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Relationship of Turfgrass Growth and Quality to Soil Nitrate Desorbed from Anion Exchange Membranes

Kelly L. Kopp* and Karl Guillard

ABSTRACT

Anion exchange membranes (AEMs) are a potential method for determining the plant available N status of soils; however, their capacity for use with turfgrass has not been researched extensively. The main objective of this experiment was to determine the relationship between soil nitrate desorbed from AEMs and growth response and quality of turfgrass managed as a residential lawn. Two field experiments were conducted with a bluegrass–ryegrass–fescue mixture receiving four rates of N fertilizer (0, 98, 196, and 392 kg N ha^{-1} yr^{-1}) with clippings returned or removed. The soils at the two sites were a Paxton fine sandy loam (coarse-loamy, mixed, active, mesic Oxyaquic Dystrudepts) and a variant of a Hinckley gravelly sandy loam (sandy-skeletal, mixed, mesic Typic Udorthents). Anion exchange membranes were inserted into plots and exchanged weekly during the growing seasons of 1998 and 1999. Nitrate-N was desorbed from AEMs and quantified. As N fertilization rates increased, desorbed NO_3-N increased. The relationship of desorbed NO_3-N from AEMs to clipping yield and turfgrass quality was characterized using quadratic response plateau (QRP) and Cate-Nelson models (C-Ns). Critical levels of desorbed NO_3-N ranged from 0.86 to 8.0 μg cm^{-2} d^{-1} for relative dry matter yield (DMY) and from 2.3 to 12 μg cm^{-2} d^{-1} for turfgrass quality depending upon experimental treatment. Anion exchange membranes show promise of indicating the critical levels of soil NO_3-N desorbed from AEMs necessary to achieve maximum turfgrass quality and yield without overapplication of N.

THERE ARE MANY EXISTING METHODS for monitoring available N in soils. Traditional chemical extractions are the most common methods; however, these measurements provide only a snapshot measurement of available N. They are unable to measure fluxes that occur with changing environmental conditions. Exchange resins, in the form of capsules or spheres, provide another technique for measuring available soil N (Binkley and Hart, 1989). Exchange resins are superior to traditional methods because they are able to measure N availability with time. Even so, the three-dimensional nature of exchange resins necessitates a great deal of soil disturbance when they are deployed. Consequently, in situ conditions, as well as the measure of available soil N, are compromised. In addition to concerns regarding soil disturbance, the prevailing view of exchange resins as infinite sinks to which ions may be adsorbed but never desorbed limits their use as an index of bioavailability (Cooperband and Logan, 1994). A further limitation of exchange resins involves their three-dimensional nature. Because of their three-dimensional shape, exchange resins do not completely contact the soil. Furthermore, it is possible that the adsorption of ions by resins is governed by two distinct diffusion coefficients, an internal and an external coefficient (Cooperband and Logan, 1994). Therefore, there is uncertainty in the calculation of exchangeable nutrients on a per weight basis from data collected using exchange resins. This is of particular concern when exchange resins are not in contact with soil long enough to negate diffusion limitations (Bhadoria et al., 1991).

Ion exchange membranes (IEMs), by virtue of their two-dimensional nature and dynamic exchange properties, provide an alternative to traditional measurements of available soil N and exchange resin techniques (Abrams and Jarrell, 1992). The nascent study using IEMs for measuring in situ soil N availability was performed by Subler et al. (1995) and involved the use of AEMs buried in a silt-loam soil with various amendments. Subler et al. (1995) found that AEMs successfully measured soil N processes and availability during a 4-wk period in soils with widely variable mineralization–immobilization rates. Other important findings of Subler et al. (1995) were that NO_3^- uptake by AEMs was nonlinear with time and that the membranes had the potential to influence some soil processes. However, they acknowledged the potential influence of the small amounts of soil used in the study (20 g) and suggested that in the field, the AEM techniques' influence on soil processes might be relatively small.

Subsequent studies using AEMs to measure available soil N have been performed. Pare et al. (1995) compared soil NO_3^- extracted by KCl to that adsorbed by AEMs and found that the quantity of NO_3-N adsorbed on AEMs was correlated (R^2 = 0.78) to the amount extracted using the traditional KCl method. Qian and Schoenau (1995) assessed the contribution of N mineralization from soil organic matter to plant-available N using AEMs and correlated the results to a 0.001 *M* $CaCl_2$ extraction. They found that 2-wk AEM incubations were more closely correlated with plant N uptake than were $CaCl_2$ extractions. Wander et al. (1995) compared AEM extractions to traditional KCl extractions for measuring changes in NO_3^- concentration in a field during winter and found that NO_3^- availability declined with both methods. However, only the AEM method produced statistically significant results.

Anion exchange membranes have been used in the field to measure NO_3^- fluxes in soils of grass hay crops. In a field study of grasslands, Ziadi et al. (1999) found that NO_3^- fluxes from AEMs were significantly corre-

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Abbreviations: AEM, anion exchange membrane; CRM, clippings removed; CRT, clippings returned; C-N, Cate-Nelson model; DMY, dry matter yield; HDPE, high density polyethylene; IEM, ion exchange membrane; QRP, quadratic response plateau model; RF, Plant Science Research and Teaching Farm; SM, Spring Manor Farm.

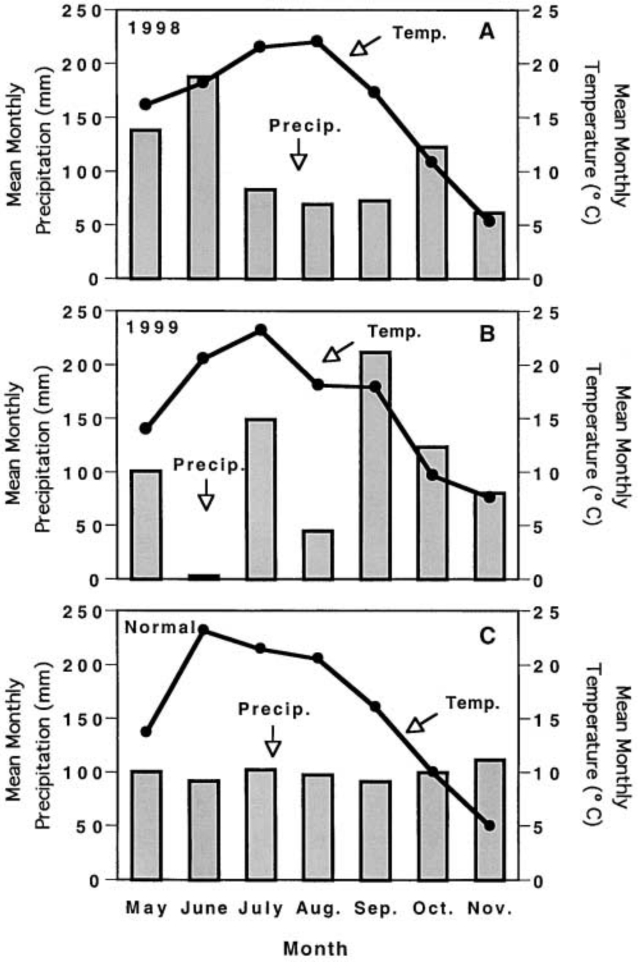

Fig. 1. Mean monthly precipitation and temperature for the growing seasons of 1998 (A) and 1999 (B), as well as 30-yr normal values (C) for Storrs, CT.

lated to water-soluble NO_3^- concentrations in soil and that NO_3^- sorbed on AEMs increased as N fertilization rates increased. In addition, forage uptake of N was better related to fluxes of desorbed NO_3^- from AEMs than to water-soluble NO_3^- concentrations measured in the soil (Ziadi et al., 1999). Collins and Allinson (1999) reported that AEMs had highly significant relationships to relative yield and applied N rates in grasslands. In addition, they were able to predict a critical level of NO_3-N in the soil, as measured by AEMs, necessary to reach maximum yield during two harvest periods.

