CHAPTER 3

SOIL NITROGEN LOSSES BENEATH THREE COOL-SEASON LAWN SPECIES IN THE COOL-HUMID REGION

Abstract

Nitrate (NO_3^- - N) losses from lawns receiving nitrogen (N) fertilizer has been proposed as one reason for declining water quality in urban areas. This field study monitored seasonal N levels for two and one half years beneath the three principal cool-season lawn species: Kentucky bluegrass (*Poa pratensis* L.) (KBG), perennial ryegrass (*Lolium perenne* L.) (PRG), and turf-type tall fescue (*Festuca arundinacea* Schreb.) (TTTF). They were fertilized with eight N programs that varied by N amount, 0 – 196 kg N ha^{-1} yr^{-1}, and seasonal application timing. Seasonal in-situ soil solution nitrate (NO_3^- - N) and ammonium (NH_4^+ -N) concentrations were measured using suction cup lysimeters located 45 cm below the soil surface. Additionally inorganic N was determined via extraction at three depths; 0-15, 15-30 and 30-45 cm in early December of each study year. Regardless of season, species or N program, NO_3^- - N and NH_4^+ -N concentrations in the soil solution were generally low < 1 mg L^{-1} throughout the study. The exception occurred for KBG on one sampling date in Nov. 2003, where NO_3^- - N concentrations measured > 17 mg L^{-1} and exceeded the EPA safe drinking water standard of 10 mg NO_3^- - N L^{-1}. Among species and across N programs, soil solution NO_3^- - N concentrations ranked KBG>PRG>TTTF. For the extracted soil N levels, NO_3^- - N and NH_4^+ -N concentrations were generally ≤ 5 mg kg^{-1} for all species and depths with concentrations ranging from 1.4 to 4.4 mg NO_3^- - N kg^{-1} and 1.7 to 4.8 mg NH_4^+ -N kg^{-1}. Among species soil N levels ranked, KBG ≥ PRG >TTTF. Based on these data, it appears that these N programs pose little threat to groundwater contamination as evidenced by overall low NO_3^- - N levels, < 1 mg L^{-1} regularly observed. Where N leaching loss is of concern, such

as in the KBG turf evaluated in this study, this turf should be judiciously fertilized with < 196 kg N ha^{-1} yr^{-1}, particularly as the lawn matures and greater N mineralization occurs. Alternatively, a species more efficient at N utilization like TTTF could also be planted.

Introduction

There is increasing concern that NO_3^- - N losses from lawns regularly receiving N fertilizer is negatively affecting the environment and human health (Vitousek et al., 1997; Erickson et al., 2001; Frank et al., 2006). Groundwater accounts for 86 % of the total water resources in the continuous USA and provides 24 to 95 % of the drinking water supply for urban and rural areas, respectively (Scott, 1985). As urban population centers, which contain turfgrass as a major land use, continue to expand many government agencies are reevaluating regulations related to fertilizer and chemical management practices used by agronomic, horticultural, landscape and golf course industries (Keeney, 1986; Geron, 1993). Nitrogen is the most widely applied fertilizer nutrient to lawns because it is required in the greatest amount by turfgrass plants in order to maintain greenness and vigor. Nitrogen losses from regularly fertilized turfgrass areas, such as residential and commercial landscapes, have been suggested as a major contributor of groundwater contamination due to the extensive acreage of turfgrass (Petrovic, 1990).

Of the N sources applied to turfgrass, NO_3^- - N poses the greatest risk to surface and ground water contamination since it is the most mobile N form (DeRoo, 1979; Pye et al., 1983; Petrovic, 1990; Watschke et al., 2000; Easton and Petrovic, 2004). Additionally, NO_3^- - N can be a limiting nutrient for eutrophication and algal blooms in surface water bodies (Mercias and Malone, 1984; Levine and Schindler, 1989; Valiela et al, 1997; Mallin and Wheeler, 2000; Bush and Austin, 2001; Easton and Petrovic, 2004). Elevated NO_3^- - N levels in drinking water are very detrimental to human health and in severe situations can cause methemoglobinemia, or blue baby syndrome, whereby the blood supply of infants, small children, and animals becomes oxygen deprived (USEPA, 2002). To address this concern the United States Environmental Protection Agency (EPA) established the safe drinking water standard of < 10 mg NO_3^- - N L^{-1}.

Although NO_3^- - N leaching from turfgrass has been widely studied, documented leaching losses have been highly variable, and the magnitude of NO_3^- - N water contamination derived from lawns is not well understood. Many factors may affect NO_3^- - N leaching including; N source, application rate, soil type, application timing, irrigation, species, and rooting characteristics (Rieke and Ellis, 1974; Petrovic, 1990; Morton et al., 1988; Mancino and Troll, 1990). These factors may impact the NO_3^- - N lost from fertilized turf areas. Numerous studies have measured NO_3^- - N leaching from cool-season turf fertilized with water soluble or quick release N sources (Gross et al., 1990; Harrison et al., 1993; Miltner et al., 1996 and Liu et al., 1997), combinations of soluble and slow release N fertilizers (Starr and DeRoo, 1981; Morton et al., 1988; Gold et al., 1990), and those who have made direct comparisons between soluble and slow release N fertilizers (Sheard et al., 1985; Petrovic et al., 1986; De Nobili et al., 1992; Geron et al., 1993; Engelsjord and Singh, 1997; Guillard and Kopp, 2004). Results from these studies indicate that NO_3^- - N leaching occurs more frequently with soluble N forms than with less soluble N forms. Although much research has been conducted regarding N loss from turfgrass, relatively few studies have measured N loss from lawn systems, which is a major land use in urban, suburban areas (Petrovic et al., 1986; Geron at al., 1993; Miltner et al., 1996; Guillard and Kopp 2004; Bigelow et al., 2005; Mangiafico and Guillard, 2006; Frank et al. 2006).

Geron et al. (1993) reported that in Ohio, NO_3^- - N leaching was not affected by fertilizer programs or N sources. The highest NO_3^- - N concentrations they reported was 3.4 mg L^{-1}, which occurred during the winter. Miltner et al. (1996) found NO_3^- - N concentrations were generally < 1.0 mg L^{-1} during the spring and fall. Guillard and Kopp (2004) reported NO_3^- - N concentrations of 0.2 to 4.6 mg L^{-1} occurring from late-fall through the early-spring. They also found that NO_3^- - N concentrations were greatest for soluble N fertilizer sources and suggested that lawn fertilizers should be formulated with predominantly slow release N fertilizers, rather than soluble N. In a mature KBG turf fertilized for > 10 yr in Michigan, Frank et al. (2006) reported that NO_3^- - N concentrations varied from < 5 mg L^{-1} for the low N (98 kg N ha^{-1} yr^{-1}) treatment to > 20 mg L^{-1} for the high N (245 kg N ha^{-1} yr^{-1}) treatment suggesting older lawns should be fertilized at reduced N rates to minimize potential NO_3^- - N leaching. Mangiafico and Guillard (2006) reported NO_3^- - N concentrations were greatest during the late-fall or winter and suggested an earlier N application (e.g. 15 October), a lower application rate (< 49 kg N ha^{-1}), or no fall N due to the potential negative impacts on water quality in the Connecticut maritime climate.

Specific lawn N fertilizer application strategies and annual application rates vary based on desired appearance, management intensity and intended use. In general, a cool-season turfgrasses located in the cool-humid region should receive a minimum of 49 kg N ha^{-1} yr^{-1} with an optimum application timing being late-summer (e.g. September 1-15th) (Reicher and Throssel, 1998). Nitrogen applied during this time stimulates growth, improves shoot density, enhances green color, and promotes recovery from summer stresses during these optimal growing conditions of the autumn months. If a higher quality turfgrass area is desired additional N is typically applied immediately prior to winter dormancy (e.g. late-fall) and mid-to late-spring following the early flush of shoot growth. The observed physiological benefits of late-season (Oct.-Dec.) N applications to cool-season species are increased carbohydrate reserves, less disease incidence, improved late-fall color retention, increased root growth, and earlier spring green-up (Powell et al., 1967; Wilkinson and Duff, 1972; Wehner et al., 1988).

