EVALUATING THREE TURFGRASSES FOR NITROGEN, PHOSPHORUS AND POTASSIUM NUTRIENT UPTAKE EFFICIENCY

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ABSTRACT

Ten cultivars each of Kentucky bluegrass (*Poa pratensis* L.), perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea* Schreb.) were included in field studies to compare the nitrate concentration of soil water collected at a depth of 60 cm and the annual cumulative nitrate losses through leaching between March 1990 and April 1992. Significant differences among genera and cultivars were identified for nitrate leaching potential and nitrogen recovery in clippings based on monthly and seasonal analyses. Some correlations between nitrate leaching potential and nitrogen recovery in clippings were identified. These results indicate that genetic differences exist among turfgrasses for nitrate utilization at both interspecific and intraspecific levels and suggest that a screening program could be developed to identify turfgrass cultivars and species having superior capacity to remove nitrate from the soil.

Increasing the capacity of low maintenance turfgrasses to recover nutrient efficiently from the soil has become an important research objective for economic and environmental reasons. Understanding cultivar variation of turfgrass species in their capacity for nitrogen, phosphorus and potassium absorption is essential to achieving this goal. The kinetic parameters of N, P, and K absorption (Vmax, Km, Cm, AIUC and CUU) were measured for six cultivars each of the three species. The cultures were grown hydroponically and N, P and K uptake kinetics were measured with a solution depletion technique. The turfgrasses varied significantly between species and within species for the uptake parameters measured. Clipping production rate, leaf blade nitrogen, phosphorus, potassium contents, N, P, and K recovery rate in clippings, and N, P and K efficiency ratio of the same six cultivars were compared during the 1990 and 1991 growing seasons under moderate N, P and K fertilization rates of 149, 37 and 59 kg N, P and K ha $^{-1}$ year $^{-1}$. Some correlations between the N, P, and K uptake parameters and field performance were identified. These results also indicate that for nutrient utilization, genetic differences exist among turfgrasses at both interspecific and intraspecific levels and suggest that a screening program could be developed to identify turfgrass species and cultivars having superior nutrient utilization characteristics.

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PREFACE

This dissertation is written in the manuscript format as specified for Agronomy Journal

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MANUSCRIPT I

NITRATE LEACHING POTENTIAL AND NITROGEN RECOVERY IN CLIPPINGS OF THREE COOL-SEASON TURFGRASSES

ABSTRACT

Variations in nitrate leaching potential and in nitrogen recovery capacity for cool-season turfgrasses are not well documented. Therefore, field studies to investigate these processes in ten cultivars each of Kentucky bluegrass (*Poa pratensis* L), perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea* Schreb.) turf were initiated. Nitrate concentrations in soil water collected at a depth of 60 cm and annual cumulative nitrate losses through leaching between March 1990 and April 1992 were determined for different turfs. Clipping production rate, leaf blade nitrogen content, nitrogen recovery rate in clippings, and nitrogen efficiency ratio of the same cultivars were compared during the 1990 and 1991 growing seasons under a moderate nitrogen fertilization rate of 149 kg N ha $^{-1}$ year $^{-1}$. Significant differences among species and cultivars were identified for nitrate leaching potential and nitrogen recovery in clippings based on monthly and seasonal analyses. Some correlations between nitrate leaching potential and nitrogen recovery in clippings were identified. These results indicate that genetic differences exist among turfgrasses for nitrate utilization at both interspecific and intraspecific levels and suggest that a screening program could be developed to identify turfgrass cultivars and species having superior capacity to remove nitrate from the soil.

INTRODUCTION

Nitrate is a highly mobile anion in the soil and it has the potential to leach to ground water. Once nitrate has leached to the ground water, there is little chance of upward movement back to the root zone. Nitrate leaching has become a concern of turf managers since relatively high rates of 250 - 300 and 120 - 150 kg N ha^{-1} $year^{-1}$ are often applied to commercial turf and home lawns, respectively (Morton et al., 1988). However, very few studies indicate that nitrate content of soil water under turf exceeds the U. S. drinking water standard of 10 mg NO_3^--N L^{-1}. Such high levels were obtained under extreme conditions (high application rate, very soluble N sources and heavy irrigation) (Rieke and Ellis, 1974; Petrovic, 1990; Morton et al., 1988; Mancino and Troll, 1990). Most studies conclude that nitrate-N leaching from turf sites is small and is partially attributed to high nitrate absorption efficiency of grass root systems (Petrovic, 1990; Morton et al., 1988). However, nitrate absorption efficiency varies among turfgrasses (Cisar, 1986; Liu, 1992) suggesting that grass selection may help to reduce nitrate leaching from turf.

Nitrate leaching is a complex process affected by plant species, cultivars, soil type, irrigation, N source, N rates, season of N application, and activities of soil organisms (Rieke and Ellis, 1974; Petrovic, 1990). Intensive studies of nitrate leaching from turf have been reported during the last two decades and have focused on environmental impacts of fertilization practices on nitrate leaching from turf-soil systems (Petrovic, 1990; Rieke and Ellis, 1974; Petrovic et al., 1986; Morton et al., 1988; Mancino and Troll, 1990).

Seasonal variation in nitrate leaching from bermudagrass (*Cynodon dactylon* L. Pers.) grown in sand was identified (Snyder et al., 1984). It was found that the greatest leaching occurred in February and March, less in April and May and least in June and July. A similar seasonal variation in nitrate leaching was found under Kentucky bluegrass (*Poa pratensis* L.cv. Nassau) fertilized with different N sources (Hull et al., 1991). Information on seasonal nitrate leaching of other cool-season turfgrasses maintained under conditions of moderate nitrogen use is lacking.

Cisar (1986) compared nitrate leaching potential among eight turfgrasses including six species. Significant differences were identified among grasses, but because a limited number of turfgrasses were studied, no comparisons at the cultivar level were possible. Very little is known about the influence of turfgrass genotype upon nitrate leaching potential.

The objectives of this study were to compare cultivars of three cool-season turfgrasses for their relative nitrate leaching potential and to correlate this with nitrogen recovery and clipping growth in the field under a moderate nitrogen fertilization regime during two growing seasons.

MATERIALS AND METHODS

I. Soil Water Nitrate Concentration

From March 1990 to April 1992, turfs of ten cultivars (Table 1) each of Kentucky bluegrass (*Poa pratensis* L), perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea* Schreb.) were compared for soil water nitrate concentration under moderate fertilization of 149 kg N ha $^{-1}$ year $^{-1}$. Fifty percent of the input nitrogen was inorganic . The cultivars were part of National Turfgrass Trials established in 1986 and 1987 at the University of Rhode Island, Turfgrass Research Station, Kingston, Rhode

Island. Plots were in a randomized complete block design with three replications. Individual plots of each cultivar were 2 x 1 m. The soil was an Enfield silt loam (Coarse loamy over sandy skeletal, mixed, mesic, Typic Dytrochrept). All plots had received three fertilizer applications annually (April, June and November) since establishment and each application was 49.7 kg N ha^{-1}.

In the fall of 1989, suction cup lysimeters (2.2 cm diameter) were installed in the center of each grass plot to a depth of 60 cm. Three replications for each cultivar yielded at total of 90 lysimeters. The lysimeters consisted of 5 cm long ceramic cups (Soilmoisture Equipment Corp., Santa Barbara, CA) attached to 55 cm long PVC pipe. Soil water samples were collected every two weeks throughout the 26 month period by evacuating the lysimeters with a portable vacuum pump.

Soil water nitrate was analyzed by the cadmium reduction method of Keeney and Nelson (1982). In this analysis, the NO_3^- in an aliquot of solution was quantitatively reduced to NO_2^- by reaction with copperized cadmium in an ammonium chloride matrix within a pH range of 5 to 8. Nitrite was estimated colometrically after the column leachate was treated with a diazotizing reagent (sulfanilimide) in hydrochloric acid and a coupling reagent (N- (1-napthy)-ethylenediamine dihydrochloride). The intensity of the pink color that developed was measured spectrophotometrically at 540 nm and compared to known standards.

II. Cumulative Nitrate Percolation Losses

The methods did not permit collection of all the percolates of rainfall and irrigation events. In order to predict mass nitrate leaching events, a hydrologic model was constructed to compute the soil moisture content on a daily basis. The model consisted of adjusting the previous day's soil moisture content based on precipitation, evapotranspiration and leaching according to the equation of Kincaid et al. (1979)

$$P_i = PPT_i - ET_i + SM_{i-1} - SM_i$$

where Pi = water percolating from the root zone on a given day (cm), PPTi = precipitation or irrigation on a given day (cm), ETi = evapotranspiration on a given day derived from the modified Penman equation (cm), SMi-1 = soil moisture content on the previous day (cm) and SMi = soil moisture content on a given day (cm).

Following the approaches of Smith and Williams (1980) and Morton et al. (1988), leaching was assumed to occur whenever the soil moisture of the root zone (30.5 cm from the surface) exceeded field capacity. All precipitation and irrigation was assumed to infiltrate into the soil. Potential evapotranspiration was computed using the modified Penman equation (Doorenbos and Pruitt, 1977). Meteorological data were obtained from the Rhode Island Agric. Exp. Stn. weather station located 500 m from the study site. Surface runoff was not considered because the study site had less than a 2% slope and was on well drained permeable soil.

Precipitation or irrigation might contribute nitrogen input to the study site but this was not considered because all of the study plots received the same N input. Previous investigations at this location showed that compared to the fertilizers applied, nitrogen input from precipitation or irrigation was negligible (Cisar, 1986).

Annual cumulative nitrate percolation for all cultivars was calculated based on the biweekly soil water samples. Plots received 330.2 mm irrigation in 1990 and 254 mm in 1991. The total of precipitation and irrigation was 1548 mm in 1990 and 1433 mm in 1991. The computed total percolation was 450 mm in 1990 and 409 mm in 1991. There were 21 soil water collections in 1990 and nine of them were collected when percolation occurred. Due to snow cover, there was only one soil water collection in January and one in February of 1991. There were also 21 collections in 1991 and 13 of them were collected when percolation occurred.

III. Nitrogen Recovery by Field Grown Turf

From the same plots used to monitor nitrate leaching, biweekly clipping harvests were collected between May and October in 1990 and 1991. The plots were mowed twice weekly during the growing season without removal of clippings except during clipping sample collections. A hand powered reel mower set at 3.8 cm mowing height and with a collecting basket attached was used for clipping collection from sampling areas 0.48 by 1.5 m.

Clippings were oven dried for 48 hours at 75 ^{0}C, weighed and ground in a Wiley mill to pass a 40 mesh screen. Total nitrogen content of clippings was determined using a micro-Kjeldahl procedure (Eastin, 1978). For 1990 and 1991, daily clipping growth rates (DCG), nitrogen content of clippings (NC), daily nitrogen recovery in clippings (DNR), and nitrogen efficiency ratio (NER) for each plot were obtained.

IV. Data Analysis

All statistical computations used procedures within the Statistical Analysis System (SAS Institute Inc., 1990). Significant means were analyzed using ANOVA and significant means were separated by Duncan's Multiple Range Test. Simple linear regressions were obtained between soil water nitrate concentration and nitrogen recovery by grass the latter being the variable.

RESULTS

I. Soil Water Nitrate Concentration

A) SPECIES COMPARISONS

Significant differences in soil water nitrate concentrations were found among the three cool-season turfgrasses during the 26 month period from March 1990 to April 1992. Means for monthly and seasonal averages (two years) were subjected to ANOVA and separated by Ducan's Multiple Range Test (Tables 2 and 3). A two to fifteen fold difference was found among the three turfgrasses in their soil water nitrate concentrations. The greater variation appeared during slow or non-growing seasons.

Under Kentucky bluegrass plots, the soil water nitrate concentrations were consistently higher than those of the other two turfgrasses based on monthly and seasonal means (Tables 2 and 3). Only one of the seasonal means of soil water nitrate concentrations was above the drinking water standard of 10 mg NO_3^-- N L^{-1} under Kentucky bluegrass plots. However, the nitrate concentrations from Kentucky bluegrass plots were often close to the standard of 10 mg L^{-1} during fall and winter months. Tall fescue appeared to be more efficient in removing soil water nitrate because the concentrations under those plots never exceeded 3 mg NO_3^--N L^{-1} . The overall average under tall fescue was 15% of that under Kentucky bluegrass and only approached 7% of the drinking water limit of 10 mg NO_3^--N L^{-1}. Perennial ryegrass was generally intermediate among the three grasses based on all seasonal or monthly means and in most cases, the soil water nitrate concentration was in a low range (< 2.0 mg NO_3^--N L^{-1}).

Large monthly and seasonal fluctuations in soil water nitrate were found among the turfgrasses. In general, lower soil water nitrate concentrations were found in late spring and early summer and higher soil water nitrate concentrations were associated with periods of slow growth. The highest nitrate concentrations were found in November for Kentucky bluegrass, October for perennial ryegrass and March for tall fescue (Table 2).

B) CULTIVAR COMPARISONS

KENTUCKY BLUEGRASS

Significant differences in soil water nitrate concentration were found among the ten Kentucky bluegrass cultivars during all months and seasons except for June (Tables 4 and 5). Soil water nitrate concentration under the ten cultivars varied over three fold range in November, and more than five fold in the fall season of October-December 1991 which yielded the highest values. Although the nitrate concentrations under all cultivars were less than 2 mg NO_3^--N L^{-1} in May and during the April-June 90 season, which produced the lowest values, significant differences were still identified.

The nitrate concentrations under 'Liberty' were above the drinking water standard of 10 mg NO_3^--N L^{-1} throughout the fall and early winter of 1991 and the overall average for 'Liberty' exceeded the standard. Both 'Blacksburg' and 'Trenton' exceeded the standard for four months in the fall but winter season and 'Midnight' surpassed it only in September. Soil water nitrate under 'Eclipse' and 'Able I' never exceeded 6 mg NO_3^--N L^{-1}. The highest nitrate concentration under 'Liberty' during December was more than two times the standard and eight fold that of the lowest value for 'Able I'.

PERENNIAL RYEGRASS

Significant differences in nitrate concentrations were found among the ten perennial ryegrass cultivars during most months in both seasons (Tables 6 and 7). In general, a five to ten fold range was observed in the monthly or seasonal means among cultivars. As with Kentucky bluegrasses, the nitrate concentrations were highest during the fall and winter seasons, lower in spring and lowest in early summer. 'J208' was the only cultivar with a soil nitrate concentration exceeding 10 mg NO_3^--N L^{-1} during the winter of 1991. In June, nitrate concentrations under 'Manhattan' and 'J207' were below the limit of detection and even the mean of the ten cultivars was less than 0.2 mg N L^{-1}.

The highest nitrate concentrations were noted during late summer and fall of 1991. During the winter and spring of 1991, soil water nitrate concentrations were less than 2.5 mg N L^{-1} and only three cultivars were found with a nitrate-N concentration which exceeded 2 mg L^{-1}. Little cultivar variation was observed during the summer and fall of 1990, and the spring and summer of 1991 yet four to nine fold differences were still found among cultivars. Unlike the Kentucky bluegrass cultivars during the two early spring seasons, soil water nitrate content under perennial ryegrasses was low.

TALL FESCUE

Tall fescue cultivars had the lowest soil water nitrate concentrations of the three species and yet significant differences were found among the ten cultivars during most months and seasons (Tables 8 and 9). A three to five fold range in soil water nitrate concentration was usually observed among cultivars when means were significantly different. Unlike Kentucky bluegrass and perennial ryegrass, the highest nitrate concentrations under the tall fescue cultivars were found in March 1990 instead of

November or December, but differences were not significant. Most nitrate concentrations were below 1 mg L^{-1} during the entire study period. The highest nitrate concentration never reached the safe limit for drinking water.

II. Nitrate Losses by Percolation

Percolation was unevenly distributed during the two years and significantly influenced the cumulative nitrate losses during this time. Cumulative nitrate losses by leaching during the period from March 1990 to February 1992 were divided into two 12 month periods which are presented in Figures 1 to 6.

A) KENTUCKY BLUEGRASS

Significant differences were found among cultivars for nitrate losses by percolation during the 24 month period (Figures 1 and 2). 'Liberty' exhibited the greatest nitrate leaching potential during the entire 24 month period. ‘Kenblue’, ‘Midnight’, ‘Parade’ and ‘Able I’ were the four cultivars which exhibited a lower nitrate leaching potential during the first 12 month period (Figure 1). ‘Eclipse’ had the lowest nitrate loss during the second 12 month period. Kentucky bluegrass cultivars exhibited a variation in nitrate leaching equivalent to from 2 to 19% of annual nitrogen application. The greatest loss occurred in December for all cultivars and ranged from 20% to 80% of the entire loss measured during the first 12 months. The average nitrate loss for all cultivars was about 1 g N m^{-2} which was about 7% of the annual N input.

During the second 12 months, the average nitrate loss for all cultivars increased to about 2 g N m^{-2} , 14% of the annual N input (Figure 2). The loss varied from 6.7% ('Eclipse') to 30% ('Liberty') of the annual N input . For most cultivars, the greatest loss occurred in late August following a hurricane event while 'Liberty', 'Joy' and 'Eclipse' experienced the greatest leaching loss in December. Soil water nitrate loss by percolation was also relatively high in November of 1991. From 10 to 40% of the total annual percolation loss was attributed to a single event.

B) PERENNIAL RYEGRASS CULTIVARS

Significant differences in nitrate loss by leaching were also found among the perennial ryegrass cultivars (Figures 3 and 4). Generally, losses by percolation were less than those observed for Kentucky bluegrass cultivars. 'J208', 'Manhattan' and 'J207' exhibited the greatest leaching potential in 1990 and 1991 while 'Linn' showed the least. Nitrate losses among the cultivars varied below a maximum 3% of the annual N input during the first 12 months (Figure 3). Similar to Kentucky bluegrass, the greatest loss for most cultivars occurred in December which ranged from 10 to 50% of the total loss. The average nitrate losses for all cultivars was about 0.3 g N m^{-2} or about 2% of the annual N input during the first 12 months (Figure 3).

The cultivars experienced greater nitrate leaching losses during the second 12 month period (Figure 4). Losses varied from 1.4% to 15% of annual N input among cultivars and the average was about 0.7 g N m^{-2}, about 4.8 % of the total input N. During the second 12 month period, 'J208' exhibited the greatest loss which was about five fold greater than its loss during the first 12 month period and almost ten fold the loss under 'Repell'. Similar to Kentucky bluegrass, the nitrate loss by percolation during late August of 1991 constituted the largest portion of the total loss for most cultivars.

C) TALL FESCUE CULTIVARS

Significant differences in nitrate leaching were found among tall fescue cultivars only during the second 12 month period and those grasses exhibited the lowest nitrate loss, never exceeding 0.5 g m^{-2} during both periods (Figures 5 and 6). Although differences were not significant during the first period, there was a six fold variation among the ten cultivars. The average for all cultivars was about 0.12 g N m^{-2} which was 0.8% of the annual N applied (Figure 5).

During the second 12 month period, the average nitrate loss for all cultivars increased slightly to about 0.2 g N m^{-2}, 1.4% of the annual N applied although 'Falcon', 'Arid', 'P164' and 'Jaguar' decreased slightly (Figure 6). During this period, a five fold variation was found among the ten cultivars. 'P160' showed the greatest leaching increase to five times its loss during the previous period (Figure 6).

III. Nitrogen Recovery in Clippings

A) SPECIES COMPARISONS

Comparing monthly means between 1990 and 1991 provided no significant differences so monthly means for the two years were combined and presented as daily clipping growth rate (DCG), nitrogen content (NC) in clippings, daily nitrogen recovery rate (DNR), and nitrogen efficiency ratio (NER) for the three turfgrasses (Table 10). Significant differences were generally found among the three turfgrasses except for DCG and DNR values in October. Seasonal and monthly variations were generally found. The grasses generally exhibited a greater variation in DCG and DNR during the spring than during the fall. A 3 to 5% variation was consistently identified in NC and NER based on all means. During May and June, DCG and DNR were more than twice those of

September and October. Nitrogen content (NC) in clippings increased about 10 to 20% and NER decreased about 10 to 20% during the later three months for all turfgrasses.

Tall fescue exhibited the greatest DCG, and NER, and the lowest NC based on overall average in May. Tall fescue showed a DNR 10 % higher than perennial ryegrasses and 33 % higher than Kentucky bluegrasses in May (Table 10).

Kentucky bluegrass cultivars had the greatest NC and the lowest NER compared to the other two grasses. The greatest DNR was found in July which was about 40% and 120% higher than that for tall fescue and perennial ryegrass, respectively. Unlike perennial ryegrass and tall fescue, Kentucky bluegrass cultivars exhibited greater DCG in June and July than in May (Table 10).

Perennial ryegrass cultivars exhibited the lowest DCG and DNR, and was intermediate for NC and NER. Perennial ryegrass exhibited its highest DCG in May and declined sharply thereafter until September. DCG declined by 50% of the previous month in June and July. During the later months, DCG remained at about 25% of its highest value. All cultivars exhibited their greatest NC and lowest NER during August (Table 10).

In general, daily clipping growth rate (DCG) and daily nitrogen recovery rate (DNR) were positively correlated while nitrogen content (NC) and DNR were negatively correlated in all grasses (Liu, 1992)

B) CULTIVAR COMPARISONS

KENTUCKY BLUEGRASS

Significant differences were identified among Kentucky bluegrass cultivars in their daily clipping growth rate (DCG) except during July (Table 11). Cultivars consistently exhibited at least a two fold difference in DCG during all months and a five fold difference was found by comparing the highest monthly mean with the lowest. DCG for all cultivars was highest during June and the lowest in October. There was a two fold difference between these two months. In general, all cultivars showed a greater DCG during the first three months than during the last three months.

Significant differences in nitrogen content in clippings (NC) were found among the ten cultivars only for the overall two year average and June (Table 12). The cultivars appeared to have a lower NC during May, June and October. However, most variation in NC was within 5%.

Significant differences were found among cultivars for daily nitrogen recovery rates (DNR) except during July and August (Table 13). Similar to DCG, a two fold variation was consistently found among those means showing significant differences. Also similar to DCG, DNR was greatest during the early months for all cultivars. There was a 50% decline in DNR between July and October.

Cultivars differed significantly in nitrogen efficiency ratio (NER) for overall two year average and means for May and June (Table 14). The greatest NER was found in June and the lowest was in August.

PERENNIAL RYEGRASS CULTIVARS

A 34% variation in DCG among the ten cultivars was observed (Table 15). The greatest DCG occurred during May and the lowest during August for most cultivars.

Cultivars differed during June, July and September in NC. A two fold variation was identified during September while the average variation was within 5%. Cultivars showed a greater NC in July, August and September (Table 16).

Significant differences among cultivars in DNR were observed only in September and for the overall average. The greatest monthly mean in DNR was found in May which was about two times the overall average for most cultivars (Table 17). The ENR values varied within 10% among the cultivars and only the means in July and the overall average showed significant differences (Table 18).

TALL FESCUE CULTIVARS

Significant differences in DCG were found among tall fescue cultivars based on seasonal means and during June, September and October (Table 19). A more than two fold variation was found in September and October when clipping growth slowed. Similar to perennial ryegrass cultivars, the largest DCG among tall fescue cultivars occurred in May after which growth gradually declined towards the end of the growing seasons. The decline was about 30% for most cultivars.

Some significant differences in NC were found among tall fescue cultivars (Table 20) where a 10% variation was observed. Cultivars differed significantly in DNR only in September or based on the overall average (Table 21). Tall fescue cultivars also varied significantly in NER based on three out of six monthly means and the overall average (Table 22).

IV. Correlations between Nitrate Leaching and Daily Nitrogen Recovery in Clippings

Linear regression models were computed between soil water nitrate concentrations (SWNC) and daily nitrogen recovery rates (DNR) at the cultivar level for the three grasses (Tables 23 to 25). Positive or negative linear correlations between SWNC and DNR were found within different months and seasons. A growing season or a non-growing season was defined based on the duration of clipping growth so May to October was a growing season and November to April was a non-growing season. The DNR used for seasonal correlations was the annual average and the SWNC was based on the growing season or the non-growing season. As defined above, the monthly correlations were calculated based on the DNR and SWNC during the same month in 1990 and 1991.

Negative correlations were found between SWNC and DNR during the growing seasons for Kentucky bluegrass cultivars (Table 23) and perennial ryegrass cultivars (Table 24). No significant correlations were found for tall fescue cultivars during the growing seasons. Correlations between SWNC and DNR were generally positive when compared between growing seasons and non-growing seasons although some correlations were negative. For Kentucky bluegrass cultivars, monthly SWNC and DNR were negatively correlated except in July which was positive but was not significant. Perennial ryegrass cultivars appeared to have three significant monthly correlations two positive for June and October and the other negative for September. There were two significant positive correlations for tall fescue cultivars during August and October.

DISCUSSION

I. Soil Water Nitrate Concentration

Significant variations in soil water nitrate concentration were constantly found at both the species and cultivar levels in this study. These results indicate that genetic differences between turfgrasses are one of the factors influencing the degree of nitrate leaching in addition to the environmental and agronomic factors , e.g. soil type, irrigation and precipitation, N sources, N rates, and season of application. One of the main factors in genetic control may be different efficiencies of nitrate absorption. 'Liberty' Kentucky bluegrass would appear to be a poor choice if high nitrate leaching potential exists. Nitrate uptake studies under greenhouse conditions showed that 'Liberty' was less efficient in absorbing nitrate (Liu, 1992). The degree of genetic diversities may differ among the three species based on the cultivars selected for this study. The measured soil water nitrate concentrations overlapped among the cultivars of the three turfgrass species. For example, the Kentucky bluegrass cultivar yielding the lowest soil water nitrate concentration was lower than some cultivars of perennial ryegrass even though the average of Kentucky bluegrass cultivars was significantly higher than the average of perennial ryegrass cultivars. Similar examples can be found between perennial ryegrass cultivars and tall fescue cultivars.

Soil water nitrate concentration at a 60 cm depth under turf does not necessarily indicate a nitrate leaching loss. The soil nitrate concentration could result from by several leaching events occurring between sampling periods provided soil water percolation did not extend below the 60 cm depth. The same soil water pool may be sampled several times if no soil water percolation occurred. During winter seasons, when the soil surface is frozen and the soil microflora are inactive soil water nitrate concentrations may differ little from the fall and this may partially explain higher soil water nitrate concentrations during the winter months.

The seasonal variation patterns are easier to explain than genetic differences. The higher leaching potentials of all grasses during fall months of 1991 were highly influenced by the uneven distribution of precipitation (Appendix A). In May, June, and July of 1991, the study area experienced a 100 mm rainfall deficit but during the summer and fall season, the area received 100 mm more rain than average. Also in 1991, fertilizer was applied in July rather than June. July of 1991 was a very dry month and little nitrogen probably was taken up by plants (Appendix A). Similar results were obtained in a nitrogen fate study at the same station and time (Hull et al, 1992).

Time of fertilizer application can influence nitrate leaching under a turf (Petrovic, 1990, Hull et al., 1992). Although all plots received fertilizers at the same time, the impacts on different turfgrasses may be different. Fall or winter fertilizer application might further enhance the leaching potential of some grasses which showed poorer nitrate use efficiency. One explanation for the relatively high leaching potential of Kentucky bluegrass may be that this grass grows most during spring and later fall season when temperatures are cool. Hot and dry summer conditions may depress root activity which will cause less absorption of nitrate during late seasons.

Clippings were not removed from the plots. These retained clippings could have two opposing influences on nitrate leaching. Retaining clippings on the turf may enhance the leaching potential for those cultivars with a poorer efficiency of nitrogen use due to the nitrogen in clippings becoming available as nitrate. On the other hand, retained clippings allow 40 to 60% of applied nitrogen (Petrovic, 1990) to recycle in the turf-soil system which may stimulate turf growth. Increased turf growth may generally reduce nitrate leaching potential. However, there is no information comparing the relationship between nitrate leaching and clipping retention.

