 | 10.92 | ---- |
| 4/24/2001 | 12.7 | 2.8 | 0.15 | 0.25 | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 4/25/2001 | 16.6 | 0.6 | 0.10 | ---- | ---- |
| 4/26/2001 | 20.3 | 5.4 | 0.16 | 0.25 | ---- |
| 4/27/2001 | 17.7 | 8.8 | 0.14 | 0.25 | ---- |
| 4/28/2001 | 16.9 | 0.7 | 0.12 | ---- | ---- |
| 4/29/2001 | 19.4 | 2.2 | 0.14 | ---- | 0.38 |
| 4/30/2001 | 27.3 | 5.8 | 0.18 | ---- | ---- |
| 5/1/2001 | 26.5 | 15.3 | 0.18 | ---- | ---- |
| 5/2/2001 | 27.9 | 16.8 | 0.17 | ---- | 0.69 |
| 5/3/2001 | 28.6 | 16.7 | 0.00 | ---- | ---- |
| 5/4/2001 | 24.7 | 11.9 | 0.00 | 0.51 | ---- |
| 5/5/2001 | 20.1 | 10.0 | 0.00 | ---- | ---- |
| 5/6/2001 | 21.3 | 9.4 | 0.18 | ---- | ---- |
| 5/7/2001 | 25.8 | 11.9 | 0.16 | 10.92 | 0.50 |
| 5/8/2001 | 24.6 | 10.8 | 0.13 | 1.52 | ---- |
| 5/9/2001 | 25.3 | 11.9 | 0.17 | ---- | ---- |
| 5/10/2001 | 25.8 | 14.8 | 0.12 | 4.57 | ---- |
| 5/11/2001 | 19.3 | 9.2 | 0.05 | 4.83 | ---- |
| 5/12/2001 | 15.8 | 5.0 | 0.00 | ---- | ---- |
| 5/13/2001 | 19.1 | 1.2 | 0.12 | ---- | ---- |
| 5/14/2001 | 19.3 | 4.0 | 0.09 | 0.25 | ---- |
| 5/15/2001 | 15.7 | 11.2 | 0.02 | 54.10 | ---- |
| 5/16/2001 | 20.3 | 11.9 | 0.06 | 33.02 | ---- |
| 5/17/2001 | 28.1 | 15.9 | 0.13 | ---- | ---- |
| 5/18/2001 | 24.3 | 12.1 | 0.14 | ---- | ---- |
| 5/19/2001 | 24.4 | 9.1 | 0.17 | ---- | ---- |
| 5/20/2001 | 24.4 | 10.1 | 0.14 | ---- | ---- |
| 5/21/2001 | 23.5 | 14.2 | 0.06 | 1.02 | ---- |
| 5/22/2001 | 17.9 | 8.1 | 0.13 | ---- | ---- |
| 5/23/2001 | 18.5 | 7.1 | 0.10 | ---- | ---- |
| 5/24/2001 | 15.3 | 7.7 | 0.05 | 2.03 | ---- |
| 5/25/2001 | 17.5 | 5.4 | 0.07 | 8.38 | ---- |
| 5/26/2001 | 17.0 | 7.3 | 0.08 | 4.32 | ---- |
| 5/27/2001 | 12.9 | 10.0 | 0.03 | 16.00 | ---- |
| 5/28/2001 | 21.0 | 9.6 | 0.10 | 3.30 | ---- |
| 5/29/2001 | 18.5 | 9.5 | 0.09 | ---- | ---- |
| 5/30/2001 | 18.3 | 3.2 | 0.14 | ---- | ---- |
| 5/31/2001 | 19.8 | 2.7 | 0.10 | ---- | ---- |
| 6/1/2001 | 14.2 | 8.7 | 0.09 | 7.37 | ---- |
| 6/2/2001 | 17.6 | 8.1 | 0.07 | 14.99 | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 6/3/2001 | 16.2 | 7.8 | 0.06 | ---- | ---- |
| 6/4/2001 | 18.5 | 9.4 | 0.08 | ---- | 0.50 |
| 6/5/2001 | 17.9 | 6.4 | 0.06 | 0.25 | ---- |
| 6/6/2001 | 16.0 | 12.1 | 0.04 | 1.02 | ---- |
| 6/7/2001 | 22.4 | 8.7 | 0.13 | ---- | ---- |
| 6/8/2001 | 25.0 | 7.5 | 0.14 | ---- | ---- |
| 6/9/2001 | 25.6 | 8.8 | 0.15 | ---- | ---- |
| 6/10/2001 | 26.3 | 12.7 | 0.13 | 4.06 | ---- |
| 6/11/2001 | 28.2 | 16.9 | 0.14 | 1.02 | ---- |
| 6/12/2001 | 28.1 | 17.9 | 0.15 | 3.81 | ---- |
| 6/13/2001 | 32.7 | 16.3 | 0.16 | ---- | 0.41 |
| 6/14/2001 | 32.4 | 24.4 | 0.18 | ---- | ---- |
| 6/15/2001 | 31.6 | 17.8 | 0.15 | 21.08 | 0.41 |
| 6/16/2001 | 26.5 | 14.0 | 0.14 | 0.25 | ---- |
| 6/17/2001 | 26.9 | 14.6 | 0.18 | ---- | ---- |
| 6/18/2001 | 28.7 | 15.2 | 0.14 | 5.59 | ---- |
| 6/19/2001 | 29.3 | 21.6 | 0.20 | ---- | ---- |
| 6/20/2001 | 24.9 | 14.7 | 0.15 | ---- | ---- |
| 6/21/2001 | 18.5 | 12.6 | 0.04 | 19.81 | ---- |
| 6/22/2001 | 23.9 | 13.1 | 0.14 | 5.59 | ---- |
| 6/23/2001 | 25.5 | 12.3 | 0.12 | ---- | ---- |
| 6/24/2001 | 27.1 | 11.4 | 0.17 | ---- | ---- |
| 6/25/2001 | 28.6 | 12.3 | 0.16 | ---- | ---- |
| 6/26/2001 | 28.6 | 13.5 | 0.17 | ---- | ---- |
| 6/27/2001 | 29.9 | 16.1 | 0.16 | ---- | 0.84 |
| 6/28/2001 | 30.8 | 18.5 | 0.17 | ---- | ---- |
| 6/29/2001 | 29.7 | 16.5 | 0.15 | ---- | 0.84 |
| 6/30/2001 | 29.8 | 17.8 | 0.15 | ---- | ---- |
| 7/1/2001 | 24.7 | 9.6 | 0.15 | ---- | ---- |
| 7/2/2001 | 21.5 | 4.0 | 0.16 | ---- | ---- |
| 7/3/2001 | 22.6 | 13.1 | 0.10 | 0.76 | 0.50 |
| 7/4/2001 | 28.0 | 14.7 | 0.14 | ---- | ---- |
| 7/5/2001 | 22.4 | 11.0 | 0.18 | ---- | 1.27 |
| 7/6/2001 | 24.7 | 5.7 | 0.15 | ---- | ---- |
| 7/7/2001 | 24.9 | 14.4 | 0.10 | 0.25 | ---- |
| 7/8/2001 | 31.3 | 19.1 | 0.17 | ---- | ---- |
| 7/9/2001 | 31.6 | 16.8 | 0.15 | ---- | 1.14 |
| 7/10/2001 | 31.1 | 19.1 | 0.17 | 1.27 | ---- |
| 7/11/2001 | 24.9 | 13.7 | 0.22 | ---- | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 7/12/2001 | 25.8 | 12.5 | 0.14 | ---- | 1.37 |
| 7/13/2001 | 25.9 | 9.1 | 0.17 | ---- | ---- |
| 7/14/2001 | 28.8 | 9.1 | 0.18 | ---- | ---- |
| 7/15/2001 | 30.9 | 11.4 | 0.14 | ---- | ---- |
| 7/16/2001 | 30.6 | 14.3 | 0.15 | ---- | 1.65 |
| 7/17/2001 | 29.7 | 15.5 | 0.11 | 0.51 | ---- |
| 7/18/2001 | 30.2 | 16.2 | 0.12 | 0.25 | ---- |
| 7/19/2001 | 31.0 | 16.1 | 0.14 | ---- | 0.94 |
| 7/20/2001 | 32.6 | 17.6 | 0.15 | ---- | ---- |
| 7/21/2001 | 28.6 | 20.5 | 0.12 | 4.06 | ---- |
| 7/22/2001 | 32.6 | 19.4 | 0.15 | ---- | ---- |
| 7/23/2001 | 28.4 | 22.2 | 0.09 | 1.02 | 0.94 |
| 7/24/2001 | 31.8 | 21.1 | 0.14 | ---- | ---- |
| 7/25/2001 | 23.4 | 16.9 | 0.09 | 7.11 | ---- |
| 7/26/2001 | 25.2 | 13.5 | 0.14 | ---- | 0.84 |
| 7/27/2001 | 25.8 | 8.9 | 0.16 | ---- | ---- |
| 7/28/2001 | 28.6 | 10.6 | 0.14 | ---- | ---- |
| 7/29/2001 | 30.6 | 17.0 | 0.13 | 8.64 | ---- |