The degree to which the turfgrass plant is actively growing and the season in which N is applied dramatically affect NO_3^- - N leaching. Liu et al. (1997) found that leaching potential fluctuated seasonally and was strongly related to precipitation, relative plant growth rates, fertilizer source, and application timing. Miltner et al. (1996) found that applying N to a KBG turf in the late-fall did not pose a threat to groundwater. It is well documented that soil N losses can be large when temperatures and evapotranspiration are low and precipitation is high (Petrovic, 1990; Gold et al. 1990; Geron et al. 1993; Guillard and Koop, 2004; Magnifico and Gulliard, 2006). These environmental conditions are common from November through April throughout cool-humid northern climates. Nitrogen fertilizer applied during these times is inefficiently absorbed and may result in N loss since the turfgrass roots are slow-growing or dormant (Petrovic, 1990; Beard and Green, 1994). Additional environmental factors such as winter rainfall (Snyder et al., 1984) and saturated soils (Baird et al., 2000) contribute further to high potential NO_3^- - N losses. Gold et al. (1990) reported 2.6 mg L^{-1} NO_3^- - N from lawn turf during the spring and attributed these losses to spring snow melt. Some researchers have suggested that due to the high leaching potential during the fall and spring, that any applied N should contain primarily slow release N to minimize N loss

(Guillard and Kopp, 2004). Magnifico and Guillard (2006) found late season N (Nov or Dec.) increased NO_3^- - N concentrations when applying N in mid-late November in southern New England. In addition to precipitation, irrigation practices also affect N loss. Morton et al. (1988) reported that frequently irrigated turf in addition to excess precipitation can result in significant episodic NO_3^- - N leaching losses. In Indiana, precipitation typically is greatest during the spring and least during late-summer or early autumn. As previously mentioned, spring precipitation coupled with spring snow melt can increase the potential for NO_3^- - N leaching, especially if the turf receives regular supplemental irrigation. For this reason and the potential for stimulating unwanted shoot growth, which may negatively affect root growth, heavy (> 49 kg N ha^{-1}) spring N applications are generally not recommended, especially soluble N.

Most studies regarding the effect of N rates on N loss have been conducted as worst case scenarios and as expected results have shown that as N rate increases, NO_3^- - N leaching through the soil profile increased (Petrovic, 1990) especially on coarse textured sandy soils (Rieke and Ellis, 1974; Brown et al., 1977; Synder et al., 1981; Sheard et al., 1985; Bigelow et al., 2001; Bowman et al., 2002). However, late-season N applications have received much attention because of the risk for NO_3^- - N leaching potential associated with slow turf growth rates and plant uptake (Petrovic, 1986; Miltner et al., 1996; Liu et al., 1997; Magnifico and Gulliard, 2006).

Petrovic (1990) concluded based on the findings of Porter et al., (1980) that mature turf, especially turf grown on soil with high organic matter should be fertilized at a reduced rate to decrease the potential for NO_3^- - N leaching. By contrast, N rates applied to younger turf (< 10 yrs) should equal the rate at which N is used by the plant. Frank et al., (2006) found that at a high N (245 kg N ha^{-1}) rate, NO_3^- - N concentrations in leachate were two to three times greater than the EPA safe drinking standard of 10 mg L^{-1}. Based on their findings, Frank et al. (2006) suggests that single dose, high rate, water soluble N applications should be avoided on mature turf (> 8 yrs.) to minimize the potential for NO_3^- - N leaching.

Turfgrass species vary in their ability to absorb NO_3^- - N which can be extremely important in designing programs which minimize NO_3^- - N leaching (Cisar et al, 1989;

Liu et al., 1993; Liu et al., 1997). These variations are attributed to genetic differences and environmental influences on NO_3^- - N uptake (Glass, 1989; Petrovic, 1990). Bowman et al. (1998) compared two creeping bentgrass (*Agrostis stolonifera* L.) genotypes, which possessed varying genetic rooting potential and found that a more extensive root system reduced NO_3^- - N leaching losses from 4 to 2 mg L^{-1}. Liu et al. (1997) found there were species differences in soil NO_3^- - N levels (KBG > PRG > TF) and that their leaching potentials were minimal when environmental conditions favored optimal plant growth. Information regarding NO_3^- - N leaching for cool-season turfgrasses maintained with minimal N inputs is lacking. Furthermore, information on NO_3^- - N leaching from TTTF lawn turf areas is even more limited (Waddill, 1994; Bigelow et al., 2005), but deserves attention since this species is being more widely planted and used for lawns throughout the lower cool-humid region. The deep extensive root system of this species may enable it to be more efficient at N uptake than species (e.g. KBG) traditionally planted in the cool-humid region and therefore enable turf managers to use less N fertilizer.

If the goal is to maximize turfgrass quality while using minimal N fertilizer inputs, lawn fertility programs need to be designed around more judicious N fertilizer use and take into account the planted species but also consider intended use, desired appearance, and management intensity in order to have minimal negative effects on water quality. The overall purpose of this study was to be able to recommend environmentally responsible N fertility programs for lawns located in the cool-humid region that maximize turfgrass quality and vigor while minimizing N inputs.. The objective of this study was to:

1. Assess seasonal soil N losses of the three species when subjected to eight N fertility programs that varied in N application rate and timing. Soil N status was determined using in-situ suction cup lysimeters and extracting soil N by depth in the late-fall (December).

Materials and Methods

A field experiment was conducted from September 2003 through December 2005 at the Purdue University, W. H. Daniel Turfgrass Research and Diagnostic Center, West Lafayette, Indiana on a Stark silt-loam (fine-silty mixed mesic Aeric Ochraqualfs) with a pH of 7.4, 67 kg P ha^{-1}, 147 kg K ha^{-1}, and 47 g kg^{-1} organic matter. Prior to planting, the entire study area was fumigated with methyl bromide to minimize existing weed competition. Cultivar blends of the three primary cool-season lawn turfgrass species: TTTF (*Festuca arundinacea* Schreb. 'Triple A'), KBG (*Poa pratensis* L. 'Premium Sod Blend'), and PRG (*Lolium perenne* L. 'Medalist Gold') were established by seed at rates of 391 kg ha^{-1}, 98 kg ha^{-1}, and 292 kg ha^{-1}, respectively in May 2003. Seed was supplied by Jacklin Seed Co. and the cultivar blends consisted of the following; 'Triple A' TTTF: [Quest (33 %), Pixie (33 %), and Arid III (33%)], 'Premium Sod Blend' KBG: [Absolute (25 %), Rugby II (25 %), Bluemoon (25 %), and Nuglade (25 %)], 'Medalist Gold' PRG; [Monterey II (33 %), Caddieshack (33 %), and Goalkeeper (33%)]. After seeding, the entire study area received an application of 73 kg P ha^{-1} from 6-24-24 (N-P-K) and was covered with Agrofabric Pro17 germination blanket (American Agrifabrics, Alpharetta, GA) for 2 wks to conserve moisture, promote germination, and prevent species contamination from adjacent plots. The study area was frequently irrigated approximately three times daily with an overhead sprinkler system to keep the soil moist and promote germination and seedling establishment.

The nitrogen fertilizer treatments were initiated on 10 September 2003. Overall, eight nitrogen fertility programs were evaluated, which varied in annual N, ranging from 0, 49, 73, 123, and 196 kg N ha^{-1} yr^{-1}, and in application timing (Table 3-1). These programs were categorized as: "Low":(49 kg N ha^{-1}, September or 73 kg N ha^{-1} November), "Medium" (123 kg N ha^{-1}, applied either spring only Apr., May, and July (AMJ), Sept. and Nov. (SN), or Sept., Oct., and May (SOM)), and "High" (196 kg N ha^{-1}, applied Sept., Oct., Nov., April, and May (SONAM) or Sept., Nov., May, and July (SNMJ)). Nitrogen was supplied either as sulfur coated urea (SCU: controlled-release, 31-0-0), urea (water soluble, 46-0-0) or a 50:50 (w/w) mixture depending on the season of application. The specific N application dates and N-sources are footnoted in Table 3-1.

Soil Nitrogen and Organic Matter

Suction cup lysimeters (Irrometer Company, INC., Riverside, CA) with 1 bar ceramic tips were installed to each plot in November 2003. A plug of turf was removed using a cup cutter (15.24 cm diam.) to make room for a 10.2 cm deep access hole centered on the south side of each plot approximately 76.2 cm from the top and bottom of the plot. A polyvinyl chloride (PVC) pipe with the same diameter and depth as the hole cut by the cup cutter was placed in the access hole. A removable plastic cover was placed on top at the surface to help protect the lysimeter from the elements and allow for easy access to the sample tubing throughout the study. Each PVC pipe had a 2.5 mm diameter hole drilled out of the right side of the pipe at a depth of 6.35 cm for the lysimeter tubing. Through this opening in the PVC pipe, a soil probe was used to make a 1.9 mm diameter hole for the insertion of the lysimeter at a depth of 45.7 cm below nondisturbed soil profiles at a 45° angle using a wooden frame (Figure 3-1). The lysimeters remained in the ground over the winter to form a good seal with the surrounding soil until sampling was initiated in April 2004.