II. Nitrate Losses by Percolation

Environmental factors, such as precipitation play an important role in nitrate leaching losses by percolation (Morton et al., 1988; Petrovic, 1990). Time of fertilizer application is also an important factor in percolation losses (Synder et al., 1984). On a yearly basis, percolation through turfgrass soils depends not only on amounts of precipitation or irrigation, but also on evapotranspiration, surface runoff, and soil water conditions. Thus, under the same fertilizer input, with the same water applied to the plots, and with the same soil type, percolation might be variable among plots because of differing water use among turfgrasses. It should also be noted that Kentucky bluegrasses had received the same annual input of nitrogen since the plots were established in 1986. For some less N efficient cultivars, such N input might exceed that utilized by the grass. 'Liberty' Kentucky bluegrass exhibited a nitrate percolation loss equivalent to 30% of the annual N input and it also showed a lower nitrate uptake efficiency under greenhouse conditions (Liu, 1992). In general, the annual nitrate losses due to leaching were less than 10% of the annual input N.

Intensively managed turfgrasses in the United States receive annual N applications of up to 300 kg ha^{-1}. The potential exists for turf to be a significant source for nitrate contamination of local ground water supplies. However, this potential can be minimized by proper management practices. For example, withholding N fertilization in the late fall can minimize nitrate leaching from cool-season turfgrasses below that occurring after early fall application (Street, 1988; Hull, 1992). A screening program could be established to monitor nutrient uptake efficiency of turfgrass genotypes so that appropriate grass selections could be made to reducing negative environmental impacts.

Morphological differences which may partially contribute to nitrate leaching characteristics can be identified at the species level . For example , Kentucky bluegrass has a shallower and smaller root system than tall fescue (Beard, 1973; Turgeon 1985). However, what determines nitrate use efficiency at the cultivar level is largely unknown. Studies focusing on root morphology at the cultivar level might help our understanding as why these differences occur.

III. Nitrogen Recovery in Clippings

Nitrogen recovery by turfgrasses is influenced by many factors (Petrovic, 1990; Turner and Hummel Jr., 1992). When the N application rate and environmental factors are near the optimum for turfgrass growth, genetic variation for their nitrogen use may become a key factor influencing nitrogen recovery. This study was designed to provide moderately intensive but near optimum growing conditions for cool-season turfgrasses. No serious diseases or insect pests compromised turf plots during this study.

The morphological differences in leaf growth angle (angle of leaf lamina to sheath) and population density of the turfgrass plants might also affect the results of nitrogen recovery in clippings. For example, 'Kenblue' an older cultivar did not exhibit the more aggressive growth pattern and low leaf angles of newer cultivars and greater clipping yields were obtained from it. This would result in greater nitrogen recovery in clippings which might be erroneously interpreted as greater nitrogen use efficiency.

IV. Correlations between Soil Water Nitrate Concentration and Nitrogen Recovery in Clippings

There are many ways to correlate nitrogen recovery parameters and nitrate leaching potential for the turfgrasses studied. The daily nitrogen recovery rate and soil water nitrate concentration were used as a first approximation to study the correlation between nitrogen use rate and nitrate levels in soil water.

Generally, a turfgrass which has a greater capacity for recovering nitrogen in clippings should remove soil water nitrate through absorption more efficiently and the relative amount of soil nitrate for leaching should be lessened. During the growing seasons, such negative correlations between soil water nitrate concentrations (SWNC) and daily nitrogen recovery rates (DNR) were usually observed. However, tall fescue cultivars showed positive correlations between SWNC and DNR during the growing season. This does not mean that there is a greater pool of soil nitrate available for leaching under tall fescue cultivars since soil water nitrate concentrations under those plots were low. However, as indicated earlier, many factors influence these parameters and a highly significant negative linear regression was not expected because the nitrogen recovered in clippings consisted of both nitrate and ammonium taken up by turfgrass roots.

The significant correlations do at least indicate that soil nitrate concentration and nitrogen recovery generally are negatively related. The more negative correlation coefficients may indicate that a larger portion of nitrogen taken up by plants is in the nitrate form. Two theories may explain the positive correlations found between nitrogen recovery and soil water nitrate concentration in tall fescue. Firstly, there might be excess nitrate available in the root zone which could easily occur since a November fertilizer application was made every year since 1986 at 49.7 kg N ha^{-1}. If this produces a surplus of nitrate in the soil for these plants nitrate uptake may occur maximally while retaining significant but low levels in the soil. Secondly, there might be a stronger preference for ammonium uptake by tall fescue competing with nitrification and permitting small amounts of nitrate to remain in the soil.

CONCLUSIONS

The following conclusions from this study compare the three cool season turfgrasses for their nitrate leaching potential and nitrogen recovery in clippings:

1. Genetic variation exists among the three cool-season turfgrasses at both the species level and cultivar level in both nitrate leaching potential and nitrogen recovery in clippings.

2. Nitrate leaching potential and nitrogen recovery fluctuated seasonally for all of the turfgrasses studied.

3. Moderate N input to turf generated very low potentials for nitrate leaching to local ground water supplies from tall fescue and perennial ryegrass cultivars. Some Kentucky bluegrass cultivars have a relatively high nitrate leaching potential.

4. A screening program should be developed to identify nitrogen use characteristics of cool-season turfgrasses which could contribute to current turfgrass improvement.

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Table 1. Cultivars selected for nitrate leaching and nitrogen recovery studies

Kentucky bluegrass	Perennial ryegrass	Tall fescue
ABLE I	DERBY	APACHE
BLACKSBURG	J-207	ARID
BRISTOL	J208	FALCON
ECLIPSE	LINN	JAGUAR
JOY	MANHATTAN	KY-31
KENBLUE	PST-2PM	P-160
LIBERTY	RANGER	P-164
MIDNIGHT	REPEL	PST-5AG
PARADE	TARA	REBEL II
TRENTON	YORKTOWN II	SYN GA

Table 2. Monthly means of soil water nitrate-N concentrations under three turfgrasses in 1990 and 1991

Grass	J	F	M	A	M	J	J	A	S	O	N	D	Average.
							NO_3^- -mg N L^{-1}						
KB	5.36a*	2.89a	3.68a	1.28a	0.78a	0.90a	1.36a	3.92a	9.19a	9.17a	9.42a	8.42a	4.64a
PR	1.26b	1.59b	2.83b	0.70b	0.23b	0.18b	0.64b	2.40b	3.16b	3.31b	2.26b	1.68b	1.75b
TF	0.37b	0.41c	1.86b	0.19c	0.18b	0.06b	0.49b	0.97b	1.10b	1.52c	0.79c	0.74b	0.70c

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 3. Seasonal means of soil water nitrate-N concentrations under three turfgrasses in 1990 and 1991

	M	A - J	J - S	O - D	J - M	A - J	J - S	O - D	J - M	A	Average
Grass	1990	1990	1990	1990	1991	1991	1991	1991	1992	1992	
					NO_3^- -mg N L^{-1}						
KB	6.95a	0.84a	1.98a	5.98a	2.70a	0.97a	7.48a	12.23a	3.64a	1.62a	4.64a
PR	5.86a	0.46b	0.71b	1.39b	0.42b	0.24b	4.07b	3.37b	1.56b	0.67b	1.75b
TF	2.85b	0.19c	0.86b	0.84b	0.27b	0.21b	0.93c	1.18c	0.37c	0.10b	0.70c

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 4. Monthly means of soil water nitrate-N concentrations under Kentucky bluegrass cultivars in 1990 and 1991

Grass	J	F	M	A	M	J	J	A	S	O	N	D	AVE
NO_3^- -mg N L^{-1}													
LIB	17.50a*	8.53a	6.19a	3.38a	1.58a	1.74	1.42abc	6.68a	17.05a	18.23a	18.40a	24.10a	10.11a
BLA	10.74b	8.51a	6.19a	3.81a	1.52a	1.40	3.01a	4.67ab	10.25bc	9.98b	10.35b	10.40bc	6.32b
TRE	5.71c	1.48b	3.28abc	0.45b	0.44c	0.54	0.69c	4.50ab	14.95ab	16.31a	16.25a	12.43b	6.19b
KEN	3.25cd	0.60b	3.68abc	0.88b	0.98abc	0.42	2.59ab	4.87ab	8.13cd	9.30b	9.55bc	4.97d	4.48c
BRI	2.09cd	1.00b	4.18ab	0.82b	0.49bc	0.30	0.86c	3.92ab	9.59bc	7.73bc	9.60bc	7.01cd	4.26c
MID	1.95cd	1.15b	4.22ab	0.84b	0.67bc	0.26	1.02b	4.76ab	10.84abc	7.68bc	6.24bc	3.56d	3.72cd
JOY	4.88cd	2.94b	2.73ab	1.11b	0.35c	0.64	0.97bc	2.38b	5.81cd	6.33bc	6.83bc	7.54cd	3.47cd
PAR	0.73d	1.33b	0.84c	0.04b	0.30c	1.84	0.73c	3.11ab	8.68bcd	8.38bc	8.83bc	4.88d	3.33cd
ECL	4.14cd	2.30b	3.65abc	0.89b	1.25ab	1.57	1.48abc	1.65b	2.82d	2.56c	3.19c	4.89d	2.54d
ABL	1.63cd	0.70b	1.70bc	0.32b	0.33c	0.30	0.60c	2.49b	5.14cd	5.10bc	5.67bc	3.22d	2.36d

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 5. Seasonal means of soil water nitrate-N concentrations under Kentucky bluegrass cultivars

Cultivar	Mar. 1990	Apr.-Jun. 1990	Jul.-Sep. 1990	Oct.-Dec. 1990	Jan.-Mar. 1991	Apr.-Jun. 1991	Jul.-Sep. 1991	Oct.-Dec. 1991	Jan.-Mar 1992	Apr. 1992
				NO_3^- -mg N L^{-1}						
LIB	7.97a*	1.97a	3.87a	15.39a	11.37a	2.21a	11.75a	25.76a	10.31a	4.53b
BLA	7.84ab	1.14ab	2.39ab	7.73bc	3.85b	1.85a	8.94ab	12.58c	10.35a	8.72a
TRE	6.81abc	0.31bc	2.57ab	8.79b	3.33b	0.70b	10.37a	20.17b	2.34bc	0.28c
KEN	7.59ab	0.89bc	1.70b	3.21d	0.72b	0.58b	9.04ab	12.57c	2.50bc	1.12c
BRI	9.10a	0.77bc	1.70b	3.77d	1.11b	0.53b	8.17ab	12.33c	1.28c	0.31c
MID	8.71a	0.15ab	1.88ab	3.93d	0.56b	0.33b	8.84ab	8.09d	1.51bc	0.03c
JOY	4.91bcd	0.53bc	1.84ab	4.54cd	1.50b	0.51b	4.30bc	9.32cd	4.06b	1.69c
PAR	2.01d	0.03c	1.36b	4.42cd	0.44b	1.10ab	6.71abc	10.19cd	0.88c	0.00c
ECL	8.96a	1.21ab	1.40b	3.14d	3.65b	1.31ab	2.83c	4.07e	1.77bc	0.62c
ABL	4.56cd	1.41bc	1.47b	1.96d	0.15b	0.27b	3.95bc	6.81de	1.11c	0.10c

* Means followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 6. Monthly means of soil water nitrate-N concentrations under perennial ryegrass cultivars in 1990 and 1991

Grass	J	F	M	A	M	J	J	A	S	O	N	D	AVE
						NO_3^- -mg N L^{-1}							
J208	4.11a*	4.25ab	4.81	1.29a	0.38ab	0.19	1.63	5.36a	5.98a	6.64a	7.15a	7.63a	4.25a
MAN	0.97b	0.53c	2.97	1.10ab	0.45a	0.00	1.33	3.67ab	5.24ab	5.19ab	2.25b	1.55b	2.24b
LIN	0.81b	1.08b	1.96	0.61ab	0.16ab	0.20	1.53	2.91ab	4.73ab	3.47ab	2.34b	1.17b	1.81bc
TAR	1.06b	1.16bc	3.39	0.53ab	0.17ab	0.01	0.34	2.36ab	4.00ab	2.84ab	2.13b	1.27b	1.71bc
YOR	0.86b	1.81bc	2.52	0.93ab	0.20ab	0.02	0.84	2.24ab	2.98ab	3.61ab	1.96b	1.03b	1.64bc
DER	0.39b	0.50c	2.08	0.33b	0.03b	0.05	0.67	2.87ab	4.19ab	4.19ab	1.58b	0.99b	1.60bcd
J207	3.37a	5.00a	4.60	0.52ab	0.14ab	0.00	0.67	1.28b	1.24b	1.36b	1.58b	1.36b	1.57bcd
RAN	0.63b	0.66c	1.66	0.51ab	0.09ab	0.07	0.67	1.53b	1.68ab	2.60ab	2.06b	0.85b	1.15cde
PST	0.42b	0.70c	1.87	0.59ab	0.41ab	0.02	0.09	0.97b	0.70b	1.54b	1.38b	0.97b	0.87de
REP	0.22b	0.69c	2.43	0.63ab	0.28	0.09	0.16	0.80b	1.00b	1.26b	0.41b	0.31b	0.75e

* Means followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 7. Seasonal means of soil water nitrate-N concentrations under perennial ryegrass cultivars

Cultivar	Mar. 1990	Apr.-Jun. 1990	Jul.-Sep. 1990	Oct.-Dec. 1990	Jan.-Mar. 1991	Apr.-Jun. 1991	Jul.-Sep. 1991	Oct.-Dec. 1991	Jan.-Mar 1992	Apr. 1992
				NO_3^--mg N L^{-1}						
J208	9.01a	0.61ab	1.10abc	2.21a	0.69	0.51a	9.74a	10.67a	2.07a	4.25a
MAN	7.13ab	0.97a	1.21ab	2.26a	0.56	0.25ab	5.94b	3.77b	0.68b	2.24b
LIN	3.42b	0.11b	0.93abc	1.49ab	0.20	0.37ab	5.37bc	2.99b	1.16ab	1.81bc
TAR	7.11ab	0.34ab	1.37a	1.15ab	0.36	0.16b	3.85bcd	2.91b	0.48b	1.71bc
YOR	4.76ab	0.50ab	0.54bc	1.34ab	0.49	0.21b	4.11bcd	2.92b	11.4ab	1.64bc
DER	5.65ab	0.28ab	0.36c	0.79b	0.22	0.09b	5.90b	3.69b	0.10b	1.60bcd
J207	8.18ab	0.14b	0.40bc	1.65ab	0.89	0.19b	1.88cd	1.19b	0.93ab	1.57cde
RAN	3.92ab	0.40ab	0.41bc	1.51ab	0.31	0.15b	2.45bcd	2.24b	0.32b	1.15cde
PST	4.05ab	0.55ab	0.28c	1.24ab	0.24	0.34ab	1.13d	1.37b	0.03b	0.87de
REP	5.95ab	0.69ab	0.70abc	0.44b	0.17	0.22ab	0.70d	0.91b	0.00b	0.75e

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 8. Monthly means of soil water nitrate-N concentrations under tall fescue cultivars in 1990 and 1991

Grass	J	F	M	A	M	J	J	A	S	O	N	D	AVE
						NO_3^- -mg N L^{-1}							
P160	0.39ab*	0.93a	1.97ab	0.21b	0.19	0.22	0.88	0.96ab	2.28a	4.19a	0.73b	1.03ab	1.21a
FAL	0.81a	0.83ab	1.77ab	0.86a	0.44	0.33	0.24	0.44ab	1.38ab	2.78ab	1.84a	1.35a	1.19a
APA	0.29ab	0.26bc	3.20a	0.10b	0.19	0.19	0.15	1.69ab	1.37ab	1.84ab	0.80ab	0.63ab	1.02ab
ARI	0.33ab	0.26bc	0.49b	0.12b	0.18	0.11	0.84	0.91ab	1.45ab	1.29b	1.36ab	0.89ab	0.71bc
KY31	0.47ab	0.44abc	0.35b	0.09b	0.17	0.26	0.63	1.46ab	1.11b	1.27b	0.62b	0.44ab	0.60c
P164	0.16b	0.19c	0.57ab	0.14b	0.12	0.01	0.35	1.83a	0.59b	0.72b	0.39b	0.75ab	0.53c
PST5	0.42ab	0.37abc	0.19b	0.09b	0.15	0.31	0.34	0.49ab	0.95b	0.91b	0.75b	0.91ab	0.49c
SYN	0.22b	0.37abc	1.67ab	0.12b	0.14	0.19	0.60	0.23b	0.63b	0.57b	0.49b	0.37b	0.47c
REB	0.17b	0.17c	0.56ab	0.03b	0.19	0.02	0.55	0.86ab	0.70b	0.75b	0.34b	0.45ab	0.42c
JAG	0.49ab	0.31bc	0.38b	0.14b	0.11	0.16	0.12	0.52b	0.50b	0.83b	0.46b	0.64ab	0.39c

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 9. Seasonal means of soil water nitrate-N concentrations under tall fescue cultivars

Cultivar	Mar.	Apr.-Jun.	Jul.-Sep.	Oct.-Dec.	Jan.-Mar.	Apr.-Jun.	Jul.-Sep.	Oct.-Dec.	Jan.-Mar	Apr.
	1990	1990	1990	1990	1991	1991	1991	1991	1992	1992
				NO_3^- -mg $N L^{-1}$						
P160	3.91	0.04a	1.20	0.62b	0.14b	0.32	1.65a	3.34a	0.83a	0.48a
FAL	3.22	1.05a	0.83	1.84a	0.78a	0.24	0.63bc	2.21ab	0.71a	0.47a
APA	7.22	0.14b	1.08	1.19ab	0.14b	0.20	1.51ab	0.93bc	0.29b	0.05b
ARI	1.21	0.11b	1.39	1.71a	0.27ab	0.21	0.68bc	0.72bc	0.25b	0.00b
KY31	0.93	0.07b	0.55	0.32b	0.47ab	0.26	1.71a	1.11bc	0.30b	0.08ab
P164	1.72	0.14b	1.49	0.72b	0.13b	0.11	0.59c	0.53bc	0.18b	0.00b
PST5	0.28	0.17b	0.46	0.24b	0.33ab	0.21	0.80bc	1.26bc	0.32b	0.00b
SYN	3.83	0.11b	0.32	0.53b	0.17b	0.25	0.78bc	0.42c	0.27b	0.00b
REB	1.49	0.02b	0.77	0.35b	0.06b	0.19	0.66bc	0.68bc	0.21b	0.00b
JAG	1.03	0.17b	0.48	0.65b	0.37ab	0.16	0.34c	0.65bc	0.26b	0.00b

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 10. Monthly nitrogen recovery in clippings for three turfgrasses (mean of 1990 and 1991)

Grass	May	June	July	Aug.	Sept.	Oct.	Ave
			DCG Dry tissue g m^{-2} day^{-1}				
TF	4.87a	3.71a	2.53a	2.47a	1.58a	1.57	2.83a
KB	2.94b	3.33b	3.16a	2.22a	1.54a	1.51	2.48b
PR	4.47a	2.25c	1.26b	1.06b	1.19b	1.55	1.98c
			NC mg N g^{-1} dry tissue				
TF	36.03c	31.64c	35.88c	43.64b	38.46b	39.43b	37.26c
KB	41.74a	37.40a	45.20a	49.00a	45.30a	43.39a	43.44a
PR	37.98b	35.22b	42.92b	49.14a	45.04a	43.99a	42.09b
			DNR mg N m^{-2} day^{-1}				
TF	183.23a	116.23a	101.33b	112.26a	62.07b	65.10	107.58a
KB	123.00b	125.14a	140.79a	109.27a	72.51a	68.96	107.25a
PR	164.62a	78.10b	64.70c	52.96b	56.18b	69.82	81.16b
			NER dry tissue mg mg^{-1} N				
TF	28.58a	38.72a	28.69a	23.24a	27.14a	25.99a	29.16a
KB	24.53c	27.01b	22.66c	20.60b	22.86b	23.80b	23.71c
PR	27.07b	29.65b	23.92b	20.58b	23.23b	23.08b	24.81b

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 11. Daily clipping growth rate (DCG) for Kentucky bluegrass cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
			g dry tissue m^{-2} day^{-1}				
KEN	4.62a	3.80b	4.17	2.74a	2.08a	1.92a	3.24a
ABL	1.98c	4.09a	4.13	2.62ab	2.06a	2.00a	2.86ab
JOY	3.99ab	3.71ab	3.36	2.06ab	1.34bc	1.35ab	2.68ab
TRE	3.59abc	3.61ab	3.24	2.32ab	1.65ab	1.26ab	2.65ab
BRI	2.92abc	3.17abc	3.01	2.57ab	2.12a	1.97a	2.65ab
ECL	2.38bc	3.46ab	2.89	2.56ab	1.63ab	1.54ab	2.45bc
PAR	2.93abc	3.31abc	2.62	1.85ab	1.37bc	1.36ab	2.28bc
LIB	2.30bc	3.95bc	3.32	1.95ab	1.23bc	1.29ab	2.20bc
MID	2.89abc	2.87bc	1.92	1.33b	0.88c	1.37ab	1.92c
BLA	1.80c	2.36c	2.94	2.20ab	1.03c	1.03b	1.91c

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 12. Nitrogen content (NC) of clippings for Kentucky bluegrass cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
				mg N m^{-2} day^{-1}			
BRI	42.33	38.22ab*	47.11	51.26	47.48	45.00	44.95a
MID	45.37	39.60a	46.13	48.85	45.36	44.62	44.76ab
KEN	41.65	39.61a	44.55	48.34	44.73	43.51	43.56ab
ECL	42.54	37.78ab	45.82	49.57	44.23	42.79	43.55ab
ABL	42.31	36.89abc	44.56	48.83	45.87	44.42	43.54ab
LIB	41.00	37.21abc	45.18	48.61	45.40	43.39	43.30ab
JOY	40.91	37.16abc	45.30	48.35	45.07	43.08	43.07ab
TRE	39.16	35.36bc	45.68	49.41	45.59	43.60	42.82ab
BLA	41.47	37.63ab	44.34	48.74	44.22	41.47	42.80ab
PAR	41.27	34.50c	43.34	47.94	45.06	42.06	42.05b

*** Means in a column followed by the same letter are not significantly different at $p<0.05$** based on Duncan's Multiple Range Test.

Table 13. Daily nitrogen recovery rates (DNR) for Kentucky bluegrass cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
	mg N m^{-2} day^{-1}						
KEN	196.28a*	149.73a	185.26	132.78	93.72ab	87.24ab	141.19a
ABL	76.52c	151.49a	181.47	127.77	98.63a	93.77a	122.81ab
BRI	117.03abc	119.85ab	140.57	132.60	103.47a	94.22a	118.03abc
JOY	166.21abc	139.85a	151.18	100.50	61.69cde	60.54ab	114.39abcd
TRE	138.20abc	128.00ab	144.47	116.01	72.92abc	58.09ab	111.47abcd
ECL	95.59bc	129.86ab	128.89	126.06	74.90abcd	66.35ab	104.98bcd
PAR	119.19abc	114.19ab	112.86	89.66	65.31bcde	60.00ab	94.38bcd
LIB	88.14bc	111.79ab	147.58	95.90	58.13cde	58.75ab	93.88bcd
MID	146.28abc	116.11ab	87.41	64.86	42.27e	63.81ab	86.37cd
BLA	83.77ab	89.69c	128.24	106.55	47.09de	44.80b	83.61d

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 14. Nitrogen efficiency ratios (NER) for Kentucky bluegrass cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
				mg dry tissue mg $^{-1}$ N			
PAR	25.15ab*	29.18	23.73	20.97	23.06	24.64	24.64a
TRE	26.24a	28.48ab	22.56	20.47	22.71	23.66	24.20ab
BLA	24.37ab	26.73bc	22.96	20.66	23.33	25.03	23.95ab
JOY	25.11ab	27.20bc	22.89	20.84	22.94	23.79	23.93ab
LIB	24.89ab	27.05bc	22.62	20.73	22.93	23.83	23.77ab
ABL	24.19ab	27.30ab	22.86	20.76	22.55	23.12	23.61ab
KEN	24.46ab	25.71c	23.06	20.89	23.12	23.71	23.58ab
ECL	23.92ab	26.56bc	22.29	20.33	23.39	24.02	23.54ab
BRI	24.25ab	26.41bc	21.65	19.67	21.85	23.33	23.00b
MID	22.35b	25.48c	22.03	20.66	22.71	22.87	22.81b

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 15. Daily clipping growth rates (DCG) for perennial ryegrass cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
			g dry tissue m^{-2} day^{-1}				
LIN	4.87	2.65	1.48	1.14ab*	1.50a	1.79	2.26a
J207	4.54	2.37	1.58	1.36a	1.49a	2.05	2.24a
PST	5.31	2.50	1.27	0.94ab	1.14ab	1.49	2.13ab
DER	4.44	2.09	1.35	1.22ab	1.34a	1.66	2.02ab
RAN	4.69	2.23	1.43	1.16ab	1.03ab	1.52	2.02ab
J208	4.20	2.25	1.17	0.97ab	1.17ab	1.77	1.93ab
MAN	4.43	2.22	1.15	1.07ab	1.01ab	1.55	1.92ab
REP	4.09	2.43	1.23	1.06ab	1.26a	1.19	1.89ab
YOR	4.13	1.96	1.23	0.99ab	1.32a	1.48	1.85ab
TAR	3.97	1.83	0.76	0.70b	0.62b	1.06	1.50b

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 16. Nitrogen content of clippings for perennial ryegrass cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
			mg N g^{-1} dry tissue				
REP	38.91	37.54a*	50.77a	50.28	61.98ab	45.25	44.44
YOR	27.25	35.77ab	44.08ab	48.64	62.43ab	44.25	42.37
PST	39.98	33.85ab	41.74b	49.60	55.98ab	44.19	42.25
J207	38.60	35.88ab	41.94b	49.52	69.71a	42.13	42.01
RAN	38.25	36.16ab	42.86b	48.04	46.89ab	44.36	41.98
DER	35.16	35.03ab	40.64b	49.47	64.78ab	45.62	41.77
TAR	39.32	35.87ab	42.01b	48.11	29.62b	42.35	41.66
LIN	36.40	35.08ab	41.14b	49.54	68.03a	44.25	41.52
MAN	38.25	32.67b	44.86ab	48.21	46.60ab	43.31	41.51
J208	37.45	34.39ab	38.94b	50.05	53.56ab	44.32	41.37

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 17. Daily nitrogen recovery rates (DNR) in clippings for perennial ryegrass cultivars monthy means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
				mg N m^{-2} day^{-1}			
J207	167.77	84.01	80.02	68.46	69.71a*	84.18	92.35a
LIN	175.88	91.92	65.87	58.33	68.03a	81.23	90.40a
PST	210.78	84.97	73.56	47.98	55.98ab	67.46	89.10a
RAN	177.55	77.71	78.43	58.22	46.89ab	69.15	84.64ab
DER	153.68	72.19	67.33	60.99	64.78a	76.68	81.61ab
REP	148.43	89.83	70.25	52.07	61.98a	58.08	81.09ab
J208	154.38	76.88	56.97	48.15	53.56ab	80.22	78.88ab
MAN	133.13	71.05	65.07	53.08	46.60ab	68.80	76.83ab
YOR	145.80	68.11	58.29	48.55	62.43a	67.27	75.02ab
TAR	147.59	64.27	39.87	33.76	29.62b	45.15	61.50b

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* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 18. Nitrogen efficiency ratios (ENR) for perennial ryegrass cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
mg dry tissue mg $^{-1}$ N							
MAN	27.37	36.72	23.23ab*	20.90	23.44	23.37	26.29a
PST	26.00	33.52	24.24ab	20.40	22.60	22.84	25.82ab
J208	27.30	29.32	26.09a	20.28	23.32	22.87	25.01ab
LIN	28.05	28.87	24.67ab	20.37	23.41	22.98	24.92ab
DER	29.14	28.79	24.94a	20.40	23.22	22.10	24.87ab
RAN	26.83	27.99	23.54ab	21.32	25.20	22.75	24.73ab
TAR	26.10	28.13	23.97ab	21.02	23.52	24.03	24.65ab
J207	26.30	28.03	24.14ab	20.30	22.74	24.50	24.49ab
YOR	27.46	28.18	23.09ab	20.75	22.48	22.84	24.31ab
REP	26.37	26.86	21.34	20.06	22.41	22.46	23.46b

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 19. Daily clipping growth rates (DCG) for tall fescue cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
			g dry tissue m^{-2} day^{-1}				
164	5.18	4.19ab	2.64	2.79	2.08a	2.09a	3.20a
160	5.30	3.62ab	2.79	2.86	1.89ab	2.27a	3.14ab
KY31	4.89	4.25ab	2.73	2.68	1.73ab	2.10a	3.11ab
FAL	4.90	4.32a	2.65	2.77	1.71ab	1.63ab	3.05ab
JAG	5.72	3.72ab	2.63	2.62	1.61ab	1.57ab	3.01ab
ARI	5.00	4.04ab	2.84	2.48	1.64ab	1.28ab	2.93ab
REB	4.86	3.61ab	2.83	2.69	1.41abc	1.43ab	2.84ab
APA	5.24	3.28ab	2.32	2.53	1.59ab	1.47ab	2.76ab
SYN	4.02	3.42ab	2.04	1.95	1.32bc	1.11ab	2.36bc
PST5	3.59	2.66b	1.84	1.50	0.82c	0.81b	1.90c

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 20. Nitrogen content (NC) of clippings for tall fescue cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
				mg N g^{-1} dry tissue			
REB	38.31	33.86a*	37.48	46.05a	40.47	41.28ab	39.35a
160	37.12	31.25ab	37.11	45.97a	40.24	45.76a	39.24a
JAG	38.26	34.01a	37.37	44.44a	38.28	38.81bc	38.34ab
ARI	37.49	33.58a	35.65	43.93ab	39.69	38.62bc	37.97ab
FAL	36.43	32.23ab	36.31	43.44ab	38.53	38.93bc	37.44ab
164	35.95	30.72ab	36.62	43.79ab	38.46	39.35bc	37.19ab
PST5	34.83	33.32a	36.54	43.40ab	37.20	38.51bc	37.04ab
KY31	34.05	30.82ab	34.97	43.44ab	38.76	39.12bc	36.59ab
APA	35.65	30.28ab	33.31	42.24ab	38.05	38.54bc	36.08b
SYN	32.24	26.49b	33.71	39.68b	34.85	34.69c	33.30c

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 21. Daily nitrogen recovery (DNR) rates in clippings for tall fescue cultivars monthly means for1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
				mg N m^{-2} day^{-1}			
160	212.15	107.18	110.45	131.53	74.96a*	96.79	121.58a
JAG	232.15	127.74	108.39	118.57	62.67a	68.05	120.75a
164	187.95	127.90	104.67	124.97	80.86a	83.02	119.12a
FAL	183.43	137.11	113.64	124.46	67.74a	70.64	117.75a
ARI	195.39	137.69	112.50	112.60	67.12a	54.45	115.08a
KY31	174.48	129.13	100.86	119.29	68.50a	75.83	112.55a
REB	190.12	121.73	117.39	125.91	56.81ab	61.03	112.55a
APA	191.12	98.19	75.76	111.03	63.97a	58.51	100.18ab
SYN	139.38	86.33	74.86	81.52	48.33ab	44.61	79.93b
PST5	125.39	89.31	95.32	69.17	31.49b	34.54	74.59b

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 22. Nitroen efficiency ratios (NER) in clippings for tall fescue cultivars monthly means for 1990 and 1991

Grass	May	June	July	Aug.	Sept.	Oct.	Average
				mg dry tissue mg $^{-1}$ N			
SYN	31.78a*	49.29	30.40	25.62a	29.88	29.52a	33.46a
APA	28.68ab	51.35	32.91	24.04ab	27.52	26.21b	32.64ab
KY31	30.39ab	42.76	29.01	23.22ab	26.71	25.74b	30.22ab
164	28.29ab	43.10	27.96	23.40ab	27.05	25.73b	29.85ab
FAL	27.82ab	38.56	28.05	23.26ab	27.02	25.97b	28.11ab
160	27.87ab	41.33	27.26	21.80b	25.90	23.14b	28.42ab
PST5	29.33ab	30.87	27.97	23.41ab	27.93	26.25b	27.83ab
ARI	27.79ab	30.20	28.57	23.06ab	26.37	26.30b	27.17ab
JAG	27.17b	29.81	27.38	22.79b	27.24	26.19b	26.89ab
REB	26.73	29.96	27.09	21.86b	25.76	24.42b	26.13b

* Means in a column followed by the same letter are not significantly different at $p<0.05$ based on Duncan's Multiple Range Test.

