Report to the Pleasant Bay Alliance on the Turfgrass Fertilizer Nitrogen Leaching Rate

By

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August 20, 2008

The Town of Chatham, on behalf of the Pleasant Bay Alliance, has authorized me to conduct a scientific review and produce a report on the following:

1. Update the 1990 literature review article on turfgrass nitrogen leaching by Petrovic (1990).

2. Determine an appropriate overall turfgrass fertilizer leaching rate for Cape Cod, MA.

3. Determine fertilizer leaching rates for different turfgrass land uses including golf courses and lawns including residential, municipal and commercial sites.

What follows is a report including the above three parts.

Part 1: Literature review of the turfgrass nitrogen leaching literature since 1990

The literature review involved all research journal articles published since 1990 on the leaching of fertilizer nitrogen applied to cool-season turfgrasses, the ones used on Cape Cod. There were some research literature on warm-season grasses, but because of the much longer growing period, more precipitation and irrigation, deeper rooted grasses and over all different hydrology, this literature was not included in this review. There were 29 research journal articles published since 1990, much more than the 6 on cool-season turfgrasses that were cited in the 1990 review article (Petrovic, 1990). Nine of the 29 studies were conducted on golf course type conditions, while most of the studies were done on lawn type turf. Table 1 contains a summary of all of the research papers included in the review. This table has 302 values of fertilizer nitrogen leaching as a percent of the amount of applied, most often as nitrate, but sometimes as a total of nitrate plus ammonium. This table also contains detailed information about each study including the loading rate (LR) in units of lbs of nitrogen leached per 1000 sq. ft. per year or in studies lasting less than a year the amount is over the study period.

Golf Results

There were only nine studies on golf course turf with more than half being greenhouse studies. The studies covered a wide range of factors that influence nitrogen leaching including cultivar and species differences, amendments of sand, nitrogen sources and rates of application, cultivars of bentgrass with different rooting depths, clipping management, soil types, and an actual green on a golf course.

The amount of leaching ranged from none to a high of 71% of the amount of fertilizer nitrogen applied with an average from all studies of 13.34%. Half of all the results (84 values) were below 3% of the amount applied. Field studies are considered a better representation of what actually occurs in the real world and greenhouse studies are good to compare factors and often give higher leaching values. When only considering the four field studies, the per cent of fertilizer nitrogen that leached averaged 3.0%, ranging from 0.02% to 13.2%. The actual golf green (USGA style green in Idaho) had the highest amount of fertilizer nitrogen that leached. The factors found to increase fertilizer nitrogen leaching were: applying increasing amount of nitrogen fertilizer especially to pure sand greens compared to ones with peat or other amendments, much more leaching occurred during the establishment phase that in subsequent years (up to 3yrs), bentgrass cultivars with shorter roots than ones with deeper roots had more leaching, the more irrigation was applied more fertilizer nitrogen leaching, the sandier the soil the greater the amount of fertilizer nitrogen that leached, and annual bluegrass had much more leaching that bentgrasses especially annual bluegrass from Canada.

<u>Lawn Results</u>

There were 20 studies on lawns with only three being greenhouse studies. The studies evaluated different nitrogen sources, rates and application timing, long term impacts, cultivar and species differences, bare soil compared to a lawn, lawns compared to corn, forests and septic systems, and the amount of irrigation.

The amount of fertilizer nitrogen that leached ranged from 0 to 95.1% with an average from all studies of 9.41%. If only field studies were considered the average leaching rate was just slightly higher (9.61% of the amount applied).

Some factors that affected the amount of fertilizer nitrogen leaching were very consistent: the higher the application rate of nitrogen, the more leaching occurred, especially when rates higher than the highest typical rate (1 lb N/1,000 sq.ft.) were applied; nitrate form of nitrogen fertilizer (ammonium or calcium nitrate) had much more leaching (nitrate forms are not typically used to fertilize lawns) than other sources (urea and slow release sources); excess irrigation caused more leaching; corn production and septic systems had much more nitrate leaching than fertilized lawns while unfertilized lawns had similar amount of nitrate leaching as a forest; and during lawn establishment more leaching occurred than in the next several years. Some species (and cultivars within a species) were more prone to nitrogen leaching. Kentucky bluegrass had higher leaching amounts that either perennial ryegrass or tall fescue (Liu et al., 1997).