Anion exchange membranes have also been used to assess NO_3^- relationships in turfgrass. Simard et al. (1998) reported the preliminary results of a study in which the decreasing N content in cuttings from bentgrass (*Agrostis stolonifera* L.) golf greens was related to similar decreases in NO_3^- desorbed from AEMs. Simard et al. (1998) corroborated the results of Pare et al. (1995) and Wander et al. (1995) in finding that NO_3^- fluxes from AEMs were better related to plant N uptake than were traditional KCl extractions of soil.

Assessing N deficiency in turfgrass is relatively easy due to the chlorotic color that may accompany insufficiency as well as decreased tillering and shoot density.

Table 1. Summary of analyses of variance indicating significant source effects on desorbed nitrate-N from AEMs (anion exchange membranes) at the Research Farm and Spring Manor sites in 1998 and 1999.

		Desorbed NO_3-N	
Source	**df**	**1998**	**1999**
Research Farm			
N rate (N)	3	***	***
Clipping (C)	1	**	***
N × C	3	NS†	***
Spring Manor			
N rate (n)	3	***	***
Clipping (C)	1	NS	***
N × C	3	NS	NS

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† NS = nonsignificant at the 0.05 level.

However, it is difficult to determine when turfgrass has reached sufficient or optimum N status without exceeding optimum levels. Many recent turfgrass studies have investigated losses of N because of concerns for the quality of surface and ground water. Optimizing N management of turfgrasses may help preserve and improve the quality of surface and ground waters by minimizing losses of N from turfgrass systems. Therefore, methods for determining the optimum N status in turfgrass should be explored so that N fertilizers are not overused in turf management. The objective of this study was to determine the relationship between soil NO_3^- desorbed from AEMs and growth and quality of turfgrass managed as a residential lawn.

MATERIALS AND METHODS

Field experiments were conducted at the University of Connecticut's Plant Science Research and Teaching Farm (RF) and Spring Manor Farm (SM) in Storrs, CT, during two consecutive growing seasons (1998 and 1999). The experiment was arranged in a 2 × 4 factorial, set out in a randomized complete block design with three replicates at each site. Plot size was 2 × 2 m and experimental treatments included four rates of N (0, 98, 196, and 392 kg N ha^{-1} yr^{-1}) applied in three equal, split applications and two clipping treatments [clippings returned (CRT) and clippings removed (CRM)]. The N source was a mixture of 65% 30-4-4 (urea, methylene urea, ammonium phosphate, and ammonium sulfate; 5.2% water insoluble N) and 35% 33-0-0 (NH_4NO_3) fertilizer.

In preparation for the study, the sod was removed from both field sites to expose bare soil during the summer of 1995. Soil testing indicated that the RF site, which had been an established lawn, required the addition of 5021 kg ha^{-1} dolomitic limestone to optimize turfgrass growth conditions. The limestone was applied on 20 Sept. 1995 and incorporated by disking and roto-tilling. The SM site, which had been an established hay field, did not require additional amendments according to soil test results. The soil at both sites was graded and rolled several times to provide a level surface for seeding. During late fall of 1995, both sites were seeded with a bluegrass–ryegrass–fescue mixture [35% common Kentucky bluegrass (*Poa pratensis* L.), 35% common creeping red fescue (*Festuca rubra* L. subsp. *rubra*), 15% 'Cutter' perennial ryegrass (*Lolium perenne* L.), and 15% 'Express' perennial ryegrass] at a rate of 244 kg ha^{-1} and were overseeded with the same mixture at a rate of 49 kg ha^{-1} during the spring of 1996.