Table 23. Linear regressions between daily nitrogen recovery rate (DNR) and soil water nitrate-N concentrations (SWNC) - Kentucky bluegrass cultivars

Regressions	Coefficient
Between DNR of 1990 and SWNC of 1990 growing seasons[‡]	
$SWNC = 28.11 - 0.20DNR$	$r = 0.172$***
Between DNR of 1990 and SWNC of 1990 non-growing seasons	
$SWNC = 5.03 - 0.01DNR$	$r = 0.206$***
Between DNR of 1991 and SWNC of 1990 non-growing seasons	
$SWNC = -41.25 + 0.51DNR$	$r = 0.179$***
Between DNR of 1991 and SWNC of 1991 growing seasons	
$SWNC = 36.30 - 0.56DNR$	$r = 0.357$***
Between DNR of 1991 and SWNC of 1991 non-growing seasons	
$SWNC = 1.75 + 0.05DNR$	$r = 0.401$***
The correlation in May - between DNR and SWNC	
$SWNC = 5.70 - 0.04DNR$	$r = 0.322$*
The correlation in June - between DNR and SWNC	
$SWNC = 8.97 - 0.06DNR$	$r = 0.537$***
The correlation in July - between DNR and SWNC	
$SWNC = -26.43 + 0.20DNR$	$r = 0.145$
The correlation in August - between DNR and SWNC	
$SWNC = 29.98 - 0.24DNR$	$r = 0.284$*
The correlation in September - between DNR and SWNC	
$SWNC = 52.82 - 0.61DNR$	$r = 0.336$**
The correlation in October - between DNR and SWNC	
$SWNC = 62.04 - 0.77DNR$	$r = 0.367$*

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

[‡] 1990 growing seasons: May to October, 1990
1990 non-growing seasons: November 1990 to April 1991
1991 growing seasons: May to October, 1991
1991 non-growing seasons: November 1991 to April 1992

Table 24. Linear regressions between daily nitrogen recovery rates (DNR) and soil water nitrate-N concentrations (SWNC) - Perennial ryegrass cultivars

Regressions	Coefficient
Between DNR of 1990 and SWNC of 1990 growing seasons‡	
$SWNC = 19.02 - 0.21DNR$	$r = 0.114$**
Between DNR of 1990 and SWNC of 1990 non-growing seasons	
$SWNC = 0.79 - 0.01DNR$	$r = 0.010$
Between DNR of 1991 and SWNC of 1990 non-growing seasons	
$SWNC = -1.49 + 0.03DNR$	$r = 0.431$***
Between DNR of 1991 and SWNC of 1991 growing seasons	
$SWNC = 29.39 - 0.30DNR$	$r = 0.183$***
Between DNR of 1991 and SWNC of 1991 non-growing seasons	
$SWNC = 1.38 + 0.06DNR$	$r = 0.134$**
The correlation in May - between DNR and SWNC	
$SWNC = 0.03 - 0.11DNR$	$r = 0.100$
The correlation in June - between DNR and SWNC	
$SWNC = 0.06 + 0.26DNR$	$r = 0.488$**
The correlation in July - between DNR and SWNC	
$SWNC = 20.28 - 16.67DNR$	$r = 0.141$
The correlation in August - between DNR and SWNC	
$SWNC = 1.51 - 0.41DNR$	$r = 0.164$
The correlation in September - between DNR and SWNC	
$SWNC = 1.47 - 0.29DNR$	$r = 0.223$*
The correlation in October - between DNR and SWNC	
$SWNC = -0.06 + 0.17DNR$	$r = 0.281$*

---

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

‡ 1990 growing seasons: May to October, 1990
1990 non-growing seasons: November 1990 to April 1991
1991 growing seasons: May to October, 1991
1991 non-growing seasons: November 1991 to April 1992

Table 25. Linear regresssions between daily nitrogen recovery rates (DNR) and soil water nitrate-N concentrations (SWNC) - Tall fescue cultivars

Regressions	Coefficient
Between DNR of 1990 and SWNC of 1990 growing seasons‡	
$SWNC = 104.92 - 0.92DNR$	$r = 0.014$
Between DNR of 1990 and SWNC of 1990 non-growing seasons	
$SWNC = 0.27 - 0.01DNR$	$r = 0.158$**
Between DNR of 1991 and SWNC of 1990 non-growing seasons	
$SWNC = -12.16 + 0.12DNR$	$r = 0.099$
Between DNR of 1991 and SWNC of 1991 growing seasons	
$SWNC = 1313.00 - 12.50DNR$	$r = 0.001$
Between DNR of 1990 and SWNC of 1991non-growing seasons	
$SWNC = 0.30 + 0.02DNR$	$r = 0.179$***
The correlation in May - between DNR and SWNC	
$SWNC = -0.04 + 0.24DNR$	$r = 0.010$
The correlation in June - between DNR and SWNC	
$SWNC = -0.24 + 0.71DNR$	$r = 0.251$
The correlation in July - between DNR and SWNC	
$SWNC = 0.01 + 0.23DNR$	$r = 0.241$
The correlation in August - between DNR and SWNC	
$SWNC = 42.05 + 100.19DNR$	$r = 0.449$**
The correlation in September - between DNR and SWNC	
$SWNC = -31.00 + 98.90DNR$	$r = 0.324$
The correlation in October - between DNR and SWNC	
$SWNC = 0.25 + 0.26DNR$	$r = 0.602$***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

‡ 1990 growing seasons: May to October, 1990
1990 non-growing seasons: November 1990 to April 1991
1991 growing seasons: May to October, 1991
1991 non-growing seasons: November 1991 to April 1992

Figure 1. Calculated cumulative nitrate losses by percolation from Kentucky bluegrass plots from March 1990 to February 1991

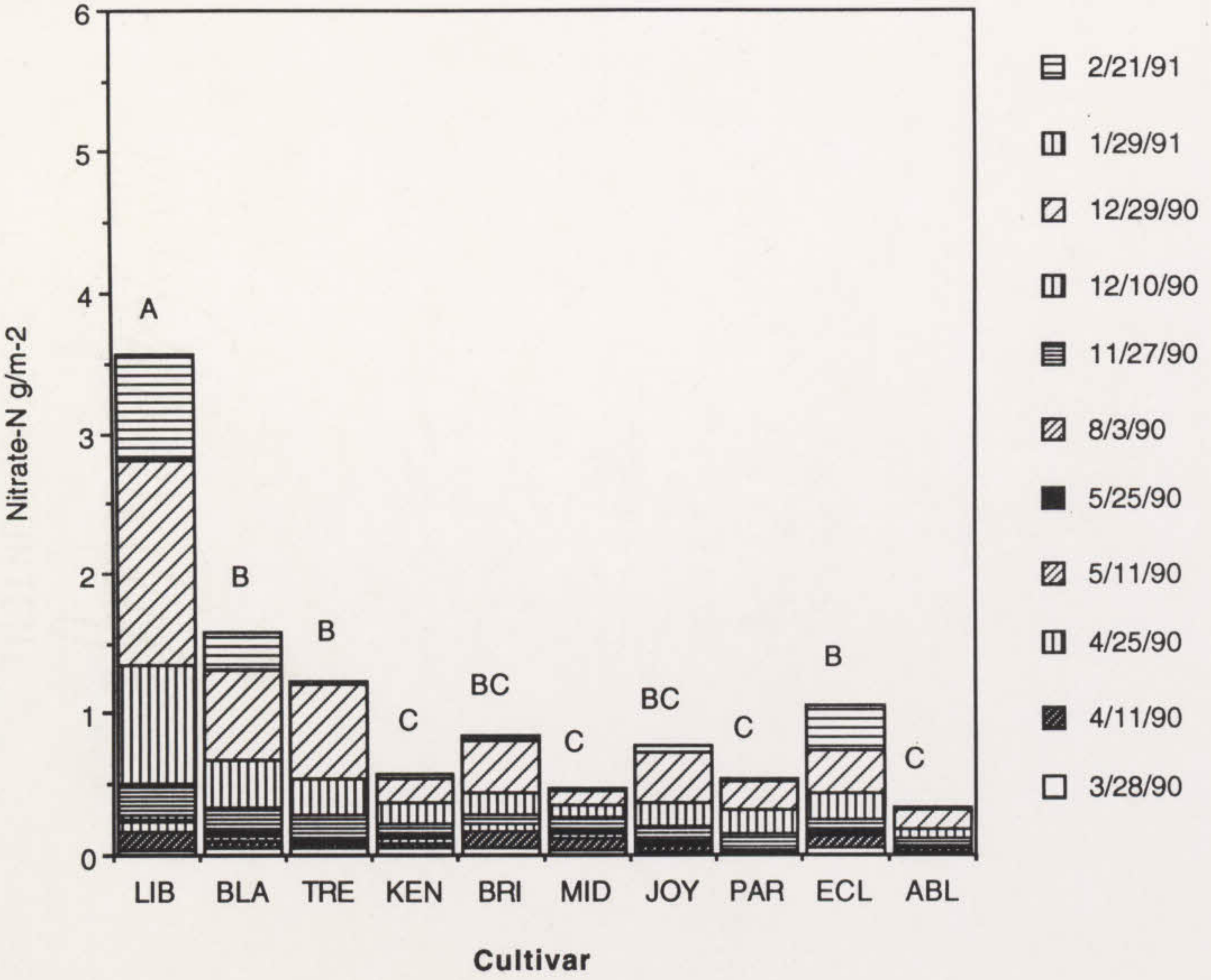

6
5
4
3
2
1
0
Nitrate-N g/m-2
A
B
B
C
BC
C
BC
C
B
C
LIB
BLA
TRE
KEN
BRI
MID
JOY
PAR
ECL
ABL
Cultivar
2/21/91
1/29/91
12/29/90
12/10/90
11/27/90
8/3/90
5/25/90
5/11/90
4/25/90
4/11/90
3/28/90

Figure 2. Calculated cumulative nitrate losses by percolation from Kentucky bluegrass plots from March 1991 to February 1992

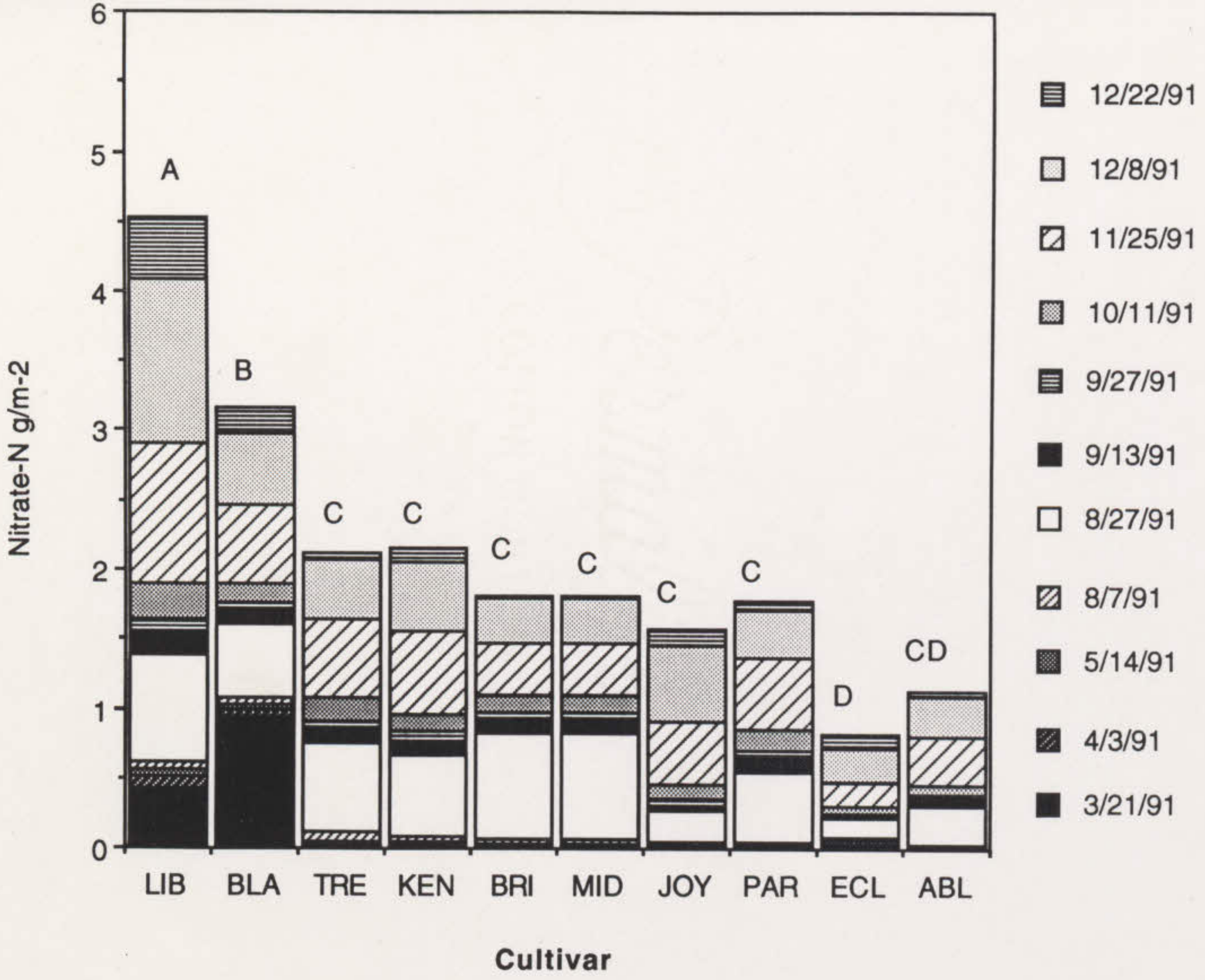

Nitrate-N g/m-2
0
1
2
3
4
5
6
A
B
C
C
C
C
C
C
D
CD
LIB
BLA
TRE
KEN
BRI
MID
JOY
PAR
ECL
ABL
Cultivar
12/22/91
12/8/91
11/25/91
10/11/91
9/27/91
9/13/91
8/27/91
8/7/91
5/14/91
4/3/91
3/21/91

Figure 3. Calculated cumulative nitrate losses by percolation from perennial regress plots from March 1990 to February 1991

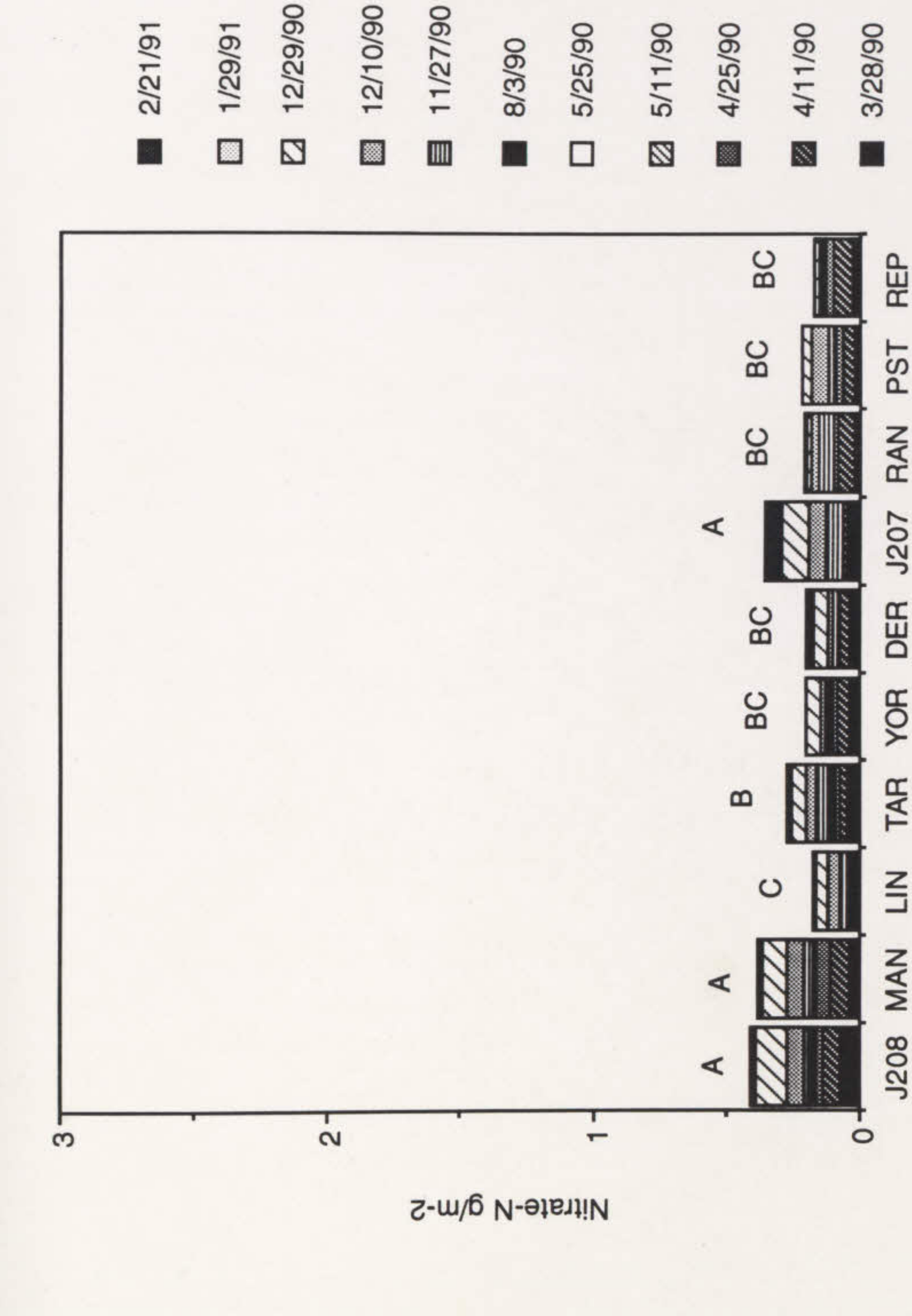

Nitrate-N g/m-2
0
1
2
3
Cultivar
J208
MAN
LIN
TAR
YOR
DER
J207
RAN
PST
REP
A
A
C
B
BC
BC
A
BC
BC
BC
2/21/91
1/29/91
12/29/90
12/10/90
11/27/90
8/3/90
5/25/90
5/11/90
4/25/90
4/11/90
3/28/90

Figure 4. Calculated cumulative nitrate losses by percolation from perennial ryegrass plots from March 1991 to February 1992

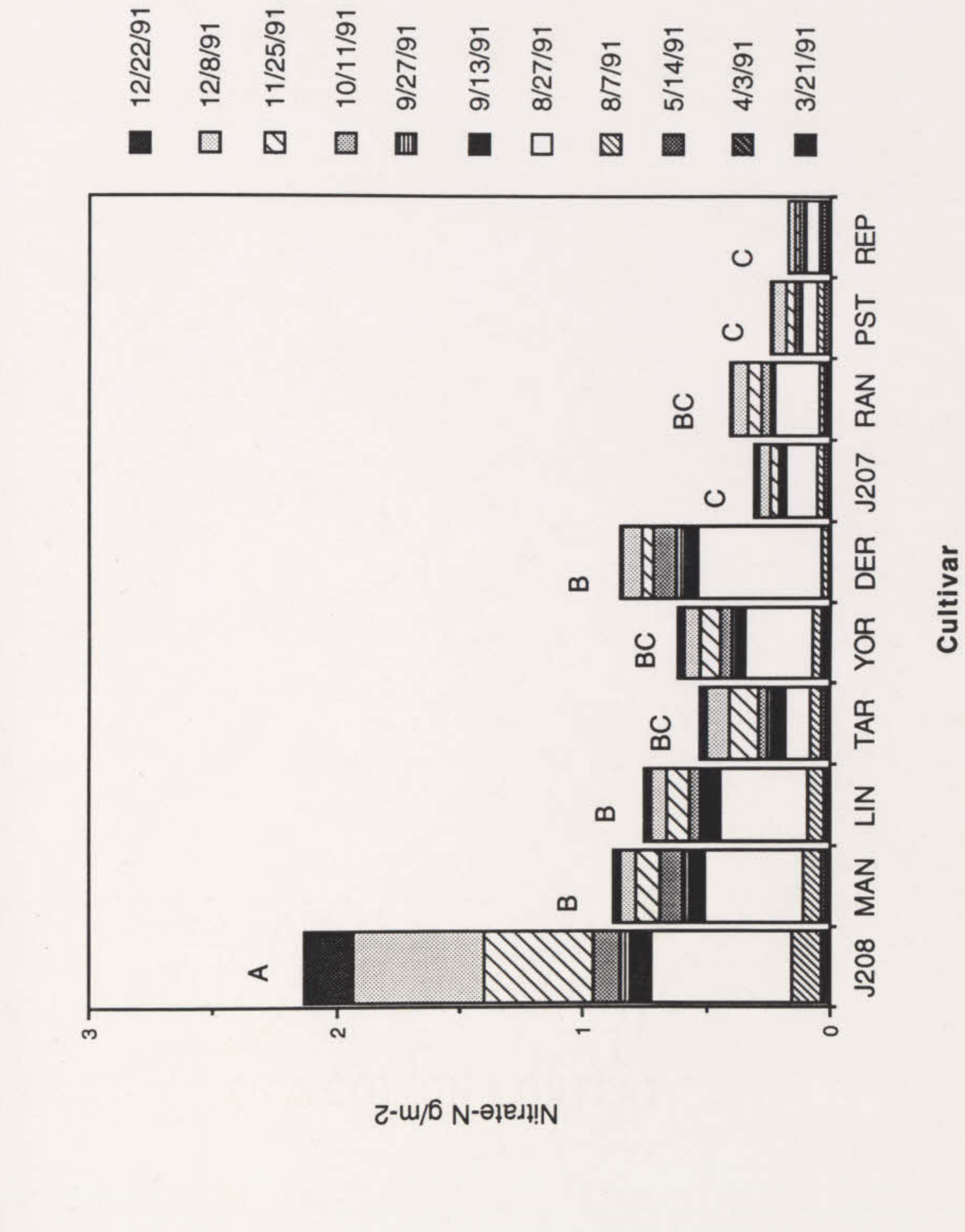

Nitrate-N g/m-2
0
1
2
3
A
B
B
BC
BC
B
C
BC
C
C
J208
MAN
LIN
TAR
YOR
DER
J207
RAN
PST
REP
Cultivar
■ 12/22/91
▨ 12/8/91
▨ 11/25/91
▨ 10/11/91
▤ 9/27/91
■ 9/13/91
☐ 8/27/91
▨ 8/7/91
▨ 5/14/91
▨ 4/3/91
■ 3/21/91

Figure 5. Calculated cumulative nitrate losses by percolation from tall fescue plots from March 1990 to February 1991