| 7/30/2001 | 29.3 | 16.5 | 0.14 | ---- | ---- |
| 7/31/2001 | 31.9 | 18.9 | 0.14 | ---- | ---- |
| 8/1/2001 | 32.0 | 19.7 | 0.14 | ---- | 0.84 |
| 8/2/2001 | 29.0 | 22.1 | 0.09 | ---- | ---- |
| 8/3/2001 | 30.0 | 18.5 | 0.15 | ---- | ---- |
| 8/4/2001 | 30.8 | 14.6 | 0.16 | ---- | ---- |
| 8/5/2001 | 32.9 | 14.6 | 0.16 | ---- | ---- |
| 8/6/2001 | 32.8 | 15.7 | 0.17 | ---- | 2.54 |
| 8/7/2001 | 33.6 | 21.9 | 0.16 | ---- | ---- |
| 8/8/2001 | 35.4 | 19.7 | 0.16 | ---- | 0.84 |
| 8/9/2001 | 33.0 | 20.4 | 0.15 | 4.83 | ---- |
| 8/10/2001 | 26.4 | 15.3 | 0.18 | 0.51 | ---- |
| 8/11/2001 | 28.2 | 12.3 | 0.14 | ---- | ---- |
| 8/12/2001 | 28.4 | 14.9 | 0.11 | ---- | ---- |
| 8/13/2001 | 26.1 | 14.1 | 0.15 | ---- | 1.17 |
| 8/14/2001 | 25.9 | 8.9 | 0.14 | ---- | ---- |
| 8/15/2001 | 27.0 | 9.5 | 0.13 | ---- | ---- |
| 8/16/2001 | 21.9 | 16.3 | 0.05 | 16.26 | ---- |
| 8/17/2001 | 22.4 | 14.5 | 0.07 | ---- | ---- |
| 8/18/2001 | 25.1 | 14.3 | 0.08 | 3.30 | ---- |
| 8/19/2001 | 22.4 | 16.2 | 0.06 | 2.54 | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 8/20/2001 | 25.3 | 15.4 | 0.11 | ---- | ---- |
| 8/21/2001 | 26.6 | 9.7 | 0.11 | ---- | ---- |
| 8/22/2001 | 21.4 | 15.5 | 0.05 | 12.70 | ---- |
| 8/23/2001 | 26.6 | 18.1 | 0.06 | ---- | ---- |
| 8/24/2001 | 26.4 | 17.7 | 0.10 | ---- | ---- |
| 8/25/2001 | 25.9 | 17.9 | 0.06 | ---- | ---- |
| 8/26/2001 | 26.8 | 17.1 | 0.08 | ---- | ---- |
| 8/27/2001 | 28.2 | 13.1 | 0.12 | ---- | ---- |
| 8/28/2001 | 26.2 | 13.4 | 0.14 | 0.76 | 0.66 |
| 8/29/2001 | 27.2 | 10.2 | 0.12 | ---- | ---- |
| 8/30/2001 | 29.2 | 13.2 | 0.14 | ---- | ---- |
| 8/31/2001 | 25.4 | 12.9 | 0.11 | ---- | ---- |
| 9/1/2001 | 22.1 | 6.4 | 0.13 | ---- | ---- |
| 9/2/2001 | 25.2 | 6.8 | 0.12 | ---- | ---- |
| 9/3/2001 | 28.2 | 12.8 | 0.12 | ---- | ---- |
| 9/4/2001 | 23.0 | 10.8 | 0.13 | ---- | 1.91 |
| 9/5/2001 | 25.0 | 7.5 | 0.11 | ---- | ---- |
| 9/6/2001 | 27.8 | 8.7 | 0.11 | ---- | 0.69 |
| 9/7/2001 | 30.6 | 18.0 | 0.13 | 3.56 | ---- |
| 9/8/2001 | 28.5 | 18.7 | 0.10 | 10.16 | ---- |
| 9/9/2001 | 25.4 | 15.4 | 0.06 | 17.53 | ---- |
| 9/10/2001 | 22.9 | 12.3 | 0.11 | ---- | ---- |
| 9/11/2001 | 23.9 | 9.4 | 0.10 | ---- | ---- |
| 9/12/2001 | 26.9 | 10.2 | 0.12 | ---- | ---- |
| 9/13/2001 | 18.7 | 8.1 | 0.09 | 2.03 | 0.50 |
| 9/14/2001 | 17.7 | 4.8 | 0.08 | ---- | ---- |
| 9/15/2001 | 18.8 | 5.0 | 0.07 | ---- | ---- |
| 9/16/2001 | 22.0 | 4.8 | 0.09 | ---- | ---- |
| 9/17/2001 | 22.1 | 7.0 | 0.06 | ---- | ---- |
| 9/18/2001 | 23.6 | 10.6 | 0.06 | ---- | ---- |
| 9/19/2001 | 19.8 | 14.5 | 0.02 | 23.11 | ---- |
| 9/20/2001 | 19.1 | 12.2 | 0.06 | 3.81 | ---- |
| 9/21/2001 | 19.8 | 11.1 | 0.04 | 19.30 | ---- |
| 9/22/2001 | 21.7 | 8.3 | 0.06 | ---- | ---- |
| 9/23/2001 | 22.0 | 10.0 | 0.05 | 13.97 | ---- |
| 9/24/2001 | 14.7 | 5.8 | 0.07 | 0.51 | ---- |
| 9/25/2001 | 6.6 | 3.6 | 0.03 | 6.10 | ---- |
| 9/26/2001 | 10.5 | 4.8 | 0.02 | 2.03 | ---- |
| 9/27/2001 | 14.5 | 7.2 | 0.06 | ---- | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 9/28/2001 | 15.4 | 8.2 | 0.04 | ---- | ---- |
| 9/29/2001 | 19.8 | 3.9 | 0.07 | ---- | ---- |
| 9/30/2001 | 21.9 | 1.8 | 0.00 | ---- | ---- |
| 10/1/2001 | 22.6 | 5.6 | 0.06 | ---- | ---- |
| 10/2/2001 | 24.4 | 7.5 | 0.08 | ---- | ---- |
| 10/3/2001 | 25.7 | 15.1 | 0.13 | ---- | ---- |
| 10/4/2001 | 16.1 | 8.8 | 0.06 | 12.45 | ---- |
| 10/5/2001 | 9.7 | 6.0 | 0.02 | 19.05 | ---- |
| 10/6/2001 | 8.4 | 1.4 | 0.05 | 0.25 | ---- |
| 10/7/2001 | 9.7 | -2.5 | 0.04 | ---- | ---- |
| 10/8/2001 | 14.3 | -3.1 | 0.06 | ---- | 0.50 |
| 10/9/2001 | 21.3 | 7.4 | 0.10 | ---- | ---- |
| 10/10/2001 | 18.5 | 11.9 | 0.06 | 1.02 | ---- |
| 10/11/2001 | 17.3 | 10.8 | 0.02 | 0.76 | ---- |
| 10/12/2001 | 18.2 | 10.7 | 0.02 | 17.02 | ---- |
| 10/13/2001 | 21.3 | 11.4 | 0.04 | 1.02 | ---- |
| 10/14/2001 | 20.6 | 7.8 | 0.02 | 13.46 | ---- |
| 10/15/2001 | 13.9 | 6.1 | 0.05 | 0.25 | ---- |
| 10/16/2001 | 8.7 | 4.2 | 0.02 | 41.15 | ---- |
| 10/17/2001 | 9.4 | -1.1 | 0.05 | ---- | ---- |
| 10/18/2001 | 15.3 | -2.2 | 0.06 | ---- | ---- |
| 10/19/2001 | 14.6 | 2.8 | 0.06 | ---- | ---- |
| 10/20/2001 | 18.9 | 5.3 | ---- | ---- | ---- |
| 10/21/2001 | 17.7 | 5.4 | 0.05 | ---- | ---- |
| 10/22/2001 | 18.5 | 4.4 | 0.05 | 2.79 | ---- |
| 10/23/2001 | 18.6 | 11.9 | 0.03 | 4.83 | ---- |
| 10/24/2001 | 21.2 | 8.5 | 0.04 | 13.72 | ---- |
| 10/25/2001 | 9.2 | 0.9 | 0.12 | 2.03 | ---- |
| 10/26/2001 | 5.2 | 0.8 | 0.02 | 4.57 | ---- |
| 10/27/2001 | 4.7 | 0.4 | 0.02 | ---- | ---- |
| 10/28/2001 | 10.4 | -3.7 | 0.04 | ---- | ---- |
| 10/29/2001 | 13.2 | 4.2 | 0.06 | ---- | ---- |
| 10/30/2001 | 8.4 | 2.3 | 0.03 | 1.52 | ---- |
| 10/31/2001 | 19.3 | 5.0 | 0.06 | 0.76 | ---- |
| 11/1/2001 | 18.3 | 12.1 | 0.10 | ---- | ---- |
| 11/2/2001 | 17.8 | 7.9 | 0.04 | 11.94 | ---- |
| 11/3/2001 | 14.9 | 3.4 | 0.06 | ---- | ---- |
| 11/4/2001 | 14.5 | 3.6 | 0.06 | ---- | ---- |