The turfgrass at each site was maintained at a home lawn

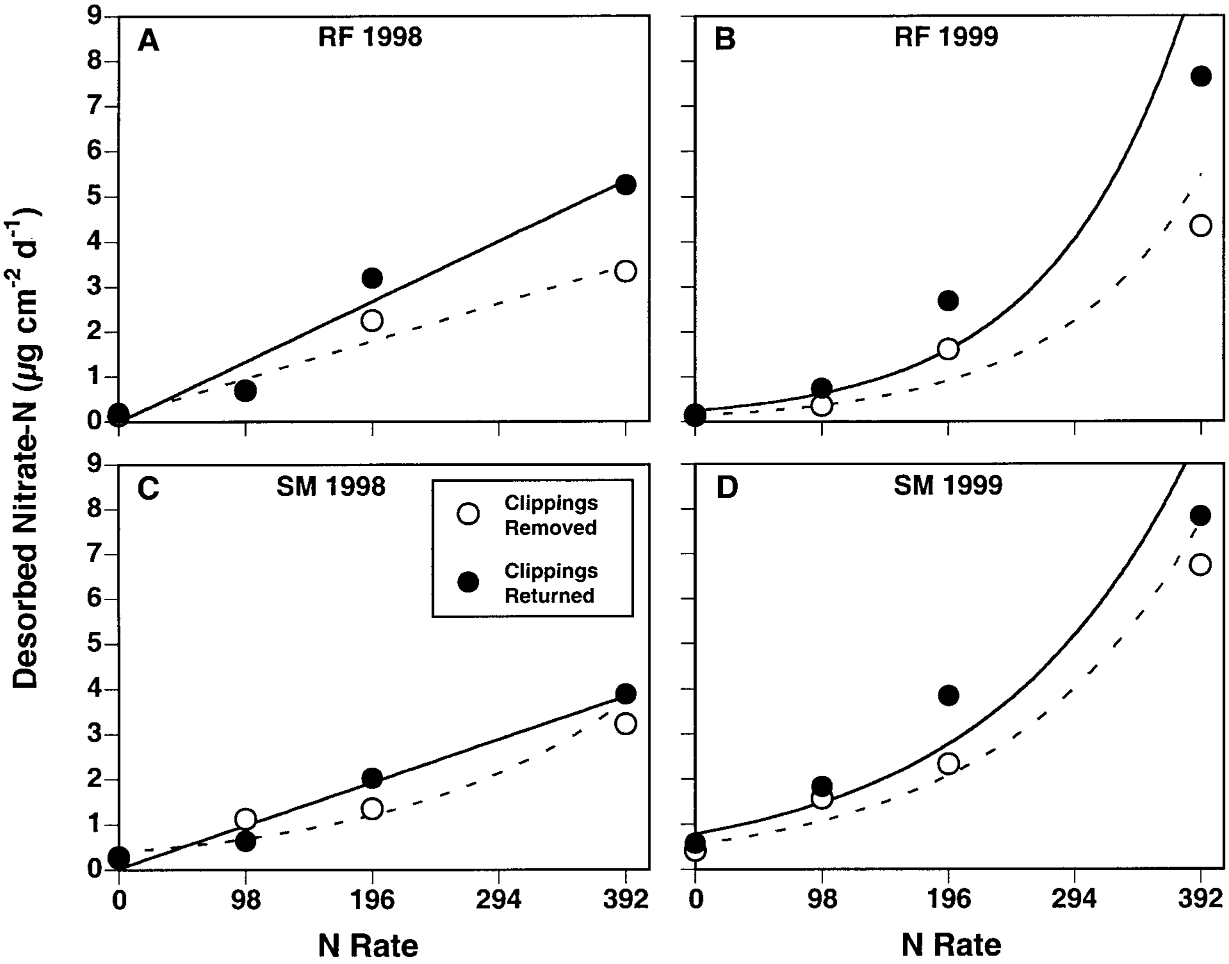

Fig. 2. Response of desorbed nitrate-N from anion exchange membranes to N fertilization rate when clippings were returned or removed at the Plant Science Research and Teaching Farm (RF) site, 1998 (A) and 1999 (B); and the Spring Manor Farm (SM) site, 1998 (C) and 1999 (D).

height of 3.8 cm throughout each growing season. Mowing was generally required once every week’ or once every 2 wk, depending on growing conditions. During the growing season of 1997, experimental data were not collected; however, the experimental plots were fertilized three times at the assigned N rates and clippings were returned to the appropriate plots. The experimental treatments were continued during the growing seasons of 1998 and 1999 and data were collected. Supplemental irrigation was not applied at any time during the course of the experiment.

Beginning in the spring and summer of 1998, subsamples of clippings (1 to 5 g) from the CRT treatments were collected. The remainder of the CRT clippings were returned to the field and spread evenly over the plots from which they had been harvested. All clippings from the CRM treatments were collected and kept for analyses. Clipping samples were dried in a forced-draft oven (70°C) until a constant weight was reached to obtain DMYs. The clippings for each plot were combined into five harvest periods. Each harvest period typically included grass clippings from one month. The exact harvest periods varied depending on year, but each year had five harvest periods. Therefore, statistical analyses of DMY data were performed on a yearly basis. Analyses were also separated by site because site responses were found to be significantly different.

The AEMs were used to make in situ measurements of plant-available soil NO_3-N at both sites beginning in May of 1998. The AEMs (type 204-U-386) used in this study are made of cross-linked vinyl copolymer reinforcing fabric embedded with NH_4^+ anion exchange groups (Ionics, 1990). Two AEMs (6.25 × 2.5 cm each) were inserted into each plot, removed, and replaced weekly throughout the growing season until the end of October. A vertical slit was made in the soil of each plot using a mason’s trowel, and the AEMs were inserted at a depth of 10 to 15 cm beneath the soil surface. Complete contact was established between the AEMs and the soil by pressing the slit closed by hand and lightly stepping on it. A monofilament line was attached to the AEMs to facilitate removal, and small flags also marked points of insertion. The plots were mowed after the AEMs were removed from the plots each week. After mowing, freshly prepared AEMs were inserted into each plot.

The methodology of preparing AEMs for use included washing the AEMs with deionized water and shaking them with 0.5 *M* HCl for five minutes in a 2-L high density polyethylene (HDPE) container. The AEMs were then rinsed three times with deionized water and saturated with 1 *M* NaCl by shaking for 1 h in a separate 2-L HDPE container. After a final deionized water rinse, the AEMs were stored in deionized water in 0.5-L HDPE containers until use to prevent dessication (Ziadi et al., 1999).

As AEMs were removed from the plots, they were rinsed lightly with deionized water to remove any adhering soil and placed in 60-mL, low-density polyethylene sample bottles containing 25 mL of 1 *M* NaCl. The AEMs were immediately transported to the laboratory for analysis. In the laboratory,