On the first day of each sampling month, soil solution samples were collected over a seven day period prior to each N application to get background levels and any N carryover from the previous month. A hand vacuum pump (70 to 80 psi) was used to extract the air out of each lysimeter and applied a vacuum to draw in the soil solution over the collecting period. Once the background soil solution samples were collected, the N application if needed (Table 3-1) for the month was applied to each plot. The vacuum was reestablished to collect a sample at three and ten days following N application. For those months where no N was applied, soil solution samples were collected the same as the background soil solution samples allowing the lysimeters to collect over the first seven days of each month. Solution samples were removed using a 50 mL syringe extracting approximately 5 to 50 mL and stored in 50 mL centrifuge tubes at 4°C until they could be analyzed for the presence of NO_3^- -N and NH_4^+-N, which were determined colorimetrically using a Lachat Quikchem auto analyzer (Lachat Instruments, Milwaukee, WI).

Inorganic NO_3^--N and NH_4^+-N concentrations in soil samples with depth were determined in December 2003, 2004, and 2005. Four soil cores (1.9 mm diameter) were removed from each plot near the corners of each plot and approximately 60 cm away from the embedded suction cup lysimeter. The shoots and any thatch layer were removed and the cores were divided into three depth increments: 0-15, 15-30, and 30-45 cm below the soil surface. The soil samples were air-dried for 96 h and ground using a mechanical soil grinder (< 2mm). Soil inorganic N was extracted using a 1 *M* KCl solution (Keeney and Nelson, 1982) and extracts were immediately filtered using Whatman No.2 filter paper to remove any soil particles. Samples were then stored at 4°C until they could be analyzed for the presence of NO_3^--N and NH_4^+-N using a Lachat Quikchem auto analyzer (Lachat Instruments, Milwaukee, WI). Soil organic matter content was also determined using the combustion method (550°C for 12 h) on the ground samples (Nelson and Sommers, 1996).

General Plot Maintenance

The study site was located in full-sun with no obstructions, which was conducive to rapid drying of the canopy in the early morning hours. Plots were mowed weekly (6.35 cm) throughout the growing season with clippings removed. In the absence of significant rainfall (12 mm per week), overhead irrigation was supplementally applied each night (approximately 5 mm) to promote growth and maintain the soil at or near field capacity during the growing season (Apr. –Nov.). Herbicides were periodically applied for weed control, broadleaf weeds, annual grassy weeds, and a single curative fungicide application was applied in July of each year for disease control.

Experimental Design and Statistical Analysis

Plot size was 1.5 x 1.5 m with 0.3 m borders of hard fescue (*Festuca tryachyphylla* [Hackel] Krujina). Each treatment was replicated three times and plots were arranged in a randomized complete-block design. Data was pooled into four seasonal growth periods per year: early spring (Apr.-June), summer (July-Aug.), early fall (Sept.-Oct.), and late-fall (Oct.-Nov.). All data was subjected to analysis of variance

(ANOVA) using the general linear model procedure in SAS (SAS Institute, Cary, NC) and treatment means for individual species separated using Fisher's protected LSD (Steel et al., 1997).

Environmental Conditions

Weather data was collected from the Purdue University Airport, West Lafayette, IN. Environmental conditions, precipitation measured as rainfall, air temperature, and soil temperature, varied dramatically between the two study years (Figure 3-2). Rainfall totaled 951 mm and 577 mm per year for 2004 and 2005, respectively. Rainfall was greater in the spring of 2004 (584 mm) compared to 2005 (176 mm). Additionally, during the autumn months (Oct.-Nov.) 2004 (97 mm) was greater than in 2005 (43 mm). Average air temperatures were slightly higher during the summer 2005 than 2004 averaging 23°C and 21°C, respectively. Furthermore, the higher air temperatures persisted longer into the autumn (Sept.) in 2005 (20°C) than in 2004 (19°C). Soil temperatures with 10 cm of grass cover were consistently the same for both years averaging 12°C.

Results and Discussion

Throughout the study, NO_3^- - N concentrations in soil solution were generally low < 1 mg L^{-1} (Table 3-2 to 3-7). However, NO_3^- - N losses were affected by species and sampling date. Among species, KBG had greater NO_3^- - N concentrations in soil solution followed by PRG, and TTTF. Ammonium (NH_4^+ -N) concentrations in soil solution (Table B-19 to B-36) were also low < 1 mg L^{-1}, for all sampling periods and species which is consistent with what Brown et al. (1982) and Miltner et al. (1996) reported. Liu et al. (1997) replicated similar results between KBG, PRG, and TF where they found a two to fifteen fold differences between species. Their results indicated that genetic differences in turfgrass species such as NO_3^- - N absorption efficiencies is one of the many factors influencing the degree of NO_3^- - N leaching.

The N fertilizer application of most concern is during the late-fall (November) when turf growth is minimal and relatively high, 74 kg N ha^{-1}, soluble N is recommended and applied (Reicher and Throssell, 1998). Therefore, soil cores were removed in December to analyze for the presence of NO_3^- - N and NH_4^+ -N. Soil NO_3^- - N and NH_4^+ - N concentrations with depth varied by species and year (Table 3-8 to 3-25). For the most part, soil NO_3^- - N and NH_4^+ -N concentrations were ≤ 5 mg kg^{-1} for all depths, however, there were some exceptions. Turf-type tall fescue NO_3^- - N and NH_4^+ -N concentrations were typically lower then PRG and KBG. Nitrate and NH_4^+ -N concentrations generally decreased in the 15-30 cm depth (< 2.5 mg kg^{-1} NO_3^- -N, < 2.0 mg kg^{-1} NH_4^+ -N) and then increased again in the 30-46 cm depth (< 3.8 mg kg^{-1} NO_3^- -N and < 3.5 mg kg^{-1} NH_4^+ - N). Soil organic matter decreased with sampling depth and ranged from > 61 g kg^{-1} to < 10 g kg^{-1} for all three species with the greatest amount of organic matter in the top 15 cm, which is where the majority of roots are located (Table B-37 to B-45). In 2005, soil organic matter decreased as much as 30 %, regardless of species or N-treatment. We attribute this loss to the unusually hot environmental conditions which persisted throughout the summer.

For TTTF, NO_3^- - N concentrations in soil solution were < 1 mg L^{-1} except for the low Nov. N-treatment in November 2003 (Table 3-2) and the high SNMJ N-treatment ten days after fertilization in October 2004 (Table 3-3). In both of these cases, two replicates had NO_3^- - N concentrations equaling 0 mg L^{-1}. Turf-type tall fescue appears to be more efficient at absorbing NO_3^- - N, potentially due to its dense fibrous root system. Henrikson et al. (1992) and Siebrecht (1995) indicated that NO_3^- - N uptake occurs predominantly in thicker roots whereas KBG has a finer root system which may be one of the reasons that it is generally considered an inefficient user of N (Sullivan et al., 2000).

For PRG, N losses in solution occurred during the fall of 2005 when NO_3^- - N concentrations ranged from 0.01- 3.40 mg L^{-1} (Table 3-5). The treatment with increased NO_3^- - N levels was the medium SOM N-treatment which consistently had NO_3^- - N in soil solution from three days after the September application to ten days after the November application (< 3.4 mg L^{-1}). The high SONAM N-treatment had NO_3^- - N in soil solution ten days after fertilization in September and three and ten days after N application in November having NO_3^- - N concentrations < 1.3 mg L^{-1}. The medium SN N-treatment had NO_3^- - N in soil solution seven days before and ten days after N application in November but again NO_3^- - N concentrations were < 1.1 mg L^{-1}. In November 2003, the medium SN N-treatment had 5.0 mg NO_3^- - N L^{-1}, however this average value was due to a single replication which had a concentration of 15.0 mg L^{-1} while the other two reps were 0 mg L^{-1} (Table 3-4). This plot is located slightly downhill from the other two reps and maybe experiencing some lateral movement of water and nutrients or a replication effect. The medium AMJ N-treatment and the unfertilized treatment had NO_3^- - N concentrations of ≤ 2.5 mg L^{-1} in November 2003 (Table 3-4). For ten days after N application in October 2004, the medium SN N-treatment had a NO_3^- - N concentration of 5.7 mg L^{-1} where the second replication had a concentration of 17.2 mg L^{-1} and the other two replications were 0 mg L^{-1} (Table B-9). For all other N-treatments and sampling periods, NO_3^- - N concentrations for PRG were < 1 mg L^{-1}. Bushoven et al. (2000) reported that NO_3^- - N losses from PRG following turf death can be greater than three times that of healthy PRG turf. The PRG plots were severely damaged by disease during the summer of 2005 to the point where some plots had < 25 % turf cover. These high NO_3^- - N concentrations in the fall of 2005 could be due to a lack of plant density. Perennial ryegrass is a bunch turf turfgrass species and recovery in these areas would take some time due to the lack of rhizomes and stolons.