The results involving several other factors were not as consistent. Four studies involved fall to late fall applications. Two (done on Long Island, NY and Connecticut) of the four clearly show the risk of applying nitrogen (as soluble sources) in mid (October) to late fall (November and December). The studies done in Ohio and Ithaca, NY found much less or no additional nitrogen leaching from late fall applications The difference is related to temperature conditions, the colder winters of Ohio and Ithaca results in less leaching compared to the milder coastal regions. Three studies considered the long term impacts. One study (Petrovic, 2004) showed that the source of nitrogen (except for calcium nitrate which is not used as a lawn fertilizer) had little to do with the amount of leaching when studies were conducted over a wide range (thus long term implications) of rainfall conditions (drier, normal and much wetter than normal). It has been suggested that younger sites with less organic matter would tie up a fair amount of fertilizer nitrogen for a long period of time (first 10-20 yrs), and thus less fertilizer nitrogen would be need. Frank (2006 & 2008 in Michigan) found that as the site became more mature (10 + yrs), if a high rate of nitrogen was maintained (5 lbs N compared to 2 lbs N/1000 sq.ft./yr) higher N leaching occurred. However, a study in Rhode Island (Duff et al., 1997) found older sites were no more prone to nitrogen leaching than younger sites. Generally, it was found that nitrogen fertilizer sources that were more water soluble had greater amounts of nitrogen leaching, except where noted above (Petrovic, 2004).

Part 2: An appropriate overall turfgrass fertilizer leaching rate for Cape Cod, MA

To answer this question, one must considered the conditions of the location in question, namely the soils, climatic factors and grasses. The best information would be from studies done on Cape Cod, MA. None of the studies were done on Cape Cod, MA, and only one was done in Massachusetts (Mancino and Troll, 1990, in the greenhouse). Therefore, the results from other studies will be used to extrapolate to the conditions of Cape Cod, MA. In general, only cool season grasses like Kentucky bluegrass, fine fescue, perennial ryegrass, annual bluegrass on golf courses and bentgrass are used on Cape Cod. Based on information from the Natural Resource Conservation Service (NCRS at http://websoilsurvey.nrcs.usda.gov/app/), a majority of the soils in the Towns of Chatham, Orleans, Harwich and Brewster, MA are Carver & Plymouth coarse sands & sands, Merrimac & Nantucket sandy loam, East Chop, Freetown and Deerfield sands, and a little silt loam (Boxford and Enfield). Thus, studies with sand to sandy loam soils would be most appropriate. The 30 year average annual rainfall for the eastern part of Cape Cod, MA (Chatham WSMO station, from the Northeast Climate Center database CLIMOD) is 46.03 inches. Thus, data from coastal New England states like Connecticut and Rhode Island and Long Island, NY that used sand to sandy loam soils in these studies would best approximate the conditions of Cape Cod, MA.

To approach the issue of how much fertilizer nitrogen leaches, there are several options. One could look at an average of all studies, thus include the worse case scenario studies, all soil types, grasses, fertilizer amounts and sources and irrigation variables. In this way it is like all sites found on Cape Cod, MA would likely be represented in at least one study. Therefore, using this approach the answer would be 10.51% including all 302 values found in Table 1. Half of the 302 values were below 4.15% of the amount applied. If only field studies were considered, which is considered the most realistic scenario, then the nitrogen fertilizer leaching rate would be 8.79% of the amount applied. A more conservative approach would be to use results from the greenhouse studies that are generally considered to give higher leaching values, then the leaching rate would be 14.99% of the amount of fertilizer nitrogen applied. Using data from studies that are most like Cape Cod (the one MA study, the sand to sandy loam studies of Rhode Island, Connecticut and Long Island, NY) then the leaching rate would be 11.10%.

Part 3: Fertilizer leaching rates for different turfgrass land uses including golf courses and lawns including residential, municipal and commercial sites.

It may be appropriate and justifiable to have a nitrogen fertilizer leaching rate separate for golf course turf and for lawns. As was done in Part 2, there are several ways to approach determining a suitable fertilizer nitrogen leaching rate; consider all data, only field data, only greenhouse data and only data most appropriate for Cape Cod.

Golf Course

The amount of leaching from golf course studies ranged from none to a high of 71% of the amount of fertilizer nitrogen applied, with an average from all studies of 13.34%. Half of all the results (84 values) were below 3% of the amount applied. When only considering the four field studies, the per cent of fertilizer nitrogen that leached averaged 3.0%, ranging from 0.02% to 13.2%. From the more conservation greenhouse studies, the fertilizer nitrogen leaching rate was 16.95%. Using data from studies that are most like Cape Cod (the one MA study, the sandy loam study of Connecticut), the leaching rate would be 9.97%.