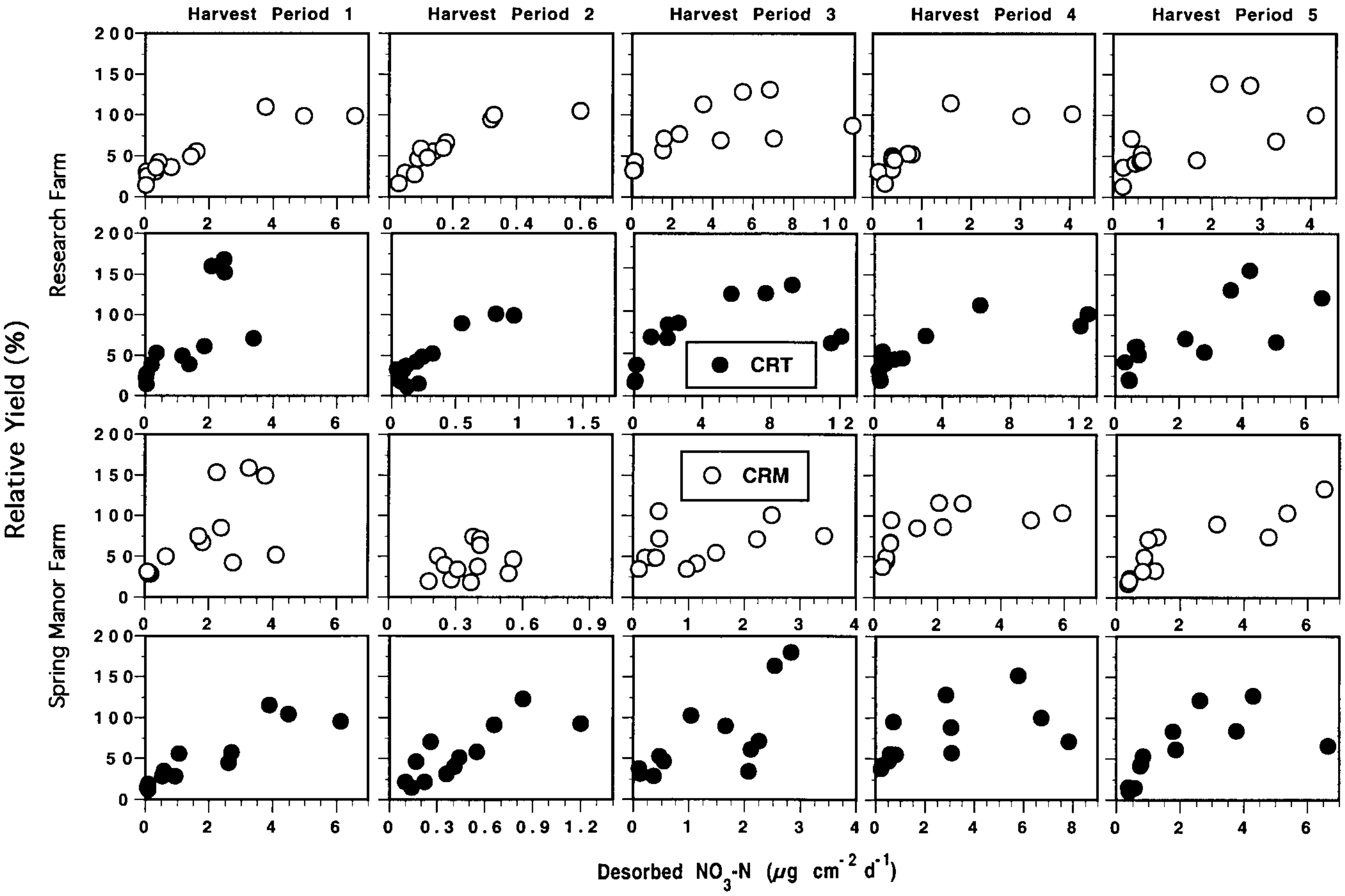

Fig. 3. Relationship of relative clipping yield by harvest to desorbed NO$_3$-N from anion exchange membranes in 1998. Although *y*-axis values are constant across harvests, *x*-axis values are variable. CRM, clippings removed; CRT, clippings returned.

the sample bottles containing the AEMs were shaken for 1 h and the resulting extracts were filtered through soil analysis papers having an 8 to 12 μm retention range (Schleicher and Schuell, Keene, NH). The extracts were analyzed for NO$_3$-N + NO$_2$-N concentration on a Scientific Instruments continuous flow analyzer (WESTCO, Danbury, CT) using a colorimetric, Cd-reduction method.

Quality ratings were made of all plots on a monthly basis. An overall quality rating for each month (ranging from 1 to 9, where 1 = lowest quality and 9 = highest quality) was determined as a function of color and density ratings (Skogley and Sawyer, 1992).

Relative clipping yield was determined by fitting QRP models to the data and then dividing raw yield values by the plateau yield generated by the model. The relationships of relative clipping yield and quality of the turfgrass to the amount of NO$_3$-N desorbed by the AEMs were determined using the QRP model and the C-N procedure (Cate and Nelson, 1971). Both methods were used to estimate critical levels of desorbed NO$_3^-$ above which additional available soil NO$_3^-$ would not increase clipping yield or improve turfgrass quality.

Quadratic response plateau models were generated using the NLIN procedure of the Statistical Analysis Software package (SAS Institute, 1999). The ANOVA procedure of SAS was used to calculate critical levels in the C-N procedure. With C-N modeling, the calculation of a vertical critical level and the manual placement of a horizontal critical level were made to best divide the data points between the upper right and lower left quadrants of the plots. Correct predictions of the model occur in the upper right and lower left quadrants of C-N plots (Nelson and Anderson, 1977). Error percentages for C-N plots of clipping yield and quality were determined by dividing the number of data points falling outside the desirable quadrants by the total number of data points and multiplying this value by 100.

RESULTS AND DISCUSSION

Weather Conditions

Normal (30-yr; Storrs, CT) weather data are presented along with data for the growing seasons of 1998 and 1999 (Fig. 1). Rainfall during the growing season of 1999 was much less consistent than rainfall during the growing season of 1998, although overall totals were comparable (735 mm in 1998 and 715 mm in 1999). June of 1999 had a particularly low amount of rainfall, 89 mm below normal. Rainfall during August of 1999 was 53 mm below normal. While several months during 1998 also had below normal rainfall, the discrepancies were not as extreme as in 1999. Periods of extreme drought occurred during the summer of 1999 in Connecticut.

Desorbed NO$_3$-N from Anion Exchange Membranes

Nitrogen fertilization, clipping treatment, and in one case, their interaction were found to have significant effects on desorbed NO$_3$-N from AEMs (Table 1). As