For KBG, the greatest NO_3^- - N losses occurred very early in the study, in the late fall of 2003 and spring of 2004 (Table 3-6). The high SONAM N-treatment had elevated NO_3^- - N levels in soil solution samples for all three sampling periods in April and May 2004. Nitrate concentrations in April ranged from 1.7 mg L^{-1} ten days after fertilization to 6.6 mg L^{-1} for seven days before fertilization in May. The low Nov. N-treatment had NO_3^- - N concentrations ≤ 3.9 three and ten days after fertilization in April 2004. The low September N-treatment had NO_3^- - N concentrations > 10 mg L^{-1} for November 2003 where at least two of the reps were > 26 mg L^{-1}. This N-treatment had a mean NO_3^- - N concentration of 1.8 and 3.9 mg L^{-1} in April 2004 for seven days before and three days after, respectively. The medium AMJ N-treatment had a NO_3^- - N concentration of 3.1 mg L^{-1} in November 2003, however, this plot was never fertilized. For the rest of the study, NO_3^- - N concentrations were < 1 mg L^{-1} except for ten days after fertilization in November 2004 (Table B-15) for the medium SN N-treatment and for three days after fertilization in November 2005 for the high SNMJ N-treatment, where the NO_3^- - N concentrations were < 2.0 mg L^{-1} (Table 3-7) The NO_3^- - N concentration for the medium SN N-treatment in November 2004 however, is most likely due to replication effect since one rep was 3.6 mg L^{-1} and the other two reps were 0 mg L^{-1} (Table B-15).

Soil NO_3^- - N concentrations by depth for TTTF were higher in the top 0-15 cm depth (< 4.2 mg kg^{-1}) than the other two depths (< 1.6 mg kg^{-1}) ranging from 1.7 to 2.5, 1.1 to 6.2, and 1.6 to 3.7 mg kg^{-1} for December 2003, 2004, and 2005, respectively (Table 3-8 to 3-10). In December 2004, soil NO_3^- - N concentrations were > 4 mg kg^{-1} for the Nov. (5.3 mg kg^{-1}) and the SONAM (6.2 mg kg^{-1}) N-treatments (Table 3-8). For the 15 to 30 cm depth, soil NO_3^- - N concentrations were < 2.5 mg kg^{-1} ranging from 0.3 to 0.7, 0.9 to 1.4, and 1.8 to 2.4 mg kg^{-1} for December 2003, 2004, and 2005, respectively. Soil NO_3^- - N concentrations for the 30-46 cm depth ranged from 1.1 to 1.7, 0.6, to 1.2, and 1.8 to 2.3 mg kg^{-1} for December 2003, 2004, and 2005, respectively.

Although NH_4^+ -N has little risk for environmental contamination excessive levels can indicate inefficient N use. Ammonium (NH_4^+ -N) concentrations in soil for TTTF (Table 3-17 to 3-19) were generally < 4 mg kg^{-1} except for the low November (4.7 mg kg^{-1}) N-treatment and the high SONAM (5.0 mg kg^{-1}) N-treatment in December 2003 at the 0-15 cm depth (Table 3-17). Also in December 2003 but at the 30-46 cm depth, the medium SN (7.0 mg kg^{-1}) and the high SONAM (5.6 mg kg^{-1}) N-treatments had soil NH_4^+ -N concentrations > 4 mg kg^{-1}(Table 3-17).

Soil NO_3^- - N concentrations by depth for PRG were greatest in the top 0-15 cm (< 4.4 mg kg^{-1}) compared to the other two depths (< 2.1 mg kg^{-1}) and ranged from 1.6 to 2.7, 1.2 to 5.4, and 1.9 to 5.1 mg kg^{-1} for December 2003, 2004, and 2005, respectively (Table 3-11 to 3-13). The medium AMJ N-treatment in 2004 and the high SNMJ N-treatment in 2005 produced NO_3^- - N concentrations > 5 mg kg^{-1} (Table 3-12). For the 15 to 30 cm depth, soil NO_3^- - N concentrations ranged from 0.3 to 0.7, 0.9 to 1.4, and 2.0 to 2.4 mg kg^{-1} for December 2003, 2004, and 2005, respectively. Soil NO_3^- - N concentrations for the 30 to 46 cm depth ranged from 1.2 to 2.1, 0.6 to 1.8, and 2.0 to 2.4 mg kg^{-1} for December 2003, 2004, and 2005 respectively.

Soil NH_4^+-N concentrations for PRG (Table 3-20 to 3-22) were low < 4 mg kg^{-1} except for the medium SN (7.2 mg kg^{-1}) N-treatment in December 2003 and the high SNMJ (5.1 mg kg^{-1}) N-treatment for the 0-15 cm depth (Table 3-20). At the 30-46 cm depth on December 2003, the high SONAM (5.9 mg kg^{-1}) N-treatment had an NH_4^+-N concentration > 4 mg kg^{-1} (Table 3-20).

Soil NO_3^- - N concentrations by depth for KBG were similar to TTTF. Concentrations were greater in the top 0-15 cm depth (< 4.2 mg kg^{-1}) than the other two depths (< 3.8 mg kg^{-1}) ranging from 1.8 to 2.8, 1.3 to 5.5, and 1.7 to 4.4 mg kg^{-1} for December 2003, 2004, and 2005, respectively (Table 3-14 to 3-16). However, the 30-46 cm depth had the greatest amount of NO_3^- - N for KBG than the other two species > 2.1 mg kg^{-1}. In December 2004, soil NO_3^- - N concentrations were > 4 mg kg^{-1} for the high SONAM N-treatment (5.3 mg kg^{-1}) and the unfertilized treatment (5.5 mg kg^{-1}) (Table 3-15). For the 15 to 30 cm depth, soil nitrate (NO_3^- - N) concentrations were < 2.5 mg kg^{-1} ranging from 0.5 to 1.8, 0.8 to 2.1, and 1.8 to 2.4 mg kg^{-1} for December 2003, 2004, and 2005 respectively. Soil NO_3^- - N concentrations for the 30-46 cm depth ranged from 1.4 to 5.2, 0.7, to 3.8, and 1.8 to 2.3 mg kg^{-1} for December 2003, 2004, and 2005 respectively. In December 2003, the low September (5.2 mg kg^{-1}), low November (4.3 mg kg^{-1}), and the medium SN (4.4 mg kg^{-1}) N-treatments had NO_3^- - N concentrations > 4 mg kg^{-1} (Table 3-14).

Soil NH_4^+-N concentrations for KBG (Table 3-23 to 3-25) were less than < 4 mg kg^{-1} except for the low November (6.7 mg kg^{-1}) N-treatment and the non-fertilized treatment (4.7 mg kg^{-1}) in December 2003 for the 30-46 cm depth (Table 3-23) and the low November (7.2 mg kg^{-1}) N-treatment in December 2005 for the 0-15 cm depth (Table 3-25).

Liu et al. (1997) found that soil water NO_3^- - N concentrations were highest for KBG during the late-fall, October to December. However, NO_3^- - N leaching potential is also influenced by uneven distribution of precipitation (Hull et al, 1992; Liu et al, 1997; Mangiafico and Guillard, 2006). Gold et al. (1990) reported the greatest NO_3^- - N concentrations from lawn turf during the spring. Geron et al. (1993) and Duff et al. (1997) observed that leaching losses were a function of climate and season instead of N application timing or form. In this study, it rained 8.3, 5.7, and 3.5 mm for March, April, and May (2004), respectively. Compared to the spring of 2005, where it rained 1.7, 1.1, and 1.2 mm for March, April, and May, respectively (Figure 3-2). Therefore, the spring of 2004 was five times wetter and may account for the higher NO_3^- - N concentrations. Morton et al. (1988) also indicated that natural rainfall plus irrigation can result in significant episodic NO_3^- - N leaching losses. This excess moisture coupled with KBG genetic differences in NO_3^- - N absorption efficiency, means more NO_3^- - N should be found in soil solution for this species. In fact, seasonal variations in climate, and disease incidence rather than fertilizer treatments, seem to have a greater effect on soil NO_3^- - N concentrations.

In regards to late-fall fertilization, Petrovic (1990) cautions against applying soluble fertilizer sources in the late fall due to the potential for NO_3^- - N losses, although Miltner et al. (1996) found that there is little potential for NO_3^- - N leaching in the late fall. Guillard and Kopp (2004) found that the potential for NO_3^- - N leaching increases with the use of soluble N sources during late-fall fertilization. They recommend that lawn fertilizers should be formulated with higher percentages of slow release N. Liu et al. (1997) reported that cool-season turfgrass species differ substantially in their N absorption efficiencies and indicated that late fall fertilization might enhance leaching potentials for some grasses such as KBG.