| 11/5/2001 | 9.6 | -2.5 | 0.04 | ---- | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 11/6/2001 | 15.6 | -2.6 | 0.05 | ---- | ---- |
| 11/7/2001 | 16.3 | 8.4 | 0.06 | ---- | ---- |
| 11/8/2001 | 14.7 | 2.0 | 0.03 | 2.29 | ---- |
| 11/9/2001 | 10.2 | -2.8 | 0.03 | ---- | ---- |
| 11/10/2001 | 12.8 | 2.7 | 0.06 | ---- | ---- |
| 11/11/2001 | 6.4 | -3.1 | 0.06 | ---- | ---- |
| 11/12/2001 | 11.5 | -4.5 | 0.03 | 6.35 | ---- |
| 11/13/2001 | 15.9 | 1.7 | 0.05 | ---- | ---- |
| 11/14/2001 | 14.7 | 10.1 | 0.04 | 0.25 | ---- |
| 11/15/2001 | 18.0 | 10.7 | 0.03 | 7.62 | ---- |
| 11/16/2001 | 15.8 | 2.9 | 0.03 | ---- | ---- |
| 11/17/2001 | 16.3 | 0.8 | 0.03 | 0.25 | ---- |
| 11/18/2001 | 16.2 | 4.6 | 0.02 | ---- | ---- |
| 11/19/2001 | 14.1 | 1.4 | 0.01 | 3.56 | ---- |
| 11/20/2001 | 5.4 | -1.0 | 0.02 | ---- | ---- |
| 11/21/2001 | 9.9 | -0.2 | 0.04 | ---- | ---- |
| 11/22/2001 | 13.5 | -1.2 | 0.03 | ---- | ---- |
| 11/23/2001 | 16.1 | 1.0 | 0.05 | ---- | ---- |
| 11/24/2001 | 17.1 | 11.2 | 0.09 | 12.70 | ---- |
| 11/25/2001 | 13.3 | 5.2 | 0.05 | 0.51 | ---- |
| 11/26/2001 | 7.7 | 4.7 | 0.02 | ---- | ---- |
| 11/27/2001 | 12.9 | 4.2 | 0.02 | 2.03 | ---- |
| 11/28/2001 | 5.0 | 3.0 | 0.03 | 1.02 | ---- |
| 11/29/2001 | 6.0 | 3.2 | 0.00 | 9.65 | ---- |
| 11/30/2001 | 11.5 | 4.1 | 0.01 | 12.70 | ---- |
| 12/1/2001 | 6.5 | 1.4 | ---- | 0.51 | ---- |
| 12/2/2001 | 8.6 | 0.0 | ---- | ---- | ---- |
| 12/3/2001 | 13.1 | 5.2 | ---- | ---- | ---- |
| 12/4/2001 | 15.2 | 9.1 | ---- | 0.51 | ---- |
| 12/5/2001 | 20.7 | 12.1 | ---- | ---- | ---- |
| 12/6/2001 | 15.8 | -0.8 | ---- | 0.51 | ---- |
| 12/7/2001 | 4.8 | -1.3 | ---- | ---- | ---- |
| 12/8/2001 | 4.9 | -0.2 | ---- | 1.27 | ---- |
| 12/9/2001 | 4.7 | -1.8 | ---- | ---- | ---- |
| 12/10/2001 | 7.9 | -3.7 | ---- | ---- | ---- |
| 12/11/2001 | 9.7 | -4.4 | ---- | ---- | ---- |
| 12/12/2001 | 8.1 | 1.0 | ---- | 5.59 | ---- |
| 12/13/2001 | 8.9 | 4.4 | ---- | 0.51 | ---- |
| 12/14/2001 | 4.8 | -0.2 | ---- | 7.62 | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 12/15/2001 | 0.6 | -1.7 | ---- | 4.32 | ---- |
| 12/16/2001 | 5.6 | -0.2 | ---- | 0.76 | ---- |
| 12/17/2001 | 5.7 | 3.5 | ---- | 4.32 | ---- |
| 12/18/2001 | 7.2 | 1.9 | ---- | ---- | ---- |
| 12/19/2001 | 4.0 | -1.5 | ---- | 4.06 | ---- |
| 12/20/2001 | 2.7 | -3.1 | ---- | ---- | ---- |
| 12/21/2001 | 3.3 | -6.3 | ---- | ---- | ---- |
| 12/22/2001 | 6.6 | -3.6 | ---- | 0.25 | ---- |
| 12/23/2001 | 7.9 | -4.7 | ---- | 0.51 | ---- |
| 12/24/2001 | -3.2 | -7.3 | ---- | ---- | ---- |
| 12/25/2001 | -3.8 | -8.8 | ---- | ---- | ---- |
| 12/26/2001 | -5.7 | -11.1 | ---- | ---- | ---- |
| 12/27/2001 | -4.1 | -9.9 | ---- | ---- | ---- |
| 12/28/2001 | -3.3 | -8.2 | ---- | 0.51 | ---- |
| 12/29/2001 | -5.4 | -9.8 | ---- | ---- | ---- |
| 12/30/2001 | -6.4 | -11.9 | ---- | ---- | ---- |
| 12/31/2001 | -5.5 | -9.5 | ---- | ---- | ---- |
| 1/1/2002 | -0.1 | -15.9 | ---- | 0.51 | ---- |
| 1/2/2002 | -1.5 | -15.3 | ---- | ---- | ---- |
| 1/3/2002 | -2.6 | -12.8 | ---- | ---- | ---- |
| 1/4/2002 | 0.4 | -9.8 | ---- | ---- | ---- |
| 1/5/2002 | 0.8 | -2.0 | ---- | ---- | ---- |
| 1/6/2002 | 1.2 | -3.9 | ---- | 1.78 | ---- |
| 1/7/2002 | -3.6 | -10.6 | ---- | ---- | ---- |
| 1/8/2002 | 2.4 | -7.4 | ---- | ---- | ---- |
| 1/9/2002 | 7.0 | 1.4 | ---- | ---- | ---- |
| 1/10/2002 | 5.6 | -0.4 | ---- | ---- | ---- |
| 1/11/2002 | 4.2 | -0.1 | ---- | ---- | ---- |
| 1/12/2002 | 3.5 | -0.8 | ---- | 0.51 | ---- |
| 1/13/2002 | 4.0 | -3.1 | ---- | 0.25 | ---- |
| 1/14/2002 | 7.7 | -0.7 | ---- | 3.81 | ---- |
| 1/15/2002 | 1.2 | -2.0 | ---- | 1.78 | ---- |
| 1/16/2002 | 0.4 | -2.3 | ---- | ---- | ---- |
| 1/17/2002 | -0.4 | -6.5 | ---- | ---- | ---- |
| 1/18/2002 | -4.7 | -12.8 | ---- | 0.25 | ---- |
| 1/19/2002 | -2.1 | -12.6 | ---- | 0.51 | ---- |
| 1/20/2002 | 1.2 | -3.9 | ---- | ---- | ---- |
| 1/21/2002 | 1.4 | -4.4 | ---- | 0.51 | ---- |
| 1/22/2002 | 10.1 | -4.6 | ---- | ---- | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 1/23/2002 | 8.6 | 2.3 | ---- | 0.51 | ---- |
| 1/24/2002 | 2.3 | -4.6 | ---- | ---- | ---- |
| 1/25/2002 | 7.0 | -2.6 | ---- | ---- | ---- |
| 1/26/2002 | 11.1 | 1.0 | ---- | ---- | ---- |
| 1/27/2002 | 13.7 | 2.8 | ---- | ---- | ---- |
| 1/28/2002 | 13.5 | 1.5 | ---- | ---- | ---- |
| 1/29/2002 | 1.8 | -1.7 | ---- | ---- | ---- |
| 1/30/2002 | -1.4 | -3.5 | ---- | ---- | ---- |
| 1/31/2002 | -1.1 | -4.5 | ---- | ---- | ---- |
| 2/1/2002 | 2.0 | -4.2 | ---- | 11.18 | ---- |
| 2/2/2002 | 0.3 | -9.0 | ---- | ---- | ---- |
| 2/3/2002 | 2.6 | -4.4 | ---- | ---- | ---- |
| 2/4/2002 | -4.3 | -14.6 | ---- | ---- | ---- |
| 2/5/2002 | -1.0 | -15.5 | ---- | ---- | ---- |
| 2/6/2002 | 4.7 | -3.9 | ---- | ---- | ---- |
| 2/7/2002 | 3.0 | -2.9 | ---- | ---- | ---- |
| 2/8/2002 | 5.7 | -3.5 | ---- | ---- | ---- |
| 2/9/2002 | 6.6 | -3.6 | ---- | ---- | ---- |
| 2/10/2002 | 8.1 | -4.7 | ---- | 0.25 | ---- |