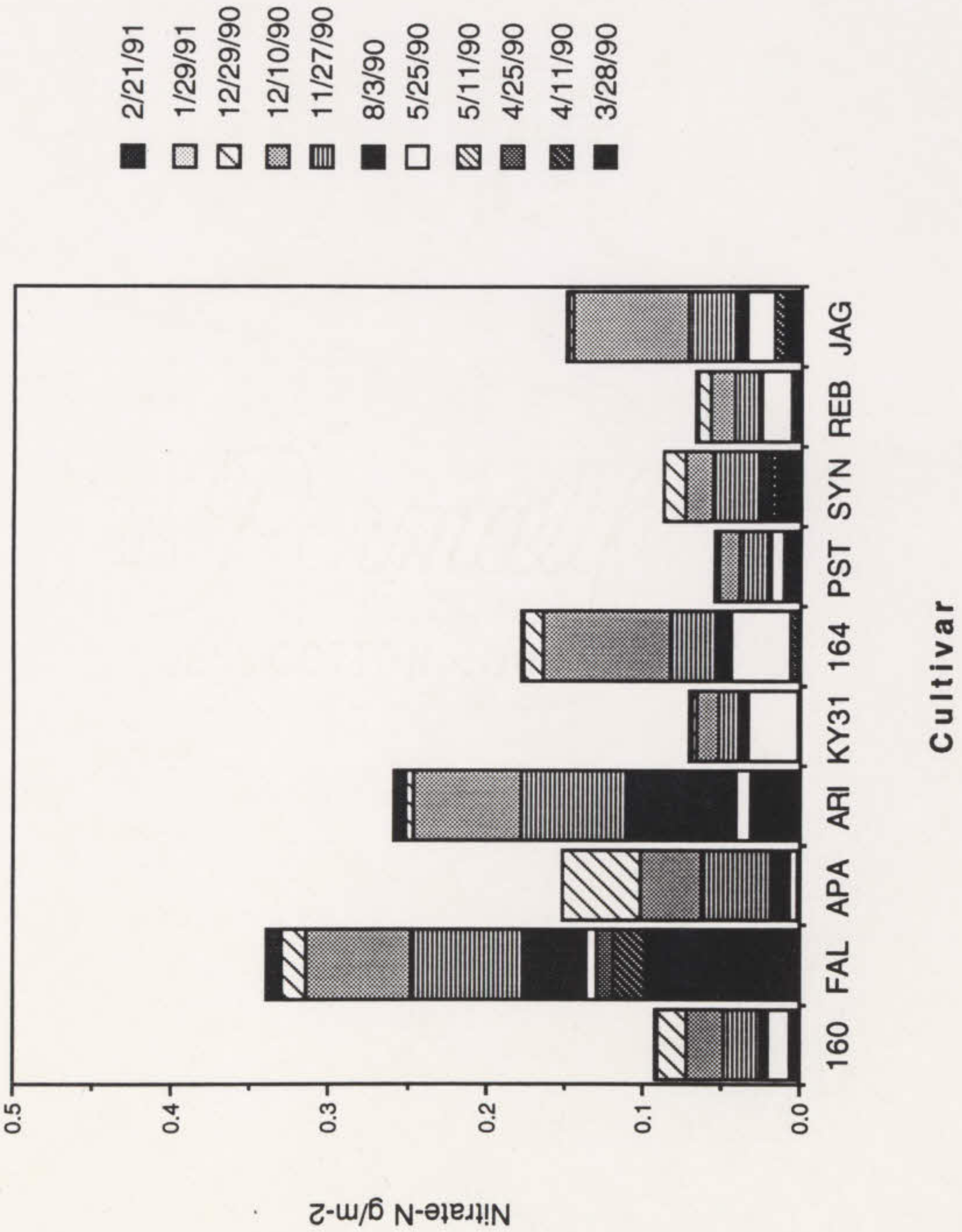
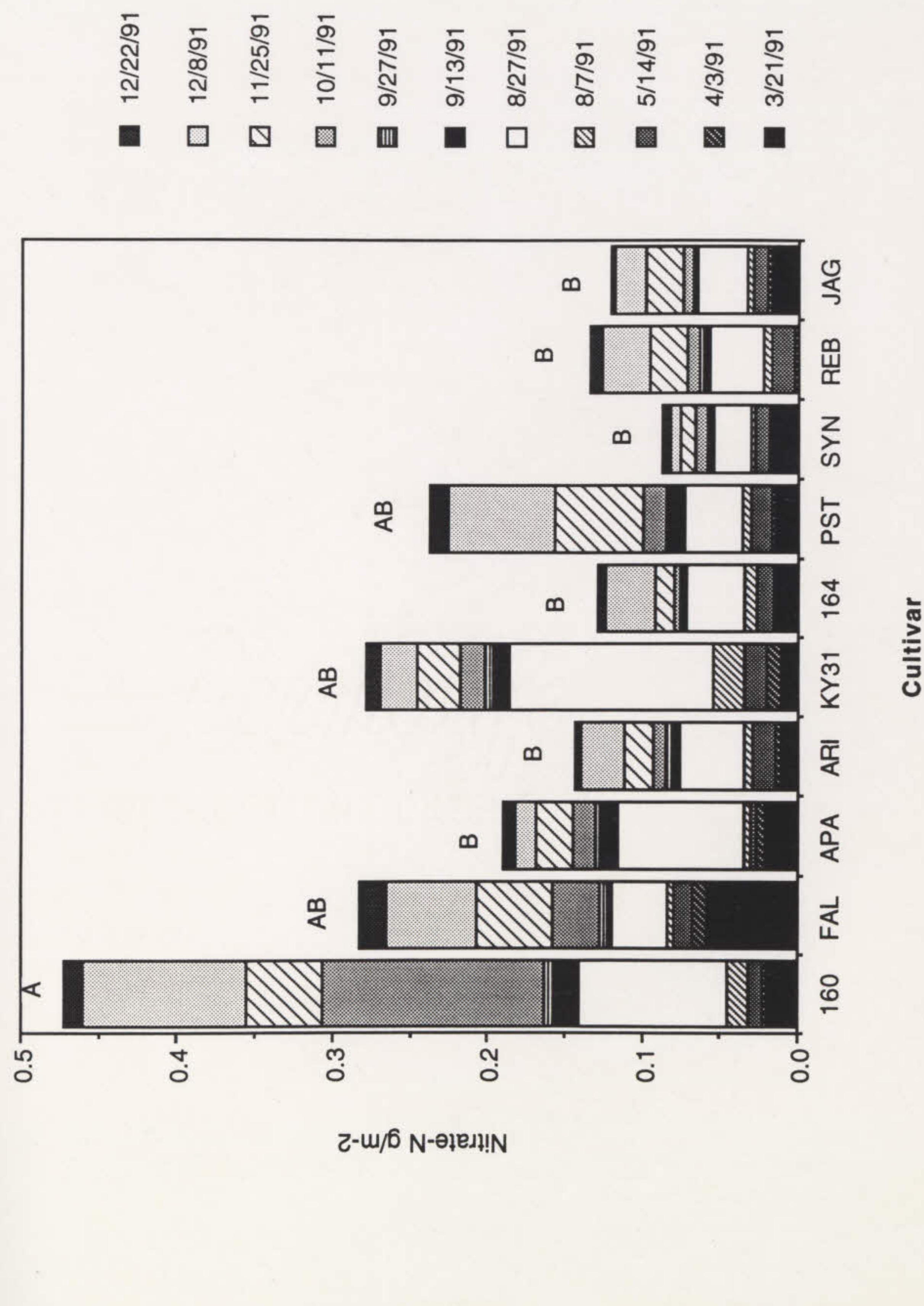

Nitrate-N g/m-2
0.5
0.4
0.3
0.2
0.1
0.0
160
FAL
APA
ARI
KY31
164
PST
SYN
REB
JAG
Cultivar
2/21/91
1/29/91
12/29/90
12/10/90
11/27/90
8/3/90
5/25/90
5/11/90
4/25/90
4/11/90
3/28/90

Figure 6. Calculated cumulative nitrate losses by percolation from tall fescue plots from March 1991 to February 1992


Nitrate-N g/m-2
0.0
0.1
0.2
0.3
0.4
0.5
A
AB
B
B
AB
B
AB
B
B
B
160
FAL
APA
ARI
KY31
164
PST
SYN
REB
JAG
Cultivar
12/22/91
12/8/91
11/25/91
10/11/91
9/27/91
9/13/91
8/27/91
8/7/91
5/14/91
4/3/91
3/21/91

MANUSCRIPT II

COMPARING CULTIVARS OF THREE COOL-SEASON TURFGRASSES FOR NITRATE UPTAKE KINETICS AND NITROGEN RECOVERY IN THE FIELD

ABSTRACT

Increasing capacity of low maintenance turf to recover nitrate efficiently from soil has become an important research objective for economic and environmental reasons. Understanding cultivar variation among turfgrass species in their capacity for nitrate absorption is essential to achieving this goal. Kinetic parameters of nitrate absorption (Vmax, Km, Cm, AIUC and CUU) were measured for six cultivars each of Kentucky bluegrass (*Poa pratensis* L.), perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea* Schreb.). Grass cultures were grown in a greenhouse and nitrate uptake kinetics were measured via a solution depletion technique. Turfgrasses varied significantly between species and between cultivars in uptake parameters measured. In 1990 and 1991, field studies of the same six cultivars each of the three species were compared for clipping production rate, leaf blade nitrogen content, nitrogen recovery rate in clippings and visual quality under a nitrogen fertilization rate of 149 kg N ha $^{-1}$ year $^{-1}$. Some correlations between the nitrate uptake parameters and field performance were identified. These results indicate that for nitrate utilization, genetic differences exist among turfgrasses at both interspecific and intraspecific levels and suggest that a screening program could be developed to identify turfgrass cultivars and species having superior nitrogen utilization characteristics.

INTRODUCTION

Nitrate is the most common form of nitrogen absorbed by turfgrasses (Petrovic, 1990; Turner and Hummel, 1992). Like agricultural crops (Epstein and Jeffries, 1964), turfgrasses vary in their ability to absorb nitrate (Cisar, 1986). This variation is attributed to genetic differences and environmental influences on nitrate uptake (Glass et al., 1989; Petrovic, 1990).

Initial research on genetic variation of nitrate uptake by plants was focused on agricultural crops. Hoener and DeTurk (1938) first reported genetic control in nitrate uptake between two lines of corn (*Zea may* L.). Harvey (1939) found differences in dry matter accumulation when he grew several genetic lines of corn in nutrient culture with NH_4^+ or NO_3^- as N sources. Warncke and Barber (1974) identified differences in nitrate uptake among the four plant species corn, soybean (*Glycine max* L.), sorghum (*Sorghum bicolor* L.), and bromegrass (*Bromus inermus* L.).

Recent studies, using several higher plant species, show nitrate uptake to be biphasic; mediated by a saturable system operating at concentrations $< 500\ \mu M$ and a nonsaturable system functional at concentrations $> 500\ \mu M$ (Siddiqi et al., 1990; Glass et al., 1992). While the nitrate concentration of soil water in a turfgrass root zone is highly variable (Petrovic, 1990), it generally falls within the range of the saturable system (Morton et al., 1988). Cisar (1986) described this system of nutrient uptake in turfgrasses using Michaelis-Menten saturation kinetics. He observed significant differences in the kinetic parameters Vmax, Km and Cm among three turfgrass species. Bowman et al. (1989) reported that nitrogen deficient perennial ryegrass exhibited a greater maximum rate of nitrate uptake (Vmax) than nitrogen sufficient controls. Nitrogen deficiency promoted a reduced affinity of roots for nitrate (increase in Km). This led them to conclude that, increased nitrogen recovery in shoots of nitrogen deficient cultures when provided adequate nitrate, resulted from an increased Vmax. Neither study investigated variation in nitrate uptake properties among cultivars of turfgrass species.

Two major factors have been observed to affect nitrogen recovery in turfgrass clippings: nitrogen application rate (Snow, 1976) and nitrogen source (Hummel and Waddington, 1981). The effect of the innate capability of turfgrass roots to absorb nitrate and consequent nitrogen recovery in shoots (clippings) has not been reported. These nitrate absorption parameters, by influencing the capability of turfgrasses to acquire nitrate, may be important in determining practices of nitrogen fertilization, achieving efficiency in nitrogen use and minimizing nitrate leaching from turf. The objectives of this study were to quantify the variation in nitrate uptake kinetics among cultivars of three cool-season turfgrasses and to correlate this to turf growth and nitrogen recovery in the field.

MATERIALS AND METHODS

I. Nitrate Uptake Kinetics

Uptake kinetic parameters of nitrate were measured under greenhouse conditions using turfgrass as grown hydroponically in 1/4 strength Hoagland solution (Hoagland and Arnon, 1956). Six cultivars each of three species were selected to represent various levels of performance in the National Turfgrass Evaluation Program trials (Table 1).

The affinity for, and capacity of , a plant root to take up a specific ion was described by Epstein and Hagen (1952) based upon Michaelis-Menten saturation kinetics. The adjusted Michaelis-Menten equation was employed to describe the following relationship:

$$V = \frac{Vmax\ Co}{Km + Co}$$

where: V = rate of ion absorption (μmoles g^{-1} roots $hour^{-1}$);

Vmax = maximum rate of ion absorption at saturating concentration;

Co = external nutrient concentration;

Km = external nutrient concentration at half the maximum uptake rate.

The parameters Km and Vmax characterize the affinity for, and the capacity of, plant roots to acquire nutrients from their soil environment, respectively (Epstein, 1972). These kinetic parameters for nitrate absorption by turfgrass roots were determined using a solution depletion procedure similar to that described by Claassen and Barber (1974). In this study, four parameters were obtained through the measurement of nitrate uptake kinetics for each cultivar. They were Vmax, Km, Cm (the nitrate concentration in the uptake solution at which no net uptake occurs) CUU (cumulative uptake μmole N g^{-1}

root), and the integrated area under uptake curves (uptake rate x external nitrate concentration) which is a dimensionless sum of nitrate uptake during the whole uptake period termed Area Index of Uptake Curve - AIUC.

Four 5-cm diameter holes were cut in a plexiglas sheet (44 x 10 x 0.5 cm). A nylon mesh was then glued to one side of the sheet to support germinating seeds within the holes. About 100 seeds were sown on the mesh within each hole and this constituted of four replicates for one cultivar. After seeding, each plexiglas sheet was placed on wet silica sand. Mist was provided every ten minutes to keep the seeds and the sand moist. After grasses germinated, roots penetrated the nylon mesh and grew into the sand. No nutrients were provided during this initial germination period.

One week after germination, each plexiglas sheet contained four uniform cultures of seedlings. The sheets with seedlings were washed free of sand and suspended over a dark colored plastic tub containing 12 liters of 1/4 strength modified Hoagland nutrient solution (Hoagland and Arnon, 1956). The solution was continually aerated through thin plastic tubes throughout the growing period. The nutrient solution was replaced every four days. The pH of the solution was adjusted with 0.01 M $Ca(OH)_2$ or 0.01 M H_2SO_4 to pH 5.5 - 6.5 during the six week growing period. Day temperature of the greenhouse was maintained at 20 - 25 ^oC and solution temperature 18 - 22 ^oC. The incident radiation at 1200 hours ranged from 400 to 600 W m^{-2}.

Twenty-four hours prior to an uptake experiment, the nutrient solution was replaced with a nitrate free modified Hoagland's solution. After that, the roots of each culture were placed in individual beakers containing 500 ml solution with a nitrate concentration of 500 μM.

The nitrate depletion analysis was based on that used by Cisar (1986). The solution was sampled at 15 minute intervals over a 6 hour period. The solution was stirred before each one ml sample was taken and an equivalent volume of deionized distilled water was returned to the beaker following each sample removal to retain a constant volume. The decrease in solution nitrate concentration during each sampling interval was used to determine the amount of nitrate absorbed and this divided by the fresh root mass yielded and nitrate absorption rate.

Solution nitrate was analyzed by the cadmium reduction method of Keeney and Nelson (1982). In this analysis, the NO_3^- in an aliquot of solution was quantitatively reduced to NO_2^- by reaction with copperized cadmium in an ammonium chloride matrix within a pH range of 5 to 8. Nitrite was estimated colometrically after the column leachate was treated with a diazotizing reagent (sulfanilimide) in hydrochloric acid and a coupling reagent (N- (1-napthy)-ethylenediamine dihydrochloride). The intensity of the pink color that developed was measured spectrophotometrically at 540 nm.

Depletion data were fit to a series of cubic equations and the nitrate uptake rate calculated as the negative of the first derivative of the depletion curve. Vmax and Km values were estimated from a Lineweaver-Burk plot of these data (Bowman et al., 1989).

II. N Recovery by Field Grown Turf

A field experiment of the same six cultivars of each species used for uptake kinetic analysis was conducted to measure relative nitrogen recovery in clippings. The cultivars were part of National Turfgrass Trials established in 1986 and 1987 at the University of Rhode Island, Turfgrass Research Station, Kingston, Rhode Island. The plots were in a randomized, complete block design with three replications. Individual plots of each cultivar were 2 x 1 m. The soil type was an Enfield silt loam (Coarse loamy over sandy skeletal, mixed, mesic, Typic Dytrochrept). All plots received three nitrogen fertilizer applications annually (April, June and November) since establishment and each application was at the rate of 49.7 kg N ha^{-1}.

Biweekly clipping harvests were collected from May to October in 1990 and 1991. The plots were mowed twice weekly during the growing seasons without removal of clippings except clipping sample collections. A hand powered reel mower set at 3.8 cm mowing height with a collecting basket attached was used for clipping collection from a sampling area 0.48 by 1.5 m.

Clippings were oven dried for 48 hours at 75 ^{o}C, weighed and ground in a Wiley mill to pass a 40 mesh screen. Total nitrogen content of clippings was determined using a micro-Kjeldahl procedure (Eastin, 1978). For 1990 and 1991, daily clipping growths (DCG), nitrogen content of clippings (NC), daily nitrogen recovery in clippings (DNR), and nitrogen efficiency ratio (NER) for each plot were obtained.

The plots were visually scored for turf quality each month during the growing seasons of 1990 and 1991 (VQ). Scores range from 1 for totally brown turf to 9 for perfect turf. Quality was based upon uniformity, density, color and freedom from weeds and diseases.

III. Data Analysis

All statistical computations employed using procedures within the Statistical Analysis System (SAS Institute Inc., 1990). Significant means were based on an analysis of variance separated by Duncan's Multiple Range Test for both nitrate uptake parameters and field data. Simple correlation coefficients were obtained between uptake parameters and field data. A multiple regression analysis was used to quantify the relationship among nitrate uptake kinetics and nitrogen recovery in the field.

RESULTS

I. NITRATE UPTAKE KINETICS

Among the three species, perennial ryegrass had the greatest Vmax value which was significantly greater than Kentucky bluegrass and tall fescue but there were no significant differences between Kentucky bluegrass and tall fescue in Vmax (Table 3). A non-significant range of Km values from 26.1 to 42.2 μM NO_3^- was found among the species. Kentucky bluegrass had the greatest Cm which was significantly greater than that of tall fescue. As with Vmax, perennial ryegrass exhibited the greatest AIUC values which were significantly greater than values for Kentucky bluegrass and tall fescue. No significant differences in AIUC were identified between Kentucky bluegrass and tall fescue. Perennial ryegrass had the lowest CUU and it differed significantly from Kentucky bluegrass and tall fescue. There were no significant differences between tall fescue and Kentucky bluegrass in CUU.

The six cultivars of Kentucky bluegrass significantly differed in all measured uptake parameters (Table 4). 'Bristol' and 'Kenblue' exhibited a significantly greater Vmax than that of 'Blacksburg' and 'Joy'. Km differed more than nine fold among the cultivars. 'Eclipse' had the greatest affinity for nitrate in its roots while 'Liberty' had the lowest affinity in terms of the greatest Km value. Although three of the six cultivars did not exceed 1 μM NO_3^- in Cm, a thirty fold variation among the cultivars was found. 'Bristol' and 'Liberty' exhibited the two greatest Km values and two greatest Cm values.

A 1.6 fold variation of AIUC was identified among the cultivars. 'Bristol' and "Kenblue' differed from the other cultivars in CUU.

Significant differences were identified among the six perennial ryegrass cultivars in all measured uptake parameters (Table 5). 'Derby' had the lowest Vmax which was significantly lower than 'Linn', 'Repell' and 'J207' and a more than two fold variation was found among the cultivars . 'Repell' exhibited the greatest Km value and a more than ten fold variation was found among the six cultivars. Cm values for the cultivars did not exceed 10 μM but a close to ten fold variation was identified. There was a two fold variation of AIUC and CUU among the cultivars.

Tall fescue exhibited less variation in nitrate uptake than Kentucky bluegrass and perennial ryegrass (Table 6). 'KY31' and 'Jaguar' had a significantly higher Vmax than 'Apache and 'Falcon'. Although a seven fold variation of Km and a seventeen fold variation of Cm were identified, there were no significant differences among the cultivars. Significant differences were found in AIUC and CUU among the six cultivars.

II. FIELD PERFORMANCE

Significant differences in daily clipping growth (DCG), nitrogen content (NC) in clippings and daily N recovery rate (DNR) were identified among the three turfgrass genera (Table 7). Tall fescue exhibited greater DCG than Kentucky bluegrass and perennial ryegrass. NC values differed significantly among the three turfgrass genera but only by 8.6%. Perennial ryegrass had the highest NC while tall fescue had the lowest. DNR was calculated based on DCG and NC and it exhibited significant differences among the three genera with perennial ryegrass being only 76% of tall fescue in DNR value.

Significant differences in N recovery were identified among perennial ryegrass cultivars (Table 8). 'Tara' was only 66% of 'Linn' in DCG value while 'Linn' was the poorest grass in visual quality. Significant differences were found in NC among the cultivars but it only varied by 7%. DNR appeared to have a similar variation pattern to DCG with 'Tara' being about 70% of the greatest 'J207'.

Kentucky bluegrass cultivars differed significantly in DCG and DNR (Table 9). Both 'Kenblue' and 'Joy' were significantly lower in visual quality but they possessed the greatest DCG values. 'Blacksburg' had the least DCG, only about 59% of 'Kenblue' but it had the highest visual quality of 7.7. No significant differences were found in NC among the cultivars. DNR value differed significantly among the cultivars with a 58% variation from the greatest, 'Blacksburg' to the lowest, 'Kenblue'.

As with the nitrate uptake results, tall fescue cultivars exhibited a less variation than cultivars within the other two species (Table 10). No significant differences were found in DCG and DNR but the cultivars differed in NC and visual quality.

III. CORRELATION ANALYSIS

Correlation coefficients between N uptake parameters and field measurements at the species level are presented in Table 11. Km was positively correlated with all field parameters and the correlations with NC and DNR were significant. CUU was positively correlated with DCG and DNR. Four regression models among uptake parameters and two regression models among field measurements are presented in Table 15.

Only one significant correlation between AIUC and VQ was identified among Kentucky bluegrass cultivars (Table 12). Four regression models among uptake parameters and one model among field measurements were statistically significant (Table 16).

One positive correlation between CUU and VQ, and one negative correlation between AIUC and NC were identified among perennial ryegrass cultivars (Table 13). Three regression models among uptake parameters and two models among field measurements were identified (Table 17).

Vmax was positively correlated with DCG and DNR among tall fescue cultivars (Table 14). Two significant regression models between uptake parameters and field measurements were identified. Four models among uptake parameters and two models among field measurements were identified (Table 18).

DISCUSSION

Greater variation in absorption parameters was observed among cultivars of each species than among the three species. A seven to ten fold variation in Km was observed among cultivars while the difference among species was less than two fold. Cm exhibited similar variation among cultivars, ten to thirty fold, but species differed only three fold. Vmax was the most consistent uptake parameter differing one to two fold among cultivars and 1.4 fold among the three species. These results indicate that cultivars selected from the three species have similar diversities in nitrate uptake instead of closer genetic relation between species.

Cm was positively correlated with Km. This is consistent with the definition of Km as an affinity constant between nitrate and its carrier in the plasma membrane of root epidermal and cortical cells. Thus a low Km results in greater depletion of nitrate from the soil solution (low Cm) which should reduce nitrate leaching potential from turf.

Bowman et al. (1989) studied nitrate uptake by perennial ryegrass and Kentucky bluegrass under N-deficient and N-sufficient conditions and observed only slight changes in Km values (14 to 24 μM) for perennial ryegrass under the two nitrogen levels employed. Similar Km values were observed for barley (14 to 17 μM) by Lee and Drew (1986). These results indicate that Km values are reasonably stable and less likely affected by the factors influencing Vmax (e.g. temperature, plant age and solution pH) (Barber, 1984).

The soil solution under established turf measured at the same location with a total application up to 244 kg N ha^{-1} $yr.^{-1}$ contains 0.2 to 5.6 mg N L^{-1} which is 14 to 400 μM NO_3^--N (Morton et al., 1988). This falls within the range of Km values for several cultivars of all grass species studied. Under these concentrations, Km will strongly influence the rate of nitrate absorption because Km is equivalent to that nitrate concentration which will support half the maximum uptake rate (Vmax). A cultivar having a high Km (50 to 80 μM) will absorb nitrate at less than half its Vmax when the soil solution is in the 20 to 30 μM range. A grass with a Km of 8 to 10 μM will absorb nitrate at a rate approaching its Vmax. Thus a cultivar with a low Km and high Vmax should be highly efficient in absorbing nitrate. Such a grass will suffer less nitrogen deprivation when managed under low maintenance conditions.

The wide range in Km values exhibited among cultivars of all three turfgrass species is supportive of efforts to develop turfgrasses more efficient in nitrate recovery. Km values in the range of 10 to 100 μM nitrate have been recorded for many crops (Barber, 1984; Glass et al., 1992). The cultivars included in this study approach this range indicating much genetic variation in the affinity of roots for nitrate. Thus the potential for genetically improving the efficiency of nitrate removal from the soil by turfgrasses is encouraging. Individual cultivars of each species exhibited Km values of about 8.0 μM. This is within the lower Km range reported for all vascular plants, indicating that some current turfgrass cultivars may be approaching the upper practical limit of root affinity for nitrate. Thus a simple turfgrass screening procedure for nitrate absorption kinetics could become a valuable part of turfgrass improvement programs.

Integrating the area under the curve for uptake rate by nitrate concentration provides a value which is termed Area Index of uptake Curve (AIUC). AI values correlated positively with Vmax and negatively with Km (Tables 15 to 18). A high Vmax coupled with a low Km will yield a large area under the uptake curve and indicate efficient nitrate absorption. This dimensionless value may prove useful in comparing grass selections for their efficiency of ion absorption.

Turfgrasses differed in both leaf growth rate and nitrogen allocation to leaves as determined by clipping yields and nitrogen contents (Tables 3 and 4). Tall fescue transported more nitrogen to leaves and its lower leaf nitrogen concentrations combined to produce the highest clipping growth rate and nitrogen use efficiency ratio. On the other hand, perennial ryegrass transported less nitrogen to leaves which together with its highest leaf nitrogen concentrations produced the lowest clipping growth rate and a lower nitrogen use efficiency. These field performance parameters correlated with daily clipping growths (DCG). Daily clipping production was negatively correlated with leaf nitrogen concentrations and positively correlated with daily nitrogen recovery and nitrogen efficiency ratio (Tables 15 to 18).

Turf quality differed significantly among cultivars but was not correlated with leaf growth or nitrogen recovery. Mehall et al. (1983) also failed to find a significant correlation between leaf growth rate (clipping yields) and turf quality for Kentucky bluegrass. 'Kenblue' Kentucky bluegrass exhibited the greatest clipping yields and highest nitrogen recovery in clippings but produced a poor quality turf. Similarly, 'Linn' perennial ryegrass produced high clipping yields and exhibited an elevated nitrogen recovery rate but produced the lowest quality turf. Thus nitrogen recovery in clippings is an indicator of nitrogen uptake under field conditions which may be influenced by nitrate absorption kinetics but does not contribute significantly to turf quality at least under the moderate fertility conditions employed in this study.

Generally, no significant correlations were observed between kinetic parameters for nitrate uptake and field measurements of nitrogen recovery in clippings. However, only two positive correlations were found between Vmax and DCG and DNR for tall fescue cultivars although they showed less variation than Kentucky bluegrass and perennial ryegrass. A weak positive correlation was noted between Km values and nitrogen recovery. Although this was contrary to expectations it may indicate an indirect relationship between ion absorption properties and nitrogen delivery to shoots.

Nutrient absorption parameters are among many root properties which have been found to correlate with shoot growth and yields (Barber 1984). Root mass and root growth rate have been identified as positively related to yields but nutrient uptake is a significant function only when nutrient limitations may restrict plant performance. It may be difficult to design field experiments which provide conditions that accentuate the relationship of nitrate absorption parameters with plant growth or nitrogen delivery to shoots. Too many poorly defined factors separate nutrient uptake by roots from its arrival rate and utilization in shoot growth to permit a clear demonstration of the relationship between these functions. The limited comparison base of this experiment (six cultivars per species) further limited our capability to demonstrate functional relationships between root activities and shoot performance.

CONCLUSION

Differences of nitrate uptake efficiency and related field performances were found among three cool-season turfgrasses and six cultivars from each species and few correlations between uptake parameters and field parameters were identified. These results suggest that a screening program could be developed to identify cultivars or species based on their nitrogen utilization parameters. Further correlation studies are needed between uptake kinetics and field performances.

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Table 1. Cultivars selected for nitrogen utilization studies

Kentucky Bluegrass	Perennial ryegrass	Tall fescue
BRISTOL	LINN	KY31
KENBLUE	REPELL	JAGUAR
ECLIPSE	J207	REBEL II
LIBERTY	J2O8	ARID
BLACKSBURG	TARA	APACHE
JOY	DERBY	FALCON

Table 2. Concentrations of essential nutrients in the solution used to grow grasses hydroponically.