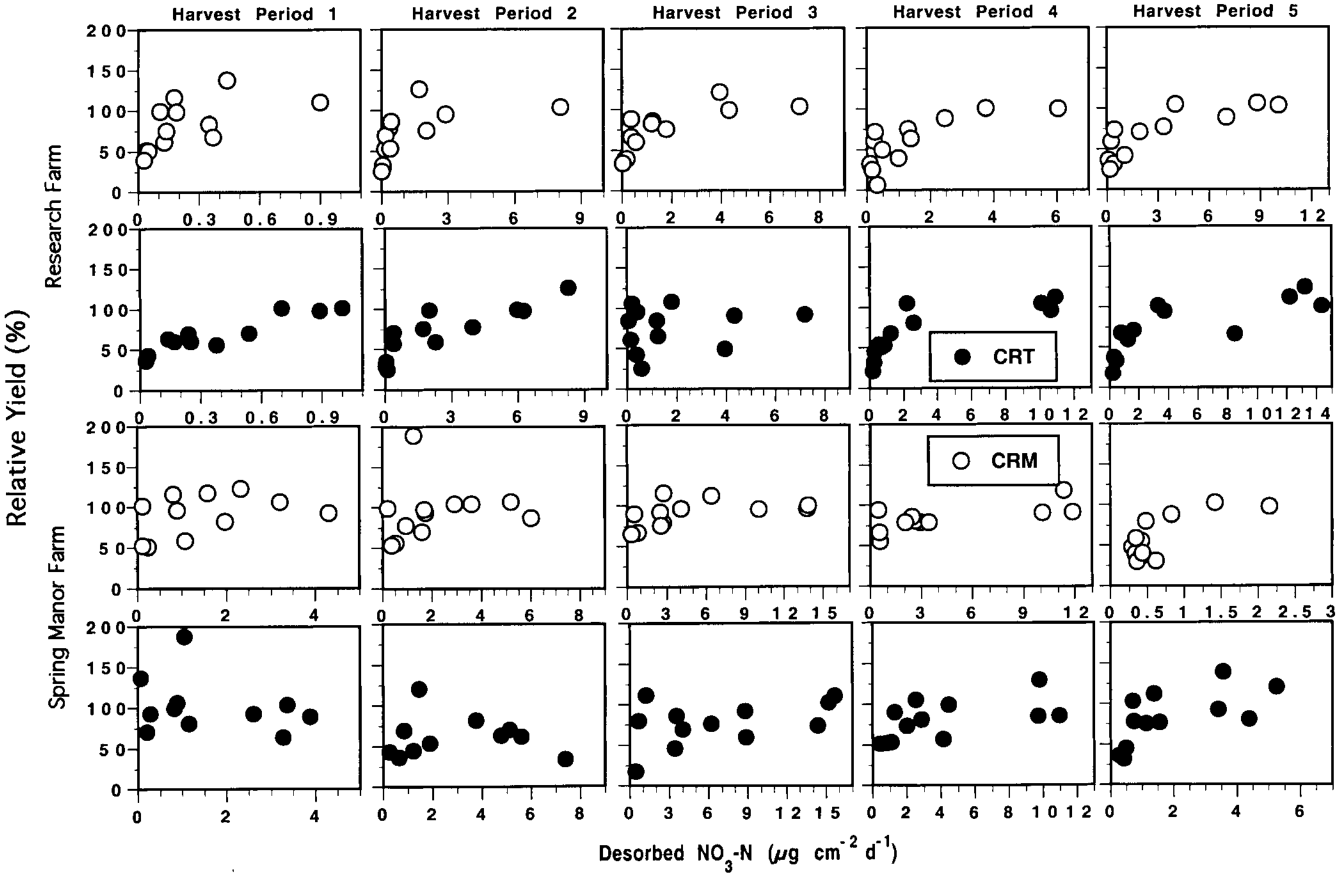

Fig. 4. Relationship of relative clipping yield by harvest to desorbed NO_3-N from anion exchange membranes in 1999. Although *y*-axis values are constant across harvests, *x*-axis values are variable. CRM, clippings removed; CRT, clippings returned.

N fertilization rates increased, desorbed NO_3-N from AEMs increased at both sites during both years (Fig. 2). The practice of returning clippings generally increased the amount of desorbed NO_3-N from AEMs at both sites during both years (Table 1, Fig. 2). These findings corroborate those of Simard et al. (1998), who reported in a preliminary study that AEMs responded to varying rates of N fertilization on bentgrass golf greens.

Clipping Yield Modeling

Although clipping production is not often a desirable component of turfgrass management, clipping yield is a measure of turfgrass growth response. We believe that this study is the first to relate turfgrass growth responses to desorbed NO_3-N from AEMs. Using QRP and C-N models, we were able to determine the relationship of desorbed soil NO_3-N from AEMs to relative DMY for turfgrass in mixed species stands across five harvest periods. Plots of relative clipping DMY vs. desorbed NO_3-N from AEMs are presented by harvest period and site for 1998 (Fig. 3) and 1999 (Fig. 4). Model parameters for QRP and C-N models of the data are presented in Table 2. At the RF site, critical levels of desorbed NO_3-N averaged 1.6 to 3.4 (CRM) and 4.1 to 4.2 (CRT) $\mu g\ cm^{-1}\ d^{-1}$ in 1998 and 1.2 to 3.1 (CRM) and 1.3 to 4.1 (CRT) $\mu g\ cm^{-1}\ d^{-1}$ in 1999. At the SM site, critical levels averaged 1.4 to 3.1 (CRM) and 0.86 to 4.1 (CRT) $\mu g\ cm^{-1}\ d^{-1}$ in 1998, and 2.5 to 8 (CRM) and 1.1 to 3.4 (CRT) $\mu g\ cm^{-1}\ d^{-1}$ in 1999.

Critical levels of desorbed NO_3-N were higher for CRT treatments than for CRM treatments at both sites in 1998, and the same relationship was observed at the RF site in 1999. However, at the SM site in 1999, critical levels were lower for CRT treatments than for CRM treatments. The generally higher critical levels that we observed for CRT treatments were indicative of higher levels of mineralizable organic matter and N in the soil–turf system when clippings were returned. One possible cause for the reversal of this trend at the SM site in 1999 was a greater sensitivity of the site to the drought conditions of 1999. The growing season of 1999 was extremely dry and departures below 30-yr normal values occurred. While departures below 30-yr normal rainfall also occurred in 1998, the discrepancy was not as extreme (Fig. 1). In addition, the soil at the SM site is a gravelly sandy loam while the soil at the RF site is a fine sandy loam. The Paxton soil at the RF site is known for its superior water holding capacity even during drought. In contrast, the Hinckley variant at the SM site is excessively well drained and droughty. Because irrigation was never applied during the experiment, the SM site tended to be drier than the RF site, especially during the growing season of 1999, and it is likely that soil moisture levels effected NO_3-N sorption by AEMs.

The critical levels generated using the QRP and C-N models ranged from 0.86 to 8.0 $\mu g\ cm^{-1}\ d^{-1}$ depending upon site, experimental treatment, and model. Collins and Allinson (1999) reported critical levels ranging from

Table 2. Parameters for quadratic response plateau (QRP) and Cate-Nelson (C-N) models relating relative dry matter yield to desorbed nitrate from anion exchange membranes.

Harvest period	Year	Site	Clippings†	QRP Model CL‡	QRP Model Plateau	QRP Model R^2	C–N Model CL	C–N Model Plateau	C–N Model R^2	C–N Model Error
				μg cm^{-2} d^{-1}	%		μg cm^{-2} d^{-1}	%		%
1	1998	RF	CRM	5.5	103	0.94***	1.7–3.7	75	0.88***	0
2	1998	RF	CRM	0.47	106	0.95***	0.18–0.31	75	0.73***	0
3	1998	RF	CRM	5.7	102	0.67**	1.6–2.3	65	0.57**	8.3
4	1998	RF	CRM	2.2	104	0.90***	0.80–1.4	75	0.87***	0
5	1998	RF	CRM	2.9	103	0.58*	1.7–2.1	80	0.7***	0
1	1998	RF	CRT	3.2	120	0.58*	1.9–2.0	80	0.77***	0
2	1998	RF	CRT	1.4	114	0.86***	0.32–0.54	75	0.84***	0
3	1998	RF	CRT	4.1	110	0.71**	0.13–0.97	60	0.63**	0
4	1998	RF	CRT	7.0	99	0.87***	1.7–2.9	65	0.80***	0
5	1998	RF	CRT	4.9	111	0.61*	2.8–3.6	80	0.67**	8.3
1	1999	RF	CRM	0.24	101	0.56*	0.05–0.09	65	0.50**	0
2	1999	RF	CRM	0.90	100	0.80***	0.40–0.45	70	0.63**	17
3	1999	RF	CRM	3.4	107	0.77**	1.8–3.9	90	0.53**	0
4	1999	RF	CRM	4.9	102	0.65**	0.99–1.2	65	0.60**	17
5	1999	RF	CRM	6.3	101	0.78**	1.1–1.9	70	0.70***	8.3
1	1999	RF	CRT	1.6	113	0.87***	0.54–0.69	80	0.7***	0
2	1999	RF	CRT	11.3	122	0.75***	0.34	50	0.65**	0
3	1999	RF	CRT	0.57	73	0.02	1.3–1.7	85	0.08	25
4	1999	RF	CRT	3.6	104	0.92***	1.3–2.0	75	0.81***	0
5	1999	RF	CRT	3.4	100	0.81***	1.7–3.2	75	0.66**	8.3
1	1998	SM	CRM	3.8	109	0.45	1.9–2.2	100	0.40*	17
2	1998	SM	CRM	0.45	48	0.14	0.37	60	0.38*	33
3	1998	SM	CRM	NA§	NA	NA	1.5–2.2	60	0.28	17
4	1998	SM	CRM	1.0	100	0.81***	0.51–0.55	75	0.79***	0
5	1998	SM	CRM	10.0	132	0.79***	1.3–3.1	75	0.64**	8.3
1	1998	SM	CRT	6.8	106	0.85***	0.94–1.1	50	0.66**	8.3
2	1998	SM	CRT	1.3	104	0.70***	0.55–0.65	75	0.73***	0
3	1998	SM	CRT	NA	NA	NA	0.55–1.0	65	0.38*	8.3
4	1998	SM	CRT	5.3	107	0.46	0.58–0.69	50	0.43*	8.3
5	1998	SM	CRT	2.9	97	0.79***	0.91–1.7	60	0.67**	0
1	1999	SM	CRM	2.4	104	0.27	1.11–1.5	75	0.25	25
2	1999	SM	CRM	1.5	102	0.13	0.94–1.2	85	0.25	17
3	1999	SM	CRM	6.3	101	0.47	2.7–2.8	80	0.48*	17
4	1999	SM	CRM	28	116	0.49*	3.5–10	85	0.44*	8.3
5	1999	SM	CRM	1.8	101	0.64*	0.62–0.82	85	0.72***	0
1	1999	SM	CRT	NA	NA	NA	1.1	75	0.20	42
2	1999	SM	CRT	1.7	65	0.12	5.6–7.3	75	0.12	17
3	1999	SM	CRT	0	77	0	0.48–0.65	50	0.48*	17
4	1999	SM	CRT	7.2	98	0.39	0.48–0.65	80	0.35*	17
5	1999	SM	CRT	1.4	102	0.62*	0.50–0.69	70	0.66**	0