This study showed that NO_3^- - N concentrations in soil solution were higher for KBG, followed by PRG, and TTTF. In general, NO_3^- - N levels were very low except for one KBG sampling date out of two and a half years. This resulted in NO_3^- - N concentrations exceeding the EPA safe water drinking standard of 10 mg NO_3^- - N L^{-1} (> 17 mg L^{-1}) (Table 3-6). Although little NO_3^- - N was measured after year one, as KBG matures (> 10 yrs), the risk for NO_3^- - N leaching may increase. Frank et al. (2006) found when a high N rate (245 kg N ha^{-1} yr^{-1}) was applied repeatedly for several years, NO_3^- - N concentrations in leachate were at least two times greater than 10 mg L^{-1}. Therefore, older lawns should be fertilized sparingly once mature.

The greatest NO_3^- - N losses occurred in the early spring 2004 for KBG and late fall 2005 with PRG which is consistent with the findings of Guillard and Kopp (2004).

Geron et al., (1993) and Liu et al. (1997) found that N leaching losses were lowest in May, June, and July as temperatures increased and plants and microbes utilized N. In fact, higher soil water NO_3^- - N concentrations are associated with slow periods of plant growth. Implementing a N fertility program that does not result in accumulation of excess soil NO_3^- - N levels is important. Miltner et al. (2001) showed that a rapid increase of soil NO_3^- - N levels during the late-fall created a situation where plant uptake of N could not keep up with the mineralization and nitrification processes especially when additional N was applied.

Soil NO_3^- - N concentrations were not affected by N program as found in a study by Gross et al. (1990) and Lee et al. (2003). In our study, soil NO_3^- - N concentrations were consistently < 4 mg kg^{-1} and NO_3^- - N levels were similar to those reported by Lee et al. (2003) and even when an exception occurred which was only twice, NO_3^- - N concentrations were < 6.2 mg kg^{-1}. Similar results for soil NO_3^- - N concentrations < 3.2 mg kg^{-1} and similar results were reported by Morton et al. (1988) and Gross et al. (1990). In field crops, elevated soil NO_3^- - N levels are often observed several weeks after fertilization (Starr and DeRoo, 1980; Wagger, 1993). They dissipate with time as it leaches or as the plant roots take up the NO_3^- - N. Soil NO_3^- - N concentrations were also consistent with depth as reported by Lee et al. (2003). This has previously been shown with cool-season grasses where inorganic N fertilizer applied at normal rates (49 kg N ha^{-1}) is efficiently taken up within 24-48 h due to their root length densities and nutrient absorption surfaces (Bowman et al., 1989).

The N-programs studied in this research appear to pose little threat to groundwater contamination due to the generally low NO_3^- - N losses measured, especially for TTTF and PRG. On only one sampling date out of the two and a half years of sampling did NO_3^- - N concentrations exceeded the EPA safe water drinking standard of 10 mg L^{-1}. This occurred with KBG in the spring following the establishment year but was not observed in subsequent years. If concerned by KBG lower absorption efficiency compared to the other two cool-season turfgrass species, then this species should be judiciously fertilized with slow release N sources especially as the lawn matures and soil organic matter mineralizes.

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Table 3-1. Eight nitrogen fertility programs varying in application timing and rate for three primary lawn species.

Application Timing	Annual Nitrogen Rate†	Monthly Nitrogen Rate					
		Apr.	May	July	Sept.	Oct.	Nov.
	(kg N ha^{-1})						
Sept. only	49	0	0	0	49	0	0
Nov. only	73	0	0	0	0	0	73
Apr., May, & Jul.	123	49	37	37	0	0	0
Sept. & Nov.	123	0	0	0	50	0	73
Sept., Oct., & May	123	0	25	0	49	49	0
S, N, M, & July	196	0	37	37	49	0	73
S, O, N, A, & May	196	24	25	0	49	49	49
Untreated	0	0	0	0	0	0	0

† Nitrogen (N) was supplied as urea alone in Oct. and Nov., in July sulfur coated urea (SCU) was applied alone, and all other times a 50/50 (w/w) mixture of urea and SCU was applied.

Table 3-2. Turf-type tall fescue nitrate concentrations in soil solution as related to various nitrogen fertility programs for November 2003 and spring 2004.

		2003	2004					
Application Timing	Nitrogen Rate†	Nov.	Apr.			May		
		7 Days Before	7 Days Before	3 Days After	10 Days After	7 Days Before	3 Days After	10 Days After
	kg N ha^{-1}	(mg NO_3^- -N L^{-1})						
Sept. only	49	0.04	0.01	0.02	0.02	0.01	0.01	0.01
Nov. only	73	2.43	0.03	0.02	0.01	0.01	0.01	0.01
Apr., May, & Jul.	123	0.04	0.02	0.02	0.02	0.01	0.01	0.01
Sept. & Nov.	123	0.06	0.01	0.06	0.02	0.01	0.02	0.03
Sept., Oct., & May	123	0.04	0.03	0.04	0.02	0.03	0.03	0.02
S, N, M, & July	196	0.04	0.02	0.04	0.04	0.01	0.01	0.01
S, O, N, A, & May	196	0.04	0.02	0.03	0.02	0.01	0.01	0.01
Untreated	0	0.07	0.01	0.02	0.02	0.01	0.01	0.01
ANOVA								
Rep		NS	NS	NS	NS	NS	NS	NS
N-Program		NS	NS	NS	NS	NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

NS refers to non-significant.

Table 3-3. Turf-type tall fescue nitrate concentrations in soil solution as related to various nitrogen fertility programs for fall 2005.

		2005								
Application Timing	Nitrogen Rate†	Sept			Oct			Nov		
		7 Days Before	3 Days After	10 Days After	7 Days Before	3 Days After	10 Days After	7 Days Before	3 Days After	10 Days After
	kg N ha^{-1}	---------------	---------------	---------------	---(mg NO_3^- -N L^{-1})---	---------------	---------------	---------------	---------------	---------------
Sept. only	49	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
Nov. only	73	0.02	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01
Apr., May, & July	123	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.02	0.00
Sept. & Nov.	123	0.01	0.01	0.08	0.01	0.01	0.01	0.02	0.02	0.02
Sept., Oct., & May	123	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.02
S, N, M, & July	196	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01
S, O, N, A, & May	196	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01
Untreated	0	0.01	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.01
ANOVA										
Rep		NS	NS	NS	NS	NS	NS	NS	NS	NS
N-Program		NS	NS	NS	NS	NS	NS	NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

NS refers to non-significant.

Table 3-4. Perennial ryegrass nitrate concentrations in soil solution as related to various nitrogen fertility programs for November 2003 and spring 2004.

		2003	2004					
Application Timing	Nitrogen Rate†	Nov	Apr			May		
		7 Days Before	7 Days Before	3 Days After	10 Days After	7 Days Before	3 Days After	10 Days After
	kg N ha^{-1}	(mg NO_3^- -N L^{-1})						
Sept. only	49	0.04	0.01	0.02	0.02	0.01	0.01	0.01
Nov. only	73	0.08	0.02	0.12	0.03	0.02	0.05	0.03
Apr., May, & July	123	2.20	0.03	0.11	0.02	0.01	0.03	0.01
Sept. & Nov.	123	4.99	0.04	0.03	0.03	0.02	0.01	0.03
Sept., Oct., & May	123	0.04	0.39	0.05	0.02	0.01	0.01	0.01
S, N, M, & July	196	0.06	0.02	0.03	0.02	0.01	0.01	0.01
S, O, N, A, & May	196	0.62	0.11	0.06	0.07	0.56	0.56	0.64
Untreated	0	2.48	0.01	0.04	0.01	0.04	0.01	0.01
ANOVA								
Rep		NS	NS	NS	NS	NS	NS	NS
N-Program		NS	NS	NS	NS	NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

NS refers to non-significant.

Table 3-5. Perennial ryegrass nitrate concentrations in soil solution as related to various nitrogen fertility programs for fall 2005.