| 2/11/2002 | 0.8 | -10.4 | ---- | ---- | ---- |
| 2/12/2002 | 3.6 | -6.2 | ---- | ---- | ---- |
| 2/13/2002 | -0.7 | -10.8 | ---- | ---- | ---- |
| 2/14/2002 | 6.0 | -3.9 | ---- | ---- | ---- |
| 2/15/2002 | 6.9 | 0.5 | ---- | ---- | ---- |
| 2/16/2002 | 2.0 | -2.5 | ---- | 4.06 | ---- |
| 2/17/2002 | 0.3 | -7.6 | ---- | ---- | ---- |
| 2/18/2002 | 6.6 | -8.0 | ---- | ---- | ---- |
| 2/19/2002 | 7.2 | 1.2 | ---- | 3.56 | ---- |
| 2/20/2002 | 11.4 | 2.8 | ---- | 13.72 | ---- |
| 2/21/2002 | 2.9 | -4.4 | ---- | 3.56 | ---- |
| 2/22/2002 | -0.5 | -7.8 | ---- | ---- | ---- |
| 2/23/2002 | 5.0 | -9.5 | ---- | ---- | ---- |
| 2/24/2002 | 13.8 | 1.9 | ---- | ---- | ---- |
| 2/25/2002 | 12.7 | -1.4 | ---- | 1.02 | ---- |
| 2/26/2002 | -1.0 | -5.5 | ---- | 0.25 | ---- |
| 2/27/2002 | -2.3 | -9.2 | ---- | 1.27 | ---- |
| 2/28/2002 | -2.8 | -11.6 | ---- | ---- | ---- |
| 3/1/2002 | 1.0 | -4.7 | ---- | 0.51 | ---- |
| 3/2/2002 | 1.8 | -2.2 | ---- | 14.22 | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 3/3/2002 | 0.3 | -11.6 | ---- | 0.76 | ---- |
| 3/4/2002 | -10.5 | -16.4 | ---- | 0.25 | ---- |
| 3/5/2002 | -1.5 | -12.9 | ---- | ---- | ---- |
| 3/6/2002 | 5.6 | -5.7 | ---- | 0.51 | ---- |
| 3/7/2002 | 0.1 | -2.9 | ---- | ---- | ---- |
| 3/8/2002 | 15.7 | -1.0 | ---- | 2.29 | ---- |
| 3/9/2002 | 15.5 | -5.3 | ---- | 11.43 | ---- |
| 3/10/2002 | -5.1 | -9.2 | ---- | ---- | ---- |
| 3/11/2002 | 2.9 | -9.3 | ---- | ---- | ---- |
| 3/12/2002 | 10.3 | -1.6 | ---- | ---- | ---- |
| 3/13/2002 | 15.1 | 1.2 | ---- | ---- | ---- |
| 3/14/2002 | 9.2 | 0.7 | ---- | ---- | ---- |
| 3/15/2002 | 12.6 | -1.2 | ---- | 2.03 | ---- |
| 3/16/2002 | 3.1 | -4.0 | ---- | ---- | ---- |
| 3/17/2002 | 3.4 | -4.7 | ---- | ---- | ---- |
| 3/18/2002 | 3.9 | -1.9 | ---- | ---- | ---- |
| 3/19/2002 | 8.5 | -3.2 | ---- | ---- | ---- |
| 3/20/2002 | 5.0 | -1.7 | ---- | 0.25 | ---- |
| 3/21/2002 | 1.9 | -9.7 | ---- | 0.51 | ---- |
| 3/22/2002 | -3.9 | -10.5 | ---- | ---- | ---- |
| 3/23/2002 | 6.0 | -5.2 | ---- | ---- | ---- |
| 3/24/2002 | 5.2 | -7.1 | ---- | ---- | ---- |
| 3/25/2002 | -2.5 | -8.7 | ---- | ---- | ---- |
| 3/26/2002 | 1.2 | -6.1 | ---- | ---- | ---- |
| 3/27/2002 | 7.7 | -7.8 | ---- | ---- | ---- |
| 3/28/2002 | 7.7 | -5.9 | ---- | ---- | ---- |
| 3/29/2002 | 8.1 | -1.1 | ---- | 8.13 | ---- |
| 3/30/2002 | 10.6 | -0.8 | ---- | 0.25 | ---- |
| 3/31/2002 | 10.4 | -3.3 | ---- | ---- | ---- |
| 4/1/2002 | 4.8 | -2.4 | 0.05 | 1.02 | ---- |
| 4/2/2002 | 5.6 | -0.2 | 0.01 | 10.92 | ---- |
| 4/3/2002 | 4.9 | -1.9 | 0.06 | ---- | ---- |
| 4/4/2002 | 3.1 | -5.5 | 0.05 | ---- | ---- |
| 4/5/2002 | 3.3 | -3.7 | 0.03 | ---- | ---- |
| 4/6/2002 | 4.9 | -5.0 | 0.06 | ---- | ---- |
| 4/7/2002 | 7.7 | -2.0 | 0.06 | ---- | ---- |
| 4/8/2002 | 14.5 | 4.6 | 0.02 | 21.34 | ---- |
| 4/9/2002 | 14.9 | 3.0 | 0.04 | 3.05 | ---- |
| 4/10/2002 | 15.2 | -2.3 | 0.10 | ---- | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 4/11/2002 | 22.8 | 3.5 | 0.16 | ---- | ---- |
| 4/12/2002 | 21.0 | 12.0 | 0.08 | 2.54 | ---- |
| 4/13/2002 | 19.1 | 8.8 | 0.10 | ---- | ---- |
| 4/14/2002 | 22.3 | 10.9 | 0.10 | ---- | ---- |
| 4/15/2002 | 29.2 | 15.4 | 0.15 | ---- | ---- |
| 4/16/2002 | 29.7 | 18.3 | 0.17 | ---- | ---- |
| 4/17/2002 | 26.5 | 15.8 | 0.14 | ---- | 2.11 |
| 4/18/2002 | 29.4 | 13.7 | 0.14 | ---- | ---- |
| 4/19/2002 | 24.5 | 10.6 | 0.15 | 2.29 | ---- |
| 4/20/2002 | 11.9 | 5.2 | 0.12 | 0.25 | ---- |
| 4/21/2002 | 7.0 | 0.4 | 0.09 | 2.54 | ---- |
| 4/22/2002 | 5.8 | -0.1 | 0.03 | 0.76 | ---- |
| 4/23/2002 | 12.3 | -2.1 | 0.10 | ---- | ---- |
| 4/24/2002 | 21.1 | 3.3 | 0.15 | 0.25 | 0.64 |
| 4/25/2002 | 10.3 | 2.4 | 0.22 | 0.76 | ---- |
| 4/26/2002 | 11.9 | -2.0 | 0.10 | ---- | ---- |
| 4/27/2002 | 11.3 | -1.3 | 0.06 | 4.57 | ---- |
| 4/28/2002 | 13.3 | 2.3 | 0.02 | 5.33 | ---- |
| 4/29/2002 | 9.6 | 1.9 | 0.05 | ---- | ---- |
| 4/30/2002 | 13.5 | 3.8 | 0.12 | ---- | ---- |
| 5/1/2002 | 15.5 | -0.7 | 0.08 | ---- | ---- |
| 5/2/2002 | 9.8 | 3.3 | 0.04 | 15.24 | ---- |
| 5/3/2002 | 12.8 | 1.3 | 0.14 | ---- | ---- |
| 5/4/2002 | 18.0 | -1.2 | 0.13 | ---- | ---- |
| 5/5/2002 | 23.9 | 5.5 | 0.18 | ---- | ---- |
| 5/6/2002 | 18.5 | 13.6 | 0.10 | 3.56 | ---- |
| 5/7/2002 | 17.9 | 10.8 | 0.08 | ---- | ---- |
| 5/8/2002 | 11.4 | 5.6 | 0.07 | 1.78 | 0.50 |
| 5/9/2002 | 18.1 | 8.6 | 0.06 | 7.11 | ---- |
| 5/10/2002 | 14.9 | 3.8 | 0.21 | ---- | ---- |
| 5/11/2002 | 13.1 | 0.0 | 0.05 | 2.54 | ---- |
| 5/12/2002 | 10.8 | 5.0 | 0.01 | 20.32 | ---- |
| 5/13/2002 | 10.7 | 5.8 | 0.02 | 0.25 | ---- |
| 5/14/2002 | 17.5 | 5.5 | 0.14 | 1.02 | ---- |
| 5/15/2002 | 21.0 | 0.6 | 0.14 | ---- | ---- |
| 5/16/2002 | 20.0 | 5.4 | 0.06 | 24.38 | ---- |
| 5/17/2002 | 7.8 | 1.2 | 0.08 | ---- | ---- |
| 5/18/2002 | 9.3 | 1.8 | 0.06 | 0.76 | ---- |
| 5/19/2002 | 10.3 | -2.1 | 0.10 | ---- | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 5/20/2002 | 7.9 | -0.3 | 0.06 | ---- | ---- |