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Clipping management: CRM = clippings removed; CRT = clippings returned.
‡ CL = critical level.
§ NA = Model was not applicable to data.

0.66 to 4.03 μg cm^{-2} d^{-1} desorbed soil NO_3-N for perennial grassland in a 3-cut hay crop. Our critical levels tended to be higher than those of Collins and Allinson (1999). However, we expected this difference due to the more intensive management of turfgrass, that is, frequent mowing, low cutting height, and the return of grass clippings. Returning clippings tended to increase the critical levels of desorbed NO_3-N that we observed for reasons previously mentioned. Returning clippings also increased overall DMY at both sites. In addition, related growth responses such as total N uptake, apparent N recovery, and N use efficiency were improved by the practice of returning clippings (Kopp and Guillard, 2002).

Correct predictions of the C-N model occur in the upper right and lower left quadrants of C-N plots (Nelson and Anderson, 1977). In 1998 at the RF site, error rates for C-N models of relative DMY averaged 1.2% for both CRM and CRT treatments. In 1999 at the RF site, error rates averaged 8.5% (CRM) and 6.7% (CRT). Error rates calculated for relative DMY at the SM site were generally higher than those calculated for the RF site. For example in 1998 at the SM site, error rates averaged 15% (CRM) and 5.0% (CRT), and in 1999 error rates averaged 14% (CRM) and 19% (CRT). These error rates may be used to compare one C-N model with another. For example, since error rates were generally higher at the SM site, C-N modeling may be said to better describe the data at the RF site.

Turfgrass Quality Modeling

To our knowledge, there are no other studies that have related turfgrass quality to desorbed NO_3-N from AEMs. Using QRP and C-N models, we were able to determine the relationship of desorbed soil NO_3-N from AEMs to turfgrass quality for mixed species stands of turfgrass across six rating periods. Plots of turfgrass quality vs. desorbed NO_3-N from AEMs are presented for 1998 (Fig. 5) and 1999 (Fig. 6). Quadratic response plateau and C-N models were fitted to the data, and the resulting model parameters are presented in Table