		2005								
Application Timing	Nitrogen Rate†	Sept			Oct			Nov		
		7 Days Before	3 Days After	10 Days After	7 Days Before	3 Days After	10 Days After	7 Days Before	3 Days After	10 Days After
	kg N ha^{-1}	(mg NO_3^- -N L^{-1})								
Sept. only	49	0.01	0.02	0.09	0.12	0.01	0.20	0.36	0.08	0.01
Nov. only	73	0.01	0.06	0.25	0.31	0.82	0.02	0.01	0.12	0.01
Apr., May, & July	123	0.01	0.01	0.06	0.08	0.02	0.02	0.01	0.01	0.01
Sept. & Nov.	123	0.01	0.03	0.01	0.02	0.26	0.35	1.15	0.01	1.01
Sept., Oct., & May	123	0.05	1.13	1.42	2.03	2.93	3.36	2.50	1.04	1.82
S, N, M, & July	196	0.01	0.01	0.19	0.02	0.07	0.07	0.01	0.01	0.01
S, O, N, A, & May	196	0.01	0.11	1.03	0.23	0.09	0.05	0.92	1.31	1.07
Untreated	0	0.01	0.01	0.01	0.07	0.02	0.02	0.01	0.01	0.01
ANOVA										
Rep		NS	NS	NS	NS	NS	NS	NS	NS	NS
N-Program		NS	NS	NS	NS	NS	NS	NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

NS refers to non-significant.

Table 3-6. Kentucky bluegrass nitrate concentrations in soil solution as related to various nitrogen fertility programs for November 2003 and spring 2004.

		2003	2004					
Application Timing	Nitrogen Rate†	Nov	Apr			May		
		7 Days Before	7 Days Before	3 Days After	10 Days After	7 Days Before	3 Days After	10 Days After
	kg N ha^{-1}	---(mg NO_3^--N L^{-1})---						
Sept. only	49	17.36 a	1.79	3.89	0.48 b	0.04 b	0.01 b	0.01
Nov. only	73	0.68 b	1.82	2.07	0.18 b	0.18 b	0.41 b	1.50
Apr., May, & July	123	3.08 b	1.03	0.18	0.20 b	1.13 b	0.11 b	1.01
Sept. & Nov.	123	0.91 b	0.31	0.07	0.03 b	0.04 b	0.03 b	0.03
Sept., Oct., & May	123	0.62 b	0.02	0.01	0.02 b	0.01 b	0.01 b	0.01
S, N, M, & July	196	0.89 b	0.02	0.03	0.01 b	0.01 b	0.01 b	0.01
S, O, N, A, & May	196	0.04 b	3.75	2.27	1.77 a	6.55 a	6.19 a	4.93
Untreated	0	0.05 b	0.02	0.03	0.02 b	0.01 b	0.02 b	0.03
ANOVA								
Rep		NS	NS	NS	NS	NS	NS	NS
N-Program		*	NS	NS	*	*	*	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

* and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-7. Kentucky bluegrass nitrate concentrations in soil solution as related to various nitrogen fertility programs for fall 2005.

		2005								
Application Timing	Nitrogen Rate†	Sept			Oct			Nov		
		7 Days Before	3 Days After	10 Days After	7 Days Before	3 Days After	10 Days After	7 Days Before	3 Days After	10 Days After
	kg N ha^{-1}	(mg NO_3^- -N L^{-1})								
Sept. only	49	0.01	0.01	0.01	0.21	0.02	0.01	0.00	0.04	0.04
Nov. only	73	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
Apr., May, & Juy.	123	0.01	0.01	0.01	0.01	0.02	0.01	0.00	0.03	0.01
Sept. & Nov.	123	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.03	0.01
Sept., Oct., & May	123	0.04	0.08	0.03	0.07	0.14	0.14	0.09	0.07	0.10
S, N, M, & July	196	0.01	0.03	0.01	0.01	0.24	0.02	0.64	1.80	0.90
S, O, N, A, & May	196	0.01	0.03	0.01	0.01	0.05	0.03	0.03	0.09	0.11
Untreated	0	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.01
ANOVA										
Rep		NS	NS	NS	NS	NS	NS	NS	NS	NS
N-Program		NS	NS	NS	NS	NS	NS	NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
NS refers to non-significant.

Table 3-8. Effect of late-fall fertilization on soil nitrate responses to various nitrogen fertility programs for turf-type tall fescue, December 2003.

Application Timing	Nitrogen Rate†	December 2003		
		0-15 cm	15-30 cm	30-46 cm
	$kg\ N\ ha^{-1}$	----------------------------	($mg\ NO_3^-$ -$N\ kg^{-1}$)	----------------------------
Sept. only	49	1.67	0.67	1.57
Nov. only	73	2.10	0.50	1.23
Apr., May, & July	123	1.73	0.63	1.43
Sept. & Nov.	123	2.30	0.33	1.67
Sept., Oct., & May	123	1.90	0.53	1.67
S, N, M, & July	196	1.83	0.53	1.70
S, O, N, A, & May	196	2.53	0.47	1.13
Untreated	0	1.70	0.73	1.53
ANOVA				
Rep		NS	*	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
* and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-9. Effect of late-fall fertilization on soil nitrate responses to various nitrogen fertility programs for turf-type tall fescue, December 2004.

Application Timing	Nitrogen Rate†	December 2004		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	----------(mg NO_3^- -N kg^{-1})----------		
Sept. only	49	2.47	1.17	0.83
Nov. only	73	5.27	1.17	0.60
Apr., May, & July	123	1.30	0.93	0.67
Sept. & Nov.	123	1.93	0.83	1.03
Sept., Oct., & May	123	1.07	1.43	1.17
S, N, M, & July	196	1.37	1.00	0.80
S, O, N, A, & May	196	6.20	0.90	1.10
Untreated	0	1.53	0.83	0.73
ANOVA				
Rep		NS	NS	*
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
* and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-10. Effect of late-fall fertilization on soil nitrate responses to various nitrogen fertility programs for turf-type tall fescue, December 2005.

Application Timing	Nitrogen Rate†	December 2005		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	(mg NO_3^- -N kg^{-1})		
Sept. only	49	1.66	2.14	1.90
Nov. only	73	1.95	1.97	2.10
Apr., May, & Juy.	123	1.56	2.24	1.76
Sept. & Nov.	123	2.23	2.10	1.97
Sept., Oct., & May	123	1.95	1.78	1.96
S, N, M, & July	196	3.71	1.91	2.33
S, O, N, A, & May	196	3.54	2.42	1.99
Untreated	0	1.75	1.97	2.31
ANOVA				
Rep		NS	NS	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
NS refers to non-significant.

Table 3-11. Effect of late-fall fertilization on soil nitrate responses to various nitrogen fertility programs for perennial ryegrass, December 2003.

Application Timing	Nitrogen Rate†	December 2003		
		0-15 cm	15-30 cm	30-46 cm
	$kg\ N\ ha^{-1}$	----------------------(mg NO_3^- -N kg^{-1})----------------------		
Sept. only	49	1.67 bc	0.67	1.47
Nov. only	73	2.27 ab	0.37	1.70
Apr., May, & July	123	1.60 c	0.33	1.67
Sept. & Nov.	123	2.73 a	0.53	2.00
Sept., Oct., & May	123	1.90 bc	0.63	2.10
S, N, M, & July	196	2.00 bc	0.37	1.87
S, O, N, A, & May	196	1.93 bc	0.70	1.93
Untreated	0	1.63 bc	0.40	1.20
ANOVA				
Rep		NS	*	NS
N-Program		*	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

*and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-12. Effect of late-fall fertilization on soil nitrate responses to various nitrogen fertility programs for perennial ryegrass, December 2004.

Application Timing	Nitrogen Rate†	December 2004		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	---(mg NO_3^- -N kg^{-1})---		
Sept. only	49	2.07	1.07	0.57
Nov. only	73	2.30	1.33	0.90
Apr., May, & July	123	5.43	1.00	1.07
Sept. & Nov.	123	1.20	0.93	0.83
Sept., Oct., & May	123	4.07	0.93	1.03
S, N, M, & July	196	1.17	0.93	0.73
S, O, N, A, & May	196	1.43	1.03	0.83
Untreated	0	1.53	1.00	1.77
ANOVA				
Rep		*	NS	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

* and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-13. Effect of late-fall fertilization on soil nitrate responses to various nitrogen fertility programs for perennial ryegrass, December 2005.

Application Timing	Nitrogen Rate†	December 2005		
		0-15 cm	15-30 cm	30-46 cm
	$kg\ N\ ha^{-1}$	------(mg NO_3^- -N kg^{-1})------		
Sept. only	49	1.86	2.11	2.04
Nov. only	73	3.06	2.23	2.16
Apr., May, & July	123	2.09	2.14	2.02
Sept. & Nov.	123	3.39	2.32	2.21
Sept., Oct., & May	123	2.51	1.95	2.41
S, N, M, & July	196	5.11	2.38	2.19
S, O, N, A, & May	196	3.14	2.11	2.32
Untreated	0	1.93	2.19	1.98
ANOVA				
Rep		NS	**	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
** and NS refer to significant at the 0.01 and non-significant respectively.

Table 3-14. Effect of late-fall fertilization on soil nitrate responses to various nitrogen fertility programs for Kentucky bluegrass, December 2003.