| 5/21/2002 | 13.5 | 2.8 | 0.10 | ---- | ---- |
| 5/22/2002 | 18.5 | 0.6 | 0.14 | ---- | ---- |
| 5/23/2002 | 23.7 | 9.0 | 0.15 | ---- | ---- |
| 5/24/2002 | 17.5 | 7.6 | 0.13 | 2.29 | 0.58 |
| 5/25/2002 | 15.1 | 3.1 | 0.06 | 3.56 | ---- |
| 5/26/2002 | 21.8 | 4.1 | 0.14 | ---- | ---- |
| 5/27/2002 | 26.2 | 6.6 | 0.15 | ---- | ---- |
| 5/28/2002 | 25.6 | 10.0 | 0.15 | ---- | ---- |
| 5/29/2002 | 24.9 | 16.4 | 0.09 | 13.72 | ---- |
| 5/30/2002 | 25.9 | 16.9 | 0.11 | 24.38 | ---- |
| 5/31/2002 | 28.3 | 14.9 | 0.19 | ---- | ---- |
| 6/1/2002 | 28.9 | 13.6 | 0.20 | ---- | ---- |
| 6/2/2002 | 22.6 | 9.5 | 0.15 | ---- | ---- |
| 6/3/2002 | 16.5 | 8.1 | 0.11 | 9.40 | ---- |
| 6/4/2002 | 22.9 | 10.3 | 0.08 | 27.94 | ---- |
| 6/5/2002 | 19.1 | 12.9 | 0.03 | 0.76 | ---- |
| 6/6/2002 | 20.9 | 10.0 | 0.13 | ---- | 0.50 |
| 6/7/2002 | 23.6 | 7.0 | 0.14 | ---- | 0.58 |
| 6/8/2002 | 26.9 | 11.8 | 0.16 | ---- | ---- |
| 6/9/2002 | 29.7 | 12.8 | 0.17 | ---- | ---- |
| 6/10/2002 | 31.1 | 17.0 | 0.18 | 1.78 | 0.58 |
| 6/11/2002 | 29.4 | 20.1 | 0.15 | 8.13 | ---- |
| 6/12/2002 | 25.9 | 16.7 | 0.11 | ---- | ---- |
| 6/13/2002 | 20.1 | 14.1 | 0.09 | 0.25 | ---- |
| 6/14/2002 | 20.7 | 14.3 | 0.10 | 2.29 | ---- |
| 6/15/2002 | 21.3 | 11.7 | 0.10 | 1.52 | ---- |
| 6/16/2002 | 21.4 | 11.2 | 0.12 | ---- | 0.38 |
| 6/17/2002 | 23.7 | 9.3 | 0.13 | 1.02 | ---- |
| 6/18/2002 | 26.5 | 7.7 | 0.16 | ---- | ---- |
| 6/19/2002 | 29.6 | 13.5 | 0.18 | ---- | ---- |
| 6/20/2002 | 32.0 | 16.1 | 0.19 | ---- | 1.27 |
| 6/21/2002 | 27.9 | 20.1 | 0.11 | ---- | ---- |
| 6/22/2002 | 32.0 | 20.0 | 0.15 | ---- | ---- |
| 6/23/2002 | 32.1 | 18.7 | 0.17 | ---- | ---- |
| 6/24/2002 | 32.6 | 18.2 | 0.15 | ---- | 1.35 |
| 6/25/2002 | 33.4 | 16.7 | 0.15 | ---- | 0.58 |
| 6/26/2002 | 29.1 | 20.8 | 0.14 | 0.76 | ---- |
| 6/27/2002 | 27.3 | 20.4 | 0.14 | ---- | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 6/28/2002 | 29.1 | 13.4 | 0.16 | ---- | 1.91 |
| 6/29/2002 | 31.1 | 13.8 | 0.16 | ---- | ---- |
| 6/30/2002 | 32.2 | 16.8 | 0.15 | ---- | ---- |
| 7/1/2002 | 33.6 | 19.9 | 0.16 | ---- | 0.76 |
| 7/2/2002 | 32.9 | 19.4 | 0.18 | ---- | ---- |
| 7/3/2002 | 33.5 | 18.7 | 0.20 | ---- | 0.50 |
| 7/4/2002 | 32.6 | 21.2 | 0.18 | ---- | ---- |
| 7/5/2002 | 24.8 | 15.0 | 0.20 | ---- | 2.54 |
| 7/6/2002 | 27.8 | 10.7 | 0.15 | ---- | 0.64 |
| 7/7/2002 | 31.8 | 12.5 | 0.18 | ---- | ---- |
| 7/8/2002 | 32.7 | 15.2 | 0.17 | 5.08 | 1.91 |
| 7/9/2002 | 27.1 | 19.4 | 0.07 | 28.96 | ---- |
| 7/10/2002 | 24.2 | 15.5 | 0.17 | ---- | ---- |
| 7/11/2002 | 25.2 | 10.2 | 0.15 | ---- | ---- |
| 7/12/2002 | 26.7 | 8.4 | 0.16 | ---- | 1.27 |
| 7/13/2002 | 30.2 | 9.7 | 0.17 | ---- | ---- |
| 7/14/2002 | 29.5 | 11.7 | 0.17 | ---- | ---- |
| 7/15/2002 | 31.3 | 12.9 | 0.16 | ---- | 0.81 |
| 7/16/2002 | 32.4 | 18.6 | 0.17 | ---- | ---- |
| 7/17/2002 | 30.4 | 17.9 | 0.18 | ---- | 0.81 |
| 7/18/2002 | 29.5 | 18.1 | 0.12 | 8.13 | ---- |
| 7/19/2002 | 28.5 | 17.0 | 0.10 | ---- | ---- |
| 7/20/2002 | 30.0 | 14.5 | 0.16 | ---- | ---- |
| 7/21/2002 | 32.9 | 18.9 | 0.13 | 0.25 | ---- |
| 7/22/2002 | 33.5 | 21.9 | 0.16 | 4.32 | ---- |
| 7/23/2002 | 23.5 | 13.9 | 0.17 | ---- | 0.69 |
| 7/24/2002 | 25.6 | 9.4 | 0.15 | ---- | ---- |
| 7/25/2002 | 26.0 | 12.6 | 0.15 | ---- | ---- |
| 7/26/2002 | 29.5 | 17.8 | 0.14 | 17.02 | ---- |
| 7/27/2002 | 27.6 | 18.1 | 0.08 | 1.52 | ---- |
| 7/28/2002 | 28.6 | 20.9 | 0.07 | 9.91 | ---- |
| 7/29/2002 | 30.2 | 20.8 | 0.10 | 19.81 | ---- |
| 7/30/2002 | 29.8 | 19.1 | 0.15 | ---- | ---- |
| 7/31/2002 | 32.2 | 19.1 | 0.18 | ---- | ---- |
| 8/1/2002 | 31.2 | 19.0 | 0.15 | ---- | 0.76 |
| 8/2/2002 | 27.5 | 16.2 | 0.17 | 1.52 | ---- |
| 8/3/2002 | 30.4 | 13.4 | 0.16 | ---- | ---- |
| 8/4/2002 | 31.1 | 19.7 | 0.12 | 0.25 | ---- |
| 8/5/2002 | 27.6 | 18.7 | 0.12 | 0.25 | 0.94 |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et† | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 8/6/2002 | 21.8 | 11.7 | 0.15 | ---- | ---- |
| 8/7/2002 | 23.9 | 8.0 | 0.11 | ---- | ---- |
| 8/8/2002 | 25.5 | 8.1 | 0.14 | ---- | 0.94 |
| 8/9/2002 | 27.6 | 10.8 | 0.14 | ---- | ---- |
| 8/10/2002 | 29.6 | 11.2 | 0.15 | ---- | 0.38 |
| 8/11/2002 | 31.5 | 16.7 | 0.15 | ---- | ---- |
| 8/12/2002 | 31.4 | 17.0 | 0.15 | ---- | ---- |
| 8/13/2002 | 30.1 | 20.3 | 0.15 | 6.60 | 0.64 |
| 8/14/2002 | 23.5 | 19.2 | 0.05 | 10.41 | ---- |
| 8/15/2002 | 28.2 | 17.3 | 0.12 | ---- | ---- |
| 8/16/2002 | 28.3 | 19.3 | 0.11 | 0.51 | ---- |
| 8/17/2002 | 28.6 | 19.1 | 0.10 | ---- | ---- |
| 8/18/2002 | 25.2 | 13.0 | 0.17 | ---- | ---- |
| 8/19/2002 | 21.5 | 12.3 | 0.06 | 4.32 | ---- |
| 8/20/2002 | 25.4 | 10.9 | 0.14 | ---- | ---- |
| 8/21/2002 | 27.5 | 11.2 | 0.14 | ---- | 0.38 |
| 8/22/2002 | 25.5 | 19.2 | 0.14 | 4.57 | ---- |
| 8/23/2002 | 22.1 | 18.3 | 0.04 | 7.11 | ---- |
| 8/24/2002 | 26.1 | 17.9 | 0.07 | ---- | ---- |