NO_3	PO_4	K	Ca**	SO_4	Mg	Fe*	Zn	Cu	Cl	B	Mo	Mn
mM							µM					
3.75	0.25	1.5	1.25	0.5	0.5	40	0.44	0.06	1.0	1.8	0.03	1.3

*: Fe was added as Sequestrene Fe-330

**: Ca values were approximate. pH was adjusted with $Ca(OH)_2$.

Table 3. Comparison of three species - nitrate uptake parameters: Vmax, Km, Cm, AIUC and CUU values (N = 24 for each species)

Species	Vmax	Km	Cm	AIUC	CUU
	µmole N g^{-1} hr^{-1}	µM	µM		µmole N g^{-1} root
Perennial ryegrass	7.22a*	33.37	3.00ab	3139a	14.58b
Tall fescue	5.43b	26.08	1.56b	2432b	19.78a
Kentucky bluegrass	5.15b	42.22	4.90a	2261b	19.01a

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 4. Comparison of six cultivars of Kentucky bluegrasses - nitrate uptake parameters: Vmax, Km, Cm, AIUC and CUU values (N = 4 for each cultivar)

Cultivar	Vmax	Km	Cm	AIUC	CUU
	μmole N g^{-1} hr^{-1}	μM	μM		μmole N g^{-1} root
Bristol	5.90a*	70.88a	13.04a	2359b	25.16a
Kenblue	5.63a	38.12ab	2.30b	2412ab	26.76a
Eclipse	5.50ab	8.00b	0.73b	2799a	14.46b
Liberty	4.97ab	76.16a	12.41a	2043bc	16.56b
Blacksburg	4.87b	35.91ab	0.39b	2242b	18.25b
Joy	4.04b	25.58ab	0.59b	1716c	12.87b

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 5. Comparison of six cultivars of perennial ryegrass - nitrate uptake parameters: Vmax, Km, Cm, AIUC and CUU values (N = 4 for each cultivar)

Cultivar	Vmax	Km	Cm	AIUC	CUU
	μmole N g^{-1} hr^{-1}	μM	μM		μmole N g^{-1} root
Linn	9.19a*	44.86ab	5.06ab	4025a	9.44b
Repell	9.05a	80.68a	7.29a	3145ab	15.74ab
J207	7.81a	25.87b	2.34ab	3790a	17.41a
J208	6.99ab	24.49b	0.76b	2952ab	10.08b
Tara	6.16ab	8.49b	1.09b	3054ab	15.50ab
Derby	4.14b	15.85b	1.47b	1806b	19.29a

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 6. Comparison of six cultivars of tall fescue - nitrate uptake parameters: Vmax, Km, Cm, AIUC and CUU values (N = 4 for each cultivar)

Cultivar	Vmax	Km	Cm	AIUC	CUU
	µmole N g^{-1} hr^{-1}	µM	µM	µmole N g^{-1} root	
KY31	7.05a*	22.54	1.24	3151a	26.58a
Jaguar	6.99a	63.78	5.29	2625ab	17.96bc
Rebel II	5.15ab	20.97	0.31	2477ab	22.94ab
Arid	5.14ab	21.42	1.32	2268b	18.75bc
Apache	4.23b	18.97	0.69	1940b	16.37c
Falcon	4.01b	8.82	0.38	2117b	16.12c

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 7. Comparison of three species: field performances - average of 1990 and 1991 from May to October

Species	Daily clipping yield (DCG)	Nitrogen content (NC)	Daily N recovery (DNR)
	g m^{-2} day^{-1}	N mg g^{-1}	N mg m^{-2} day^{-1}
Tall fescue	2.95a*	37.63c	113.12a
Kentucky bluegrass	2.52b	42.12b	109.50a
Perennial ryegrass	1.97c	43.54a	86.08b

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 8. Comparison of field performances of six cultivars of perennial ryegrass - average of 1990 and 1991 from May to October

Cultivar	Daily clipping yield (DCG)	Clipping N content (NC)	Daily N recovery (DNR)	Visual Quality (VQ)
	g m^{-2} day^{-1}	N mg g^{-1}	N mg m^{-2} day^{-1}	
Linn	2.26a*	41.52ab	90.40a	4.20b
Repell	1.89ab	44.44a	81.09ab	7.00a
J207	2.24ab	42.01ab	92.35a	6.50a
J208	1.93ab	41.37b	78.88ab	6.20ab
Tara	1.50b	41.66ab	61.50b	6.70a
Derby	2.02ab	41.77ab	81.61ab	6.30ab

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 9. Comparison of field performances of six cultivars of Kentucky bluegrass - average of 1990 and 1991 from May to October

Cultivar	Daily clipping yield (DCG)	Clipping N content (NC)	Daily N recovery (DNR)	Visual Quality (VQ)
	g m^{-2} day^{-1}	N mg g^{-1}	N mg m^{-2} day^{-1}	
Bristol	2.65abc*	44.95	118.03ab	6.9a
Kenblue	3.24a	43.56	141.19a	5.4b
Eclipse	2.45bcd	43.55	104.98bcd	7.6a
Liberty	2.20cd	43.29	93.88bc	7.0a
Blacksburg	1.91d	42.82	83.61c	7.7a
Joy	2.67abc	43.07	114.39ab	5.3b

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 10. Comparison of field performances of six cultivars of tall fescue - average of 1990 and 1991 from May to October

Cultivar	Daily clipping yield (DCG)	Clipping N content (NC)	Daily N recovery (DNR)	Visual Quality (VQ)
	g m^{-2} day^{-1}	N mg g^{-1}	N mg m^{-2} day^{-1}	
Ky31	3.11	36.59b*	112.55	4.6b
Jaguar	3.01	38.34ab	120.75	6.9a
Rebel II	2.84	39.35a	112.55	6.9a
Arid	2.93	37.97ab	115.08	6.3a
Apache	2.76	36.08b	100.18	6.2ab
Falcon	3.05	37.44ab	117.75	5.9ab

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 11. The correlation coefficients between nitrate uptake kinetic parameters and field performances based on the average results of 1990 and 1991 at the interspecific level

Uptake parameter	Daily clipping yield (DCG)	Clipping nitrogen content (NC)	Daily nitrogen recovery (DNR)	Visual quality (VQ)
Vmax	0.265	-0.060	0.050	-0.172
Km	0.116	0.226*	0.224*	0.088
Cm	-0.022	0.173	0.049	0.085
AIUC	0.037	-0.0169	-0.020	0.184
CUU	0.230*	-0.135	0.206*	0.014

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 12. The correlation coefficients between nitrate uptake kinetic parameters and field performances based on the average results of 1990 and 1991 - Kentucky bluegrass

Uptake parameter	Daily clipping yield (DCG)	Clipping nitrogen content (NC)	Daily nitrogen recovery (DNR)	Visual quality (VQ)
Vmax	0.219	0.032	0.247	0.062
Km	0.239	-0.049	0.270	0.037
Cm	-0.038	-0.089	-0.034	0.042
AIUC	0.024	0.036	0.035	0.413*
CUU	-0.045	0.017	0.024	-0.189

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 13. The correlation coefficients between nitrate uptake kinetic parameters and field performances based on the average results of 1990 and 1991 - Perennial ryegrass

Uptake parameter	Daily clipping yield (DCG)	Clipping nitrogen content (NC)	Daily nitrogen recovery (DNR)	Visual quality (VQ)
Vmax	0.237	-0.208	0.210	0.261
Km	-0.010	0.306	0.110	0.024
Cm	0.111	0.117	0.243	0.045
AIUC	0.301	-0.335*	0.233	-0.325
CUU	0.130	-0.089	0.048	0.411*

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 14. The correlation coefficients between nitrate uptake kinetic parameters and field performances based on the average results of 1990 and 1991 - Tall fescue

Uptake parameter	Daily clipping yield (DCG)	Clipping nitrogen content (NC)	Daily nitrogen recovery (DNR)	Efficiency ratio of nitrogen (ERN)	Visual quality
Vmax	0.356*	-0.067	0.427**	-0.080	-0.178
Km	0.195	0.162	0.308	-0.217	0.093
Cm	0.133	0.269	0.284	0.251	0.107
AIUC	0.289	-0.233	0.274	0.080	-0.259
CUU	0.196	-0.134	0.140	0.114	-0.277

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 15. Significant regression equations and correlation coefficients between parameters - interspecific level

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters	
AIUC	= 362.205 + 431Vmax - 10.650Km	0.956***
Vmax	= 5.309 + 0.0185Km	0.327***
Vmax	= 5.607 + 0.104Cm	0.271*
Km	= 20.091 + 4.396Cm	0.645***
	Between field parameters	
DCG	= 1.179 - 0.042NC + 0.023DNR	0.989***
NC	= 45.391 - 0.042DNR	0.310***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 16. Significant regression equations and correlation coefficients between parameters - Kentucky bluegrass cultivars

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters	
AIUC	$= 186.081 + 494.971\mathrm{Vmax} - 6.375\mathrm{Km}$	0.943***
CUU	$= 4.925 + 8.787\mathrm{Vmax}$	0.610*
Vmax	$= 4.566 + 0.014\mathrm{Km}$	0.479**
Vmax	$= 4.891 + 0.053\mathrm{Cm}$	0.401*
Km	$= 31.651 + 2.198\mathrm{Cm}$	0.477**
	Between field parameters	
DCG	$= 1.831 + 0.023\mathrm{DNR}$	0.993***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 17. Significant regression equations and correlation coefficients between parameters - perennial ryegrass cultivar

Regression equation Dependent variable	 Independent variable	r
	Between uptake parameters	
AIUC	= 400.111 + 462.632Vmax - 14.670Km	0.959***
Vmax	= 6.357 + 0.216Cm	0.345*
Km	= 12.197 + 7.019Cm	0.850***
	Between field parameters	
DCG	= -16.042 + 0.163NC + 0.228DNR	0.987***
NC	= 51.663 - 0.117DNR	0.548***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 18. Significant regression equations and correlation coefficients between parameters - tall fescue cultivrs

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters and field parameters	
DCG	= 1.662 + 0.226Vmax	0.356*
DNR	= 60.243 + 9.277Vmax	0.427**
	Between uptake parameters	
AIUC	= 333.435 + 392.510Vmax - 9.187Km	0.985***
CUU	= 4.994 + 0.006AIUC	0.745***
Vmax	= 4.809 + 0.023Km	0.560***
Vmax	= 4.940 + 0.317Cm	0.612***
Km	= 9.167 + 10.187Cm	0.897***
	Between field parameters	
DCG	= 2.311- 0.064NC + 0.024DNR	0.995***
NC	= 45.821 - 0.045DNR	0.421**

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

MANUSCRIPT III

COMPARING CULTIVARS OF THREE COOL-SEASON TURFGRASSES FOR POTASSIUM UPTAKE KINETICS AND POTASSIUM RECOVERY IN THE FIELD

ABSTRACT

Soil potassium use by turf depends on the ability of roots to absorb a high proportion of the fertilizer potassium applied to the soil. Variation in K^+ absorption kinetics of roots among turfgrass genotypes and its inheritance is important in the development of genotypes that are more efficient in K^+ absorption from the soil. Therefore, in 1990 and 1991, field studies of six cultivars each of Kentucky bluegrass (*Poa pratensis* L), perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea* Schreb.) were conducted comparing clipping production rate, leaf blade potassium content, potassium recovery rate in clippings, potassium efficiency ratio and visual quality under a moderate potassium fertilization of 59 kg K ha^{-1} $year^{-1}$. Potassium uptake kinetics of the same cultivars were compared under greenhouse conditions by measuring Vmax, Km, Cm, CUU and AIUC. Significant differences between genera and cultivars were obtained for both absorption kinetics and field recovery of potassium. Significant correlations between some potassium uptake parameters and field performance were identified. These results show that for potassium utilization, genetic differences exist among turfgrasses at both the interspecific and intraspecific levels and suggest that a screening program could be developed to identify turfgrass genotypes possessing superior potassium utilization.

INTRODUCTION

Turfgrass growth requires a continuos flow of inorganic ions from the rooting medium into root cells. Potassium is the second most abundant element absorbed by turfgrass roots (Beard, 1973; Turner and Hummel Jr. 1992). There are clear indications that K^+ absorption by plants is under genetic control and that considerable differences exist both between and within genera (Glass, 1989; Barber, 1984).

Since Epstein and Hagen (1952) first applied Michaelis-Menten enzyme kinetics to ion transport, there have been many studies on ion uptake kinetics. Epstein et al., (1963) showed a biphasic pattern of K^+ uptake by barley (*Hordum vulgare* L.) roots which indicated that saturation was attained at a low external K^+ concentration (<0.5 mM), but at higher concentrations the curves appeared to reach a second level of saturation (>0.5 mM to 50 mM). In the low K^+ concentration range (<0.5 mM), a K^+ transport system with a high affinity for K^+ was hypothesized. Kochian and Lucas (1982) developed an experimental apparatus which enabled them to generate K^+ uptake data over an extended concentration range. They found that the curves describing K^+ transport into corn roots (*Zay mays* L.) approached linearity at concentrations above 1 mM and exhibited no tendency towards saturation at concentrations up to 50 mM. Now, it is generally accepted that K^+ transport exhibits saturation kinetics and is under the control of enzyme activity at low concentrations (<0.5 mM) (Jensen et al., 1987), while at higher K^+ concentrations, absorption increases linearly with external concentration exhibiting first order kinetics (Barber, 1984).

Turfgrass cultivar variation in K utilization was first reported by Mehall et al. (1983). They studied 15 Kentucky bluegrass cultivars and significant differences were identified in leaf blade K content and K efficiency ratio.

The only research indicating variation among turfgrass species for potassium uptake kinetics was conducted based on short-term (6 hr) solution depletion experiments with six grasses at low potassium concentration ($K^+ < 500\ \mu M$) (Cisar, 1986). Thus, variation in potassium uptake efficiency at both the species and cultivar levels remains poorly defined. There has been no information correlating the parameters of potassium uptake kinetics with potassium recovery by turfgrasses under field conditions.

It is important to identify the variation among turfgrass species and cultivars for their potassium uptake characteristics in order to achieve improved potassium use efficiency through proper turfgrass selection, and to breed turfgrasses with enhanced potassium absorption capacity.

The objectives of this study were to identify the variation among six cultivars each of three cool-season turfgrasses for potassium uptake kinetics under greenhouse conditions and to correlate this to field potassium recovery and growth under a moderate potassium fertilization.

MATERIALS AND METHODS

I. Potassium Uptake Kinetics

Kinetic parameters for K absorption were measured under greenhouse conditions using intact turfgrass cultures grown hydroponically in 1/4 strength Hoagland solution (Hoagland and Arnon, 1956). Six cultivars each of three species were chosen to represent various levels of performance as reported in the National Turfgrass Evaluation Program trials (Table 1).

The affinity for, and capacity of, a plant root to take up a specific ion was described by Epstein and Hagen (1952) based upon Michaelis-Menten saturation kinetics. The adjusted Michaelis-Menten equation was employed to describe the following relationship:

$$V = \frac{Vmax\ Co}{Km + Co}$$

where: V = rate of ion absorption (μmoles g^{-1} roots $hour^{-1}$);

Vmax = maximum rate of ion absorption at saturating concentration;

Co = external nutrient concentration;

Km = external nutrient concentration at half the maximum uptake rate.

The parameters Km and Vmax characterize the affinity for, and the capacity of, plant roots to acquire nutrients from their soil environment, respectively (Epstein, 1972). These kinetic parameters for potassium absorption by turfgrass roots were determined using a solution depletion procedure similar to that described by Claassen and Barber (1974). In this study, five parameters were obtained through the measurement of potassium uptake kinetics for each cultivar. They were Vmax, Km, Cm (the potassium concentration in the uptake solution at which no net uptake occurs) CUU (cumulative uptake µmole K g^{-1} root), and the integrated area under uptake curves (uptake rate against external potassium concentration) which is a dimensionless sum of potassium uptake during the entire uptake period termed Area Index of Uptake Curves - AIUC.

Four 5-cm diameter holes were cut in a plexiglass sheet (44 x 10 x 0.5 cm). A nylon mesh was glued to one side of the sheet to support germinating seeds within the holes. About 100 seeds were sown on the screen in each hole and the four seeded holes in a plexiglass sheet represented four replicates for one cultivar. After seeding, each plexiglass sheet was placed on wet silica sand. Mist was provided every ten minutes to keep the seeds and the sand moist. After grasses germinated, roots penetrated the nylon mesh and grew into the sand. No nutrients were provided during this initial germination period.

One week after germination, each plexiglass sheet contained four uniform cultures of seedlings. The sheets with seedlings were washed free of sand and suspended over a dark colored plastic tub containing 12 liters of 1/4 strength modified Hoagland nutrient solution (Hoagland and Arnon, 1956) (Table 2). The solution was continually aerated through thin plastic tubes throughout the growing period. The nutrient solution was replaced every four days. The pH of the solution was adjusted with 0.01 M $Ca(OH)_2$ or 0.01 M H_2SO_4 to pH 5.5 - 6.5 during the six week growing period. Day temperature of the greenhouse was maintained at 20 - 25 C and solution temperature 18 - 22 C. The incident radiation at 1200 hours ranged from 400 to 600 W m^{-2}.

Twenty-four hours prior to an uptake experiment, the nutrient solution was replaced with a potassium free modified Hoagland's solution. The roots of each culture were then suspended in individual beakers containing 500 ml of solution with a potassium concentration of 600 μM.

The K depletion analysis was based on that used by Cisar et al. (1986). The solution was sampled at 15 minute intervals over a 6 hour period. The solution was stirred before each 1-ml sample was taken and an equivalent volume of deionized distilled water was returned to the beaker following each sample removal to retain a constant volume. The decrease in solution K concentration during each sampling interval was used to determine the amount of K absorbed and this divided by the fresh root mass yielded a potassium absorption rate for each concentration.

Solution K was analyzed by atomic absorption spectrophotometry (Christain and Feldman, 1970). Depletion data were fit to a series of cubic equations and the potassium uptake rate calculated as the negative of the first derivative of the depletion curve. Vmax and Km values were estimated from a Lineweaver-Burk plot of these data (Bowman et al., 1989).

II. K Recovery by Field Grown Turf

A field experiment of the same six cultivars of each species used for uptake kinetic analysis was conducted to measure relative potassium recovery in clippings. The cultivars were part of National Turfgrass Evaluation Program trials established in 1986 and 1987 at the University of Rhode Island, Turfgrass Research Station, Kingston, Rhode Island. The plots were in a randomized complete block design with three replications. Individual plots of each cultivar were 2 x 1 m. The soil type was an Enfield silt loam (Coarse loamy over sandy skeletal, mixed, mesic, Typic Dytrochrept). All plots had received three K fertilizer applications of 17.6 kg K ha^{-1} annually (April, June and November) since establishment.

Biweekly clipping harvests were collected from May to October in 1990 and 1991. The plots were mowed twice weekly during the growing seasons without removal of clippings. A hand powered reel mower set at 3.8 cm mowing height with a collecting basket attached was used for clipping collection from a sampling area 0.48 by 1.5 m.

Clippings were oven dried for 48 hours at 75 °C, weighed and ground in a Wiley mill to pass a 40 mesh screen. Dry tissue samples of 500 mg were ashed in a muffle furnace at 475 C for 5 hours. The ash was dissolved in 5 ml of 0.3 M HCl, filtered, and K content determined using a Perkin Elmer 5000 atomic absorption spectrophotometer. For the growing seasons of 1990 and 1991, daily clipping growths (DCG), potassium content of clippings (KC) and daily potassium recovery in clippings (DKR) for each plot were obtained.

The plots were visually scored for turf quality each month during the growing seasons of 1990 and 1991 (visual quality: VQ). The score system used had values from 1 for totally brown turf to 9 for perfect turf. Quality was based upon uniformity, density, color and freedom from weeds and diseases.

III. Data Analysis

All statistical computations were conducted by using procedures within the Statistical Analysis System (SAS Institute Inc., 1990). Significant means based on ANOVA were separated by Duncan's Multiple Range Test for both potassium uptake parameters and field data. Simple linear correlation coefficients were obtained between uptake parameters and field data and a multiple regression procedure was used to quantify relationships among those parameters.

RESULTS

I. Potassium Uptake Kinetics

Significant differences were identified among the three genera for all parameters measured (Table 3). Similar to nitrate uptake kinetics, perennial ryegrasses exhibited the greatest Vmax for K absorption while Kentucky bluegrasses showed the least. No significant differences were found between perennial ryegrasses and tall fecues for Vmax, Cm and AIUC. A high Vmax for perennial ryegrasses was associated with a low Km value, a low Cm and a high AIUC. Kentucky bluegrass cultivars showed the opposite results. Tall fescues were intermediate in all values except CUU which was the greatest among the three grasses. The greatest variation was found in Cm values relative to other uptake parameters compared at the species level. Kentucky bluegrasses had a Cm value almost 20 times greater than perennial ryegrasses. The average Km for Kentucky bluegrasses was more than three fold that of perennial ryegrasses and almost two fold that of tall fescues, however, Kentucky bluegrass cultivars were only 53% of perennial ryegrasses and 60% of tall fescues in AIUC value. Tall fescues showed a 25% higher CUU value than the other two grasses (Table 3).

Kentucky bluegrass cultivars differed significantly in all parameters (Table 4). The cultivars exhibited the greatest variation in Vmax, 1.32 to 7.96 µmole K g^{-1} hr^{-1}, with a mean of 4.07 µmole K $g^{-1}hr^{-1}$. The Vmax value of 'Kenblue' was more than six fold that of 'Liberty'. Km values varied from 50.4 to 159.9 µM K^+ among the six cultivars. A ten fold variation in Cm values was found between "Eclipse' and 'Bristol'. Although 'Bristol' was only 29% of 'Kenblue' in AIUC value, it exhibited the greatest CUU value (Table 4).

The Vmax values of perennial ryegrass cultivars differed between 4.68 (Linn) and 9.22 (J207) with a mean value of 6.63 μmole K g^{-1} hr^{-1} (Table 5). The Km values varied 11 fold between 'Derby' 5.03 and 'Linn' 57.71 μM K^+. 'PST-2PM' and 'J207' had identical Cm values of 2.91 μM K^+, about six fold greater than that of 'Derby'. The AIUC values of 'J207' and 'J208' differed only by 56% while 'Derby' exhibited the greatest CUU value of 21.72 μmole K g^{-1} of root (Table 5).

Tall fescue cultivars exhibited a variation in Vmax values from 3.54 to 6.82 μmole K^+ g^{-1} hr^{-1} with a mean value of 5.80 (Table 6). Similar to perennial ryegrass, less than a two fold difference was found between the highest, 'Falcon' and the lowest, 'Rebel II'. The greatest variation in Km was found among tall fescue cultivars, ranging from 2.07 to 90.63 μM K^+ for a 43 fold difference. A more than 147 fold difference in Cm was found between 'Jaguar' and 'PST-5AG'. The AIUC for 'Rebel II' was only 42% of that for 'Jaguar' but 'Rebel II' exhibited the greatest CUU value (Table 6).

II. Field Performance

Significant differences in daily clipping growth (DCG), potassium content (KC) in clippings and daily K recovery rate (DKR) were identified among the three turfgrass genera (Table 7). Both tall fescue and Kentucky bluegrass exhibited a greater DCG than perennial ryegrass. KC values differed significantly among the three turfgrass genera but only by 7%. Perennial ryegrass had the highest KC while Kentucky bluegrass had the lowest. DKR was calculated based on DCG and KC and it exhibited significant differences among the three genera with perennial ryegrass being only 79% of tall fescue.

With the exception of leaf K concentration, significant differences in K recovery parameters were identified among perennial ryegrass cultivars (Table 8). 'Tara' was only 66% of 'Linn' in DCG value while 'Linn' was the poorest grass in visual quality. DKR appeared to have a similar variation pattern as DCG with 'Tara' being about 70% of the highest 'Linn' (Table 8).

Kentucky bluegrass cultivars differed significantly in all measured or calculated parameters for K recovery (Table 9). Both 'Kenblue' and 'Joy' were of significantly lower visual quality but they showed the two highest DCG values. 'Blacksburg' had the least DCG, only about 59% of 'Kenlue' but it had the highest visual quality of 7.7. 'Eclipse' alone exhibited a higher KC value. DKR values differed significantly among the cultivars ranging from 57.27 ('Blacksburg') to 97.55 ('Kenblue') mg K m^{-2} day^{-1} (Table 9).

Tall fescue cultivars showed significant differences in DCG, DKR and visual quality but not in KC (Table 10). 'Falcon' had the poorest visual quality score but it exhibited the highest DCG value. 'PST5' had the lowest DCG value, about 62% of 'Falcon', while it showed an acceptable visual quality. Similar to perennial ryegrass, KC value for tall fescue varied by 4% which was not significant. The greatest DKR value for 'Falcon' was 40% higher than that for 'PST5'. Visual quality score differences among the cultivars ranged from 5.5 to 6.9 (Table 10).

III. Correlation Analysis

Correlation coefficients between K uptake parameters and field measurements at the species level are presented in Table 11. Vmax was positively correlated with clipping potassium content (KC) but showed no relationship to DCG or visual quality. Km was positively correlated with both DCG and DKR but negatively correlated with KC. A negative correlation was also found between Cm and KC. AIUC was the only uptake parameter significantly correlated with K recovery in clippings. It was a positively correlated with KC but was negatively correlated with the other parameters. Cumulative K uptake (CUU) exhibited no significant correlations with field recovery of K (Table 11). Two significant regression models were identified between uptake parameters and field measurements (Table 15). Three significant regression models among uptake parameters and two among field measurements are also presented in Table 15.

Only two negative correlations (between KC and Km; between KC and Cm) and a positive correlation between CUU and visual quality were identified among Kentucky bluegrass cultivars (Table 12). No significant regression models were identified between uptake parameters and field measurements. Two significant regression models among uptake parameters and one model among field measurements were found to be significant (Table 16).

Two positive correlations between visual quality and Vmax, and between visual quality and CUU were identified among perennial ryegrass cultivars. The other significant correlation identified was negative between Km and visual quality (Table 13). Two significant regression models among uptake parameters and one model among field measurements were identified (Table 17).

More significant correlations were identified between tall fescue K uptake parameters and field recovery of K (Table 14). DCG exhibited a positive correlation with Km and a negative correlation with AIUC. KC had a negative correlation with both Km and Cm but a positive correlation with AIUC. DKR showed a positive correlation with Km, AIUC and CUU. Visual quality was positively correlated only with CUU (Table 14).

Four significant regression models between uptake parameters and field measurements, three models among uptake parameters and one model among field measurements were identified (Table 18).

DISCUSSION

There were substantial differences among turfgrasses in potassium uptake which appear to be genetically based (Tables 3 to 6). Similar cultivar differences in K^+ uptake properties have been observed in crop species, e. g. barley (Glass and Perley, 1980), wild oats (*Avena fatua* L.) (Siddiqi et al., 1987), wheat (*Triticum aestivum* L.) (Woodend et al., 1987), and corn (Baligar and Barber, 1979). Potassium was one of the first ions used in studying ion-absorption mechanisms in plant roots (Barber, 1984). However, very few publications focused on turfgrasses. These results suggest that a screening program could be developed to identify turfgrass cultivars or species having superior potassium utilization characteristics.

Provided with a proper potassium supply under normal field conditions, a grass with a greater Vmax, a lower Km, a lower Cm and a greater AIUC is ideally suited for efficient K absorption. At the species level, perennial ryegrasses had such a beneficial combination of K uptake parameters and a greater KC was identified as well during the field study (Tables 2 and 7). At the cultivar level, cultivars with greater K uptake efficiency and field K recovery were 'Kenblue' and 'Eclipse' Kentucky bluegrass, 'Linn' perennial ryegrass and 'Falcon', and 'Jaguar' tall fescue (Tables 4 to 10). In this study as in others (Liu, 1992), a greater Vmax was not always associated with a lower Km and a lower Cm for most grasses (Tables 3 to 6). In such cases, AIUC may be a more useful parameter demonstrating K uptake efficiency.

Vmax is positively influenced by external K concentrations (Kochian and Lucas 1982a; Barber, 1984). Under most field conditions, soil solution K concentration is highly variable (Barber, 1984). Potassium uptake normally occurs via the saturable system even through the K concentration may be as high as 30 to 50 mM when a K fertilizer is applied (Barber, 1984). Under field conditions, even at high maintenance, turfgrasses may not always be under appropriate optimal nutrient conditions. Under K deficient conditions, a grass with a lower Km and Cm may suffer less stress (Barber, 1984; Glass, 1980).