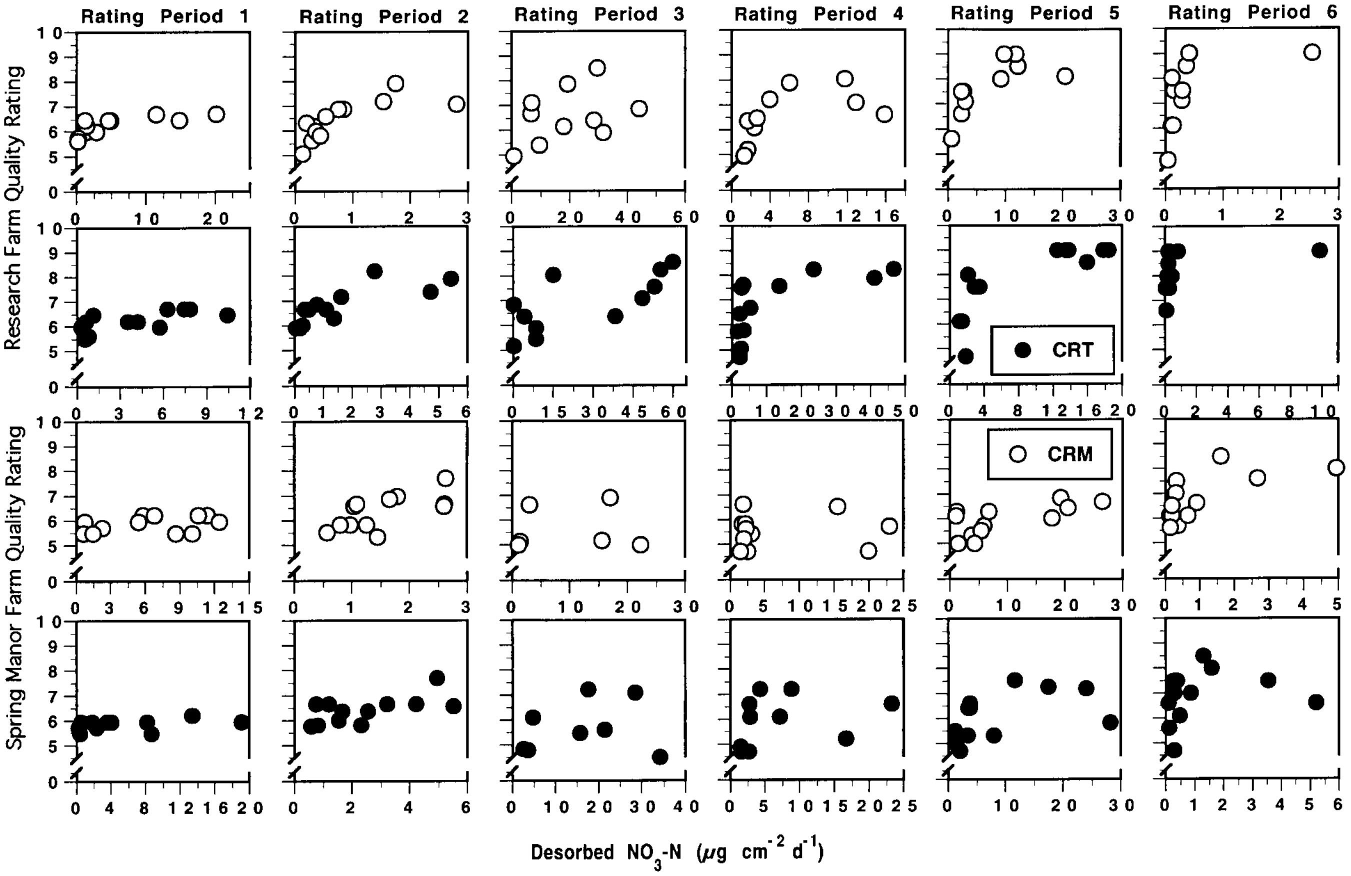

Fig. 5. Relationship of overall turfgrass quality by rating period to desorbed NO_3-N from anion exchange membranes in 1998. Although *y*-axis values are constant across harvests, *x*-axis values are variable. CRM, clippings removed; CRT, clippings returned.

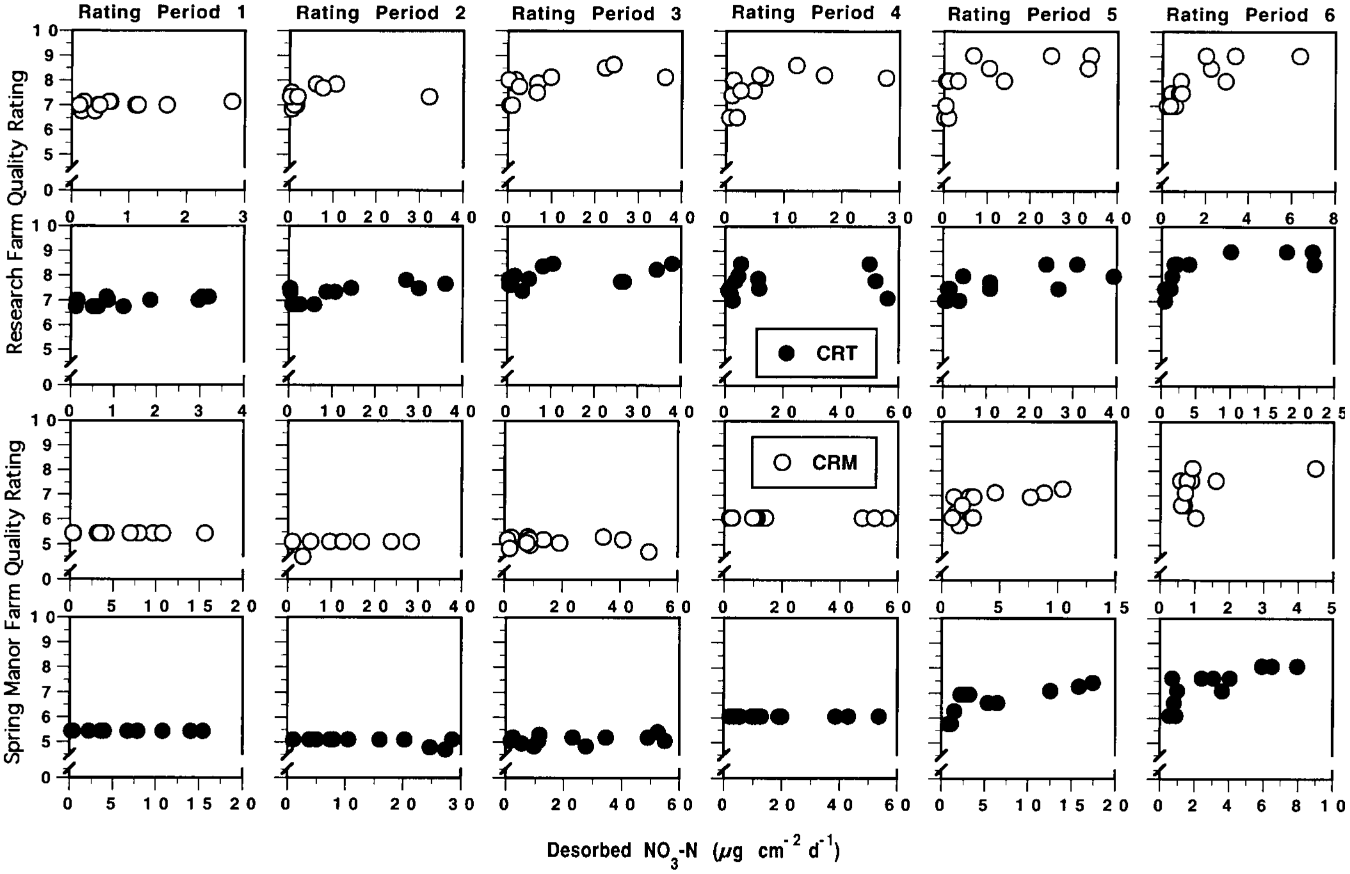

Fig. 6. Relationship of overall turfgrass quality by rating period to desorbed NO_3-N from anion exchange membranes in 1999. Although *y*-axis values are constant across harvests, *x*-axis values are variable. CRM, clippings removed; CRT, clippings returned.

Table 3. Parameters for quadratic response plateau (QRP) and Cate-Nelson (C-N) models relating turfgrass quality ratings to desorbed nitrate from anion exchange membranes.