| 8/25/2002 | 26.8 | 13.9 | 0.12 | ---- | ---- |
| 8/26/2002 | 28.2 | 13.8 | 0.12 | ---- | ---- |
| 8/27/2002 | 26.8 | 14.3 | 0.12 | ---- | ---- |
| 8/28/2002 | 25.2 | 11.7 | 0.14 | ---- | ---- |
| 8/29/2002 | 27.4 | 13.7 | 0.12 | ---- | 0.64 |
| 8/30/2002 | 27.8 | 12.6 | 0.12 | ---- | ---- |
| 8/31/2002 | 28.8 | 11.9 | 0.12 | ---- | ---- |
| 9/1/2002 | 29.7 | 12.9 | 0.14 | ---- | ---- |
| 9/2/2002 | 28.1 | 18.2 | 0.08 | ---- | ---- |
| 9/3/2002 | 27.4 | 14.7 | 0.15 | ---- | 0.95 |
| 9/4/2002 | 27.1 | 11.6 | 0.14 | ---- | ---- |
| 9/5/2002 | 25.9 | 9.4 | 0.12 | ---- | 0.97 |
| 9/6/2002 | 29.8 | 10.6 | 0.13 | ---- | ---- |
| 9/7/2002 | 33.0 | 10.8 | 0.14 | ---- | 0.64 |
| 9/8/2002 | 33.4 | 13.8 | 0.14 | ---- | ---- |
| 9/9/2002 | 32.5 | 13.8 | 0.12 | ---- | 0.76 |
| 9/10/2002 | 32.0 | 16.2 | 0.11 | 0.25 | ---- |
| 9/11/2002 | 23.7 | 11.4 | 0.14 | ---- | ---- |
| 9/12/2002 | 25.4 | 6.9 | 0.11 | ---- | ---- |
| 9/13/2002 | 26.8 | 9.2 | 0.10 | ---- | 0.50 |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 9/14/2002 | 29.7 | 10.0 | 0.10 | ---- | ---- |
| 9/15/2002 | 20.1 | 11.4 | 0.06 | ---- | ---- |
| 9/16/2002 | 24.4 | 5.6 | ---- | ---- | 0.81 |
| 9/17/2002 | 28.1 | 6.6 | ---- | ---- | ---- |
| 9/18/2002 | 25.7 | 12.2 | 0.06 | 1.27 | ---- |
| 9/19/2002 | 29.7 | 18.7 | 0.09 | 4.57 | ---- |
| 9/20/2002 | 24.8 | 18.0 | 0.05 | 2.79 | ---- |
| 9/21/2002 | 26.5 | 13.8 | 0.11 | ---- | ---- |
| 9/22/2002 | 16.3 | 7.2 | 0.07 | 3.56 | ---- |
| 9/23/2002 | 18.4 | 4.3 | 0.07 | ---- | ---- |
| 9/24/2002 | 17.4 | 4.8 | 0.09 | ---- | ---- |
| 9/25/2002 | 22.2 | 2.0 | 0.10 | ---- | ---- |
| 9/26/2002 | 23.9 | 7.8 | 0.08 | ---- | 0.64 |
| 9/27/2002 | 22.6 | 12.3 | 0.08 | ---- | ---- |
| 9/28/2002 | 22.2 | 7.8 | 0.10 | ---- | ---- |
| 9/29/2002 | 25.4 | 13.2 | 0.10 | 0.76 | ---- |
| 9/30/2002 | 29.5 | 16.2 | 0.13 | ---- | 1.02 |
| 10/1/2002 | 29.9 | 19.7 | 0.11 | ---- | ---- |
| 10/2/2002 | 24.5 | 12.9 | 0.06 | 0.25 | ---- |
| 10/3/2002 | 15.4 | 11.1 | 0.04 | 3.81 | ---- |
| 10/4/2002 | 25.3 | 14.8 | 0.02 | 9.14 | ---- |
| 10/5/2002 | 16.5 | 5.2 | 0.13 | ---- | ---- |
| 10/6/2002 | 19.5 | 4.2 | 0.07 | 2.54 | ---- |
| 10/7/2002 | 12.2 | 1.7 | 0.12 | ---- | ---- |
| 10/8/2002 | 17.1 | 1.6 | 0.06 | ---- | ---- |
| 10/9/2002 | 20.5 | 5.2 | 0.08 | ---- | ---- |
| 10/10/2002 | 21.9 | 3.6 | 0.06 | ---- | ---- |
| 10/11/2002 | 22.2 | 5.7 | 0.06 | ---- | ---- |
| 10/12/2002 | 21.6 | 5.8 | 0.04 | 1.52 | ---- |
| 10/13/2002 | 11.9 | -1.6 | 0.08 | 3.05 | ---- |
| 10/14/2002 | 13.7 | -0.5 | 0.06 | ---- | ---- |
| 10/15/2002 | 17.2 | 1.0 | 0.07 | ---- | 0.50 |
| 10/16/2002 | 9.2 | -0.7 | 0.11 | ---- | ---- |
| 10/17/2002 | 6.5 | -4.4 | 0.02 | 2.03 | ---- |
| 10/18/2002 | 11.5 | 3.0 | 0.02 | 2.29 | ---- |
| 10/19/2002 | 10.9 | 4.6 | 0.03 | ---- | ---- |
| 10/20/2002 | 9.8 | -2.0 | 0.04 | ---- | ---- |
| 10/21/2002 | 10.4 | -4.1 | 0.03 | ---- | ---- |
| 10/22/2002 | 8.9 | 4.6 | 0.03 | ---- | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 10/23/2002 | 7.3 | -0.3 | 0.03 | ---- | ---- |
| 10/24/2002 | 7.8 | -0.7 | 0.04 | ---- | ---- |
| 10/25/2002 | 5.8 | -2.7 | 0.02 | 6.60 | ---- |
| 10/26/2002 | 8.2 | 4.2 | 0.01 | 0.25 | ---- |
| 10/27/2002 | 8.0 | 3.2 | 0.03 | ---- | ---- |
| 10/28/2002 | 8.9 | -0.5 | 0.03 | ---- | ---- |
| 10/29/2002 | 4.3 | -1.4 | 0.03 | ---- | ---- |
| 10/30/2002 | 8.4 | -3.0 | 0.04 | ---- | ---- |
| 10/31/2002 | 8.3 | -4.3 | 0.02 | ---- | ---- |
| 11/1/2002 | 3.4 | -2.0 | 0.04 | ---- | ---- |
| 11/2/2002 | 5.2 | -2.1 | 0.03 | ---- | ---- |
| 11/3/2002 | 8.6 | -7.0 | 0.02 | ---- | ---- |
| 11/4/2002 | 9.2 | -3.7 | 0.03 | ---- | ---- |
| 11/5/2002 | 4.0 | -1.5 | 0.02 | 4.06 | ---- |
| 11/6/2002 | 4.6 | 1.0 | 0.00 | ---- | ---- |
| 11/7/2002 | 10.1 | -3.9 | 0.05 | ---- | ---- |
| 11/8/2002 | 17.1 | 7.4 | 0.10 | ---- | ---- |
| 11/9/2002 | 15.7 | 7.6 | 0.04 | 1.78 | ---- |
| 11/10/2002 | 18.4 | 10.9 | 0.02 | 11.18 | ---- |
| 11/11/2002 | 10.8 | 3.1 | 0.02 | 0.51 | ---- |
| 11/12/2002 | 4.8 | 1.0 | 0.01 | ---- | ---- |
| 11/13/2002 | 9.7 | -0.6 | 0.03 | ---- | ---- |
| 11/14/2002 | 12.7 | 0.9 | 0.05 | 5.08 | ---- |
| 11/15/2002 | 1.1 | -3.7 | 0.04 | 0.76 | ---- |
| 11/16/2002 | -0.5 | -5.8 | 0.01 | ---- | ---- |
| 11/17/2002 | 1.6 | -4.3 | 0.02 | ---- | ---- |
| 11/18/2002 | 4.8 | -6.5 | 0.02 | ---- | ---- |
| 11/19/2002 | 11.6 | 1.7 | 0.04 | 4.32 | ---- |
| 11/20/2002 | 13.4 | 3.0 | 0.03 | ---- | ---- |
| 11/21/2002 | 7.5 | -0.4 | 0.01 | 3.30 | ---- |
| 11/22/2002 | 1.4 | -1.0 | 0.03 | 0.51 | ---- |
| 11/23/2002 | 4.9 | -0.7 | 0.02 | 0.25 | ---- |
| 11/24/2002 | 4.6 | -1.9 | 0.02 | ---- | ---- |
| 11/25/2002 | -0.2 | -4.3 | 0.01 | 1.78 | ---- |
| 11/26/2002 | -1.2 | -5.7 | ---- | ---- | ---- |
| 11/27/2002 | -0.7 | -10.3 | ---- | 0.25 | ---- |
| 11/28/2002 | -2.1 | -4.1 | ---- | ---- | ---- |
| 11/29/2002 | 7.9 | -2.5 | ---- | ---- | ---- |
| 11/30/2002 | 4.0 | -7.3 | ---- | 0.76 | ---- |