Comparisons of K uptake kinetics indicate that greater variations at both the species and cultivar levels occurred in Km and Cm rather than Vmax which agree with the results of other crops or turfgrasses (Glass, 1980; Siddiqi et al., 1987; Cisar, 1986). This may imply that genetic improvement in K stress tolerance of turfgrasses could be rewarding since soil solution K concentration ranges from 1.5 to 5.5 ppm (38 μM to 141 μM) based on an analyses of water samples taken from the same soil used in this study. Consequently, most turfgrasses absorb K^+ at rates equal to half of their Vmax or lower.

Genotypic variation among turfgrasses for nutritional requirements and efficiency of nutrient utilization exists (Cisar, 1986; Liu, 1992). However, identification of specific physiological mechanisms and morphological features which contribute to this variation is very limited. In general, tall fescue has a deeper and larger root mass than perennial ryegrass and Kentucky bluegrass. Kentucky bluegrass is generally considered to be a turfgrass demanding high fertility (Turgeon, 1985). The results of this K^+ uptake analyses showed that perennial ryegrass had almost a two fold greater AIUC than Kentucky bluegrass (Table 3). This was the result of a higher average of Vmax and lower Km for perennial ryegrass cultivars.

Besides K^+ absorption, K^+ distribution and utilization may also under genetic control (Baligar and Duncan, 1990) and result in significant variation in the K content of clippings among turfgrasses. In the field study, entire plants were not analyzed. However, clippings represent currently growing tissues which reflect the nutrient status of the entire grass plant (Mehall et al., 1983; Cisar, 1986). Potassium content in leaves varied only from 30.6 to 34.1 mg g^{-1} for all cultivars and no significant differences were identified among cultivars of perennial ryegrass or tall fescue (Tables 7 to 10). By comparison, the range of K content in leaves of Kentucky bluegrass was greater than that reported by Mehall et al. (1983) but only the cultivar 'Kenblue' was common to both studies. Monroe et. al (1969) demonstrated that leaf K content of Kentucky bluegrass cultured in sand varied five fold (1.0 to 4.8 % dry weight basis) when receiving solutions containing K at 0 - 400 mg L^{-1}. The field results of this study were the average of 25 clipping collections in 1990 and 1991.

Significant correlations between some K uptake parameters and K recovery in clippings were identified at the species level and among cultivars of Kentucky bluegrass and tall fescue (Tables 11 - 18). For all grasses except perennial ryegrass, a negative correlation between leaf K content and Km was noted. Similarly leaf K content and Cm were also negatively correlated. This would be expected if a high affinity between K and the ion carrier of the root (low Km) resulted in a low soil water K content (low Cm) and a greater K level within the grass (higher KC). The lack of more positive correlations between Vmax and K content of leaves might indicate that the turfgrasses rarely were growing at soil K levels that approached their Vmax values. At such K concentrations, uptake by roots is more influenced by K affinity for its transport carrier than by the uptake rate at saturating concentrations.

The few significant correlations between K uptake parameters and daily clipping yield or K recovery are not surprising. Clipping yields and K recovery are influenced by many factors besides the absorption properties of the roots. Grasses having an upright leaf growth pattern will lose more leaf mass during mowing than grasses exhibiting more procumbant growth. Such grasses will display a greater daily clipping yield and K recovery independently of K absorption. The extent of K transport to shoots and partitioning into leaves will also influence clipping recovery but may be unrelated to K uptake properties of the roots. For these reasons, it is surprising that significant correlations between K absorption and clipping yields or daily K recovery in clippings were observed as often as they were (Tables 15 - 18). Such correlations reinforce the thesis that nutrient uptake parameters may be useful selection criteria for improving the nutrient use efficiency of turfgrasses.

Significant correlations were identified at the species level and among Kentucky bluegrass and tall fescue cultivars for some K uptake parameters and some field recovery measurements (Tables 11 to 18). Except for perennial ryegrass cultivars, a negative correlation was identified between KC and Km and between KC and Cm. A positive correlation between AIUC and KC was identified at the species level and among tall fescue cultivars. These results suggest that a greenhouse screening program could be developed to predict K utilization efficiency under field conditions.

CONCLUSION

The following are conclusions from this study of comparison of three cool season turfgrasses in K uptake efficiency and K recovery in clippings:

1. Genetic variation exists among certain cool-season turfgrasses at both the species and cultivar levels in K uptake efficiency and K recovery in clippings.

2. A screening program could be developed to further identify K use characteristics of cool-season turfgrasses which can contribute to current breeding programs.

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Table 1. Cultivars selected for potassium utilization studies

Kentucky Bluegrass	Perennial ryegrass	Tall fescue
BLACKSBURG	DERBY	ARID
BRISTOL	J207	FALCON
ECLIPSE	J208	JAGUAR
JOY	LINN	PST-5AG
KENBLUE	PST-2PM	REBEL II
LIBERTY	TARA	SYN GA

Table 2. Concentrations of essential nutrients in the solution used to grow grasses hydroponically.

NO_3	PO_4	K	Ca**	SO_4	Mg	Fe*	Zn	Cu	Cl	B	Mo	Mn
mM							μM					
3.75	0.25	1.5	1.25	0.5	0.5	40	0.44	0.06	1.0	1.8	0.03	1.3

*: Fe was added as Sequestrene Fe-330

**: Ca values were approximate. pH was adjusted with $Ca(OH)_2$.

Table 3. Comparison of three species for potassium uptake parameters: Vmax, Km, Cm, AIUC and CUU (N = 24 for each species)

Species	Vmax	Km	Cm	AIUC	CUU
	µmole K g^{-1} hr^{-1}	µM	µM		µmole K g^{-1} root
Perennial ryegrass	6.63a*	26.62c	1.74b	3368a	15.03b
Tall fescue	5.80a	57.18b	8.17b	2991a	20.07a
Kentucky bluegrass	4.07b	96.30a	33.71a	1802b	15.45b

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 4. Comparison of six cultivars of Kentucky bluegrasses for potassium uptake parameters: Vmax, Km, Cm, AIUC and CUU (N = 4 for each cultivar)

Cultivar	Vmax	Km	Cm	AIUC	CUU
	μmole K g^{-1} hr^{-1}	μM	μM		μmole K g^{-1} root
Kenblue	7.96a*	62.54bc	14.34b	2665a	10.59c
Eclipse	5.53b	50.38c	10.12b	2133a	14.36bc
Blacksburg	4.44bc	121.25ab	34.39b	1419ab	18.19ab
Bristol	3.02cd	159.89a	100.88a	774b	22.53a
Joy	2.18d	56.73c	19.20b	2168a	10.93c
Liberty	1.32d	127.03a	23.29b	1717ab	16.10abc

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 5. Comparison of six cultivars of perennial ryegrass - potassium uptake parameters: Vmax, Km, Cm, AIUC and CUU (N = 4 for each cultivar)

Cultivar	Vmax	Km	Cm	AIUC	CUU
	μmole K g^{-1} hr^{-1}	μM	μM	μmole K g^{-1} root	
Linn	9.22a*	57.71a	2.38ab	3749ab	10.09c
J208	7.09ab	20.99ab	0.54b	4191a	11.96bc
Tara	7.05ab	17.89b	1.22ab	3952ab	17.13ab
Pst-2PM	6.61b	25.68ab	2.91a	3150abc	17.10ab
Derby	5.15b	5.03b	0.50b	2806bc	21.72a
J207	4.68b	32.4ab	2.91a	2357c	11.58ab

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 6. Comparison of six cultivars of tall fescue for potassium uptake parameters: Vmax, Km, Cm, AIUC and CUU (N = 4 for each cultivar)

Cultivar	Vmax	Km	Cm	AIUC	CUU
	μmole K g^{-1} hr^{-1}	μM	μM		μmole K g^{-1} root
Falcon	6.82a*	90.63b	4.05b	3124ab	20.95a
Jaguar	6.31a	2.07d	0.24b	4119a	22.20a
Pst-5AG	6.30a	176.91a	35.46a	2315bc	21.73a
Syn GA	6.25a	15.08cd	0.69b	3118ab	16.37b
Arid	5.04ab	10.17cd	5.39b	3244ab	16.55b
Rebel II	3.54b	45.20c	1.51b	1748c	23.48a

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 7. Comparison of three turfgrass species for field recovery of K - average of May to October for 1990 and 1991

Species	Daily clipping yield (DCG)	Clipping K content (KC)	Daily K recovery (DKR)
	g K m^{-2} day^{-1}	mg K g^{-1}	mg K m^{-2} day^{-1}
Tall fescue	2.68a*	32.24b	85.90a
Kentucky bluegrass	2.52a	31.25c	76.59b
Perennial ryegrass	2.01b	33.60a	67.80c

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 8. Comparison of field recovery of K for six cultivars of perennial ryegrass - average of May to October for 1990 and 1991

Cultivar	Daily clipping yield (DCG)	Clipping K content (KC)	Daily K recovery (DKR)	Visual quality (VQ)
	g K m^{-2} day^{-1}	mg K g^{-1}	mg K m^{-2} day^{-1}	
Linn	2.26a*	33.48	76.02a	4.2c
J207	2.24ab	34.06	76.01a	6.5ab
Pst-2PM	2.13ab	32.78	71.81ab	6.1b
Derby	2.02ab	33.36	67.04ab	6.3ab
J208	1.93ab	34.01	64.42ab	6.2ab
Tara	1.50b	33.92	52.88b	6.7a

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 9. Comparison of field K recovery by six cultivars of Kentucky bluegrass - average of 1990 and 1991 from May to October

Cultivar	Daily clipping yield (DCG)	Clipping K content (KC)	Daily K recovery (DKR)	Visual quality (VQ)
	g m^{-2} day^{-1}	mg g^{-1}	mg m^{-2} day^{-1}	
Kenblue	3.24a*	31.21b	97.55a	5.4b
Joy	2.67ab	30.88b	80.27ab	5.3b
Bristol	2.65ab	30.59b	79.67ab	6.9a
Eclipse	2.45bc	32.73a	78.84ab	7.6a
Liberty	2.20bc	31.04b	65.83bc	7.0a
Blacksburg	1.91c	31.01b	57.27c	7.7a

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 10. Comparison of field K recovery by six cultivars of tall fescue - average of May to October for 1990 and 1991

Cultivar	Daily clipping yield (DCG)	Clipping K content (KC)	Daily K recovery (DKR)	Visual quality (VQ)
	g K m^{-2} day^{-1}	mg K g^{-1}	mg K m^{-2} day^{-1}	
Falcon	3.05a*	32.50	100.63a	5.9c
Jaguar	3.01a	32.69	97.16a	6.9a
Arid	2.93a	32.24	93.37ab	6.2bc
Rebel II	2.84a	32.32	91.66ab	6.9a
Syn GA	2.36ab	31.49	72.24bc	5.5d
Pst-5AG	1.90b	32.23	60.92c	6.4b

* Values in a column followed by the same letter are not different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 11. The correlation coefficients between potassium uptake kinetic parameters and field performances based on the average results of 1990 and 1991 for all grasses.

Uptake parameter	Daily clipping yield (DCG)	Clipping potassium content (KC)	Daily potassium recovery (DKR)
Vmax	-0.05	0.290**	0.001
Km	0.326***	-0.574***	0.264*
Cm	0.147	-0.467***	0.083
AIUC	-0.275**	0.513***	-0.218*
CUU	0.051	0.017	0.088

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 12. The correlation coefficients between potassium uptake kinetic parameters and field performances based on the average results of 1990 and 1991 - Kentucky bluegrass

Uptake parameter	Daily clipping yield (DCG)	Clipping potassium content (KC)	Daily potassium recovery (DKR)	Visual quality (VQ)
Vmax	0.017	0.136	0.017	0.094
Km	0.171	-0.468**	0.208	0.337
Cm	0.114	-0.398*	0.097	0.172
AIUC	-0.010	0.279	-0.010	-0.318
CUU	-0.293	-0.285	-0.302	0.377*

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 13. The correlation coefficients between potassium uptake kinetic parameters and field performances based on the average results of 1990 and 1991 - Perennial ryegrass

Uptake parameter	Daily clipping yield (DCG)	Clipping potassium content (KC)	Daily potassium recovery (DKR)	Visual quality (VQ)
Vmax	0.070	0.083	0.090	0.575***
Km	0.199	-0.053	0.205	-0.572***
Cm	-0.082	-0.034	-0.076	-0.212
AIUC	-0.155	0.050	-0.162	-0.148
CUU	-0.101	0.110	-0.076	0.342*

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 14. The correlation coefficients between potassium uptake kinetic parameters and field performances based on the average results of 1990 and 1991 - Tall fescue

Uptake parameter	Daily clipping yield (DCG)	Clipping potassium content (KC)	Daily potassium recovery (DKR)	Visual quality (VQ)
Vmax	0.020	0.195	0.020	0.305
Km	0.595***	-0.546***	0.570***	0.024
Cm	0.214	-0.551***	0.152	0.041
AIUC	-0.510**	0.607***	0.486**	0.062
CUU	0.294	0.228	0.401*	0.512**

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 15. Significant regression equations and correlation coefficients between K absorption and field recovery for all grasses.

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters and field parameters	
DCG	= 2.51 + 0.0055Km	0.391*
KC	= 31.06 - 0.018Km	0.634***
	Between uptake parameters	
AIUC	= 1361.550 + 311.34Vmax - 8.760Km	0.825***
Vmax	= 1.040 + 0.190Km	0.769***
Km	= 36.560 + 1.076Cm	0.798***
	Between field parameters	
DCG	= 3.92 - 0.095KC + 0.032DKR	0.993***
KC	= 52.51 - 0.389VQ.	0.946***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 16. Significant regression equations and correlation coefficients between K uptake parameters and field K recovery by Kentucky bluegrass cultivars

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters	
AIUC	= 2341.570 + 111.140Vmax	0.764*
Km	= 44.750 + 0.744Cm	0.833***
	Between field parameters	
DCG	= 5.665 - 0.115KC + 0.034DKR	0.997***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 17. Significant regression equations and correlation coefficients between K uptake parameters and field K recovery by perennial ryegrass cultivars

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters	
AIUC	= 761.308 + 546.790Vmax - 27.290Km	0.878***
Km	= 12.197 + 7.019Cm	0.850***
	Between field parameters	
DCG	= 1.045 - 0.037KC + 0.307DKR + 0.040VQ.	0.994***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 18. Significant regression equations and correlation coefficients between K uptake parameters and field K recovery by tall fescue cultivars.

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters and field parameters	
DCG	= 3.320 + 0.137Km	0.750*
KC	= 21.796 + 0.002AIUC	0.827***
DKR	= 80.080 + 0.396Km - 1.032Cm	0.762**
VQ	= 4.829 + 0.077CUU	0.649*
	Between uptake parameters	
AIUC	= 484.560 + 449.330Vmax - 11.500Km	0.875***
Vmax	= 1.701 + 0.023Km - 0.038Cm + 0.002AIUC	0.866*
Km	= -53.049 + 22.730Vmax - 0.040AIUC + 3.950CUU	0.913**
	Between field parameters	
DCG	= 1.72 + 0.030DKR	0.992***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

MANUSCRIPT IV

COMPARING CULTIVARS OF THREE COOL-SEASON TURFGRASSES FOR PHOSPHATE UPTAKE KINETICS AND PHOSPHORUS RECOVERY IN THE FIELD

ABSTRACT

Phosphorus is an important nutrient in turfgrass culture and many soils do not contain sufficient available P to maximize turfgrass growth . Although P is generally required in substantially smaller amounts than either nitrogen or potassium, wide ranges in tissue P have been reported in turfgrasses. Variation in P absorption kinetics of roots among turfgrass genotypes and its inheritance are important in development of genotypes that are more efficient in P absorption. Therefore, in 1990 and 1991, field studies of six cultivars each of Kentucky bluegrass (*Poa pratensis* L), perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea* Schreb.) were conducted comparing clipping production rate, leaf blade P content, P recovery rate in clippings, and visual quality under a moderate P fertilization rate of 37 kg ha^{-1} $year^{-1}$. Phosphorus uptake kinetics of the same cultivars were compared under greenhouse conditions by measuring: Vmax, Km, Cm, CUU and AIUC. Significant differences between genera and cultivars were observed for both absorption kinetics and field recovery of P. Significant correlations between some P uptake parameters and field performance were identified. These results indicate that genetic differences in P absorption may exist among turfgrasses at both the interspecific and intraspecific levels and further suggest that studies involving larger numbers of turfgrass cultivars are needed to assess the full range in P use efficiency.

INTRODUCTION

Phosphorus is an important nutrient for turfgrass management and many soils contain insufficient available P to maximize turfgrass growth (Beard. 1973; Turgeon, 1985; Turner and Hummel Jr. 1992). Although turfgrasses generally required substantially smaller amounts of P than either nitrogen or potassium, wide ranges of tissue P have been reported in turfgrass clippings (Turner and Hummel Jr. 1992).

Waddington and Zimmerman (1972) reported that leaf tissue P ranged from 5.3 to 7.6 mg g^{-1} dry weight among four turfgrass genera (*Poa, Agrostis, Festuca* and *Lolium*). Butler and Hodges (1967) found that the mean difference in tissue P between 'Meyer' zoysiagrass (*Zoysia japonica* Steud.) and 'Kentucky 31' tall fescue was 3 mg g^{-1} dry weight. Cultivar variation in tissue P was first reported for a turfgrass by Mehall et al. (1983). They found that the tissue P of 15 Kentucky bluegrass cultivars ranged from a low of 1.0 to a high of 4.4 mg g^{-1} dry weight during a 1-yr. period.

Phosphate absorption by plant roots has been investigated using excised roots or those of intact plants grown in nutrient solution culture (Barber, 1984; Glass, 1989). Phosphate uptake over a concentration range of 0 to 300 μM can be described by Michaelis-Menten kinetics (Barber, 1984). Differences in P absorption were identified among several crop species (Asher and Loneragan, 1967; Clark, 1983; Barber, 1984; Fohse et al., 1988). Diversity in P uptake and use among cultivars within a plant species has also been recognized for many years (Clark, 1983; Barber, 1984; Gerloff and Gableman, 1983). Differences in P absorption were noted among genotypes of corn (Clark and Brown, 1974; Baligar and Barber, 1979), bean (*Phaseolus vulgaris* L.) (Lindgren, et al., 1977) sorghum (*Sorghum bicolor* L.) (Clark et al., 1978), white clover

(*Trifolium repens* L.) (Caradus, 1983) and barley (*Hordunm vulgare* L.) (Nielsen and Schjorring, 1983).

The only research measuring variation among turfgrass species for P uptake kinetics was conducted based on short-term (6 hr) solution depletion experiments at low P concentration ($P < 100\ \mu M$) (Cisar, 1986). However, variation in P uptake efficiency at both the species and cultivar levels remains poorly defined. There also is no information correlating parameters of P uptake kinetics and P recovery by turfgrasses grown under field conditions.

It is important to identify variation among turfgrass species and cultivars for their characteristics of P uptake and utilization under field conditions in order to minimize the probability of excess P fertilization, to maximize P use efficiency through proper turfgrass selection, and to breed turfgrasses with enhanced P absorption capacity.

The objectives of this study were to identify the variation in P uptake kinetics among six cultivars of each of three cool-season turfgrasses and to correlate these with P recovery and growth in the field under moderate P fertilization.

MATERIALS AND METHODS

I. Phosphorus Uptake Kinetics

Parameters for P uptake kinetics were measured under greenhouse conditions using intact turfgrass cultures grown hydroponically in 1/4 strength Hoagland solution (Hoagland and Arnon, 1956). Six cultivars each of three species were chosen to represent various levels of performance as reported in the National Turfgrass Evaluation Program trials (Table 1).

The affinity for, and capacity of, a plant root to take up a specific ion was described by Epstein and Hagen (1952) based upon Michaelis-Menten saturation kinetics. The adjusted Michaelis-Menten equation was employed to describe the following relationship:

$$V = \frac{Vmax\ Co}{Km + Co}$$

where: V = rate of ion absorption (μmoles g^{-1} roots hour^{-1});
Vmax = maximum rate of ion absorption at saturating concentrations;
Co = external nutrient concentration;
Km = external nutrient concentration supporting half the maximum uptake rate.

The parameters Km and Vmax characterize the ability of plant roots to acquire nutrients from their soil environment (Epstein, 1972). These kinetic parameters for P absorption by turfgrass roots were determined using a solution depletion procedure similar to that described by Claassen and Barber (1974). In this study, five parameters were obtained by measuring P uptake kinetics for each cultivar. The parameters were Vmax, Km, Cm (the P concentration in the uptake solution at which no net uptake occurs), CUU (cumulative uptake of P μmole g^{-1} root), and the integrated area under uptake curves (uptake rate against external P concentration) which is a dimensionless sum of P uptake during the entire uptake period termed Area Index of Uptake Curve - AIUC.

Four 5-cm diameter holes were cut in a plexiglass sheet (44 x 10 x 0.5 cm). A nylon mesh was glued to one side of the sheet to support germinating seeds within the holes. About 100 seeds were sown on the screen in each hole and the four holes represented four replicates for one cultivar. After seeding, each plexiglass sheet was placed on wet silica sand. Mist was provided every ten minutes to keep the seeds and the sand moist. During germination, roots penetrated the nylon mesh and grew into the sand. No nutrients were provided during this initial germination period.

One week after germination, each plexiglass sheet contained four uniform cultures of seedlings. The sheets with seedlings were washed free of sand and suspended over a dark colored plastic tub containing 12 liters of 1/4 strength modified Hoagland nutrient solution (Hoagland and Arnon, 1956). The solution was continually aerated with compressed air delivered through thin plastic tubes. The nutrient solution was replaced every four days and its pH was adjusted with 0.01 M $Ca(OH)_2$ or 0.01 M H_2SO_4 to pH 5.5 - 6.5 during the six week growing period. Day temperature of the greenhouse was maintained at 20 - 25 °C and solution temperature at 18 - 22 °C. The night temperature was maintained about 5 degrees lower than the day temperature. The incident radiation at 1200 hours ranged from 400 to 600 W m^{-2}.

Twenty-four hours prior to an uptake experiment, the nutrient solution was replaced with a P free modified Hoagland's solution. After that, the roots of each culture were emerged in individual beakers containing 500 ml solution having a phosphate concentration of 100 μM to carry out the P uptake experiments.

The P depletion analysis was based on that of Cisar et al. (1986). The solution was sampled at 15 minute intervals over a 6 hour period. The solution was stirred before each 1-ml sample was taken and an equivalent volume of deionized distilled water was returned to the beaker following each sample removal to retain a constant volume. The decrease in solution P concentration during each sampling interval was used to determine the amount of P absorbed and this divided by the fresh root mass yielded the P absorption rate.

Depletion data were fit to a series of cubic equations and the P uptake rate calculated as the negative of the first derivative of the depletion curve. Vmax and Km values were estimated from a Lineweaver-Burk plot of these data (Bowman et al., 1989).

II. P Recovery by Field Grown Turf

A field experiment of the same six cultivars of each species used for kinetic uptake analysis was conducted to measure relative P recovery in clippings. The cultivars were part of National Turfgrass Evaluation Program Trials established in 1986 and 1987 at Turfgrass Research Station, the University of Rhode Island, Kingston, Rhode Island. Plots were in a randomized complete block design with three replications. Individual plots of each cultivar were 2 x 1 m. The soil type was an Enfield silt loam (Coarse loamy over sandy skeletal, mixed, mesic, Typic Dytrochrept). All plots received three P fertilizer applications of 12.3 kg P ha^{-1} annually (April, June and November) since establishment.

Biweekly clipping harvests were collected from May to October in 1990 and 1991. Plots were mowed twice weekly throughout the growing seasons without removal of clippings. A hand powered reel mower set at 3.8 cm cutting height with a collecting basket attached was used for clipping collection from a sampling area 0.48 by 1.5 m.

Clippings were oven dried for 48 hours at 75 °C, weighed and ground in a Wiley mill to pass a 40 mesh screen. Dry tissue samples of 500 mg were ashed in a muffle furnace at 475 °C for 5 hours. The ash was dissolved in 5 ml of 0.3 M HCl and filtered. The P content was determined using the method of molybdate blue and assayed in a spectrophotometer (Murphy and Riley, 1962). For the growing seasons of 1990 and 1991, daily clipping growths (DCG), P content of clippings (PC), and daily P recovery in clippings (DPR) for each plot were calculated.

Plots were visually scored for turf quality each month during the 1990 and 1991 growing seasons (visual quality: VQ). Scores ranged from 1 for totally brown turf to 9 for perfect turf. Quality was based upon uniformity, density, color and freedom from weeds and diseases.

III. Data Analysis

All statistical computations were conducted by using procedures within the Statistical Analysis System (SAS Institute Inc., 1990). Significant means based on ANOVA were separated by Duncan's Multiple Range Test for both P uptake parameters and field data. Simple correlation coefficients between P uptake parameters and field recovery of P in clippings were obtained and quantified by multiple regression procedures.

RESULTS

I. Phosphorus Uptake Kinetics

Significant differences were identified among the three genera for all parameters measured except Vmax value (Table 3). Similar to NO_3^- and K^+ uptake kinetics, perennial ryegrasses exhibited the highest Vmax value for P absorption while tall fescues had the lowest. Kentucky bluegrass cultivars showed the greatest AIUC and CUU values. Tall fescues exhibited the lowest values of all parameters except CUU which was greater than that of perennial ryegrass but not significantly different from Kentucky bluegrasses. Greater variation was found in Cm values than in other uptake parameters at the species level. Perennial ryegrasses had a Cm value almost 3 fold of that tall fescues. Both Kentucky bluegrass and perennial ryegrass exhibited similar Km values which were about 30% greater than that of tall fescues. Kentucky bluegrasses showed a 25% higher AIUC value than tall fescues (Table 3).

Kentucky bluegrass cultivars only differed significantly in AIUC and CUU values (Table 4). About two fold AIUC variation and more than three fold CUU variation were found among the six cultivars. The AIUC value for 'Liberty' was 47% less than that of 'Eclipse', it showed the greatest CUU value of 7.17 μmole P g^{-1} root . Cultivars of KB showed a variation in Vmax values from, 0.89 to 1.34 μmole P g^{-1} hr^{-1}, with a mean value of 1.15 μmole P $g^{-1}hr^{-1}$. Km values varied from 14.70 to 29.93 μM [$H_2PO_4^-$] among the Kentucky bluegrass cultivars and the least Km value was never lower than 14% of the initial solution concentration of 100 μM. Although a 3.7 fold variation of Cm values was found between 'Blacksburg' and 'Eclipse', differences were not significant (Table 4).

Km and CUU were the only two parameters found significantly different among perennial ryegrass cultivars (Table 5). Km value varied from 15.44 to 24.37 µM $H_2PO_4^-$ among the cultivars with a mean of 19.83 µM which was about 20% of the initial concentration. The cultivars differed in CUU which ranged from 1.95 to 3.59 µmole P g^{-1} root. The Vmax values of perennial ryegrass cultivars ranged between 1.10 and 1.75 µmole P g^{-1} hr^{-1} with a mean value of 1.44 µmole P g^{-1} hr^{-1}. Cm value was never higher than 7.30 µM which was about 3 fold that of the least of 2.34 µM. Although 'J208' exhibited the greatest AIUC value which was about 62% greater than the least 'PST-2PM', no significant differences were identified (Table 5).

No significant differences were identified among tall fescue cultivars for any phosphate uptake parameter except CUU (Table 6). CUU varied from 5.37 to 2.67 µmole P g^{-1} root among the six cultivars. Tall fescue cultivars exhibited a range in Vmax values from 0.91 to 1.55 with a mean value of 1.11 µmole P g^{-1} hr^{-1}. Km value ranged from 8.75 of 'Jaguar' to 15.21 µM $H_2PO_4^-$ for 'Apache'. More than a two fold variation was found among the cultivars in Cm value. The greatest AIUC value of 'Jaguar' was 50% more than the least of 'Apache'(Table 6).

