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Evaluation of Turfgrass Nitrogen Fertilizer Leaching Rates in Soils on Cape Cod, Massachusetts

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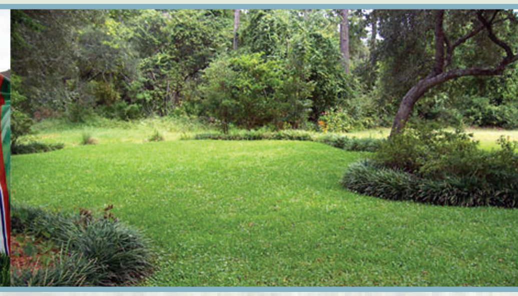

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EXECUTIVE SUMMARY

This study was conducted by the Horsley Witten Group, Inc. (HW) on behalf of the Massachusetts Department of Environmental Protection (DEP) to review existing information on nitrogen leaching rates from fertilizer applied to turfgrasss, and make a recommendation on an appropriate rate to be applied to water quality assessments conducted by the Massachusetts Estuaries Project (MEP) on 89 Cape Cod and southeastern Massachusetts embayments (the MEP embayments).

The MEP Model assumes a 20% nitrogen leaching rate within the embayments, based on research conducted by Dr. Brian Howes (MEP Reports). A recent study conducted by Dr. A. Martin Petrovic, on behalf of the Pleasant Bay Alliance (Petrovic, 2008), determined that a 10% nitrogen leaching rate would be appropriate for the embayments. HW reviewed the MEP Reports and Dr. Petrovic's study, and interviewed Dr. Howes to discuss his calculation method used in deriving the MEP Model leaching rate. HW also conducted a literature search and review of publications cited by both researchers, and of relevant articles published in related peer-reviewed journals. Finally, HW obtained and analyzed 20 years of water quality monitoring data and fertilizer use on greens and fairways from a Cape Cod golf course, the Bayberry Hills golf course in Harwich, MA. This analysis showed a leaching rate under greens of approximately 14% in the first ten years of the golf course, and 26% in the subsequent ten years.

Nitrogen leaching rates reported in the literature ranged from 0% (Mancino et al., 1990) to 95% (Mancino et al., 1991), and were affected by a number of factors. Based on the information available, HW identified factors affecting nitrogen leaching, including grass type, establishment method, and maturity; soil type, content, and slope; nitrogen fertilization type, rate, and timing; and climate and water application. HW described the impacts of each of these factors on nitrogen leaching, as quantified by research documented in the reviewed publications.

After summarizing the impacts from grass, soil, fertilization, and climate conditions, HW compared the factors to conditions typical of the MEP embayments. Exact Cape Cod conditions were not replicated in the literature reviewed, and based on the importance of climate to leaching rates, HW narrowed the literature search to studies conducted in the states of Massachusetts, Connecticut, and New York. HW analyzed the leaching rate results for each relevant study to obtain one leaching rate representative of the study. The resulting average leaching rate across all studies is 13%. Studies representative of New England weather conditions span a variety of soil types. When considering leaching rate results from studies conducted only on sand, or loamy sand, as are likely to exist on Cape Cod and southeastern coast, the average leaching rate increases to 19%.

The results from the literature review, MEP Model assumptions, and Bayberry Hills golf course water quality data analysis suggest that the MEP leaching rate estimate of 20% is reasonable.

1.0 INTRODUCTION

1.1. PURPOSE OF THE STUDY

The leaching of nitrogen from fertilizer is one input in the nitrogen loading models used by the Massachusetts Estuaries Project (MEP) in their water quality assessments of 89 embayments in southeastern Massachusetts. The MEP has used a leaching rate of 20% in their modeling efforts, based on their review of the available literature. Recently, Dr. Martin Petrovic completed a report for the Pleasant Bay Alliance recommending a leaching rate of 10% for the conditions experienced on Cape Cod.

The Horsley Witten Group, Inc. (HW) was retained by the Massachusetts Department of Environmental Protection (DEP) to review existing information on leaching rates for nitrogen applied in turfgrass fertilizer and make a recommendation on an appropriate rate for use in the MEP assessments. The goal of this research is to determine if there is one leaching rate that is appropriate for the MEP assessments or if a range of values is more appropriate.

1.2. USE OF FERTILIZER LOADING RATES IN NITROGEN LOADING MODELS

Multiple nitrogen loading models have been used in southeastern Massachusetts to predict the impacts from land development on drinking water quality and coastal embayments. They include those developed by the Cape Cod Commission, the Buzzards Bay Project, the Waquoit Bay National Estuarine Reserve in Falmouth, Massachusetts (the Waquoit Bay model), and that used by the MEP. These models are based on the same premise. The loading from all sources of nitrogen are tabulated and diluted by the overall recharge of water to the underlying aquifer. The watershed sources of nitrogen in most scenarios include septic system discharges, lawn fertilization and road runoff. In some cases, the loadings from centralized wastewater treatment plants, landfills, agricultural activities and golf course or athletic field fertilization must also be taken into account.

The models developed by the Cape Cod Commission and the Buzzards Bay Project are used to predict impacts from future development and contain some conservative input values to account for future variation in land use activities. This is appropriate in a planning context where it is difficult to determine, or control, how someone's land use practices will change over time. MEP researchers believe the Waquoit Bay model under-predicts the impacts to coastal embayments based on their use of the MEP model's data to calibrate, and validate a water quality model for a case study embayment (MEP, 2001). The MEP model uses similar inputs to the Cape Cod Commission and Buzzards Bay Project with some changes to reflect actual, instead of conservative loading assumptions.

One goal of the MEP assessments is to predict how current nitrogen loadings from land within a coastal watershed affect the quality of water within the embayment. A detailed hydrodynamic and water quality model of each embayment is calibrated based on the inputs from all sources of nitrogen entering the embayment. Therefore, the loading values used to predict these nitrogen inputs must reflect current conditions. Some of the conservative assumptions used by the other models are inappropriate for this purpose.

Fertilizer use in most nitrogen loading models is the result of a number of assumptions, including fertilizer application and leaching rates, average lawn size, and the number of households that fertilize their lawns. Nitrogen loading models account for land use, and a distinction is likely to exist between recreational (e.g., golf course) use and other land uses (e.g., residential). Turf management for recreational areas is likely to vary across land uses (e.g., golf course vs. public park). Nitrogen leaching from fertilized lawns should be placed into perspective when compared to the significant loads from other land uses, in particular septic systems. A comparative study of nitrogen loading under various land uses (Gold et al., 1990) showed that the amount of nitrogen leaching from a fertilized lawn was on average four times greater than that of an unfertilized lawn or forested area, but was also on average ten times lower than that from septic systems on half-acre lots.

1.3. USE OF FERTILIZER APPLICATION AND LEACHING RATES IN THE MEP MODEL

The loading from turfgrass fertilizers is a function of both the amount of fertilizer applied on an annual basis and the rate at which it leaches to groundwater. Both are considered in the MEP modeling efforts.

The UMASS/Dartmouth School of Marine Science and Technology (SMAST) team used a survey methodology to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. Based on hundreds of individual interviews and thousands of site surveys, they determined that half of the residences did not apply lawn fertilizer (White, 2003), and that the weighted average application rate is 1.44 applications per year, rather than the 4 applications per year recommended by many fertilizer companies. The average residential fertilizer application rate was then applied a 20% leaching rate to obtain a nitrogen fertilizer contribution to groundwater of 1.08 pounds of nitrogen (lbs N) per residential lawn, with an assumed size of 5,000 square feet (s.f.). MEP Reports (SMAST/MEP, 2006) suggest that this nitrogen load from residential lawns may still represent a conservative estimate of nitrogen load. The survey (White, 2003) also noted that professionally maintained lawns had much higher fertilizer application rates, and hence higher estimated loss to groundwater of 3 lbs/lawn/yr.

In addition, for certain embayments, the MEP analyzed supplemental watershed-specific information (SMAST/MEP, 2004), such as fertilizer survey results for the Town of Orleans. The results of this survey showed a higher number of fertilizations per lawn in Orleans compared to Falmouth, Mashpee, and Barnstable: 1.76 versus 1.44. This was due to a very high number of homes serviced by commercial lawn companies (>30%), which tend to fertilize more frequently than individual homeowners. The overall survey results indicated a potentially higher nitrogen loading per lawn in Orleans of 1.51 lb/lawn/yr. This higher rate was not incorporated into the MEP Model due to uncertainties in the regional percentage of lawns maintained professionally; and to a sensitivity analysis that showed that applying the Orleans rate to the entire Pleasant Bay watershed would result in a nitrogen load change of less than 2%.

1.4. OVERVIEW OF THE REPORT

The analysis conducted by HW began with a review of both Dr. Petrovic's report for the Pleasant Bay Alliance and the MEP's evaluation of fertilizer leaching rates. The literature sources cited by Dr. Petrovic were examined, along with additional sources identified by HW. An annotated bibliography is provided in matrix format summarizing the information gathered from these sources, including information relevant to factors affecting nitrogen leaching, and leaching rates (Appendix A). HW also interviewed Dr. Brian Howes, the lead researcher for the MEP to discuss this issue in more detail. Finally, HW evaluated 20 years of water quality data from the Bayberry Hills Golf Course in Yarmouth, Massachusetts. Nitrogen data from lysimeter and monitoring well samples beneath golf course greens and fairways were coupled with fertilizer application data to estimate the long-term leaching of nitrogen underneath the course.

2.0 OVERVIEW OF INFORMATION SOURCES

In preparation of this report, HW gathered information sources in various formats, including literature sources (articles, theses, reports), data relevant to Cape Cod and southeastern Massachusetts conditions (Yarmouth golf course water quality monitoring data), and conversations with Dr. Brian Howes.