Application Timing	Nitrogen Rate†	December 2003		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	----------(mg NO_3^- -N kg^{-1})----------		
Sept. only	49	1.83	1.03	5.23
Nov. only	73	2.80	1.40	4.27
Apr., May, & July	123	2.03	0.63	2.68
Sept. & Nov.	123	2.60	1.77	4.37
Sept., Oct., & May	123	1.93	0.60	1.60
S, N, M, & July	196	2.20	0.53	2.43
S, O, N, A, & May	196	2.33	0.90	3.03
Untreated	0	2.57	0.90	1.43
ANOVA				
Rep		*	*	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
* and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-15. Effect of late-fall fertilization on soil nitrate responses to various nitrogen fertility programs for Kentucky bluegrass, December 2004.

Application Timing	Nitrogen Rate†	December 2004		
		0-15 cm	15-30 cm	30-46 cm
	$kg\ N\ ha^{-1}$	$(mg\ NO_3^-\ -N\ kg^{-1})$		
Sept. only	49	1.37	1.07	0.83
Nov. only	73	2.00	0.93	0.70
Apr., May, & July	123	2.13	1.20	1.07
Sept. & Nov.	123	1.37	1.17	2.00
Sept., Oct., & May	123	3.40	2.13	0.67
S, N, M, & July	196	1.33	1.10	0.77
S, O, N, A, & May	196	5.27	0.77	3.79
Untreated	0	5.47	1.07	1.03
ANOVA				
Rep		*	NS	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
* and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-16. Effect of late-fall fertilization on soil nitrate responses to various nitrogen fertility programs for Kentucky bluegrass, December 2005.

Application Timing	Nitrogen Rate†	December 2005		
		0-15 cm	15-30 cm	30-46 cm
	$kg\ N\ ha^{-1}$	----------($mg\ NO_3^-$ -N kg^{-1})----------		
Sept. only	49	1.69	2.05	1.77
Nov. only	73	4.38	1.99	2.34
Apr., May, & July	123	1.88	2.00	2.27
Sept. & Nov.	123	3.02	2.26	2.30
Sept., Oct., & May	123	1.97	2.04	2.25
S, N, M, & July	196	2.32	2.40	2.18
S, O, N, A, & May	196	3.30	2.35	2.18
Untreated	0	1.86	1.82	2.03
ANOVA				
Rep		NS	NS	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

NS refers to non-significant.

Table 3-17. Effect of late-fall fertilization on soil ammonium responses to various nitrogen fertility programs for turf-type tall fescue, December 2003.

Application Timing	Nitrogen Rate†	December 2003		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	---------(mg NH_4^+ -N kg^{-1})---------		
Sept. only	49	1.82	0.27	1.07
Nov. only	73	4.73	0.37	3.87
Apr., May, & July	123	1.47	0.33	2.03
Sept. & Nov.	123	4.20	0.50	7.00
Sept., Oct., & May	123	2.70	0.57	3.37
S, N, M, & July	196	2.17	0.57	2.37
S, O, N, A, & May	196	5.00	0.50	5.57
Untreated	0	1.00	0.17	1.13
ANOVA				
Rep		NS	NS	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

NS refers to non-significant.

Table 3-18. Effect of late-fall fertilization on soil ammonium responses to various nitrogen fertility programs for turf-type tall fescue, December 2004.

Application Timing	Nitrogen Rate†	December 2004		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	---------(mg NH_4^+ -N kg^{-1})---------		
Sept. only	49	4.23	0.80	1.40
Nov. only	73	3.40	0.87	1.17
Apr., May, & July	123	2.37	0.53	0.77
Sept. & Nov.	123	3.23	0.60	1.10
Sept., Oct., & May	123	2.73	0.90	1.10
S, N, M, & July	196	3.43	0.47	1.00
S, O, N, A, & May	196	3.17	0.90	1.67
Untreated	0	2.10	0.43	1.07
ANOVA				
Rep		NS	NS	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
NS refers to non-significant.

Table 3-19. Effect of late-fall fertilization on soil ammonium responses to various nitrogen fertility programs for turf-type tall fescue, December 2005.

Application Timing	Nitrogen Rate†	December 2005		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	-----------------(mg NH_4^+ -N kg^{-1})	-----------------	-----------------
Sept. only	49	3.61	1.16	1.35
Nov. only	73	3.02	1.39	1.52
Apr., May, & July	123	3.24	1.53	1.15
Sept. & Nov.	123	2.60	2.26	1.43
Sept., Oct., & May	123	3.30	1.56	1.30
S, N, M, & July	196	3.02	1.47	1.42
S, O, N, A, & May	196	3.74	1.62	1.45
Untreated	0	2.09	1.15	1.22
ANOVA				
Rep		NS	NS	*
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

* and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-20. Effect of late-fall fertilization on soil ammonium responses to various nitrogen fertility programs for perennial ryegrass, December 2003.

Application Timing	Nitrogen Rate†	December 2003		
		0-15 cm	15-30 cm	30-46 cm
	$kg\ N\ ha^{-1}$	----------------	($mg\ NH_4^+$ -N kg^{-1})	----------------
Sept. only	49	1.02	0.27	1.27 c
Nov. only	73	3.17	0.57	3.67 abc
Apr., May, & July	123	3.40	0.40	3.70 abc
Sept. & Nov.	123	7.20	0.30	1.33 bc
Sept., Oct., & May	123	2.83	0.57	4.07 ab
S, N, M, & July	196	3.50	0.53	2.07 bc
S, O, N, A, & May	196	2.90	0.77	5.87 a
Untreated	0	1.77	0.27	2.40 bc
ANOVA				
Rep		NS	NS	NS
N-Program		NS	NS	*

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
* and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-21. Effect of late-fall fertilization on soil ammonium responses to various nitrogen fertility programs for perennial ryegrass, December 2004.

Application Timing	Nitrogen Rate†	December 2004		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	(mg NH_4^+ -N kg^{-1})		
Sept. only	49	2.47	1.20	0.60
Nov. only	73	2.80	0.83	1.23
Apr., May, & July	123	2.83	0.63	1.23
Sept. & Nov.	123	2.50	1.77	0.90
Sept., Oct., & May	123	4.63	0.73	1.10
S, N, M, & July	196	2.37	0.27	0.97
S, O, N, A, & May	196	3.73	0.50	0.87
Untreated	0	2.13	0.53	1.27
ANOVA				
Rep		NS	NS	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
NS refers to non-significant.

Table 3-22. Effect of late-fall fertilization on soil ammonium responses to various nitrogen fertility programs for perennial ryegrass, December 2005.

Application Timing	Nitrogen Rate†	December 2005		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	---------------------	(mg NH_4^+ -N kg^{-1})	---------------------
Sept. only	49	2.47	1.17	1.08
Nov. only	73	2.96	1.44	1.39
Apr., May, & July	123	2.59	1.47	1.58
Sept. & Nov.	123	2.97	1.45	1.52
Sept., Oct., & May	123	3.21	1.36	1.68
S, N, M, & July	196	5.13	1.40	1.88
S, O, N, A, & May	196	3.28	1.57	1.46
Untreated	0	2.70	1.31	1.42
ANOVA				
Rep		NS	*	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
* and NS refer to significant at the 0.05 and non-significant respectively.

Table 3-23. Effect of late-fall fertilization on soil ammonium responses to various nitrogen fertility programs for Kentucky bluegrass, December 2003.

Application Timing	Nitrogen Rate†	December 2003		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	----------------	(mg NH_4^+ -N kg^{-1})	----------------
Sept. only	49	1.23	0.40	2.37
Nov. only	73	2.03	0.47	6.67
Apr., May, & July	123	1.23	0.30	2.53
Sept. & Nov.	123	3.23	0.43	2.60
Sept., Oct., & May	123	1.80	0.30	1.47
S, N, M, & July	196	2.47	0.23	2.40
S, O, N, A, & May	196	3.50	0.67	3.47
Untreated	0	2.67	2.97	4.70
ANOVA				
Rep		NS	NS	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
NS refers to non-significant.

Table 3-24. Effect of late-fall fertilization on soil ammonium responses to various nitrogen fertility programs for Kentucky bluegrass, December 2004.

Application Timing	Nitrogen Rate†	December 2004		
		0-15 cm	15-30 cm	30-46 cm
	kg N ha^{-1}	(mg NH_4^+ -N kg^{-1})		
Sept. only	49	1.93	0.77	0.90
Nov. only	73	3.83	1.10	0.90
Apr., May, & July	123	2.40	0.47	1.17
Sept. & Nov.	123	2.17	0.83	1.60
Sept., Oct., & May	123	2.27	1.00	0.83
S, N, M, & July	196	2.67	0.53	0.90
S, O, N, A, & May	196	3.20	0.87	1.53
Untreated	0	2.07	0.90	1.60
ANOVA				
Rep		NS	NS	NS
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.
Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
NS refers to non-significant.