One other approach is to use groundwater quality data from an actual golf course and determine the fertilizer nitrogen leaching rate to correspond with the ground water nitrogen concentration. To do this with any degree of accuracy you need a sound understanding of the ground water hydrology of the site, many groundwater monitoring wells, and good knowledge of the amount of nitrogen that was applied. This was done by me on behalf of the Peconic Estuary Program for a golf course on eastern Long Island, NY (The Bridge in Bridgehampton, NY) where there are 14 groundwater monitoring wells that were sampled four times per year, a soil typical of Cape Cod (Carver sand) and a good knowledge of ground water hydrology. Based on the amount of fertilizer applied to the golf course (6,449 lbs on 113.27 acres/yr), the groundwater recharge amount based on rainfall and irrigation, and average nitrogen concentration in the ground water wells (0.81 mg nitrate/l), it was determined that 8.87% of the fertilizer nitrogen leached into the groundwater for this golf course. This value is close to the research studies similar to Cape Cod conditions (9.97%). Based on my analysis and conclusion that golf course turf on eastern Long Island, NY had a fertilizer nitrogen leaching rate of 10%, the Peconic Estuary Program made a voluntary agreement with the 35 east end golf courses to limit the amount of nitrogen applied to golf courses to be on average 2.8 lbs of nitrogen/1,000 sq.ft./yr. to meet a groundwater quality goal of 2 mg of nitrogen/L under golf courses.

Lawns

The amount of fertilizer nitrogen that leached based on 20 studies ranged from zero to 95.1%, with an average from all studies of 9.41%. If only field studies were considered the average leaching rate was just slightly higher (9.61% of the amount applied). Using data from studies that are most like Cape Cod then the leaching rate would be 11.10%.

Based on the nature of these studies it is difficult to separate out residential lawns from municipal or commercial lawns. It is, however, possible to separate lower maintenance lawns (0-2 lbs nitrogen fertilizer/1,000 sq.ft./yr), medium maintenance (2-4 lbs nitrogen fertilizer/1,000 sq.ft./yr) from high maintenance lawns (>4 lbs nitrogen fertilizer/1,000 sq.ft./yr). Low maintenance leaching rate is 9.66%, medium maintenance is 8.60% and 12.43% for high maintenance lawns.

Conclusions

The basic question that was posed to me; is the Massachusetts Estuary Program turfgrass fertilizer nitrogen leaching rate of 20% suitable for turfgrass in the Pleasant Bay region of Cape Cod? In my professional opinion, based on results from 35 studies published on the leaching of fertilizer nitrogen from cool-season turfgrasses, 20 % fertilizer rate leaching would be considered an overestimation by about two times. Only 14 % of the time in the 35 studies reviewed in this report was the leaching rate 20% or higher. Based on the analysis done above, an overall leaching rate of around 10% (10.5% was the overall average leaching rate) would be appropriate to cover the wide range of factors that could occur on Cape Cod such as: very sandy soil, over-irrigation, excessive nitrogen application rates, excessively wet years, improper timing of application, use of highly water soluble-high leaching potential fertilizers and all grasses that could be used on Cape Cod. There was not a substantial difference found overall between lawns and golf course turf, thus one number (10%) would be appropriate.

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Table 1. Summary of published research on the leaching of nitrogen fertilizer applied to cool-season turfgrass since 1990.