2.1. LITERATURE SOURCES

The Pleasant Bay Alliance Study (Petrovic, 2008) as provided in DEP's Request for Responses for this project, and online MEP reports were the first literature sources reviewed by HW. These initial sources led to other references relevant to fertilizer nitrogen leaching on Cape Cod and southeastern Massachusetts. HW located and reviewed most of these references. In addition, HW consulted turfgrass, nutrient, soil, and environmental publications, as well as the Woods Hole Oceanographic library for additional relevant sources. Literature sources for this report are described below, and listed in the References Section of this report.

2.1.1. Pleasant Bay Alliance Study by Dr. A. Martin Petrovic

In his report on fertilizer nitrogen leaching (Petrovic, 2008), Dr. Petrovic reviewed turfgrass nitrogen leaching literature to determine an appropriate fertilizer leaching rate for Cape Cod, MA. His literature search excluded sources relevant to warm-season grasses, which is appropriate given the climate on Cape Cod.

Dr. Petrovic grouped literature studies according to two land uses: golf and lawn. Within each land use, he separated field from greenhouse experimental conditions. For each combination of land use and experimental condition, he calculated an average across reported studies. Table 1 summarizes the study results by providing leaching rate ranges and averages for different land uses.

Table 1. Pleasant Bay Alliance Study Summary Results (Petrovic, 2008)

Land Use	Nitrogen Leaching Rate (% of nitrogen applied)		Number of Studies	Number of Reported Values
	Range	Average		
Golf	0-71%	13.3%	9	84
Lawn	0-95.1%	9.4%	20	218
All	0-95.1%	10.5%	29	302

Based on his report, it appears that Dr. Petrovic averaged leaching rates across all 302 values reported in his 29 literature sources. Not all research studies provide the same number of leaching values (i.e., data points). By averaging across all reported values, Dr. Petrovic is creating an artificially weighted average leaching rate for which studies reporting more values are given more weight than studies reporting a smaller number of leaching rates. Some studies report individual data points, while others report an average leaching rate for certain conditions, and the average across all 302 reported values may not provide a leaching rate representative of all studies. HW was unable to find all 302 reported values from the literature cited by Dr. Petrovic, and could not directly recalculate an average across these studies.

2.1.2. Pleasant Bay Alliance Study References

The Pleasant Bay Alliance report (Petrovic, 2008) describes 29 studies and lists 30 references in its bibliography, of which two references by Dr. Franck may be published from the same data. HW researched all 30 references, and was able to locate full publications for 23 of them, and abstracts for an additional 5 references, one of which described research conducted in Norway (Engelsjord, 1997), and is therefore less applicable. While not directly listed in the references for the study, HW also reviewed Dr. Petrovic's 1990 literature review article on turfgrass nitrogen leaching (Petrovic, 1990) described in the introduction to the Pleasant Bay Alliance report.

2.1.3. Massachusetts Estuaries Project Reports and Related Sources

HW accessed the online report repository for MEP embayment projects completed to date (http://www.oceanscience.net/estuaries/reports.htm) to determine nitrogen loading assumptions used in the MEP model developed in cooperation with SMAST. The MEP nitrogen loading calculations for fertilizer applications within each watershed separated residential lawns from recreational (e.g., golf) and agricultural (e.g., cranberry bogs) activities. Fertilizer applications on golf courses and other recreational areas were researched for each watershed. Residential lawn application assumptions were based on a survey assessing fertilizer use in the Towns of Falmouth, Mashpee and Barnstable, as well as supplemental watershed-specific information when available (e.g., Orleans-specific fertilizer application study).

Dr. Brian Howes, from SMAST was contacted to determine the source of the Falmouth/ Mashpee/Barnstable survey, as well as the supplemental Orleans data. The survey data came from a University of Rhode Island Master's thesis on *The Contribution of Lawn Fertilizer to the Nitrogen Loading of Cape Cod Embayments* (White, 2003), which HW was able to obtain and review. The Town of Orleans provided HW with a summary report (SMAST/MEP, 2004) regarding the Orleans-specific supplemental information. Relevant information from these sources is described under Section 1.3 of this Report.

2.1.4. Other Literature Sources

During the review of the references from the Pleasant Bay Alliance study (Petrovic, 2008) and MEP reports, HW took note of cited publications, and obtained and reviewed a copy when possible. HW conducted searches for the keywords "nitrogen" and "leach" in online archives and downloaded publications from a number of journals, including Acta Horticulturae, Crop Science, Journal of Environmental Quality, Journal of Soil and Water Conservation, United States Golf Association (USGA) Green Section Record, and USGA Turfgrass and Environmental Research Online. HW also reviewed references provided by the DEP in the context of this study.

After review of the publications described above, HW sorted them based on a number of criteria. Research conducted on warm-season turfgrass, or for which nitrogen leaching rates were not reported, were not included in this report, unless the publication provided evidence on impact factors to nitrogen leaching from turfgrass. HW reviewed more literature than is listed in the References Section. The References Section provides references for the literature cited in this report, and for which research results were used in developing the recommended leaching rate.

2.2. INTERVIEW OF DR. BRIAN HOWES OF SMAST

HW spoke with Dr. Brian Howes of SMAST to learn more about how a 20% leaching rate was selected for use in the MEP modeling efforts. According to Dr. Howes, it was based on a detailed evaluation of the available literature, which included a review of the Cape Cod Commission, Buzzards Bay Project and Waquoit Bay models.

Dr. Howes also pointed out that the leaching rate is only one factor that affects the overall load from nitrogen applied to turfgrass. The actual application rate is also significant as this has a direct result on the overall mass of nitrogen available for leaching. He directed us to a study of application rates (White, 2003) that has been used to develop the application rates used in the MEP model.

Finally, Dr. Howes discussed the overall impact of fertilizer loading rates relative to other sources of nitrogen in the MEP model. Leaching from turfgrass fertilizers is the second largest source of nitrogen from land-based sources, but falls far short of the loadings provided by septic systems. He mentioned that a variation in the leaching rate from turfgrass may not be all that significant given the variations in other nitrogen sources, such as the flux from benthic sediments, within an embayment that are also inputs to the MEP model.

2.3. DATA RELEVANT TO CAPE COD AND SOUTHEASTERN MASSACHUSETTS

In 1999, HW analyzed over 10 years of water quality data obtained from the Bayberry Hills golf course in Yarmouth, Massachusetts (Horsley & Witten, 1999) to determine an appropriate leaching rate for nitrogen applied to golf course turf. Water quality samples at the golf course were collected following a full-fledged monitoring program (Nash, 1998). Over the first 10 years of golf course operation, the average total nitrogen concentration was estimated at 3.85 milligrams per Liter (mg/L) and the leaching rate at 14%.

As part of this study, HW contacted the Bayberry Hills golf course to obtain additional years of water quality measurements. Data provided by the golf course include total nitrogen concentration measurements from samples obtained from lysimeters and groundwater monitoring wells under certain greens and fairways, as well as fertilizer application rates.

Based on lysimeter monitoring data collected under three greens between 2000 and 2008 (see Appendix B for data tables), total nitrogen concentrations ranged from 0.75 to 26.6mg/L across 64 data points, with an average concentration across the three greens of 6.42 mg/L. Only three of the 64 measurements were above 20 mg/L. Annual nitrogen application for these greens is 3.5 lbs N/1,000 s.f. To determine the leaching rate, HW assumed the same annual recharge rate of 27.25 inches per year as used in the MEP Report for the Three Bays (SMAST/DEP, 2006). The load (in lbs N/1,000 s.f.) divided by the recharge (in feet) corresponds to a concentration (lbs N/ 1,000 cubic feet) which can be converted into mg/L. The leaching rate is then calculated by taking the ratio of the average nitrogen concentration measured in leachate to the concentration of fertilizer applied. The average concentration across all three greens (6.42 mg/L) therefore corresponds to a leaching rate of approximately 26%, by using Equation 1.

Equation 1. Leaching Rate Calculation

$$LeachingRate(\%) = \frac{MeasuredConcentration(mg/L) * Recharge(feet) * 1{,}000}{LoadAppliedAsFertilizer(lbsN/1{,}000 s.f.) * 453{,}592 * 0.0353} * 100$$

If the average for each green is calculated on an annual basis (i.e., average across all data points in a given year prior to averaging across years), the average concentration across all greens is very similar: 6.61 mg/L, and corresponds to a leaching rate of approximately 23.5%. Both methods of analyzing the data are very similar, and produce leaching rate discrepancies of less than 1%.

The concentrations measured in the lysimeters under three golf greens at the Bayberry Hills golf course are not unreasonable for a golf green turf. A study of nitrate concentrations in lysimeter leachate collected after natural storm events on 16 outdoor golf greens with various organic amendments (Boniak et al., 2005) found nitrogen concentrations up to 313 mg/L for a newly established green after the first storm, and exceeding 16 mg/L thereafter. A short-term pesticide and nutrient leaching study of and experimental fairway turf (Petrovic, 1995) also found average concentrations under fairways ranging from 3.5 to 6.6 mg/L, with two of the study's 1,385 samples exceeding the 10 mg/L drinking water standard for nitrate.

Analysis of water quality data for three fairways (see data in Appendix B) shows total nitrogen concentrations ranging from 1.1 to 59 mg/L across 65 data points, with only three measurements above 20 mg/L. Average concentration across the three fairways is 7.14 mg/L. Annual nitrogen application for these fairways is 3 lbs N/1,000 square feet. Assuming a recharge rate of 24 inches per year, and using Equation 1, the average concentration across all three fairways corresponds to a leaching rate of approximately 33.8%. Calculating the average for fairways on an annual basis reduces the concentration to 6.83 mg/L, for a leaching rate of 32.2%, a difference on the order of 1%. Table 2 provides concentrations and leaching rates representative of three greens and three fairways at the Bayberry Hills golf course.