				QRP Model			C–N Model			
Rating period	**Year**	**Site**	**Clippings†**	**CL‡**	**Plateau**	**R^2**	**CL**	**Plateau**	**R^2**	**Error**
				μg cm^{-2} d^{-1}	%		μg cm^{-2} d^{-1}	%		%
1	1998	RF	CRM	7.4	6.6	0.75**	2.9–4.6	6.3	0.61**	17
2	1998	RF	CRM	1.5	7.4	0.80***	1.7	7.0	0.20***	0
3	1998	RF	CRM	2.5	6.8	0.62*	0.76–6.7	5.3	0.60**	0
4	1998	RF	CRM	4.2	7.4	0.77**	2.4–2.5	6.0	0.63**	8.3
5	1998	RF	CRM	5.9	8.5	0.80***	1.6–2.3	6.5	0.78***	0
6	1998	RF	CRM	0.48	8.9	0.77**	0.10	6.0	0.66**	0
1	1998	RF	CRT	10.4	6.6	0.48*	5.8–6.2	6.4	0.57**	8.3
2	1998	RF	CRT	3.7	7.7	0.77**	1.4	7.0	0.71***	0
3	1998	RF	CRT	30	7.6	0.53*	8.6–15	6.0	0.62**	17
4	1998	RF	CRT	19	8.1	0.57*	5.3–14	7.3	0.51**	17
5	1998	RF	CRT	7.3	8.9	0.78**	1.9–2.1	7.0	0.79***	0
6	1998	RF	CRT	0.35	8.7	0.55*	0.08–1.4	8.7	0.62**	8.3
1	1999	RF	CRM	4.1	7.1	0.13	0.40–0.45	6.8	0.28	25
2	1999	RF	CRM	8.4	7.7	0.48*	1.8–6.1	7.6	0.53**	0
3	1999	RF	CRM	26	8.4	0.51*	0.87–1.4	7.4	0.41*	8.3
4	1999	RF	CRM	12	8.3	0.45	4.9–5.7	7.8	0.46*	17
5	1999	RF	CRM	7.2	8.7	0.67**	1.1–3.2	8.2	0.61**	17
6	1999	RF	CRM	2.6	8.7	0.81***	0.79–2.0	7.8	0.76***	8.3
1	1999	RF	CRT	NA§	NA	NA	0.62–0.82	6.8	0.31	25
2	1999	RF	CRT	0.56	7.3	0.04	5.9–8.6	7.2	0.53**	17
3	1999	RF	CRT	12	8.2	0.31	5.0–8.1	8.2	0.41*	17
4	1999	RF	CRT	5.9	7.9	0.24	2.6–3.5	7.6	0.35*	17
5	1999	RF	CRT	3.2	7.8	0.36	3.7–4.7	7.2	0.56**	17
6	1999	RF	CRT	3.8	8.8	0.88***	1.6–1.9	8.2	0.80***	8.3
1	1998	SM	CRM	0.74	5.9	0.14	2.3–5.4	5.8	0.23	25
2	1998	SM	CRM	4.1	7.3	0.46	0.97–1.0	6.3	0.31	17
3	1998	SM	CRM	20	5.1	0.04	8.8–16	5.5	0.10	25
4	1998	SM	CRM	1.7	5.6	0.26	16–20	6.2	0.03	33
5	1998	SM	CRM	NA	NA	NA	5.9–6.7	5.9	0.54**	17
6	1998	SM	CRM	2.4	7.9	0.57*	1.5	7.3	0.26	8.3
1	1998	SM	CRT	20	6.1	0.23	2.4–3.5	5.7	0.17	25
2	1998	SM	CRT	NA	NA	NA	2.6–3.2	7.0	0.42*	25
3	1998	SM	CRT	7.4	5.6	0.34	3.7–4.8	5.0	0.33	17
4	1998	SM	CRT	4.5	6.1	0.26	2.5–2.7	5.0	0.32	33
5	1998	SM	CRT	14	6.8	0.44	3.4	5.8	0.56**	8.3
6	1998	SM	CRT	1.5	7.6	0.31	0.85–1.2	7.3	0.29	25
1	1999	SM	CRM	NA	NA	NA	NA	NA	NA	NA
2	1999	SM	CRM	NA	NA	NA	6.1–9.6	4.7	0.08	25
3	1999	SM	CRM	NA	NA	NA	2.0–2.3	4.9	0.05	25
4	1999	SM	CRM	NA	NA	NA	NA	NA	NA	NA
5	1999	SM	CRM	7.3	7.1	0.45	2.7	6.7	0.51**	25
6	1999	SM	CRM	3.7	8.1	0.22	0.72–0.75	8.0	0.25	17
1	1999	SM	CRT	NA	NA	NA	NA	NA	NA	NA
2	1999	SM	CRT	NA	NA	NA	4.7–5.0	4.8	0.10	33
3	1999	SM	CRT	NA	NA	NA	11–12	5.2	0.19	17
4	1999	SM	CRT	NA	NA	NA	NA	NA	NA	NA
5	1999	SM	CRT	3.1	7.0	0.79***	1.5–2.1	6.5	0.76***	0
6	1999	SM	CRT	8.5	8.1	0.64**	0.98–2.4	6.9	0.53**	17

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
‡ CL =critical level.
† Clipping management; CRM = clippings removed; CRT = clippings returned.
§ NA = Model was not applicable to data.

3. At the RF site, critical levels of desorbed NO_3-N averaged 2.3 to 3.7 (CRM) and 5.4 to 12 (CRT) μg cm^{-1} d^{-1} in 1998, and 2.4 to 10 (CRM) and 3.4 to 5.1 (CRT) μg cm^{-1} d^{-1} in 1999. At the SM site, critical levels averaged 5.8 to 7.2 (CRM) and 9.3 to 10 (CRT) μg cm^{-1} d^{-1} in 1998, and 3.4 to 5.5 (CRM) and 5.1 to 5.8 (CRT) μg cm^{-1} d^{-1} in 1999.

Critical levels of desorbed NO_3-N were higher with CRT treatments than CRM treatments at both sites in 1998, and a similar relationship was observed at the SM site in 1999. However, at the RF site in 1999, the opposite relationship was observed and the CRM treatments generated higher critical levels of desorbed NO_3-N than the CRT treatments. Once again, the generally higher critical levels that we observed for CRT treatments were probably attributable to higher levels of mineralizable organic matter and N in the soil–turf system when clippings were returned.

In 1998 at the RF site, error rates for C-N models of turfgrass quality averaged 4.2% (CRM) and 8.4% (CRT). In 1999 at the RF site, error rates averaged 13% (CRM) and 17% (CRT). Error rates calculated for turfgrass quality at the SM site were generally higher than those calculated for the RF site. For example in 1998 at the SM site, error rates averaged 21% (CRM) and 22% (CRT), and in 1999, error rates averaged 23% (CRM) and 17% (CRT). As with relative DMY, C-N modeling of turfgrass quality better described the data at the RF site than at the SM site when error rate is considered.

While no other studies have related turfgrass quality to desorbed NO_3-N from AEMs, other researchers have considered the effects of returning clippings upon turfgrass quality. In general, it has been reported that turfgrass color and quality improve when clippings are returned (Murray and Juska, 1977; Johnson et al., 1987; Hipp et al., 1992; Heckman, 2000). Average turfgrass quality tended to improve when clippings were returned in 1998, but tended to decline in 1999 (Kopp and Guillard, 2002). As with relative DMY, the extreme drought conditions of 1999 likely contributed to this finding.

CONCLUSIONS

Anion exchange membranes were used to relate relative DMY and quality of turfgrass to desorbed soil NO_3-N for mixed species stands of turfgrass managed as residential lawns. Two models, QRP and C-N, were used to describe the relationships. The practice of returning clippings clearly influenced the relationship of desorbed NO_3-N from AEMs to turf growth and quality. Climatic conditions, particularly soil moisture availability, were also important. Further study utilizing more rates of fertilization at closer intervals will help to refine this method, and additional work utilizing irrigation and different turfgrass species is also necessary. Critical levels of desorbed NO_3-N could then be established for different turfgrass species and management regimes. In the future, the AEM technique could be used to determine whether N fertilizer applications are truly warranted. This would provide an advantage over traditional fertilizer scheduling based on the time of year or turfgrass color because unnecessary and excessive N fertilizer use would be avoided. With further experimentation, AEMs may provide a useful tool in the management of turfgrass that will help to insure the judicious use of N fertilizers.

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