| DATE | Air Temperature (Maximum °C) | Air Temperature (Minimum °C) | 80% Et[†] | Precipitation (cm) | Irrigation (cm) |
|---|---|---|---|---|---|
| 12/1/2002 | -1.0 | -9.2 | ---- | ---- | ---- |
| 12/2/2002 | -1.0 | -13.7 | ---- | ---- | ---- |
| 12/3/2002 | -3.8 | -19.0 | ---- | 4.06 | ---- |
| 12/4/2002 | -3.0 | -20.5 | ---- | ---- | ---- |
| 12/5/2002 | -2.0 | -12.1 | ---- | ---- | ---- |
| 12/6/2002 | -2.8 | -8.7 | ---- | ---- | ---- |
| 12/7/2002 | 2.2 | -4.7 | ---- | ---- | ---- |
| 12/8/2002 | -0.1 | -15.7 | ---- | ---- | ---- |
| 12/9/2002 | -3.0 | -19.4 | ---- | ---- | ---- |
| 12/10/2002 | 5.5 | -5.8 | ---- | ---- | ---- |
| 12/11/2002 | 5.0 | -8.0 | ---- | ---- | ---- |
| 12/12/2002 | 6.0 | -5.5 | ---- | ---- | ---- |
| 12/13/2002 | 1.2 | -0.6 | ---- | ---- | ---- |
| 12/14/2002 | 1.8 | -1.0 | ---- | ---- | ---- |
| 12/15/2002 | 4.5 | -1.9 | ---- | ---- | ---- |
| 12/16/2002 | -1.7 | -9.0 | ---- | ---- | ---- |
| 12/17/2002 | 0.1 | -7.5 | ---- | ---- | ---- |
| 12/18/2002 | 8.7 | -0.3 | ---- | 6.10 | ---- |
| 12/19/2002 | 10.3 | 0.7 | ---- | 9.65 | ---- |
| 12/20/2002 | 1.6 | -2.4 | ---- | 1.52 | ---- |
| 12/21/2002 | -0.1 | -3.5 | ---- | ---- | ---- |
| 12/22/2002 | -0.2 | -2.7 | ---- | ---- | ---- |
| 12/23/2002 | -1.0 | -4.5 | ---- | ---- | ---- |
| 12/24/2002 | -2.8 | -5.3 | ---- | ---- | ---- |
| 12/25/2002 | -0.5 | -4.7 | ---- | 1.78 | ---- |
| 12/26/2002 | -0.2 | -8.0 | ---- | 0.76 | ---- |
| 12/27/2002 | -3.3 | -9.1 | ---- | ---- | ---- |
| 12/28/2002 | 0.1 | -6.1 | ---- | 1.27 | ---- |
| 12/29/2002 | 2.0 | -4.7 | ---- | ---- | ---- |
| 12/30/2002 | 11.4 | -1.7 | ---- | 0.76 | ---- |
| 12/31/2002 | 10.4 | -3.7 | ---- | ---- | ---- |