Table 2. Nitrogen Leaching under Greens and Fairways at the Bayberry Hills Golf Course

Calculation Method	Green		Fairway	
	Concentration (mg/L)	Leaching Rate (%)	Concentration (mg/L)	Leaching Rate (%)
Overall Average	6.42	26	7.14	33.8
Annual Average	6.61	26.9	6.83	32.2
Median	4.18	16.9	4.40	20.8

At the Bayberry Hills golf course, the largest and smallest concentration measurements may be the result of short-term weather-related conditions not representative of the overall year. By calculating the median concentration, nitrogen leaching rates for the greens and fairways decrease to 16.9 and 20.8% respectively, but are still above the 1999 14% estimate. It should be noted that median concentrations across measured data points were never reported in the literature, only average concentrations across measurements. The increase in nitrogen leaching over time at the Bayberry Hills golf course is in agreement with other studies' similar results for aging fertilized turfgrass. A USGA study (Frank et al., 2006a) showed nitrogen concentrations in leachate increasing from a mean of 2.6 mg/L to 4.8mg/L over five years of sampling at the "low" fertilizer application rate of 2 lbs N/ 1,000 s.f./ year; and increasing from a mean of 5.0 to 25.3 mg/L over five years of sampling at the "high" fertilizer application rate of 5 lbs N/1,000 s.f./year.

3.0 FACTORS THAT AFFECT NITROGEN LEACHING FROM TURFGRASS MANAGEMENT PRACTICES

Turfgrass, like other crops, is part of an ecosystem including the crop itself, the soil, microbial activity, water, and the atmosphere. After application of a nitrogenous fertilizer, the presence of nitrogen can be expected in all elements of the turfgrass ecosystem. The intent of fertilization is plant uptake, but nitrogen can also be released to the atmosphere in the form of nitrogen gas (N_2), ammonia (NH_3), or nitrous oxide (N_2O); stored in the soil or thatch layer; and lost in leaching and surface runoff which can contribute to groundwater contamination and surface water eutrophication. Mass balance and a number of factors dictate the proportion of applied fertilizer reaching turfgrass ecosystem elements. For example, a greenhouse experiment, (Horgan et al., 2002) measured labeled nitrogen recovered in all elements of the turfgrass ecosystem, and found diurnal variability in gas emissions, and seasonal variability in the distribution of labeled nitrogen across turfgrass ecosystem elements and soil depth.

While this study focuses solely on nitrogen leaching from fertilization, the fate of nitrogen within the ecosystem provides valuable information on factors influencing the ecosystem, and therefore nitrogen leaching. These factors include: crop type and maturity; soil type, content and slope;

microbial activity; nitrogen fertilization type, rate, and timing; and climate and water application (e.g., temperature, precipitation, and irrigation).

3.1. Grass Type and Maturity

Three main factors associated with the crop itself (i.e., turfgrass) affect nitrogen leaching: the type of turf (species, and cultivars or genotypes), its establishment method (seeding vs. sodding), and its maturity (e.g., density of the root system).

A greenhouse experiment (Paré et al., 2006) simulated a golf green profile using materials in the root zone mixture selected to meet standards of a golf green profile as stipulated by the U.S. Golf Association. This experiment was conducted with 11 cultivars of annual bluegrass, and three cultivars of bentgrass, and showed lysimeter leaching rates ranging from 6 to 71% across all cultivars, with lower rates for bentgrass (6-11% with an average of 9.0%) than bluegrass (28-71% with an average of 46.9%) cultivars. It also showed that nitrogen uptake by the crop was positively correlated to total biomass (clippings, shoots, and roots), and negatively correlated to leaching: the more nitrogen is absorbed by the crop, the larger it is and the lower its leaching rate. The researchers determined that the more extensive root development for bentgrasses compared to annual bluegrasses was critical to reducing nitrogen leaching.

A field experiment (Liu et al., 1997) conducted over two years for ten cultivars of three different species (Kentucky bluegrass, perennial ryegrass, and tall fescue) also reported much variability across turf species: up to fivefold variability within the same turf species. Average leaching rates were as follows:

- Kentucky bluegrass: 7% in year 1; 14% in year 2, with much variability (up to five fold) and up to 30% leaching for one of the cultivars;
- Perennial ryegrass: 2% in year 1; 4.8% in year 2, varying from 1.5 to 14%; and
- Tall fescue: 0.8% in year 1; 1.4% in year 2, with much variability (up to five fold).

Arguments for explaining the discrepancies across species and cultivars include the variability of root characteristics for the turf. A study of two creeping bentgrass genotypes differing in rooting characteristics (Bowman et al., 1998) showed that deep-rooted turfgrass absorbs nitrogen more efficiently than shallow-rooted turfgrass. This study reported cumulative leaching rates averaged across three irrigation practices of 18 and 38.2% for deep and shallow-rooted genotypes respectively.

A related study (Geron et al., 1993) compared sodded and seeded Kentucky bluegrass leaching rates, and determined that the establishment method affects nitrate concentrations and total nitrogen loss. After the establishment period, more nitrogen leaching was observed from sodded plots than seeded plots. At the end of the study, root mass measurements were greater for seeded than sodded plots, which suggest that nitrogen leaching differences may be due to differences in root depth and mass.

Some studies seeking long-term nitrogen leaching rate estimates distinguish the establishment period of turfgrass from the rest of the study, because it is the period with the most leaching. For example, a two-year study of various nitrogen sources fertilizing Kentucky bluegrass and perennial ryegrass (Easton et al., 2004) showed that total nitrogen losses were significantly reduced after establishment. Some studies do not report on data collected during the establishment period (Mangiafico et al., 2006), while others are conducted on already established turf.

The establishment period represents a small fraction of the average turf's life, but it is also the time during which turfgrass is the most prone to leaching. When assessing long-term leaching rates, leaching rates during establishment should not be overlooked. This is even more applicable when considering turf managers' observed tendency to over-fertilize during the establishment period, especially for golf courses, where highly soluble nitrogen sources are applied at almost twice the regular application rate (Bigelow et al., 2003).

Finally, turf maturity is an important factor in estimating nitrogen leaching rates, and some researchers recommend fertilizing older turfs at reduced nitrogen rate to minimize nitrogen leaching (Frank et al., 2006b). This factor was also discussed under Section 2.3 when comparing nitrogen leach rates at the Bayberry Hills golf course between the first ten years of golf operation, and the past ten years.

For mature turf, nitrogen may leach from the soil itself, despite the lack of recent fertilization. A study of 12-year old turf plots (Jiang et al., 2000) showed leaching from soil with no recent fertilization, with 2% of soil nitrogen content leached from a healthy turf, and 7% soil nitrogen leaching for turf following sudden death after herbicide application. A study of the fate of labeled nitrogen applied to Kentucky bluegrass (Horgan et al., 2002) found similar results where labeled fertilizer nitrogen leaching was four times greater for bare soil than for turfgrass. Soil is therefore an important component of the turfgrass ecosystem, and its characteristics affect nitrogen leaching.

3.2. SOIL TYPE, CONTENT, AND SLOPE

Studies have found nitrogen leaching to vary based on soil type or texture (e.g., sand, loam), content (e.g., organic matter), and slope.

A study of nitrogen leaching from sand and modified sand (with 10% sphagnum peat) putting greens (Brauen et al., 1995) showed that leaching rates from pure sand were significantly higher (up to one order of magnitude) than for sand modified with peat under various nitrogen application rates. Leaching rates in that study ranged 0.04-7.55% for sand, and 0.02-3.37% for modified sand. Another field study (Petrovic, 2004) compared nitrogen and labeled nitrogen leaching for three soil types: sand, sandy loam, and silt loam seeded with creeping bentgrass. Table 3 shows the soil properties and leaching results.

Table 3. Nitrogen and Labeled Nitrogen Leaching for Three Soil Types (Petrovic, 2004)

Soil	Sand (%)	Silt (%)	Clay (%)	Organic Matter (%)	Total N in leachate (%)	^{15}N in leachate (%)
Sand	97	0	3	0.8	1.5	1.4
Sandy loam	64	25	11	4.4	3.1	2.3
Silt loam	30	52	18	5.8	9.1	15.4

Leaching rates for total nitrogen and for labeled nitrogen (last two columns in Table 3) are not identical, because they are measures of different compounds. Labeled nitrogen is almost inexistent in the turfgrass ecosystem prior to application of labeled nitrogen fertilizer. The labeled nitrogen leached is therefore only from fertilizer application. Total nitrogen leached, however, may include nitrogen that was already available for leaching (e.g., in the soil) prior to fertilizer application.

Organic matter in soil is correlated with nitrogen leaching of certain types of fertilizers, because it changes the potential for denitrification. In a study of thatch influence on nitrogen mobility (Nelson et al., 1980), fertilization with urea resulted in 2.5 times as much nitrogen leaching from thatch than soil. For slower release nitrogen sources, thatch leaching was reduced from 81 to 5% of the applied N. Volatilization results from the study showed that 39% of urea nitrogen was lost as ammonia from thatch cores compared to only 5% from soil cores.

A greenhouse study of nitrate leaching from Kentucky bluegrass (Mangiafico et al., 2006) showed that soil nitrate available for leaching decreases with microbial immobilization, and increases with mineralization of nitrogen-bearing organic matter. The researchers recommended that available soil nitrate could serve as a better indicator for potential nitrogen leaching than nitrogen application rates.

A thatch layer may serve as storage for organic nitrogen forms. Fate studies of a single ^{15}N application made either in late fall or early spring to a Kentucky bluegrass over fine sandy loam (Branham et al., 1993, Branham et al., 1996), found that the amount of ^{15}N in the thatch layer exceeded 25% of the nitrogen applied in the first year for both fertilizer application dates.

However, organic amendments to sandy soil do not prevent nitrogen leaching. A study of nitrate concentrations in leachate collected after natural storm events on 16 outdoor golf greens (Boniak et al., 2005) amended with various organic amendments (including sphagnum peat moss, treated steer manure) found nitrogen concentrations up to 313 mg/L after the first storm, and a few in excess of 16 mg/L thereafter.

In addition, older turfs with accumulated organic matter are subject to nitrogen leaching. In a 1980 study, Porter et al. (in Frank et al., 2006b) examined total nitrogen content in soil for 105 turfgrass ecosystems ranging in age from one to 125 years, and hypothesized that soil organic matter accumulation is rapid in the first 10 years after establishment, and slowly builds to an equilibrium at 25 years, when no further net immobilization of nitrogen occurs.