II. Field Performance

Significant differences in daily clipping growth (DCG), P content (PC) in clippings, and daily P recovery rate (DPR) were identified among the three genera (Table 7). Since visual quality was scored by comparison within species, the comparison between species was not valid. The three genera exhibited a significant variation in DCG value which ranged from 2.01 to 2.95 g dry clipping tissue m^{-2} day^{-1}. PC values differed significantly among the three turfgrass genera and they ranged from 3.73 to 4.72 mg g^{-1} which differed by about 20%. DCG and PC varied inversely among the three genera.

DPR was calculated based on DCG and PC and exhibited significant differences between tall fescue and perennial ryegrass. Kentucky bluegrass was not significantly different from either. DPR by perennial ryegrass was 84% that of tall fescue while its PC value was 20% greater than that of tall fescue (Table 7).

Significant differences were identified among perennial ryegrass cultivars except for PC value. The cultivars showed only a 5% variation in PC. DCG of 'Tara' was only 66% of 'Linn' while 'Linn' was the poorest grass in visual quality. DPR appeared to have a similar variation pattern to DCG and 'Tara' was significantly less than 'Linn' and 'J207' (Table 8).

Kentucky bluegrass cultivars differed significantly in all measured or calculated parameters (Table 9). Both 'Kenblue' and 'Joy' had a lower visual quality but they showed the two greatest DCG values. 'Blacksburg' exhibited the least DCG, only about 59% of 'Kenblue', but it had the highest visual quality of 7.7 based on 1 to 9 scale and the lowest PC value which differed significantly from the other cultivars. DPR ranged between 7.21 and 12.28 mg P m^{-2} day^{-1} and followed the trend of DCG (Table 9).

No significant differences were identified among tall fescue cultivars in clipping yield and P recovery in clippings. Visual quality was the only parameter found to differ significantly among the six cultivars. 'KY31' had a poor visual quality score but it had the greatest DCG and DPR. DCG value ranged from 2.76 to 3.11 g dry clipping tissue m^{-2} day^{-1}. PC value varied within 4% of the greatest PC value. The greatest DPR value of 'KY31' was about 10% higher than the least of 'Apache'. Visual quality scores among the cultivars ranged from 4.6 to 6.9 (Table 10).

III. Correlation Analysis

Correlation coefficients between uptake parameters and field measurements at the species level are presented in Table 11. Barely significant correlations were found between AIUC and DPR and negatively between CUU and PC. Based on regression analysis, no regression models were identified between uptake parameters and field measurements. Four regression models among uptake parameters and two regression models among field measurements are presented in Table 15.

Kentucky bluegrass showed significant positive correlations (Table 12) between AIUC and DCG, between AIUC and DPR, and a negative correlation between Cm and PC, and between AIUC and PC. Two regression models were identified between uptake parameters and field measurements. Two significant regression models among uptake parameters and one model among field measurements are listed in Table 16.

PC of perennial ryegrass was negatively correlated with all P uptake parameters among which three were significant (Table 13). VQ was also negatively correlated with all uptake parameters only two of which were significant. Positive correlations were identified between DCG and all uptake parameters and between DPR and all uptake parameters among which only one significant correlation between Vmax and DCG was found. One regression model was identified between uptake parameters and field measurements. Three regression models among uptake parameters and two models among field measurements were identified (Table 17).

Between uptake parameters and field performance, tall fescue showed all positive correlations except between PC and CUU (Table 14). Among these correlations, four were significant. CUU showed a significant negative correlation with visual quality. Four regression models between uptake parameters and field measurements, three models among uptake parameters and three models among field measurements were identified (Table 18).

DISCUSSION

The results show that the three genera of turfgrasses differed in their P uptake efficiency and their field measurements. Similar results were found by Cisar (1986) when he studied three turfgrass genera (*Poa*, *Lolium*, and *Festuca*) for P uptake efficiency although only four grasses were used. Differences in P absorption have also been identified among crops (Asher and Loneragan, 1967; Clark, 1983; Barber, 1984; Fohse et al., 1988). Wide ranges of P uptake parameters, growth rates, and P efficiency were obtained and these ranges indicate that individual species differ qualitatively and quantitatively with regard to their requirements for P (Clark, 1983; Barber, 1984; Glass, 1989). These differences may be under genetic control or environmentally driven. However, very limited information on P utilization for turfgrasses is available.

The results show that turfgrass cultivars were also different in P utilization either during the uptake process or accumulation (recovery in clippings) although not all parameters measured differed significantly. Differences in P absorption were found among genotypes of corn (Clark and Brown, 1974; Baligar and Barber, 1979), bean (Lindgren, et al., 1977) sorghum (Clark et al., 1978), white clover (Caradus, 1983) and barley (Nielsen and Schjorring, 1983). Cisar (1986) identified the differences in P absorption between two Kentucky bluegrass cultivars, 'Baron' and "Enmundi'. Compared to nitrogen and potassium (Liu, 1992), fewer significant differences were identified among cultivars of the three species for P uptake or P recovery. This may be due to less luxury uptake of P compared to N and K and turfgrasses are more sensitive to internal P concentrations (Barber, 1984). For example, a highly efficient turfgrass may not increase its P uptake when external P concentration is high. This explanation can be supported by two observations. First, there is no linear absorption of P after the saturable phase has been reached for most plants (Barber, 1984). Second, if P concentration in plant tissue exceed 0.9% of dry weight it was reported toxic and P uptake is genetically controlled (Loneragan and Asher, 1967; Bernard and Howell, 1964).

At the species level, P uptake was not clearly related to the field performance. Among Kentucky bluegrass cultivars and tall fescue cultivars, DPR was positively related to AIUC, and PC was negatively related to AIUC. DCG was negatively related to PC at both the species level and cultivar level. PC negatively expresses P use efficiency ratio (mg dry tissue produced per mg P). These correlations may indicate that if a turfgrass has a high P content it may be a poor grass in P use efficiency and P uptake. In other words, a grass having better P uptake may result in better growth with a low P content in tissue. However, the relationship between P uptake efficiency and growth have shown variable relations in different plants. Both a high P uptake efficiency with a poor growth and a low uptake efficiency with a high growth were reported (Barber, 1984; Fohse et al., 1988).

Variation of P status due to fluctuations in soil pH and soil moisture as well as other factors might have very strong influences on the field measurements of P recovery by turfgrasses. However, these were not considered in this study since they should influence all turfgrasses compared and the field plots were within 100 m of each other.

CONCLUSION

The following are conclusions from this study of comparing three cool season turfgrasses in P uptake efficiency and P recovery in clippings:

1. Genetic variation exists among the three cool-season turfgrasses at both the species and cultivar level in P uptake efficiency and P recovery in clippings.
2. A screening program can be developed to further identify P use characteristics of cool-season turfgrasses which can contribute to current breeding programs but the potential for improving P use is less than that for nitrate and potassium.

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Table 1. Cultivars selected for P utilization studies

Kentucky Bluegrass	Perennial ryegrass	Tall fescue
BRISTOL	DERBY	APACHE
BLACKSBURG	J207	ARID
ECLIPSE	J208	FALCON
JOY	LINN	JAGUAR
KENBLUE	PST-2PM	KY31
LIBERTY	TARA	REBEL II

Table 2. Concentrations of essential nutrients in the solution used to grow grasses hydroponically.

NO_3	PO_4	K	Ca**	SO_4	Mg	Fe*	Zn	Cu	Cl	B	Mo	Mn
mM							µM					
3.75	0.25	1.5	1.25	0.5	0.5	40	0.44	0.06	1.0	1.8	0.03	1.3

*: Fe was added as Sequestrene Fe-330

**: Ca values were approximate. pH was adjusted with $Ca(OH)_2$.

Table 3. Comparison of three species for phosphate uptake parameters: Vmax, Km, Cm, AIUC and CUU values (N = 24 for each species)

Species	Vmax	Km	Cm	AIUC	CUU
	P μmole g^{-1} hr^{-1}	μM	μM		P μmole g^{-1} root
Perennial ryegrass	1.44	19.83a*	4.84a	135.4ab	2.73b
Kentucky bluegrass	1.15	18.97a	3.22ab	149.1a	3.90a
Tall fescue	1.11	12.45b	1.74b	113.4b	3.71a

* Values in a column followed by the same letter are not significantly different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 4. Comparison of six cultivars of Kentucky bluegrasses for phosphate uptake parameters: Vmax, Km, Cm, AIUC and CUU values (N = 4 for each cultivar)

Cultivar	Vmax	Km	Cm	AIUC	CUU
	P µmole g^{-1} hr^{-1}	µM	µM	P µmole g^{-1} root	
BLA	1.34	29.93	4.42	129.06bc*	3.74bc
ECL	1.30	14.70	1.27	194.32a	2.84bc
BRI	1.24	17.65	4.91	168.39ab	4.95ab
JOY	1.09	16.02	3.21	156.79ab	2.58bc
KEN	1.06	16.37	3.34	143.96abc	2.11c
LIB	0.89	18.12	2.16	101.98c	7.17a

* Values in a column followed by the same letter are not significantly different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 5. Comparison of six cultivars of perennial ryegrass for phosphate uptake parameters: Vmax, Km, Cm, AIUC and CUU values (N = 4 for each cultivar)

Cultivar	Vmax	Km	Cm	AIUC	CUU
	P µmole g^{-1} hr^{-1}	µM	µM		P µmole g^{-1} root
J208	1.75	15.50b*	5.16	193.52	2.17ab
LIN	1.72	24.37a	5.73	133.23	3.59a
J207	1.54	24.29a	7.30	124.25	1.95b
DER	1.41	20.11ab	4.43	122.83	3.46ab
TAR	1.13	19.29ab	2.34	119.35	2.40ab
PST	1.10	15.44b	4.10	119.17	2.82ab

* Values in a column followed by the same letter are not significantly different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 6. Comparison of six cultivars of tall fescue for phosphate uptake parameters: Vmax, Km, Cm, AIUC and CUU values (N = 4 for each cultivar)

Cultivar	Vmax	Km	Cm	AIUC	CUU
	P µmole g^{-1} hr^{-1}	µM	µM		P µmole g^{-1} root
REB	1.55	12.52	1.92	128.12	3.43bc*
ARI	1.08	14.72	2.89	118.37	2.67c
KY31	1.06	12.44	1.17	110.47	5.37a
JAG	1.06	8.75	1.28	134.09	3.70b
FAL	0.98	10.94	1.24	100.73	3.42bc
APA	0.91	15.31	1.96	88.80	3.73b

* Values in a column followed by the same letter are not significantly different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 7. Phosphorus recovery comparisons of three species in the field - average of 1990 and 1991 from May to October

Species	Daily clipping yield (DCG)	Clipping P content (PC)	Daily P recovery (DPR)
	g m^{-2} day^{-1}	P mg g^{-1}	P mg m^{-2} day^{-1}
Tall fescue	2.95a*	3.73c	11.02a
Kentucky bluegrass	2.52b	3.86b	9.81ab
Perennial ryegrass	2.01c	4.72a	9.49b

* Values in a column followed by the same letter are not significantly different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 8. Comparison of P recovery by six cultivars of perennial ryegrass - average of 1990 and 1991 from May to October

Cultivar	Daily clipping yield (DCG)	Clipping P content (PC)	Daily P recovery (DPR)	Visual quality (VQ)
	g m^{-2} day^{-1}	P mg g^{-1}	P mg m^{-2} day^{-1}	
LIN	2.26a*	4.60	10.56a	4.2c
J207	2.24ab	4.78	10.83a	6.5ab
PST	2.13ab	4.68	9.80ab	6.1b
DER	2.02ab	4.83	9.66ab	6.3ab
J208	1.93ab	4.74	8.97ab	6.2ab
TAR	1.50b	4.65	7.05b	6.7a

* Values in a column followed by the same letter are not significantly different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 9. Comparison of P recovery by six cultivars of Kentucky bluegrass - average of 1990 and 1991 from May to October

Cultivar	Daily clipping yield (DCG)	Clipping P content (PC)	Daily P recovery (DPR)	Visual quality (VQ)
	g m^{-2} day^{-1}	P mg g^{-1}	P mg m^{-2} day^{-1}	
KEN	3.24a*	3.97a	12.28a	5.4b
JOY	2.67ab	4.01a	10.19ab	5.3b
BRI	2.65ab	3.91a	10.69ab	6.9a
ECL	2.45bc	3.99a	9.97abc	7.6a
LIB	2.20bc	3.78a	8.45bc	7.0a
BLA	1.91c	3.51b	7.21c	7.7a

* Values in a column followed by the same letter are not significantly different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 10. Comparison of P recovery by six cultivars of tall fescue - average of 1990 and 1991 from May to October

Cultivar	Daily clipping yield (DCG)	Clipping P content (PC)	Daily P recovery (DPR)	Visual quality (VQ)
	g m^{-2} day^{-1}	P mg g^{-1}	P mg m^{-2} day^{-1}	
KY31	3.11	3.73	11.61	4.6b*
FAL	3.05	3.64	11.27	5.9ab
JAG	3.01	3.78	11.18	6.9a
ARI	2.93	3.69	10.85	6.3a
REB	2.84	3.78	10.81	6.9a
APA	2.76	3.74	10.39	6.2ab

* Values in a column followed by the same letter are not significantly different at the 5% level of probability based on Duncan's Multiple Range Test.

Table 11. The correlation coefficients between phosphate uptake kinetic parameters and field performances based on the average results of 1990 and 1991 at the interspecific level

Uptake parameter	Daily clipping yield (DCG)	Clipping P content (PC)	Daily P recovery (DPR)
Vmax	0.072	0.175	0.164
Km	-0.035	0.183	0.031
Cm	-0.037	0.050	0.026
AIUC	0.173	-0.119	0.197*
CUU	0.084	-0.221*	-0.017

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 12. The correlation coefficients between phosphate uptake kinetic parameters and field performances based on the average results of 1990 and 1991 - Kentucky bluegrass

Uptake parameter	Daily clipping yield (DCG)	Clipping P content (PC)	Daily P recovery (DPR)	Viausl quality (VQ)
Vmax	0.249	0.001	0.297	0.193
Km	-0.155	0.069	-0.208	0.289
Cm	-0.121	-0.339*	-0.163	-0.095
AIUC	0.549***	-0.467**	0.580***	-0.318
CUU	-0.281	0.297	-0.312	0.312

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 13. The correlation coefficients between phosphate uptake kinetic parameters and field performances based on the average results of 1990 and 1991 - Perennial ryegrass

Uptake parameter	Daily clipping yield (DCG)	Clipping P content (PC)	Daily P recovery (DPR)	Visual quality (VQ)
Vmax	0.345*	-0.361*	0.306	-0.154
Km	0.161	-0.285	0.124	-0.319
Cm	0.234	-0.402*	0.183	-0.017
AIUC	0.226	-0.425**	0.181	-0.391*
CUU	0.160	-0.057	0.139	-0.471**

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 14. The correlation coefficients between phosphate uptake kinetic parameters and field performances based on the average results of 1990 and 1991 - Tall fescue

Uptake parameter	Daily clipping yield (DCG)	Clipping P content (PC)	Daily P recovery (DPR)	Visual quality (VQ)
Vmax	0.032	0.214	0.091	0.128
Km	0.356*	0.057	0.419**	0.001
Cm	0.273	0.195	0.386*	0.074
AIUC	0.098	0.040	0.084	-0.101
CUU	0.359*	-0.073	0.211	-0.523***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 15. Significant regression equations and correlation coefficients between parameters - interspecitic level

Regression equation		
Dependent variable	Independent variable	r
	Between field parameters	
AIUC	= 78.258 + 51.387 Vmax	0.660***
Km	= 10.367 + 0.803Cm	0.450***
CM	= -0.335 + 0.165Km + 0.013AIUC	0.492***
CUU	= 3.006 + 0.05 Km - 0.127 Cm	0.364**
	Between field parameters	
DCG	= 1.569 - 0.439PC + 0.241DPR	0.985***
VQ	= 14.94 - 0.930PC	0.515***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 16. Significant regression equations and correlation coefficients between parameters - Kentucky bluegrass cultivars

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters and field parameters	
PC	= 4.410 + 0.559Vmax - 0.044Cm - 0.007AIUC	0.699***
DPR	= 4.38 + 0.042AIUC	0.603*
	Between uptake parameters	
AIUC	= 96.414 + 70.641Vmax	0.661*
CUU	= 2.757 + 0.092Km	0.303***
	Between field parameters	
DCG	= 3.19 - 0.720PC + 0.268DPR	0.978***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 17. Significant regression equations and correlation coefficients between parameters - perennial ryegrass cultivars

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters and field parameters	
VQ	= 8.38 - 0.009AIUC	0.676*
	Between uptake parameters	
AIUC	= 39.59 + 39.61Vmax	0.721***
Vmax	= 1.17 + 0.55Cm	0.430**
Cm	= 10.940 - 2.230 CUU	0.434**
	Between field parameters	
DCG	= 0.514 - 0.159PC + 0.209DPR	0.994***
PC	= 3.622 + 0.189VQ	0.560***

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Table 18. Significant regression equations and correlation coefficients between parameters - tall fescue cultivars

Regression equation		
Dependent variable	Independent variable	r
	Between uptake parameters and field parameters	
DCG	= -1.250 -2.140Vmax + 0.034AIUC	0.699***
PC	= 4.62 + 0.468Vmax - 0.006AIUC - 0.156 CUU	0.830***
DPR	= -2.310 - 7.02Vmax + 0.115AIUC	0.670**
VQ	= 8.970 - 0.019AIUC - 0.457CUU	0.681**
	Between uptake parameters	
Vmax	= -0.631 + 0.014AIUC	0.926***
Km	= -1.29 + 4.670CM	0.914***
CUU	= 2.557 +0.132Km - 0.650Cm	0.586*
	Between field parameters	
DCG	= 2.71- 0.624PC + 0.238DPR - 0.078VQ	0.994***
PC	= 2.39 + 0.222 VQ	0.647***
DPR	= 25.76 - 2.45VQ	0.527*

*, **, *** Significant at 10, 5, and 1% levels of probability, respectively.

Appendix A Weather Summary - Jan. 1990 to Apr. 1992

Table A1. 1990 summary of temperature - Agricultural Experiment Station, University of Rhode Island, Kingston, Rhode Island

					Extremes	
Month	Avg.	Dep.*	Mean-Max.	Mean-Min.	Max.	Min.
			Temperature - ^{0}C			
JAN	2.28	4.39	7.17	-2.67	15.56	-7.78
FEB	1.39	2.89	7.17	-4.33	14.44	-20.56
MAR	4.39	1.72	11.06	-2.28	25.00	-15.00
APR	8.67	0.61	14.61	2.72	31.11	-6.11
MAY	12.50	-0.72	19.50	6.89	22.70	1.11
JUN	18.78	0.61	24.22	12.06	28.89	3.89
JUL	21.94	0.78	27.39	16.50	32.22	8.89
AUG	22.17	1.50	27.72	16.56	31.67	10.56
SEP	16.94	0.17	23.44	10.39	29.44	0.00
OCT	13.78	2.50	20.67	6.83	26.67	-5.00
NOV	7.28	1.28	14.06	0.56	25.56	-7.22
DEC	4.06	3.89	9.67	-1.61	15.00	-11.11

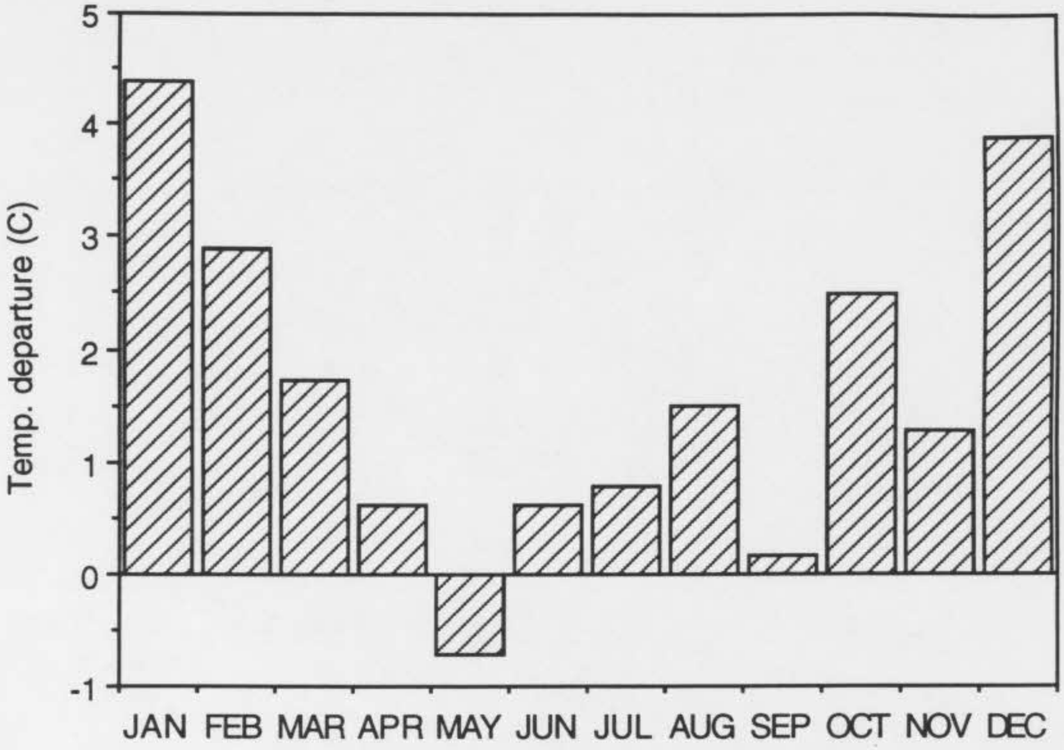
* Departure from normal are based on the period 1951-1980 (30 yr).

Table A2. 1990 summary of precipitation- Agricultural Experiment Station, University of Rhode Island, Kingston, Rhode Island

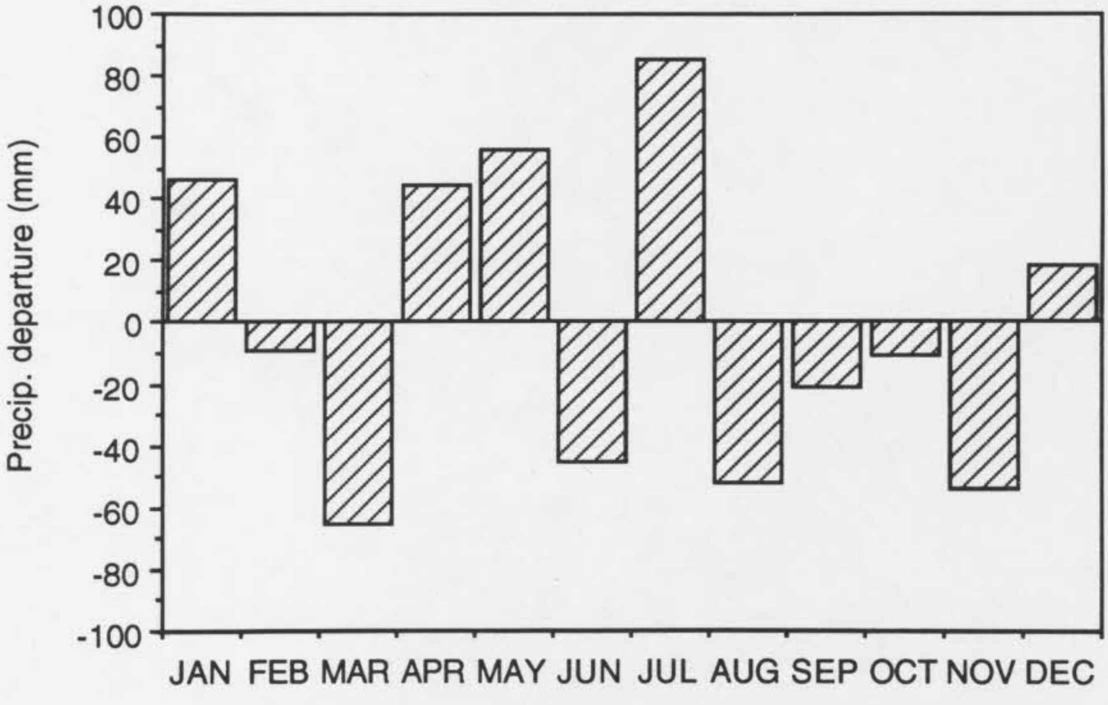
			Days over			
Month	Total	Dep.*	2.54 (0.1 in)	12.70 (0.5 in)	Snowfall	Evap
			Precipitation - mm			
JAN	149.45	45.82	7	6	93.10	0.00
FEB	80.61	-9.80	7	3	232.75	0.00
MAR	48.51	-65.42	7	0	73.50	0.00
APR	145.53	44.35	10	5	58.80	0.00
MAY	156.31	55.37	11	6	0.00	109.27
JUN	25.48	-46.06	2	0	0.00	137.45
JUL	158.03	84.77	10	4	0.00	135.70
AUG	56.11	-53.17	6	1	0.00	126.66
SEP	79.38	-21.32	6	2	0.00	90.16
OCT	85.51	-11.52	11	3	3.50	0.00
NOV	59.54	-54.39	3	2	0.00	0.00
DEC	130.34	18.13	9	3	147.00	0.00

* Departure from normal are based on the period 1951-1980 (30 yr).

Figure A1. 1990 monthly temperature and precipitation departures from normal - Agricultural Experiment Station, University of Rhode Island, Kingston, Rhode Island.



Mean monthly temperature departure from normal - 1990



Monthly precipitation departure from normal - 1990

Table A3. 1991 summary of temperature - Agricultural Experiment Station, University of Rhode Island, Kingston, Rhode Island

Month	Avg.	Dep.*	Mean-Max.	Mean-Min.	Extremes Max.	 Min.
			Temperature - ^{0}C			
JAN	-1.00	1.11	5.06	-7.11	13.89	-20.56
FEB	1.83	3.33	8.39	-4.72	19.44	-12.22
MAR	4.67	2.00	10.44	-1.17	24.44	-7.22
APR	9.78	1.72	16.56	3.00	28.33	-3.89
MAY	16.44	3.22	24.00	8.89	31.11	0.56
JUN	19.28	1.11	26.56	12.00	33.89	5.00
JUL	21.72	0.56	28.67	14.72	36.67	6.67
AUG	21.83	1.17	28.00	15.67	32.22	9.44
SEP	16.28	-0.50	22.61	9.94	31.11	-1.11
OCT	12.33	1.06	18.50	6.11	24.44	-5.56
NOV	6.28	0.28	11.44	1.11	18.89	-10.00
DEC	2.11	1.94	7.72	-3.56	18.33	-14.44

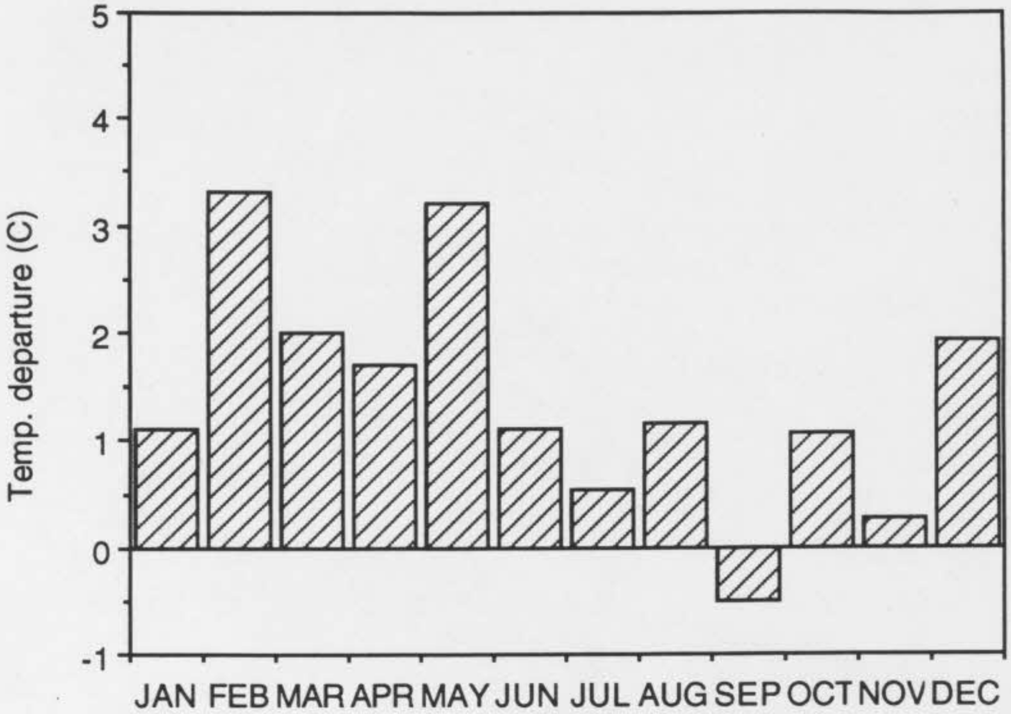
* Departure from normal are based on the period 1951-1980 (30 yr).