## Bibliography


Beard, J.B. 1973. Turfgrass: Science and culture. Prentice-Hall, Englewood Cliffs, NJ.

Bhumbla, D.K., 2002. Agricultural practices and nitrate pollution of water. West Virginia University Extension Service. Available on the web: http://www.caf.wvu.edu/~forage/foragelst.htm.

Bouldin, D.R. and D.J. Lathwell. 1968. Behavior of soil organic nitrogen. Bulletin 1023, Cornell University Agriculture Experiment Station.

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

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

Carrow, R.N., D.V. Waddington, and P.E. Rieke. 2001. Turfgrass soil fertility and chemical problems: Assessment and management. Ann Arbor Press, Chelsea, MI.

Duff, D.T., H. Liu, R.J. Hull, and C.D. Sawyer. 1997. Nitrate leaching from long established Kentucky bluegrass turf. International Turfgrass Society Research Journal. 8:175-186.

Frank, K.W. 2000. Nitrogen allocation of three turfgrass species and turf-type buffalograss management. Ph.D. diss. Univ. of Nebraska, Lincoln, NE.

Gold, A.J. and P.M. Groffman. 1993. Leaching of agrichemicals from suburban areas. p. 182-190. In Racke, K.D. and A.R. Leslie (eds) Pesticides in urban environments: Fate and significance. ACS symposium series 522. American Chemical Society. Washington D.C.

Hauck, R.D., and J.M. Bremner. 1976. Use of tracers for soil and fertilizer nitrogen research. Adv. Agronomy 28:219-266.

Horgan, B.P., B.E. Branham, and R.L. Mulvaney. 2002. Mass balance of $^{15}N$ applied to Kentucky bluegrass including direct measurement of denitrification. Crop Sci. 42:1595-1601.

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

Kessavalou, Anabayan. 1994. Evaluation of tillage, rotation, cover crop and N rate effects on nitrogen cycling in a corn-soybean rotation system. Ph.D. diss. Univ. of Nebraska, Lincoln, NE.

Mancino, C.F., W.A. Torello, and D.J. Wehner. 1988. Denitrification losses from Kentucky bluegrass sod. Agron. J. 80:148-153.

Miltner, E.D., B.E. Branham, E.A. Paul, and P.E. Rieke. 1996. Leaching and mass balance of $^{15}$N-labeled urea applied to Kentucky bluegrass turf. Crop Sci. 36:1427-1433.

Moran, K.K., R.L. Mulvaney, and S.A. Khan. 2002. A technique to facilitate diffusions for nitrogen-isotope analysis by direct combustion. Soil Sci. Soc. Am. J. 66:1008-1011.

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.

Nelson, K.E., A.J. Turgeon, and J.R. Street. 1980. Thatch influence on mobility and transformation of nitrogen carriers applied to turf. Agron. J. 72:487-492.

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

Porter, K.S., D.R. Bouldin, S. Pacenka, R.S. Kossack, C.A. Shoemaker, and A.A. Pucci, Jr. 1980. Studies to assess the fate of nitrogen applied to turf: Part I. Research project technical complete report. OWRT Project A-086-NY. Cornell Univ., Ithica, NY.

Power, J.F. and J.O. Legg. 1984. Nitrogen-15 recovery for five years after application if ammonium nitrate to crested wheatgrass. Soil Sci. Soc. Am. J. 48:322-326.

Rolston, D.E., A.N. Sharpley, D.W. Toy, and F.E. Broadbent. 1982. Field measurement of denitrification: III. Rates during irrigation cycles. Soil Sci. Soc. Am. J. 46:289-296.

Torello, W.A., D.J. Wehner, and A.J. Turgeon. 1983. Ammonia volatilization from fertilized turfgrass stands. Agron. J. 75:454-456.

SAS Institute Inc. 2001. The SAS system release 8.2 for Windows. SAS Inst., Cary, N.C.

Starr, J.L., and H.C. DeRoo. 1981. The fate of nitrogen fertilizer applied to turfgrass. Crop Sci. 21:531-536.

United States. Environmental Protection Agency. 2002. National primary drinking water regulations: Technical factsheet on: nitrate/ nitrite. Available on the web: http://www.epa.gov/safewater/dwh/t-ioc/nitrates.html.

Valiela, I., G. Collins, J. Kremer, K. Lajtha, M. Geist, B. Seely, J. Brawley, and C.H. Sham. 1997. Nitrogen loading from coastal wetlands to receiving estuaries: New method and application. Ecol. Applic. 7:358-380.

Vitousek, P.M., J.A. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and G.D. Tilman. 1997. Human alterations of the global nitrogen cycle: Causes and consequences. Ecol. Applic. 7:737-750.