Finally, turfgrass slope directly impacts the amount of water infiltrating into the ground, with higher slopes leading to higher runoff and lower infiltration. For topical fertilizer application, soil slope can therefore directly affect the amount of nitrogen leaching, as opposed to nitrogen in surface water runoff. For example, the leaching rates ranging from approximately 1 to 40% across a two-year study of various nitrogen sources fertilizing Kentucky bluegrass and perennial ryegrass (Easton et al., 2004) on a 7-9% sloped terrain could differ under less sloped experimental conditions.

3.3. NITROGEN FERTILIZATION – TYPE, RATE, AND TIMING

Nitrogen fertilization characteristics, such as fertilizer type, application rate and timing, and clippings management are key factors to control nitrogen leaching.

Nitrogen fertilizer is available in solid and liquid form, organic and inorganic form, and can be grouped into instantaneous and delayed (slow) release types. A study comparing soluble (urea) and slow release (coated urea, biosolid) late fall fertilizer applications in sandy coastal areas (Petrovic, 2004) showed leaching rates of 29-47% of applied urea, and much lower rates of nitrogen from slow release sources (0-12%). Another study comparing nitrogen leaching rates of fast- and slow-release nitrogen sources applied to a mix of three cool season turfs (Guillard & Kopp, 2004) found large differences across nitrogen sources. Leaching rates for this study were reported as follows: ammonium nitrate: 16.8%; coated urea: 1.7%; and organic product: 0.6%.

Nutrient uptake by turfgrass is limited, and excessive fertilization will lead to nutrient assimilation by other elements of the turfgrass ecosystem, including leachate. The application rate of nitrogen fertilizer is therefore an important factor influencing nitrogen leaching from turfgrass. A recent study of nitrogen leaching from natural fertilizer sources and rates (Easton et al., 2004) showed that doubling single fertilizer application rates from 50 to 100 kg N/hectare (approximately 1 to 2 lbs N/1,000 s.f.) increased nitrogen leaching by 50 to 300% during the first year following establishment for all nitrogen sources, except swine compost. Another comparative study of light to moderate nitrogen fertilizer applications (Mancino et al., 1990) monitored leaching over ten weeks at very low and frequent fertilization application rates (9.76 kg/ha, or 0.2 lbs/1,000 s.f. every 7 days) and over 11 days after a single application of 48.8 kg N/ha (1 lb N/1,000 s.f.). The study reported almost no leaching at the low fertilization rate, and significantly more leaching for the higher single application. These results show the relevance of fertilization timing for leaching rates, and that more frequent applications at very low rates are preferable to single applications at higher rates to avoid leaching.

Timing can be measured in terms of application frequency, but also in terms of application time relative to the growing season. A one-year study comparing the fate of nitrogen applied in the spring, summer and fall (Roy et al., 2000) showed that fertilizer applied during the fall was dissolved and rapidly transported with the infiltrating water. Another three-year study, including a first year of establishment period (Mangiafico et al., 2005), compared leaching rates for mid-September to mid-December fertilization dates in Connecticut. Leaching rates were found to linearly increase with the application date. The researchers recommended adjusting fall fertilization to account for residual available soil nitrate from previous applications and mineralization, especially in soils of high organic content.

A study across three New York sites of different soil properties (Petrovic, 2004) compared average annual nitrogen leaching between a single late fall application, and two to four "non-late fall applications" across various nitrogen sources. Nitrogen leaching for "non-late fall" applications during a normal precipitation year ranged from 0.5 to 7.4%, depending on fertilizer source. The range widened to 0 - 47% when fertilizer was applied at the end of the growing season.

Fertilization management seeks to optimize nutrient application to maximize uptake by the crop. Nitrogen and other nutrients are therefore present in turfgrass clippings, and may contribute to nitrogen leaching following microbial mineralization. Dr. Petrovic's 1990 literature review indicated that returned clippings allow 25 to 50% of fertilizer nitrogen to recycle in the turf-soil system. At equal fertilization rates, if clippings are returned, they may increase the local leaching rate, as demonstrated in a greenhouse study of creeping bentgrass (Kopp, Guillard, 2005). Under standard irrigation treatment, nitrogen leaching rate ranges increased from 0.9-7.6% with clippings removed to 12.8-23.6% with clippings returned to the turf. Most publications reviewed for this study reported on clipping management.

3.4. CLIMATE AND WATER APPLICATION

Plant uptake of nutrients and leaching rates for established and mature turfgrass vary during seasons. On a golf green experiment (Johnston et al., 2001), the highest quantity of leaching occurred in late autumn and early spring when flow was high and growth was minimal. A study of nitrate leaching from sand and sand/peat putting greens (Brauen et al., 1995) also observed no nitrate leaching during the summer through mid-fall, but significantly higher leaching rates during winter months under various nitrogen application rates. Data collected in a Storrs, CT experiment (Guillard & Kopp, 2004) indicated similar results. More water infiltrated past the root zone during the winter and early spring months, and contributed a significant portion of the annual nitrate leaching. Researchers recognized the importance of continuous sampling in turf leaching studies during all seasons.

Due to the high variability in seasonal leaching rates, continued nitrogen leachate sampling during all seasons influences the measured leaching rate. In a one-year study comparing the fate of nitrogen applied in the spring, summer and fall (Roy et al., 2000), very little, if no, nitrogen leaching was measured until October, but by early winter, over 16.5% of applied nitrogen had leached. Researchers noted that higher evapotranspiration rates during the summer season can result in virtually no drainage of water past a certain soil depth. Nitrogen leaching can therefore be limited by the flow of water below the rootzone. When sampling for this study ceased, measured nitrate concentrations in the lysimeters exceeded 200 mg/L. Researchers suggested that nitrogen remaining in the soil could be washed out in the late fall/early winter in a single pulse that may be difficult to detect.

A Kingston, RI nitrogen mobility study in mature turf (Jiang et al., 2000) showed that over 50% of nitrogen leaching occurs between November and March for both healthy turf, and turf following "sudden death" from herbicide application. Therefore, climate has a significant impact on fertilizer leaching rates.

Denitrification is an anaerobic and temperature-dependent process, during which elevated temperatures may lead to larger atmospheric emission rates (Horgan et al., 2002). Fertilizer nitrogen released to the atmosphere by denitrification is no longer available for leaching. Temperature of the soil and environment during fertilization is likely to impact the amount of fertilizer lost to denitrification, and therefore the amount of nitrogen leached. The research reviewed for this study did not provide evidence of the effect on nitrogen leaching rates of temperature variations alone, but two studies (Duff et al., 1997; and Mangiafico et al., 2005) showed that the combination of water application and temperature variations has a direct impact on nitrogen leaching. The second study (Mangiafico et al., 2005) determined that high temperature and precipitation variability could result in high leaching variability. Leaching rates for the first year (warmer, +3.5 ºC, and drier than normal, -46% precipitation) ranged from 1.6 - 16.8%. This range increased significantly to 29.1-66.1% during the second year, which was representative of "normal" conditions, with average temperature and precipitation within 1º C and 1%.

Water is another environmental factor affecting nitrogen leaching rates. Its application rate and frequency directly affect leaching through infiltration of precipitation and irrigation water. A simulated urban lawn experiment recording nitrogen movement through the unsaturated zone (Exner et al., 1991) showed that frequent irrigation in large amounts (overwatering) can cause nitrate fertilizer to move rapidly below the root zone, and potentially reach groundwater. A study of nitrate leaching from sand and sand / peat putting greens (Brauen et al., 1995) showed significantly lower leaching rates (0.02 to 1.26%) in the year with the lowest precipitation than in the other year (0.16 to 4.28%). A third study of Kentucky bluegrass under light and heavy irrigation regimes (Starrett et al., 1995) showed that a single heavy irrigation application generated five times more leaching than the same irrigation volume separated in four applications. Finally, a Kingston, RI study (Morton et al., 1988) showed that overwatering could significantly increase nitrogen leaching, especially for turf with higher fertilization rates (5 lbs N/1,000 s.f.).

Most studies did not report nitrogen concentration in irrigation or precipitation water because they used unfertilized (control) plots to account for other nitrogen sources, but its impact to leaching rates should not be ignored. A 34-day study in the Midwest (Exner et al., 1991) reported that the uniform nitrate levels observed in the upper ten feet of the unfertilized plot were consistent with the 8 mg/L nitrate concentration of the irrigation water from the municipal supply.

Finally, the timing of water application (irrigation or precipitation) relative to fertilization is the last additional water-related factor proven to affect nitrogen leaching rates. In a greenhouse creeping bentgrass genotype comparison study (Bowman et al., 1998), researchers demonstrated that delayed irrigation after fertilization (1, 3, and 5 days) decreased nitrogen leaching, and greater irrigation resulted in greater leaching for both shallow- and deep- rooted turfgrass. The exact genotypes were not provided in the research publication, but were described as "shallow-rooted" and "deep-rooted." Results for this study are reported in Table 4.

Table 4. Cumulative Nitrogen Leached from Two Genotypes of Creeping Bentgrass with Delayed Irrigation after Fertilization (Bowman et al., 1998)

Delayed irrigation after fertilization (days)	Cumulative Nitrogen Leached (% of applied nitrogen)	
	Shallow-rooted genotype	Shallow-rooted genotype
1	16.7	4.7
3	4.5	0.2
5	2.0	0.1
Mean	7.7	1.7

4.0 SYNTHESIS OF LITERATURE DATA ON NITROGEN LEACHING RATES

Nitrogen leaching rates reported in the literature reviewed for this study ranged from 0% (Mancino et al., 1990) to 95% (Mancino et al., 1991), with a number of factors affecting these rates. This Section provides a summary of these factors, and how they affect leaching rates, and compares them to Cape Cod conditions.