Table A4. 1991 summary of precipitation- Agricultural Experiment Station, University of Rhode Island, Kingston, Rhode Island

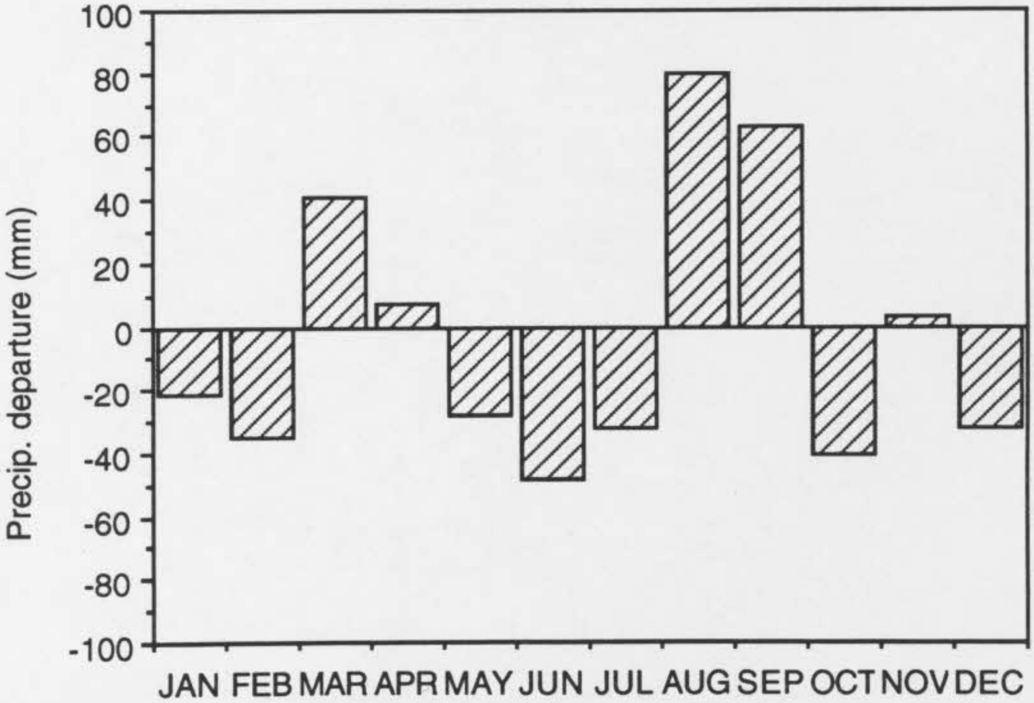
Month	Total	Dep.*	Days over 2.54 (0.1 in)	 12.70 (0.5 in)	Snowfall	Evap.
			Precipitation - mm			
JAN	86.11	-21.34	6	2	127.00	-
FEB	58.93	-34.80	6	1	114.30	-
MAR	159.51	41.40	11	4	63.50	-
APR	112.78	7.87	5	4	0.00	-
MAY	77.22	-27.43	6	4	0.00	155.48
JUN	26.16	-48.06	4	0	0.00	149.08
JUL	43.69	-32.28	4	2	0.00	143.51
AUG	193.04	79.76	6	4	0.00	139.70
SEP	167.37	62.99	7	5	0.00	95.25
OCT	60.20	-40.38	6	2	0.00	72.16
NOV	121.41	3.30	7	4	0.00	-
DEC	84.58	-31.75	9	1	76.20	-

* Departure from normal are based on the period 1951-1980 (30 yr).

Figure A2. 1991 monthly temperature and precipitation departures from normal - Agricultural Experiment Station, University of Rhode Island, Kingston, Rhode Island.



Mean monthly temperature departure from normal - 1991



Monthly precipitation departure from normal - 1991

Table A5. 1992 summary of temperature - Agricultural Experiment Station, University of Rhode Island, Kingston, Rhode Island

Month	Avg.	Dep.*	Mean-Max.	Mean-Min.	Extremes	
					Max.	Min.
			Temperature - ^{0}C			
JAN	-1.11	1.00	4.72	-7.00	13.33	-17.20
FEB	0.28	1.22	5.22	-5.83	13.33	-19.44
MAR	1.50	-1.17	6.72	-3.78	13.33	-13.30
APR	6.78	-1.28	13.11	0.44	23.89	-6.67

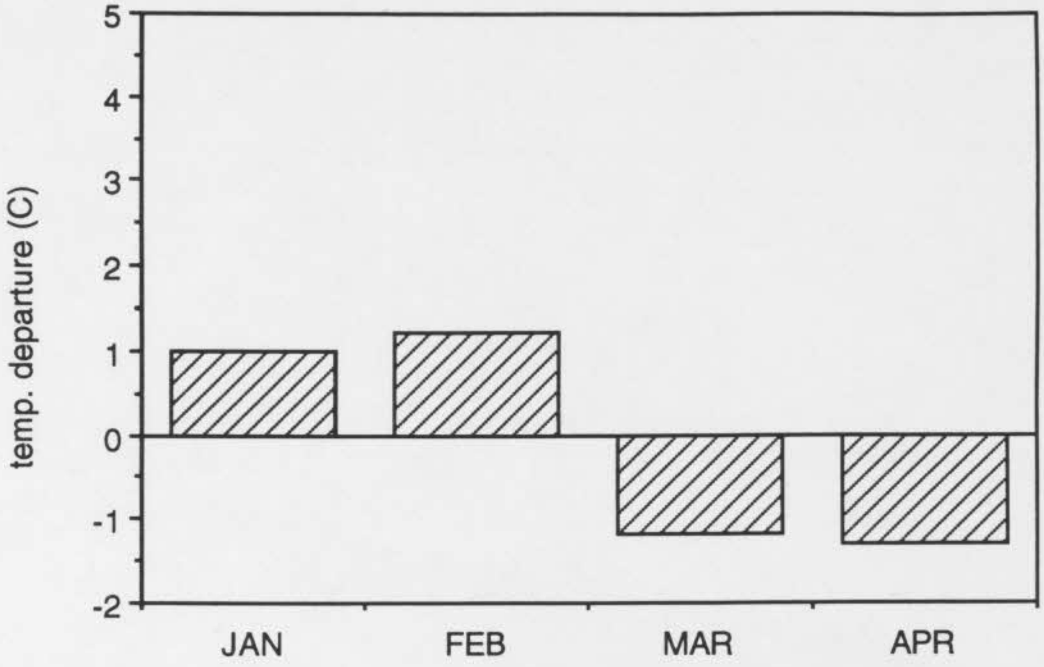
* Departure from normal are based on the period 1951-1980 (30 yr).

Table A6. 1992 summary of precipitation- Agricultural Experiment Station, University of Rhode Island, Kingston, Rhode Island

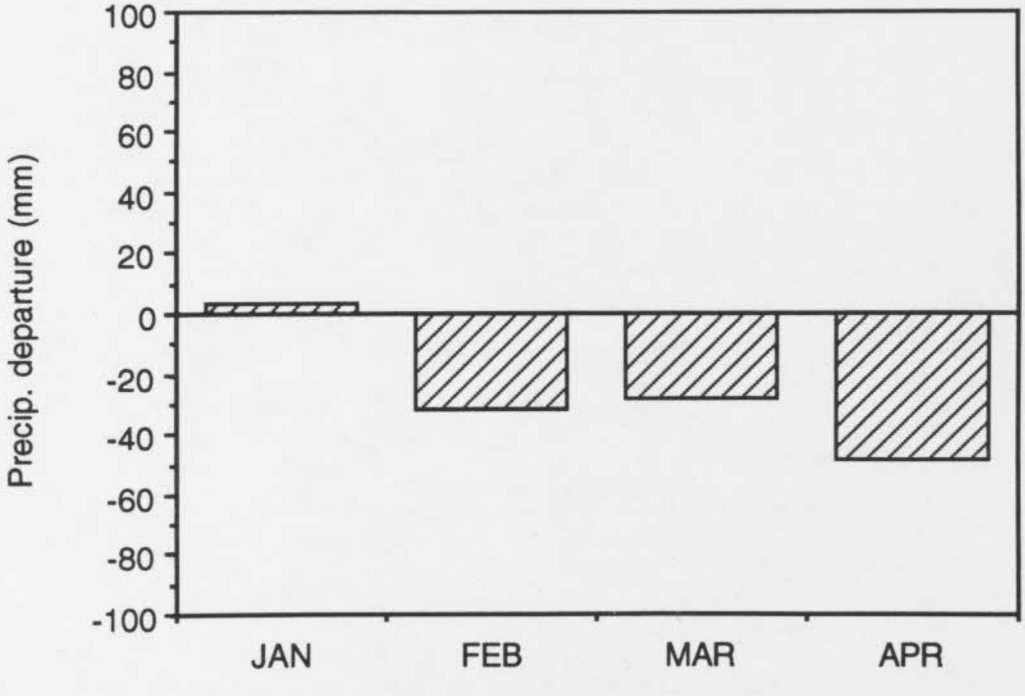
Month	Total	Dep.*	Days over		Snowfall	Evap
			2.54 (0.1 in)	12.70 (0.5 in)		
			Precipitation - mm			
JAN	110.10	3.56	6	4	72.20	-
FEB	61.72	-32.00	4	1	60.96	-
MAR	90.17	-27.94	6	2	195.18	-
APR	55.88	-49.02	6	1	38.10	-

* Departure from normal are based on the period 1951-1980 (30 yr).

Figure A3. 1992 monthly temperature and precipitation departures from normal - Agricultural Experiment Station, University of Rhode Island, Kingston, Rhode Island.



Mean monthly temperature departure
from normal - 1992



Monthly precipitation departure
from normal - 1992

Appendix B Dates of clipping harvests and soil water sample collections

Table B1. Dates of clipping harvests and soil water sample collections

	Dates of clipping harvests		Dates of soil water sample collections		
	1990	1991	1990	1991	1992
					Jan. 10
				Jan. 29	Jan. 24
					Feb. 16
				Feb. 21	Feb. 28
			Mar. 14		Mar. 18
			Mar. 28	Mar. 21	Mar. 30
			Apr. 11	Apr. 3	Apr. 13
			Apr. 25	Apr. 17	Apr. 24
	May 9	May 9	May 11	May 14	
	May 18	May 24	May 25	May 28	
	Jun. 1	Jun. 7	Jun. 8	Jun. 13	
	Jun. 15	Jun. 20	Jun. 22	Jun. 26	
	Jun. 29				
	Jul. 13	Jul. 5	Jul. 6	Jul. 10	
	Jul. 30	Jul. 19	Jul. 20	Jul. 24	
	Aug. 10	Aug. 2	Aug. 3	Aug. 7	
	Aug. 24	Aug. 26	Aug. 17.		
			Aug. 31	Aug. 27	
	Sep. 11	Sep. 6	Sep. 14	Sep. 13	
	Sep. 21	Sep. 24	Sep. 28	Sep. 27	
	Oct. 10	Oct. 8	Oct. 12	Oct. 11	
	Oct. 20	Oct. 22	Oct. 31	Oct.25	
			Nov. 9	Nov. 8	
			Nov. 27	Nov. 25	
			Dec. 10	Dec. 8	
			Dec. 26	Dec. 22	
Total	13	12	21	21	8

Appendix C Monthly cumulative soil water percolation from Jan. 1990 to Apr. 1992

Table C1 Monthly cumulative soil water percolation from Jan. 1990 to Apr. 1992

Month	1990	1991	1992
	Percolation - mm		
JAN	120.42	0.94	0.00
FEB	62.33	68.58	0.00
MAR	6.05	113.44	131.52
APR	75.18	35.76	4.57
MAY	14.78	0.00	0.00
JUN	0.00	0.00	0.00
JUL	17.60	0.00	0.00
AUG	0.00	62.66	99.95
SEP	13.64	21.59	21.08
OCT	0.00	0.00	-
NOV	35.12	55.75	-
DEC	104.47	49.91	-

Appendix D Calculation of nutrient uptake parameters - an example

CALCULATION OF NUTRIENT UPTAKE PARAMETERS - AN EXAMPLE

Step 1: The development of depletion curve

Data of K concentrations at different times were entered in CRICKET. GRAPH (CA-CRICKET GRAPH, 1990) in a Macintosh personal computer. The depletion curve was developed by time against K µmole and a regression equation was obtained.

Step 2: Calculation of uptake rate

Based on Bowman et al. (1989) the first negative derivative of the regression equation developed from depletion curve is the uptake rate of the entire culture.

$Y = 248.16 - 76.359X + 5.8907X^2 + 0.01769X^3 \quad R^2 = 0.996$

So the negative derivative: $Y' = 76.359 - 11.78X - 0.051X^2$

For the exact uptake rate at every sample time, it was obtained by calculating Y'/root weight, where X = time, root weight = 15.47 g for 'Eclipse'.

Step 3. Development of uptake kinetic curve

By using K µM against K uptake rate, the uptake kinetic curve was developed (Figure D2). A logarithmic regression equation was obtained. Based on the equation, when Y = 0, or no uptake, Cm was obtained. In this case, Cm = 13.30 µM.

Step 4. Calculation of AIUC and CUU

Based on the definition of AIUC, AIUC equals the integration of the uptake curve which equals to:

$\text{AIUC} = \int (-3.2407 + 2.84 * \log x)$ beginning at Cm and ending at the initial K concentration which was 526.57. In this case, AIUC = 1725.29.

CUU = (Initial concentration - Cm)/root = (263.38 µmole - 6.65 µmole) 15.47 g
= 16.59 µmole K/g root.

Step 5. Calculation of Vmax and Km

Vmax and Km were calculated based on a linear plot. The linear plot was obtained by using !/K mM against 1/uptake rate (Figure D3). In this case, Vmax = 5.86 µmole K g^{-1} hr^{-1} and Km = 156.29 µM K.

Table D1 Raw data of 'Eclipse' Kentucky bluegrass replicate 4 for K uptake

Time	K in ppm	K µM	K µmole	uptake rate	1/K µM	1/uptake rate
				µmole K/g^{-1} hr^{-1}		
0.00	20.59	526.57	263.28	4.94	0.002	0.203
0.25	17.02	435.27	217.64	4.75	0.002	0.211
0.50	16.26	415.83	207.92	4.55	0.002	0.220
0.75	14.62	373.89	186.95	4.36	0.003	0.229
1.00	13.76	351.89	175.95	4.17	0.003	0.240
1.25	12.59	321.97	160.99	3.98	0.003	0.251
1.50	11.72	299.73	149.86	3.79	0.003	0.264
1.75	10.90	278.76	139.38	3.59	0.004	0.278
2.00	9.44	241.42	120.71	3.40	0.004	0.294
2.25	8.25	210.97	105.49	3.21	0.005	0.312
2.50	7.41	189.50	94.75	3.01	0.005	0.332
2.75	6.41	163.93	81.97	2.82	0.006	0.355
3.00	6.07	155.23	77.62	2.62	0.006	0.381
3.25	5.08	129.92	64.96	2.43	0.008	0.412
3.50	4.20	107.41	53.71	2.23	0.009	0.449
3.75	3.54	90.53	45.27	2.03	0.011	0.492
4.00	2.92	74.67	37.34	1.84	0.013	0.545
4.25	1.96	50.13	25.06	1.64	0.020	0.610
4.50	1.62	41.43	20.72	1.44	0.024	0.694
4.75	1.93	49.35	24.68	1.24	0.020	0.804
5.00	1.23	31.46	15.73	1.05	0.032	0.957
5.25	0.96	24.55	12.28	0.85	0.041	1.183
5.50	0.76	19.44	9.72	0.65	0.051	1.548
5.75	0.52	13.29	6.65	0.45	0.075	2.240
6.00	0.58	14.83	7.42	0.25	0.067	2.981

Figure D1 Depletion curve of K uptake for 'Eclipse'

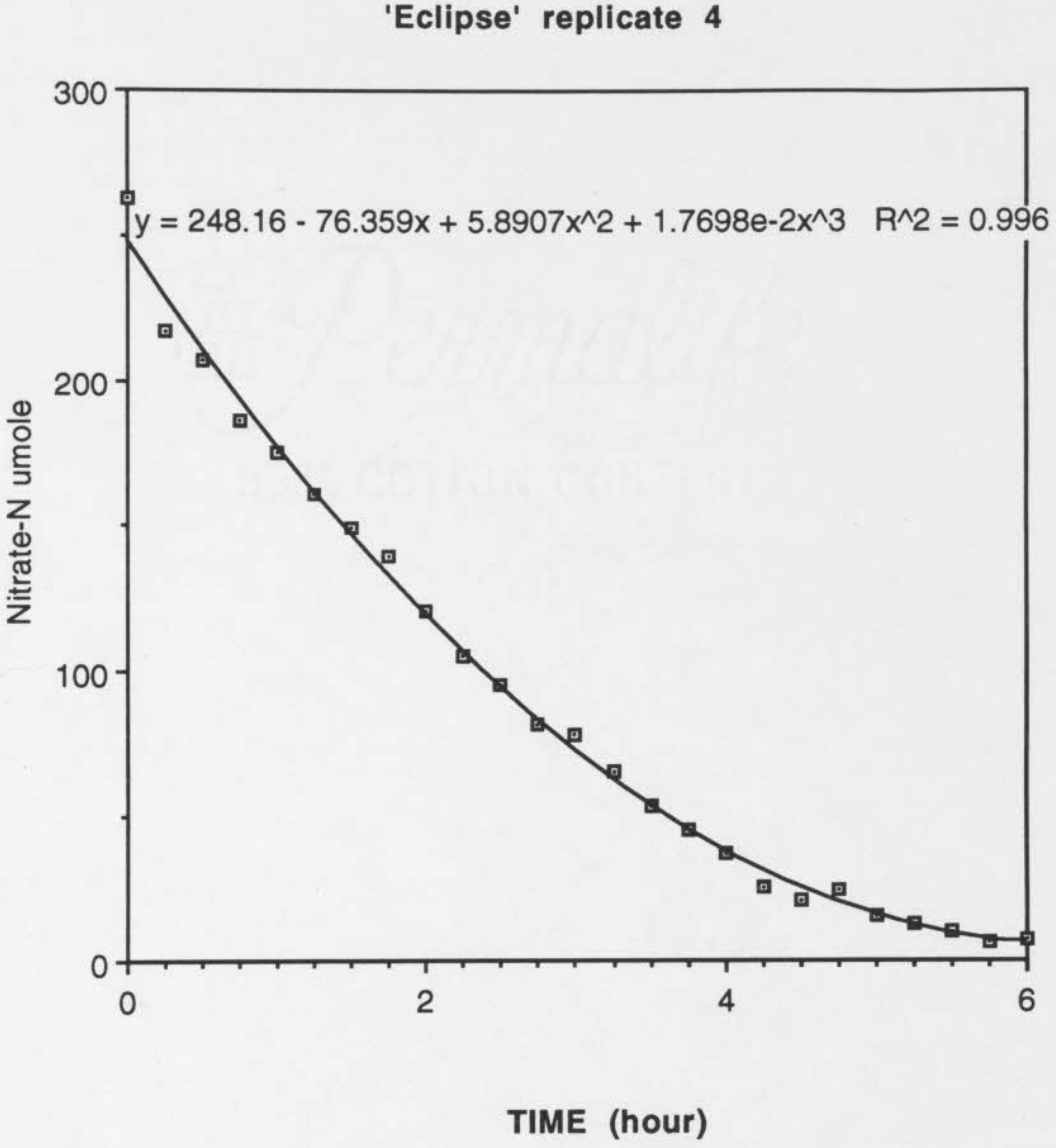

'Eclipse' replicate 4
y = 248.16 - 76.359x + 5.8907x^2 + 1.7698e-2x^3 R^2 = 0.996
Nitrate-N umole
300
200
100
0
0
2
4
6
TIME (hour)

Figure D2 Uptake kinetic curve for 'Eclipse'

'Eclipse' replicate 4

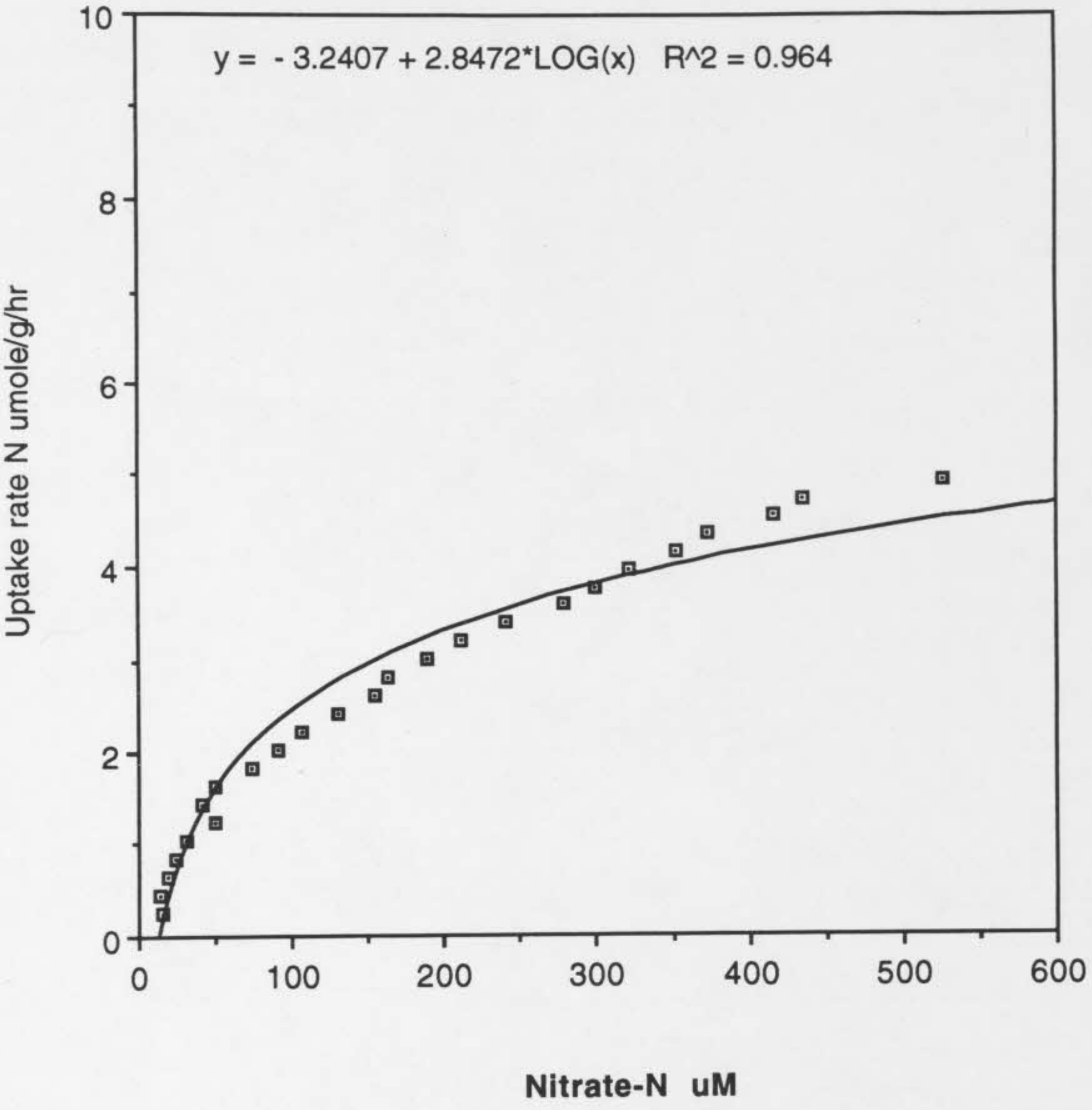
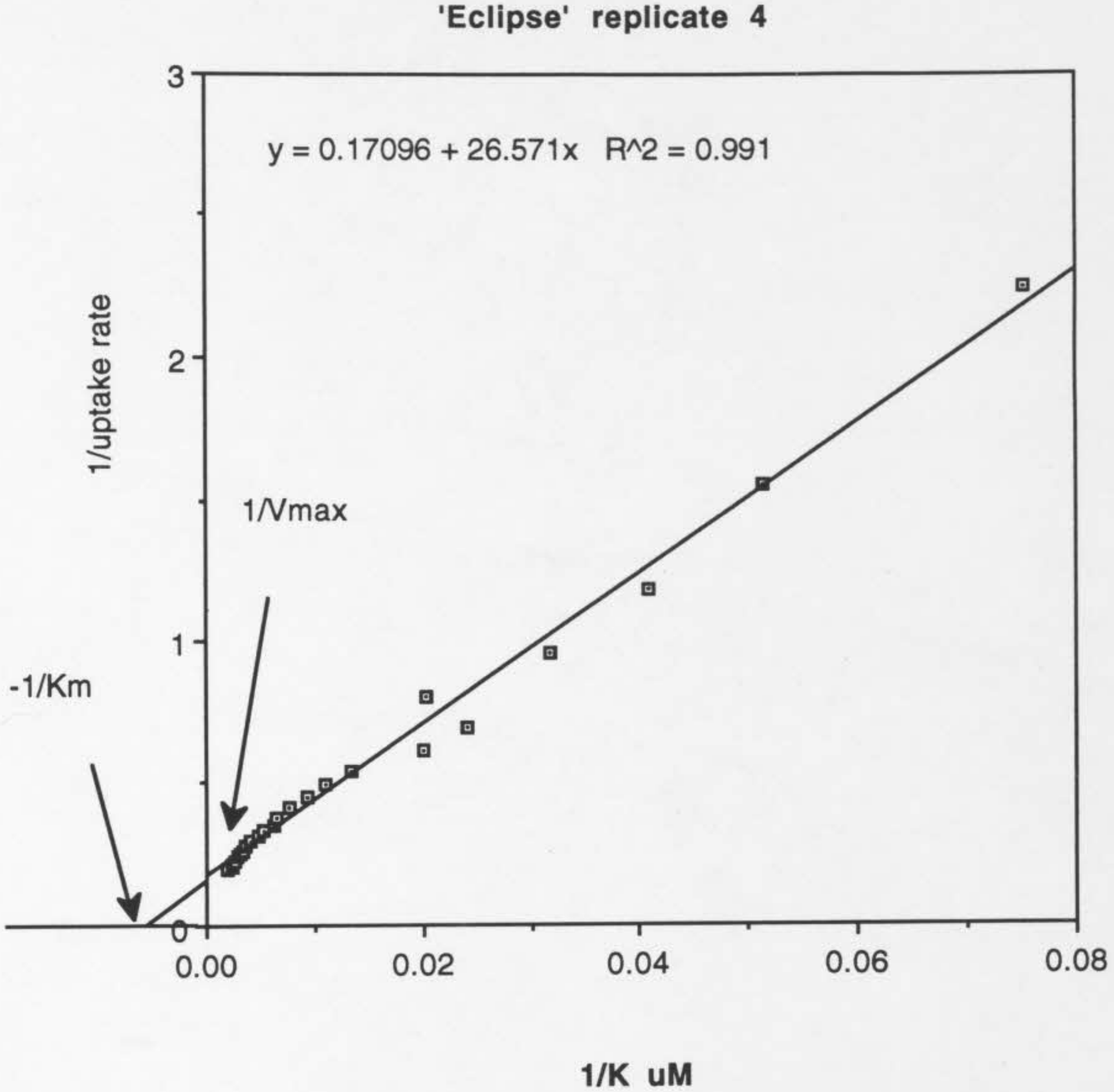


Figure D3 Linear plot using 1/K μM against 1/uptake rate for 'Eclipse'


'Eclipse' replicate 4
y = 0.17096 + 26.571x R^2 = 0.991
1/uptake rate
1/Vmax
-1/Km
3
2
1
0
0.00
0.02
0.04
0.06
0.08
1/K uM

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