Grass	**Turf Type**	**Nitrogen source**	**Single N app Rate (lbs. N/1000 sq.ft)**	**Total N applied/yr (lbs. N/1000 sq.ft)**	**Season Applied**	**Soil Texture**	**Amount of Irrigation (inch/day)**	**% of applied N leached as NO3- N & NO3-Loading rate (lbs. N/1000 sq.ft/yr)**	**Conc. of NO3-N in water mg/L**	**Reference**	Notes
Creeping bentgrass – Oct. seeded, Washington	Greens-32 sq.ft. lysimeter (USGA profiles) 3 yr field study	Am. Phosphate Am. Sulfate urea Slow release*	0.02 0.10 0.02 0.10 0.18	4	2 week interval, Feb-Dec., 22 apps	Sand (3 layer-12" sand, 3" coarse sand, 3" pea gravel, pH 6.8	Amount not given	1^{st} yr - 5.4% 2^{nd} yr- 0.06% 3^{rd} yr- 2.7% Ave. 2.7 % Ave. LR of 0.11	-	Brauen & Stahnke, 1995	Started at establishment
"	"	Am. Phosphate Am. Sulfate urea Slow release*	0.02 0.10 0.04 0.20 0.36	8	"	"	"	1^{st} yr -6.3% 2^{nd} yr-0.04% 3^{rd} yr-3.2% Ave. 3.2% Ave. LR of 0.26	Max. 10 in first yr.	"	
"	"	Am. Phosphate Am. Sulfate urea Slow release*	0.02 0.10 0.07 0.36 0.55	12	"	"	"	1^{st} yr -7.6% 2^{nd} yr-0.7% 3^{rd} yr-4.3% Ave. 4.2% Ave. LR of 0.50	Max 37 in first yr, 2-5 in 2^{nd} 7 3^{rd} yr	"	
Creeping bentgrass – Oct. seeded	Greens-32 sq.ft. lysimeter (USGA profile)	Am. Phosphate Am. Sulfate urea Slow release*	0.02 0.10 0.02 0.10 0.18	4	2 week interval, Feb-Dec., 22 apps	Sand-peat-soil (88% sand,10% sphagnum peat, 2 % silt loam) (3 layer-12" root zone, 3" coarse sand, 3" pea gravel	Amount not given	1^{st} yr-0.33% 2^{nd} yr- 0.40% 3^{rd} yr- 0.16% Ave. 0.30 % Ave. LR of 0.012	-	Brauen & Stahnke, 1995	
"	"	Am. Phosphate Am. Sulfate	0.02	8	"	"	"	1^{st} yr-0.91% 2^{nd} yr - 0.02% 3^{rd} yr - 0.17%	Max. 3 in first yr.	"	

		urea Slow release*	0.10 0.04 0.20 0.36					Ave. 0.39% Ave. LR of 0.03			
“	“	Am. Phosphate Am. Sulfate urea Slow release*	 0.02 0.10 0.07 0.36 0.55	12	“	“	“	1st yr - 3.4% 2nd yr - 1.26% 3rd yr – 2.31% Ave.2.3 Ave. LR of 0.28	Max 10 in first yr,16 in 2nd , 8 in 3rd yr	“	
Kentucky bluegrass, Ohio	Lawn, 21 month field study, 4 sq.ft. lysimeters	None –seeded None – sodded				Silt loam, 31.5 inches deep	Amt not given but irrigated to prevent wilt	LR of 0.78 for 2 yrs, 0.77 in 1st yr and 0.01 in 2nd yr LR of 0.89 for 2 yrs, 0.83 in 1st yr and 0.06 in 2nd yr	Max 15.7 in 1st yr, 1.8 in 2nd yr Max 19.3 in 1st yr, 4.3 in 2nd yr	Geron et al., 1993	NS** for timing or source, started at establishment
“	“	Urea and resin coated urea	4 @ 1.0 1 @ 0.5	4.5	Apr., June. July, Aug., Sept.	“	“	9.7% for the 2 yrs with 12.9 % in 1st yr, 6.5% in 2nd yr LR of 0.87	Ave 15.2 in 1st yr, 2.3 in 2nd yr		
“	“	“	“	“	Apr., June, July, Sept., Nov.	“	“	6.0% for the 2 yrs with 6.7% in 1st yr, 5.2% in 2nd yr LR of 0.54	Ave 13.9 in 1st yr, 2.3 in 2nd yr		
“	“	urea	“	“	“	“	“	10.2% for 2 yrs with 12.6% in 1st yr, 7.6% in 2nd yr LR of 0.91	Ave 15.4 in 1st yr, 2.8 in 2nd yr		
“	“	Resin coated	“	“	“	“	“	5.3% for 2 yrs with	Ave 13.8 in		

		urea						6.9% in 1st yr, 3.7 % in 2nd yr	1st yr, 1.8 in 2nd yr		
creeping bentgrass, cultivars with different rooting patterns	Green, short term greenhouse study, 0.2 sq.ft. lysimeters	Ammonium nitrate	1	1		Sand, 24 inches deep				Bowman et al., 1998	Study run 5 weeks
	Shoot roots						0.4"/day 0.8"/day 1.2"/day	33.8% 38.9% 41.9% 38.2% ave	26.0 23.1 30.3 26.5 ave		
	Long roots						0.4"/day 0.8"/day 1.2"/day	14.5% 18.6% 22.4% 18.5% ave Lsd=8.3%	14.6 13.2 12.8 13.4 ave Lsd=11.9		
"	Short roots		"	"			0.8 inches/day 1 day after application 3 days after application 5 days after application	 16.7% 4.5% 2.0 7.7 % ave Lsd=7.7%	 16.2 4.3 1.9 7.4 Lsd=7.4		
	Long roots						0.8 inches/day 1 day after application 3 days after application	 4.7% 0.2%	 4.1 0.2		