4.1. SYNTHESIS AND SUMMARY OF FACTORS AND RESULTS REPORTED TO AFFECT VARIATIONS IN LEACHING RATES

Factors affecting nitrogen leaching rates, and their qualitative impact on nitrogen leaching are summarized in Table 5.

Table 5. Summary of Nitrogen Leaching Factors and their Impacts

Factor		Impact on N Leaching
Grass	Type	N leaching variability is very large across species and cultivars of cool-season turfgrass. Within the same study, leaching rate variability of up to tenfold was reported (Paré et al., 2006).
	Establishment	N leaching for non-established turfgrass can be orders of magnitude greater than for established turfgrass. The time-frame for this impact is limited to the first few months to a year of turf growth.
	Maturity	About a decade after the establishment period, soils under fertilized turfgrass become saturated in nutrients, and nitrogen leaching may start to increase.
Soil	Type	Variability across soil type can span an order of magnitude, with sandy soils showing the highest leach rates.
	Organic content	May provide a nitrogen sink, and nutrient source for turfgrass, depending on fertilization and climate.
	Slope	No direct measurement of the impact of slope on nitrogen leaching was found within the literature reviewed, but slope directly impacts runoff, and may reduce nitrogen availability for leaching.
Nitrogen Fertilization	Type	Slow release nitrogen showed lower nitrogen leaching rates than other types of fertilizer. Variability across nitrogen fertilizer type is very large (an order of magnitude in leaching rates for certain studies).
	Rate	Frequent fertilization at very low rates (e.g., 0.2 lbs N/1,000 s.f.) showed very little leaching, while higher fertilization rates showed a very wide range of nitrogen leaching rates across studies.
	Timing	Seasonal timing, and frequency greatly affect leaching rates. Late fall applications have been shown to cause increased nitrogen leaching.
	Clippings	Differences in clippings management increase the variability of leaching rates significantly. Returning clippings to the turf is a source of nitrogen, and should be taken into account when determining the amount of fertilizer required.
Time of Year	Season	Seasons are particularly important for nitrogen leaching management, and fertilization should be avoided outside the growing season. Monitoring nitrogen leaching across all seasons also has a direct impact on the measurements.
	Temperature	Temperature impact was not directly measured in the publications reviewed, but it is directly related to the seasonality of nitrogen leaching rates.
Water Application	Rate	Overwatering can increase nitrogen leaching rates.
	Timing relative to fertilization	The longer the time between fertilization and irrigation or precipitation, the lower the leaching rate, because the additional time provides an opportunity for nitrogen uptake by the plant.
	Nitrogen Concentration	Only one study reported nitrogen concentration in irrigation water, at a rate of 8 mg/L. This may be an important factor, particularly for irrigation with wastewater reuse water.

4.2. COMPARISON OF THESE FACTORS AND RESULTS TO CAPE COD CONDITIONS

The literature summary provided in Appendix A compiled information on a number of factors affecting turfgrass. Turfgrass species and cultivars thriving on Cape Cod and the South Coast are unlikely to include warm-season turfgrass cultivars. The studies reviewed for this report were therefore restricted to cool-season turfs. The exact species and cultivars used across Cape Cod vary, but grass type for each study was recorded. Given the importance of the establishment period and root density to leaching rates, Appendix A also recorded the maturity of the turf, including whether the study results included the establishment of newly seeded turf.

In terms of soil characteristics, Cape Cod soils are mostly sandy, especially within most coastal watersheds known to be sensitive to nitrogen impacts. They may be amended with organic content, either intentionally by the turf manager, or over time as the turf ages. Most of the Cape is flat, and slope would not be a factor very relevant to local conditions.

A survey of certain Cape Cod towns (White, 2003) found that not all residents fertilize their lawns, and that the average application rate is lower than was previously thought. Nitrogen application timing information specific to Cape Cod was not found. Where clippings are concerned, if clippings are removed from a particular turf area, where are they disposed of? Would the clippings be disposed within the same yard, or watershed? If that is the case, higher leaching rates to account for nitrogen release from the clippings may be appropriate.

Given the importance of the climate factor to leaching rates, it may be relevant to limit the pool of studies to locations with similar weather to the Cape so as to approximate climate conditions and irrigation needs. None of the publications reviewed were exactly representative of overall Cape Cod conditions, and an average across studies may be more appropriate to recommend a nitrogen leaching rate.

5.0 LEACHING RATE RECOMMENDATIONS FOR CAPE COD AND THE SOUTHEASTERN COAST

Exact Cape Cod conditions are not replicated in the literature reviewed. To average local conditions, a sub-set of the full publication results may need to be selected. HW first selected experimental sites located in the northeast only (NY, MA, CT) to approximate similar precipitation and weather conditions, which are very important factors. In addition, the study focusing on nitrogen leaching from soil content (Jiang et al., 2000) was not taken into account, and neither were the results of the study limited to periods of 11 days to ten weeks (Mancino & Troll, 1990) as it does not capture annual leaching and is not representative of long-term nitrogen fertilizer effects on nutrient loads to embayments.

In the Pleasant Bay Alliance Study, Dr. Petrovic averaged nitrogen leaching rates across all data points from his bibliography. As discussed in Section 2.1.1, the resulting nitrogen leaching rate is artificially weighted towards studies providing more data points. HW created an average leaching rate for each study directly relevant to the Cape Cod weather pattern. The resulting average leaching rate across all studies is 13%. This average rate can be further subdivided between studies removing clippings (11.1%) or returning clippings (22.7%). It should be noted that not all studies reported on clippings management.

Studies representative of New England weather conditions span a variety of soil types. When considering leaching rate results from studies conducted only on sand, or loamy sand, as are likely to exist on Cape Cod and the South Coast, the average leaching rate increases to 18.8%.

Leaching rates measured from the Bayberry Hills golf course (Section 2.3) averaged 14% for the first ten years, and above 20% for the subsequent ten years, with a median between 16.9% and 20.8%. These leaching rates are consistent with the 13% leaching rate average across studies with similar weather patterns, and the 18.8% average over studies on predominantly sandy soils.

The MEP Model accounts for a fertilizer application rate on Cape Cod lawns adjusted to account for survey results of local residential fertilizer practices. Data from the Town of Orleans (SMAST/MEP, 2004) showed that some towns on Cape Cod may apply more fertilizer than was estimated by the initial three-Town survey (White, 2003). A 20% leaching rate is then applied to the reduced fertilizer load to compute a total nitrogen load for the watershed.

Based on the literature review, the Bayberry Hills golf course data analysis, and MEP Model assumptions for nitrogen fertilizer applications, HW would recommend keeping the current 20% leaching rate for turfgrass.

6.0 CONCLUSIONS

Based on the information reviewed as part of this study, and described in depth in Section 2.1, leaching rates ranged from 0% (Mancino et al., 1990) to 95% (Mancino et al., 1991). When narrowing the studies to climate conditions similar to those encountered in the Cape Cod and South Coast watersheds under review by the MEP, HW calculated a 13% nitrogen leaching rate. When only studies with sandy soils were considered, as expected in the MEP coastal watersheds, the nitrogen leaching rate increased to 18.8%. Nitrogen leaching rates calculated from lysimeter water quality data collected over 20 years on a Cape Cod golf course were of the same order of magnitude. A sensitivity analysis of the MEP Model applied to the Pleasant Bay watershed, as described under Section 1.3 showed that a nitrogen load increase to lawns of 40% (from 1.08 to 1.51 lbs N/lawn/year) resulted in a nitrogen load change of less than 2% for the embayment. HW therefore believes that given nitrogen loading results for studies closest to Cape Cod conditions, the use of the nitrogen rate by the MEP Model, and its limited sensitivity to nitrogen loading to lawns, a 20% nitrogen loading rate is adequate for the Model.

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Appendix A - Nitrogen Fertilizer Leaching Rate from Turfgrass Literature Summary