Table 3-25. Effect of late-fall fertilization on soil ammonium responses to various nitrogen fertility programs for Kentucky bluegrass, December 2005.

Application Timing	Nitrogen Rate†	December 2005		
		0-15 cm	15-30 cm	30-46 cm
	$kg\ N\ ha^{-1}$	----------($mg\ NH_4^+$ -N kg^{-1})----------		
Sept. only	49	2.13	1.63	1.30
Nov. only	73	7.19	1.31	1.33
Apr., May, & July	123	2.43	1.22	1.60
Sept. & Nov.	123	2.85	1.41	1.42
Sept., Oct., & May	123	2.62	1.32	1.23
S, N, M, & July	196	3.24	1.40	1.05
S, O, N, A, & May	196	3.33	1.54	1.44
Untreated	0	2.03	1.11	1.34
ANOVA				
Rep		NS	NS	*
N-Program		NS	NS	NS

† Nitrogen was supplied as urea alone in Oct. and Nov., in July SCU was applied alone, and all other times a 50/50 (w/w) mixture of urea and sulfur coated urea was applied.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

* and NS refer to significant at the 0.05 and non-significant respectively.

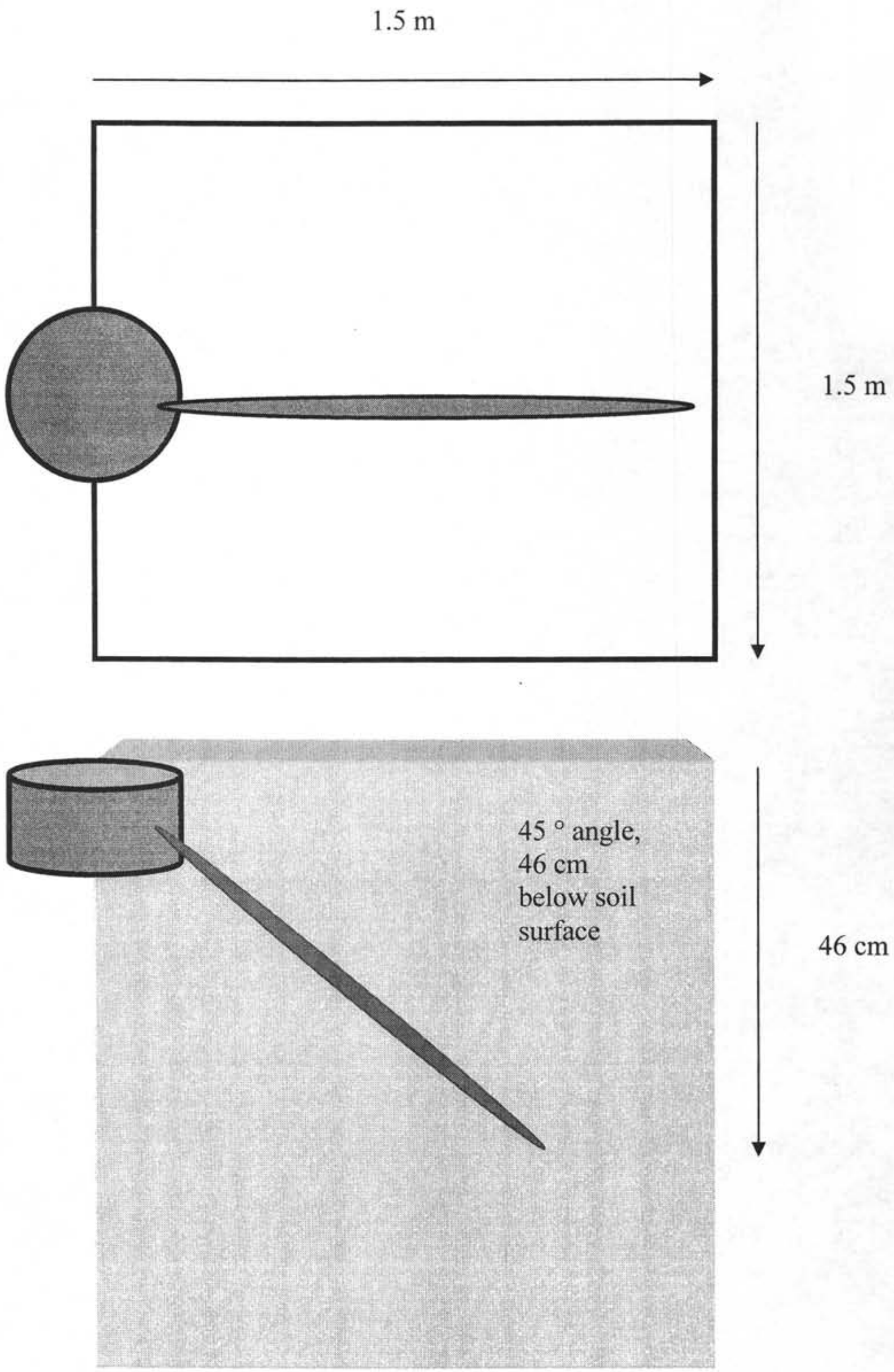

Figure 3-1. Suction cup lysimeters were installed at a 45° angle from the soil surface to collect the soil solution 46 cm prior to N fertilizer application and three and ten days following.

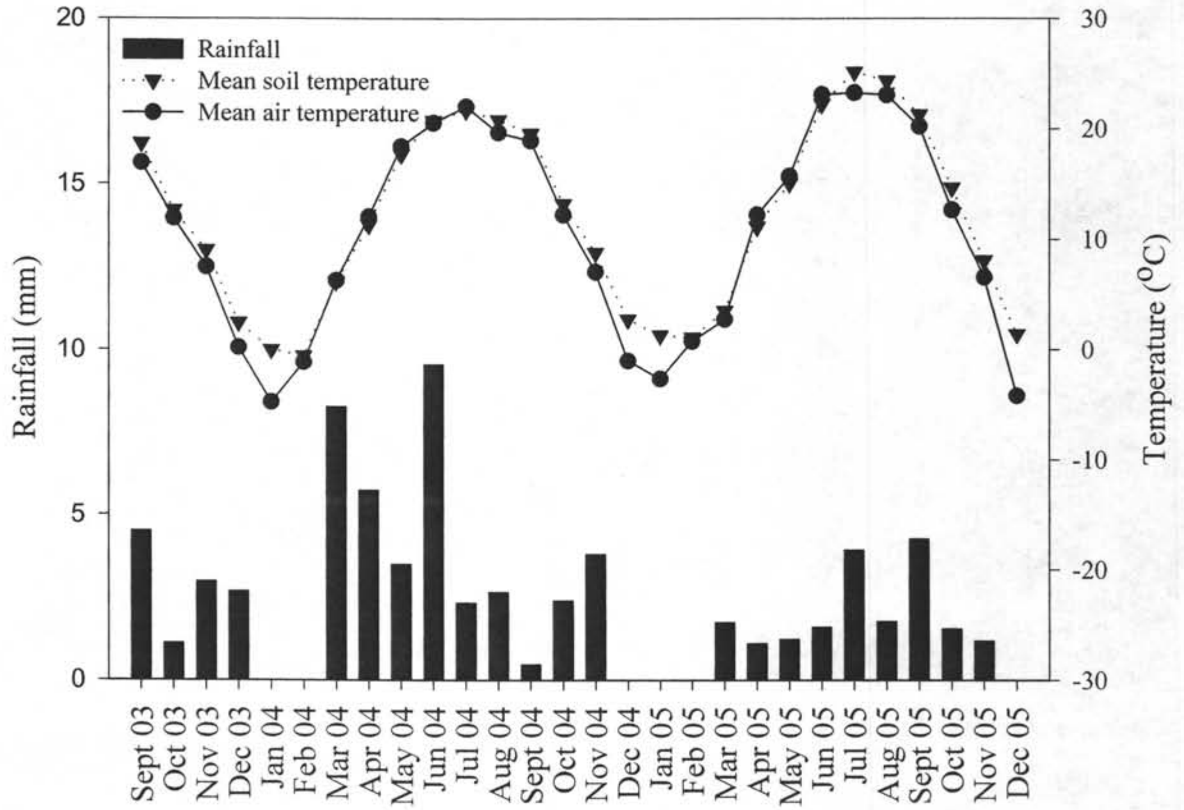

Figure 3-2. Rainfall, air and soil (grass cover, 10 cm) temperatures from September 2003 to December 2005.