Title	Author(s)	Year	Journal	Purpose / Objectives	Conditions										Results	
					Grass		Soil		Fertilization			Irrigation	Field / greenhouse	Location	Leaching Rate (s)	Comments
					Type	Age		Slope	Type	Rate	Clippings					
Root Architecture Affects Nitrate Leaching from Bentgrass Turf	Bowman, Devitt, Engelke, Rufty	1998	Crop Science Society of America	Examine the effects of rooting depth and density on NO3 leaching from creeping bentgrass turf.	2 types of creeping bentgrass, shallow and deep-rooted	4 months	Medium / coarse washed sand		Ammonium nitrate	50 kg N/ha	Removed	Exp.1: 1, 2 & 3 cm/day, starting 1 day after fert. Exp.2: 2 cm/ 1-2 days, starting 1, 3, and 5 days after fert.	Greenhouse	Reno, NV	Exp.1: Shallow root: 33.8, 38.9, & 41.9% for 1, 2, & 3 cm/day Deep root: 14.5, 18.6, 22.4% for 1, 2, & 3 cm/day Exp.2: Shallow root: 17, 4, & 2% for 1, 3, & 5 day delay Deep root: 5, 0.2, and 0.1% for 1, 3, & 5 day delay	Deep-rooted turf absorbs N more efficiently than shallow-rooted turf, with similar turf densities.
Groundwater Contamination Potential of Pesticides and Fertilizers Used on the Golf Course	Branham	1993	United States Golf Association (USGA) Green Section	Monitor the movement of pesticides and fertilizers through soil and their potential to contaminate groundwater.	Kentucky bluegrass	Already established	sandy loam		urea	single application at 0.8 lb N/1,000 ft2 enriched with 25% 15N, two timings (early spring, late fall)		Yes, immediately after fertilization			spring application: 0.01% of 15N fall application: 0.005% of 15N	Thatch layer is important to the fate of N applied to turf. In both treatments, the amount of 15N in the thatch represents 25% of applied N. There may be long term build up of N in the soil. Most of the 15N found in the soil is in the top 5 cm layer.
Leaching of Nitrate from Sand Putting Greens	Brauen, Stahnke	1995	United States Golf Association (USGA) Green Section	Quantify the effect of rooting medium, fertilization interal, and annual nitrogen rate on nitrate nitrogen leached from creeping bentgrass putting greens.	Creeping bentgrass	New (includes establishment) to 1-year old	pure sand, or sand-peat-silt loan (88, 10, 2)		granular ammonium sulfate, ammonium phosphate, isobutylidene fiurea, sulfur-coated urea, and methylene urea	4, 8, 12 lb N/ 1,000 s.f./year in 11 applications from Feb to December				Puyallyp, WA (south of Seattle)	Sand 4 lb/1000sf: 0.06 - 5.37% 8 lb/1000sf: 0.04-6.31% 12 lb/1000sf: 0.7-7.55% Modified (sand/peat) 4 lb/1000sf: 0.16 - 0.33% 8 lb/1000sf: 0.02-0.91% 12 lb/1000sf: 1.26-3.37%	Precipitation was much lower in the year with the lowest N leaching results. Variations in leaching could be related to variations in precipitation. 4 lbs N/1,000 sf is insufficient to support nentgrass or bluegrass in putting greens. "Applying N fertilizers with at least 70% of the nitrogen source in slow-release form on a frequent interval such as every 14 days provided excellent protection from nitrate leaching."
Nitrate Leaching from Long Established Kentucky Bluegrass Turf *	Duff, Liu, Hull, Sawyer	1997	International Turfgrass Society Research Journal		Kentucky bluegrass	Long established			Urea	0, 10.3, 18.0, and 25.7 g/ m2/ year in 5 factional treatments	Harvested monthly			RI		Efficiency of fall N fertilizer application may be low because of abundance of nitrate in soil. Temperature and rainfall affect nitrate leaching from established turf.
Fertilizer Source Effect on Ground and Surface Water Quality in Drainage from Turfgrass	Easton, Petrovic	2004	Journal of Environmental Quality	Determine (1) if fertilizer properties and rate affect ground and surface water quality in drainage from turfgrass, and (2) what other factors can affect surface and ground water quality.	Mixed Kentucky bluegrass (80%) and perennial ryegrass (20%)	New (establishment) - 2 years	Arkport sandy loam	7-9%	compost and biosolid (natural organic), and urea and sulfur coated urea (synthetic organic)	Total: 200 kg N/ha/year 50 and 100 kg N/ha in 4 and 2 applications.	Removed	5 mm			Approximately (extrapolated from graph): 1.5-40% depending on fertilizer source and rate.	The establishment period has the highest nutrient leaching losses (12 - 80%). "Long term repeated use of natural organic sources could result in massive amounts of P and N being stored in the soil, eventually being released and subject to runoff and leaching losses."
Effects of Slow-Release Fertilizers on Growth and on Uptake and Leaching of Nutrients in Kentucky Bluegrass Turfs Established on Sand-Based Root zones *	Engelsjord, Singh	1997	Canadian Journal of Plant Science	Determine the effect of slow-release and water-soluble fertilizers on growth, nutrient uptake and leaching from a sandbased Kentucky bluegrass turf.	Kentucky bluegrass		Sand-peat mix: 80:20 and 60:40		Coated, and water soluble "NPK" treatment	Frequent application with water soluble, or spring application with slow-release				southern part of Norway	1.1 - 2.9 %	Outside the U.S. (Norway)

Title	Author(s)	Year	Journal	Purpose / Objectives	Conditions										Results	
					Grass		Soil		Fertilization			Irrigation	Field / greenhouse	Location	Leaching Rate (s)	Comments
					Type	Age		Slope	Type	Rate	Clippings					
Deep Nitrate Movement in the Unsaturated Zone of a Simulated Urban Lawn	Exner, Burbach, Watts, Shearman, Spalding	1991	Journal of Environmental Quality	Record deep NO3 movement under fixed irrigation with variable N application rates.	Kentucky bluegrass and creeping red fescue	Existing (no establishment)	Bayard fine sandy loam		Ammonium nitrate NH4NO3	Fertilizer alone: 0, 1, 1.5, 2, and 2.4 kg N/100 m2 (2-5 times recommended use) Total irrigation adds ~0.5 kg N/100 m2		Starting immediately after fertilization: 51 mm every 3rd day, total of 640 mm over 34 days	Field	Sidney, NE	1 kg N/100 m2: 90% 1.5 kg N/100 m2: 93% 2 kg N/100 m2: 95% 2.4 kg N/100 m2: 83%	Uniform 8mg/L NO3-N levels in the upper 3m of unfertilized plot reflective of municipal water supply. Frequent application of excess water caused N03 fertilizer to move rapidly below the root zone. Vertical profiles showed a pulse (spike) of N corresponding to the fertlization event. NO3 in irrigation water must be accounted for as a N source.
The Fate of Nitrogen Applied to a Mature Kentucky Bluegrass Turf	Frank, O'Reilly, Crum, Calhoun	2006	Crop Science Society of America	Quantify N03-N and N04-N concentrations in leachate & determine fate of labeled fertilizer N among clippings, verdure, thatch, soil, roots and leachate for a Kentucky bluegrass turf 10-year after establishment.	Kentucky bluegrass	10 year	Marlette fine sandy loam		Urea - (NH2)2CO	Total: 98 and 245 kg N / ha in 5 applications	Returned	80% of potential evapotranspiration	Field	Hancock Turfgrass Research Center, Michigan State University	1% for low N-fertilization, 11% for high fertilization	Older turf sites should be fertilized at reduced N rate to minimize N03-N leaching. High-rate, water-soluble, nitrogen applications can cause elecated levels of NO3-N leaching from mature turfgrass.
The Effects of Establishment Methods and Fertilization Practices on Nitrate Leaching from Turfgrass	Geron, Danneberger, Traina, Logan, Street	1993	Journal of Environmental Quality	Determine the effects of turfgrass establishment method, late season fertilization and different N sources on N leaching on silt loam soil under field conditions.	Kentucky bluegrass (sodded, and seeded)	New (includes establishment)	Miamian silt loam		Urea, and resin-coated urea (120-day release)	Annual: 218 kg N / ha / yr in 5 applications: spring / summer, or including late season	Returned	yes	Field	Columbus, OH	Only concentrations were reported. Leach rates could not be calculated.	Establishment method affected leach rate: sodded turf had greater NO3-N losses than seeded turf, especially atfer turfgrass matured. Probably related to deeper roots. Little effect of N sources on leaching rates. Highest leach rates observed in late summer and early fall.
Movement of Nitrogen Fertilizer in a Turfgrass System	Gibeault, Yates, Meyer, Leonard	1998	California Turfgrass Culture	Monitor N movement below the root system of cool-season turfgrasses when the nutrient is applied at high rates and frequent intervals.	Mixed Kentucky bluegrass and perennial ryegrass	Mature	Hanford fine sandy loam		granular urea (soluble), sulfur-coated urea (slow release), blood meal (natural organic)	2.5 lb N / 1,000 ft2 every eight weeks (study over 2 applications)	Removed	Based on 50% moisture depletion		Riverside, CA	Not specified	Urea N source resulted in highest concentration of nitrate in leachate, peaking 10-14 days after fertilization.
Nitrate-Nitrogen Losses to Groundwater from Rural and Suburban Land Uses	Gold, DeRagon, Sullivan, Lemunyon	1990	Journal of Soil and Water Conservation	Quantify and rank nitrate-N contributions from the major land use types found in aquifer recharge zones of southern New England.		At least one year old	Merrimac sandy loam		50% urea plus 50% ureaform (liquid)	49-24-24-49-98 kg/ha over 5 applications, for total of 244 kg/ha			Field	Kingston, RI	1.9 - 9.3 kg/ha /year, or 1-4%	Other land uses compare to septic system, which showed a 21% removal (79% loss) of N by the septic tank and absorption trenches. Replacing production agriculture with unsewered residential development will not reduce N-losses to the ground water
Vadose Zone Processes and Chemical Transport	Guillard, Kopp	2004	Journal of Environmental Quality	Determine (1) NO3-N concentrations and losses from turfgrass managed as lawn from various foms of N, and (2) the season when the losses are most likely to occur.		2 years	Paxton fine sandy loam		Ammonium nitrate, coated urea, and organic product	147 kg N / ha/ yr, split into 3 applications		None	Field	Storrs, CT	Ammonium nitrate: 16.8% Coated urea: 1.7% Organic prduct: 0.6%	NO3-N losses affected by N source, and season. Lower solubility fertilizers present lower risk. Most of the NO3-N leaching occurred from late fall to early spring.
Mass Balance of 15N Applied to Kentucky Bluegrass Including Direct Measurement of Denitrification	Horgan, Branham, Mulvaney	2002	Crop Science Society of America	Determine (i) the fate of N applied to turfgrass, including direct measurement of denitrification, and (ii) whether the completeness of recovery of 15N-labeled fertilizer applied to turfgrass is influenced by the presence of plants.	Kentucky bluegrass	Established	Flanagan soil (sand, silt, clay contents: 125, 588, 287 g/kg)		Potassium nitrate	49 kg N/ha	Removed	Twice a week to replace 80% of potential evapotranspiration when rain was not sufficient	Field and greenhouse	Urbana, IL		Thatch layer collected ~25% of applied 15N. Bare soil (no turf) had similar soil N content, but leachate had 4 times greater N content.

Title	Author(s)	Year	Journal	Purpose / Objectives	Conditions										Results	
					Grass		Soil		Fertilization			Irrigation	Field / greenhouse	Location	Leaching Rate (s)	Comments
					Type	Age		Slope	Type	Rate	Clippings					
Clinoptilolite Zeolite Influence on Nitrate Leaching and Nitrogen Use Efficiency in Simulated Sand Based Golf Greens	Huang, Petrovic	1992	Journal of Environmental Quality	Determine the NO3 and NH4 leaching potential from a simulated sand putting green amended with Clinoptilolite Zeolite and the N fertilizer uptake efficiency by creeping bentgrass grown on this medium.	Creeping bentgrass	15 weeks (after establishment)	Acidic sand, & Sand mixed with Clinoptilolite Zeolite (9:1)		(NH4)2SO4	0, 98, 196, and 293 kg N/ha in 4 applications of increasing concentrations	Removed	At least once a week, to lysimeter capacity	Greenhouse		Sand: 2.8, 2.3, and 6.6% at 98, 196, and 293 kg N/ha Sand + Clinoptilolite Zeolite: 2.5, 1.1, and 0.9% at 98, 196, and 293 kg N/ha	Presence of Clinoptilolite Zeolite lowers leachate concentrations at all fertilization rates, the more N applied, the less leaching. Visual quality of turfgrass in sand (not in sand + CZ) declined with higher N app. rates, suggesting potential phytotoxicity of fertilizer.
Mobility of Soil Nitrogen and Microbial Responses Following the Sudden Death of Established Turf	Jian, Bushoven, Ford, Sawyer, Amador, Hull	2000	Journal of Environmental Quality	Quantify responses of the microbial community and the mobility of soil nitrogen following the sudden death of established turf.	Kentucky bluegrass, red fescue, perennial ryegrass, and hard fescue	10 + years, and dead	Enfield silt loam (coarse silty over sandy)		None during study - soil estimated to have ~2,250 kg N / ha	None	Returned			Kingston, RI	7% leaching from soil content (no fertilization) for dead turf, 2% for live turf. Turf species had no impact.	Not relevant, no fertilization.
Nitrogen Leaching Through a Floating Sand-Based Golf Green under Golf Course Play and Management *	Johnston, Golob, Kleene, Pan, Miltner	2001	International Turfgrass Society Research Journal	(1) Quantify N concentration and quantity in leachate, flow, and percent N recovered, and (2) Determine if microlysimeter data correlate with that obtained from the whole-green system.			Sand			0.5 g N/m2 every 7-10 days, additional applications of 1.5 - 4.5 g N/m2			Field	Coeur d'Alene, ID		
Clipping Contributions to Nitrate Leaching from Creeping Bentgrass under varying Irrigation and N Rates	Kopp, Guillard	2005	International Turfgrass Society Research Journal	Determine combined effects of clipping management, irrigation, and N fertilizer rate on nitrate leaching from creeping bentgrass.	Creeping bentgrass	6 months	Agawam fine sandy loam (60% sand, 30% silt, 10% clay)		Aqueous NH4NO3	4 rates from 0 to 392 kg N/ ha split in 3 applications	Returned and Removed	Standard (S) and Standard + precip (S+P)	Greenhouse	Storrs, CT	Removed clippings: Standard irrig.: 0.9 - 7.6% S+P irrig: 14.3 - 41.8% Returned clippings: Standard irrig.: 12.8 - 23.6% S+P irrig: 39.2 - 62.9%	Delays observed between the time of fertilization and the appearance of peak NO3-N concentrations.
Comparing Cultivars of Three Cool-Season Turfgrasses for Soil Water NO3 Concentration and Leaching Potential	Liu, Hull, Duff	1997	Crop Science Society of America	Compare three cool-season turfgrasses for their relative NO3 leaching potential as determined by (i) seasonal NO3-N concentrations in leachate from each grass, and (ii) total seasonal N03-N leached per unit area under each grass.	10 cultivars of Kentucky bluegrass, perennial ryegrass, and tall fescue	3-5 years at beginning of 2-year study	Enfield silt loam (coarse loamy over sandy)		50% inorganic ammonium nitrae, 50% urea and methyl urea	149 kg N/ha/yr in 3 applications of 49.7 kg N/ha	Returned		Field	Kingston, RI	Kentucky bluegrass: 7% in year 1, 14% in year 2 across 10 cultivars, with much variability (up to five fold) and up to 30% leaching for the Liberty cultivar Perennial ryegrass: 2% in year 1, 4.8% in year 2 across cultivars, varying from 1.5 - 14% Tall Fescue: 0.8% in year 1, 1.4% in year 2 across 10 cultivars, with much variability (up to five fold)	Hydrologic model built to determine soil moisture content on daily basis. For Kentucky bluegrass and perennial ryegrass, the greatest losses occurred in December, ranging from 20 to 80%, and 10-50% of the annual loss, respectively. Differences between turfgrasses influence N leaching.
Nitrate and Ammonium Leachin Losses from N Ferilizers Applied to 'Penncross' Creeping Bentgrass	Mancino, Troll	1990	HortScience	Quantify maximum leaching losses of NO3 and NO4 N from green turf receiving weekly and biweekly light to moderate N applications coupled with thice weekly heavy irrigation.	Penncross' creeping bentgrass	10 months	Sand-peat (80:20)		Calcium nitrate, ammonium nitrate, ammonium sulfate, urea, urea formaldehyde, and isobutylediene urea	Over 10 weeks: * 9.76 kg N/ha per 7 days * 19.52 kg N/ha per 14 days Single application: 48.8 kg N/ha	Removed	38 mm/ week	Greenhouse		Over 10 weeks: 0.0 to 0.2% for 9.76 kg N/ha 0.0 to 0.32% for 19.52 kg N/ha Single application: 0.0 to 4.13 %	Highest leaching occurred from NH4NO3 source for single and multiple fertilizer applications. Urea N source showed no leaching. Ammonium N leaching was negligible in all leachate.
Nitrate Leaching from Kentucky Bluegrass Soil Columns Predicted with Anion Exchange Membranes (AEMs)	Mangiafico, Guillard	2007	Soil Science Society of America	Determine if soil NO3-N desorbed from AEMs might serve as predictor of N03-N leaching from turfgrass.	Kentucky bluegrass	New (includes establishment)	Agawam fine sandy loam		Aqueous NH4NO3	16 rates from 0 to 587 kg N /ha/yr		2.5 cm/ week	Greenhouse	Storrs, CT	7 - 28%	Leaching rates may be high, because leaching for zero N application treatment was significant. May be due to differences in N mineralization potential of soil.

Title	Author(s)	Year	Journal	Purpose / Objectives	Conditions										Results	
					Grass		Soil		Fertilization			Irrigation	Field / greenhouse	Location	Leaching Rate (s)	Comments
					Type	Age		Slope	Type	Rate	Clippings					
Fall Fertilization Timing Effects on Nitrate Leaching and Turfgrass Color and Growth	Mangiafico, Guillard	2006	Journal of Environmental Quality	Investigate the timing effects of fall fertilization on both leaching losses and turfgrass color, density, root mass, and clipping yield for a turf stand in southern New England under a home lawn management practice.	90% Kentucky bluegrass, 10% creeping red fescue lawn	sodded in the first summer (excluded from results) of a 3-year experiment	Loamy sand under 20 cm of topsoil (loamy sand)		Spring, and summer: 60% NH4, 40% urea Fall: 9% Nh4, 74% urea, and 17% water insoluble	49 kg N/ha each of 3 applications for a total of 147 kg N/ha for fertilized plot, 98 kg N/ha for control	Returned	2.5 cm/ week May to September	Field	Storrs, CT	Year 1: 1.6 - 16.8% (warmer, +3.5 deg C, and drier than normal, -46% precip) Year 2: 29.1-66.1% (-1.2 deg C vs. normal, -1% precip vs. normal)	NO3 concentrations above 40 mg/L were observed during establishment, and data were removed from results. "Mean cumulative NO3-N mass collected in percolate water was significantly linearly correlated to the date of fertilization. The later the date of application of fall fertilization, the more NO3-N was collected in the perclate water."
Leaching and Mass Balance of 15N-Labeled Urea Applied to a Kentucky Bluegrass Turf	Miltner, Branham, Paul, Rieke	1996	Crop Science Society of America	Construct a mass balance for the fertilizer nitrogen applied to turf in the early spring or late fall, paying special attention to quantitative leachate collection, soil transformation, plant uptake, and soil microbial activity.	Kentucky bluegrass	6 months	Marlette fine sany loam		urea	5 equal apps at 38 day intervals of 39.2 kg N/ha for total of 196 kg N/ha/yr, 1 using 15N	Removed	Total of 56 cm irrigation in addition to 218 cm of precipitation	field		spring application: 0.23% of 15N fall application: 0.18% of 15N	Thatch was a significant sink for the labeled N (15N). Soil 15N increased over 1 year, following decreased thatch 15N, indicating possible downward movement of mineralized 15N from thatch. Late fall application resulted in greater N leaching, which was still small.
Nitrogen Uptake and Leaching under Annual Bluegrass Ecotypes and Bentgrass Species: A Lysimeter Experiment	Paré, Chantigny, Carey, Johnston, Dionne	2006	Crop Science Society of America	Compare N-uptake and potential mineral leaching among various annual bluegrass ecotypes and bentgrass species.	11 annual bluegrass ecotypes, 3 bentgrass species	3.5 months	Sand-peat mix (similar to golf green)		Water-soluble NH4NO3	4 applications of 25 kgN / ha (equivalent to 350 kg N/ha/yr		1.9 cm every other day	Greenhouse	Guelph, ON, Canada	6 - 71% Bentgrass: 6-11% Bluegrass: 28-71%	Greatest leaching in unplanted control, with losses at 116% of applied N. May be due to exp. Error, or mineralization and subsequent leaching
Nitrogen Source and Timing Impact on Nitrate Leaching from Turf	Petrovic	2004	Acta Horticulturae	Determine effect of N source and timing on NO3 leaching from Kentucky bluegrass.	Kentucky bluegrass	2-4 years	Sandy soils: sand: 51-67% silt: 17-36% clay: 16-21%	< 2%	water soluble (urea) and slow release (coated urea, biosolid, urea-formaldehydes)	9.8 and 19.7 g N/m2 in 1 - 4 applications			Field	Riverhead, St. Charles, and Ithaca, NY	Normal precipitation: Water-soluble N: 0.9-5% Slow release N: 0.5-7.4% 291 mm above normal precip: Water-soluble N: 12-29% Slow release N: 2-7% N at end of growing season: Water-soluble N: 29-47% Slow release N: 0-12%	N losses with applications in the late fall result in high leaching rates.
Impact of Soil Texture on Nutrient Fate	Petrovic	2004	Acta Horticulturae	Determine if (i) soils with water flow rates either have a larger proportion of leaching through soil or at least have more leaching under very wet conditions, (ii) more nutrient recovery in the plant could mean less nutrient available for leahing loss, (iii) and nutrient accumulation in soil, as part of soil organic matter, including roots, is much faster at a low initial organic matter content.	Creeping bentgrass		sand, sandy loam, and silt loam		urea-methylene urea	150 kg N/ha /year in applications of 48 kg N/ha	Removed	Rainfall controlled by rainout shelter, simulated rain pattern used (min 25 mm per week)	Field	Ithaca, NY	sand: 9.1% sandy loam: 1.5% silt loam: 3.5%	Most of the N recovery was in the clippings for sandy loam (52%), and silt loam (91%) compared to sand (8%). No measurable N from fertilizer applied was found in sandy or silt loam. Nitrate concentrations in leachate were high during establishment in only 2 samples from sand lysimeters. More water leached from sand than other soils. Because of the high amount of fertilizer found in the clippings, "care must be given on where clippings are disposed."

Title	Author(s)	Year	Journal	Purpose / Objectives	Conditions										Results	
					Grass		Soil		Fertilization			Irrigation	Field / greenhouse	Location	Leaching Rate (s)	Comments
					Type	Age		Slope	Type	Rate	Clippings					
Timing of Nitrate Leaching from Turfgrass after Multiple Fertilizer Applications	Roy, Parkin, Wagner-Riddle	2000	Water Quality Research Journal of Canada	Determine the contribution of N applied in May, July, and September to leaching.	Kentucky bluegrass	sodded	25 cm sandy loam, over 25 cm loamy sand, over sand		Ammonium nitrate	154 kg N/ha /year in three applications	Returned		Field	Guelph, ON, Canada	average of 16.5% of applied nitrogen, with up to 21% but sampling stopped in mid-December due to snow and cold, at which time N concentrations in the leachate were still high.	Very little leaching occurred in the spring and summer months (following fertilization), probably limited by the precipitation and evapotranspiration rates. By early winter, lysimeters had lost up to 21% of the applied nitrogen. "For fertilizer applied under similar conditions, nitrogen remaining in the soil proile may be washed out in the autumn (...) The chances of detecting the contamination with regular water testing are not great, however, since the contamination is arriving in a single pulse."
Fate of Amended Urea in Turfgrass Biosystems	Starrett, Christians, Austin	1995	Communications in Soil Science and Plant Analysis	(i) Investigate the hydrology of 20cm diameter by 50cm deep undisturbed soil columns covered with a Kentucky bluegrass turf under a heavy (one 2.5 cm application) and a light (four 0.64 cm applications) irrigation regime, and (ii) quantify the fate of 15-N labeled urea when it is applied to an undisturbed soil column having intact macropores.	Kentucky bluegrass						Removed	heavy (one 2.5 cm application) and a light (four 0.64 cm applications) irrigation regime				"The heavy irrigation regime significantly increased the transport of N below 30cm by 5 times, compared with the light irrgation regime. 85% of the N found in the leachate from the 50cm columns was in the urea form indicating that macropores may have played a major role in transport of surface applied N through the soil profile."

* Only abstract was reviewed. Article not available

Appendix B – Bayberry Hills Golf Course Data (2000 – 2008)

This Appendix provides detailed data reported by the Bayberry Hills golf course, in West Yarmouth, MA, including water quality measurements under certain greens and fairways. Table B1 provides the nitrogen concentrations measured in lysimeters under three greens, and expressed in milligrams per Liter (mg/L). Another three data tables are provided in this Appendix.

Table B1. Nitrogen Concentration Measurements in Lysimeters under Three Greens

13 Green		9 Green		7 Green	
Date	**Total Nitrogen (mg/L)**	**Date**	**Total Nitrogen (mg/L)**	**Date**	**Total Nitrogen (mg/L)**
2/9/2000	4.4	2/9/2000	2.1	2/9/2000	4.4
10/4/2000		10/4/2000		10/4/2000	
12/5/2000		12/5/2000	8.18	12/5/2000	20.95
4/3/2001	2.58	4/3/2001	2.36	4/3/2001	2.19
7/12/2001		7/12/2001	26.6	7/12/2001	6.12
12/17/2001	24.2	12/17/2001	13.5	12/17/2001	6.04
3/28/2002	3.19	3/28/2002	1.94	3/28/2002	2.3
6/12/2002	3.5	6/12/2002	5.14	6/12/2002	4.73
9/27/2002	16.7	9/27/2002	18.3	9/27/2002	13.2
4/4/2003	2.26	4/4/2003	1.83	4/4/2003	2.65
6/20/2003	3.65	6/20/2003	5.4	6/20/2003	3.93
10/7/2003	18.8	10/7/2003	6.92	10/7/2003	12.7
3/25/2004	3.5	3/25/2004	4.77	3/25/2004	4.24
4/1/2004	1.89	4/1/2004	1.51	4/1/2004	0.75
6/24/2004	3.24	6/24/2004	3.24	6/24/2004	0.84
9/27/2004	11.6	9/27/2004	3.38	9/27/2004	9.38
11/24/2004	4.12	11/24/2004	2.08	11/24/2004	3.32
4/7/2006	2.9	4/7/2006	4.4	4/7/2006	4.8
9/1/2006	11.2	9/1/2006	6	9/1/2006	9.8
5/18/2007	1.9	5/18/2007	2.9	5/18/2007	5.6
10/5/2007	18.2	10/5/2007	4.9	10/5/2007	7.2
4/29/2008	3	4/29/2008	2.5	4/29/2008	4.6
12/2/2008	3.8	12/2/2008	3.2	12/2/2008	3.6
Average	**7.23**	**Average**	**5.96**	**Average**	**6.06**

Table B2 provides the annual averages of the concentration measurements under the same greens, calculated based on data points from Table B1.

Table B2. Annual Average Nitrogen Concentrations in Lysimeters under Three Greens

13 Green		9 Green		7 Green	
Year	**Annual Average Nitrogen Concentration (mg/L)**	**Year**	**Annual Average Nitrogen Concentration (mg/L)**	**Year**	**Annual Average Nitrogen Concentration (mg/L)**
2000	4.40	2000	5.14	2000	12.68
2001	13.39	2001	14.15	2001	4.78
2002	7.80	2002	8.46	2002	6.74
2003	8.24	2003	4.72	2003	6.43
2004	4.87	2004	3.00	2004	3.71
2006	7.05	2006	5.20	2006	7.30
2007	10.05	2007	3.90	2007	6.40
2008	3.40	2008	2.85	2008	4.10
Average	**7.40**	**Average**	**5.93**	**Average**	**6.52**

Table B3 provides the nitrogen concentrations measured in lysimeters under three fairways from the Bayberry Hills golf course, and expressed in milligrams per Liter (mg/L).

Table B3. Nitrogen Concentration Measurements in Lysimeters under Three Fairways

13 Fairway		9 Fairway		7 Fairway	
Date	**Total Nitrogen (mg/L)**	**Date**	**Total Nitrogen (mg/L)**	**Date**	**Total Nitrogen (mg/L)**
2/9/2000	3.2	2/9/2000	4.4	2/9/2000	
10/4/2000		10/4/2000		10/4/2000	
12/5/2000	2.81	12/5/2000	5.05	12/5/2000	3.18
4/3/2001	2.05	4/3/2001	1.92	4/3/2001	1.49
7/12/2001	5.76	7/12/2001	5.11	7/12/2001	4.96
12/17/2001	10.5	12/17/2001	4.44	12/17/2001	28.2
3/28/2002	1.79	3/28/2002	2.26	3/28/2002	2.1
6/12/2002	5.88	6/12/2002	7.14	6/12/2002	5.88
9/27/2002	11.7	9/27/2002	8.61	9/27/2002	9
4/4/2003	1.08	4/4/2003	1.91	4/4/2003	1.56
6/20/2003	9.42	6/20/2003	5.52	6/20/2003	2.79
10/7/2003	8.5	10/7/2003	19.2	10/7/2003	12.9
3/25/2004	1.12	3/25/2004	4.12	3/25/2004	3.43
4/1/2004	2.36	4/1/2004	2.72	4/1/2004	1.35
6/24/2004	2.44	6/24/2004	2.5	6/24/2004	1.22
9/27/2004	16	9/27/2004	59	9/27/2004	16.1
11/24/2004	4.5	11/24/2004	8.45	11/24/2004	6.02
4/7/2006	1.5	4/7/2006	2.4	4/7/2006	4.1
9/1/2006	11	9/1/2006	5.7	9/1/2006	18.4
5/18/2007	3.4	5/18/2007	1.3	5/18/2007	4.8
10/5/2007	10.4	10/5/2007	29.3	10/5/2007	19.8
4/29/2008	5.9	4/29/2008	3.5	4/29/2008	4.3
12/2/2008	1.6	12/2/2008	3	12/2/2008	1.8
Average	**5.59**	**Average**	**8.53**	**Average**	**7.30**

Table B4 provides the annual averages of the concentration measurements under the same fairways, calculated based on data points from Table B3.

Table B4. Annual Average Nitrogen Concentrations in Lysimeters under Three Fairways

13 Fairway		9 Fairway		7 Fairway	
Year	**Annual Average Nitrogen Concentration (mg/L)**	**Year**	**Annual Average Nitrogen Concentration (mg/L)**	**Year**	**Annual Average Nitrogen Concentration (mg/L)**
2000	3.01	2000	4.73	2000	3.18
2001	6.10	2001	3.82	2001	11.55
2002	6.46	2002	6.00	2002	5.66
2003	6.33	2003	8.88	2003	5.75
2004	5.28	2004	15.36	2004	5.62
2006	6.25	2006	4.05	2006	11.25
2007	6.90	2007	15.30	2007	12.30
2008	3.75	2008	3.25	2008	3.05
Average	**5.51**	**Average**	**7.67**	**Average**	**7.30**