							5 days after application	<u>0.1</u> 1.7 ave Lsd=4.3%	<u><0.1</u> 1.4 ave Lsd=4.6		
Kentucky bluegrass, Michigan	Lawn, sodded 1 yr before fertilizer treatment, 12.6 sq.ft. lysimeters	urea	0.81	1.62	April 26 November 8	Fine sandy loam, 4 feet deep	0.2 " after application, no further irrigation was reported	After 748 days after treatment 0.013% LR of 0.0001 After 752 days after treatment 0.17% LR of 0.0014	Max of 3.1, 20 days after treatment, not above 1 after that. Max of 1.8 420 days after treatment, not above 1.5 after that	Miltner et al., 1996	Initial data of along term field study
Kentucky bluegrass, perennial ryegrass, creeping red fescue, Connecticut	Typical lawn, 10ft by 12ft plots with 10" zero tension funnel lysimeters placed 15" into the soil	Ammonium nitrate Polymer-sulfur coated urea Organic (Sustane) Unfertilized control	1	3	Yr 1-Oct Yr 2-May, July, Nov Yr 3-June, July, Nov. Yr 4, May, June	Fine sandy loam field site	No irrigation	16.8%/yr (a)[#], LR of 0.53(a) 1.7%(b), LR of 0.08(b) 0.6%(b), LR of 0.04(b) LR of 0.02(b)	Flow weighted ave 4.6(a) 0.57(b) 0.31(b) 0.18(b)	Guillard and Kopp, 2004	10 yr old site prior to study, field study
Rhode Island Kentucky bluegrass, 10 cultivars	Lawn, 3 ft by 5 ft plots with 0.9 inch suction lysimeter in each plot 15 inches deep, 2-5 yrs old	50% ammonium nitrate, 50% urea/methylene urea	1	3	Apr, June, Nov.	Silt loam	13"/yr in yr 1 & 47.9" of precipitation 10"/yr in yr 2 & 46.4" of precipitation	Range 2.0% to 23.5%, ave of all 10 cultivars was 6.7% Range 6.7% to 30.2%, ave of all 10 cultivars was 13.4%	Lowest ave was 0.8 for Apr-June, highest 6.9 for March Lowest ave was 1.0 for Apr-June, highest 12.2 for Oct-Dec	Liu et al., 1997)	Suction collection not free drainage, values likely

	prior to study										high than in drainage water
Perennial ryegrass, 10 culitvars							13”/yr in yr 1 & 47.9” of precipitation	Range 1.3% to 2.7%, ave of all 10 cultivars was 2.0%	Lowest ave was 0.5 for Apr-June, highest 5.9 for March		
							10”/yr in yr 2 & 46.4” of precipitation	Range 0.7% to 14.5%, ave of all 10 cultivars was 4.7%	Lowest ave was 0.3 for Apr-June, highest 4.0 for July-Sept		
Tall fescue, 10 cultivars							13”/yr in yr 1 & 47.9” of precipitation	Range 0.3% to 2.2%, ave of all 10 cultivars was 0.8%	Lowest ave was 0.2 for Apr-June, highest 2.5 for March		
							10”/yr in yr 2 & 46.4” of precipitation	Range 0.5% to 3.1%, ave of all 10 cultivars was 1.4%	Lowest ave was 0.2 for Apr-June, highest 1.2 for Oct-Dec		
Kentucky bluegrass	Lawn, greenhouse study in 8” dia by 10 “ deep intact soil columns from field plots, 3 week study	Potassium nitrate	1	1		Silt loam (3.03% organic C)	Yes, but amount not given	Bare soil=19.8% for a LR of 0.20 Kentucky bluegrass= 4.9% for a LR of 0.05	Not given	Horgan et al., 2002	
Creeping bentgrass, seeded 6 month prior to treatments, Connecticut	Green, greenhouse study in 8” dia by 30” deep intact soil columns	Ammonium nitrate	0 0.66	0 2	Applied week 1, 12 and 22 of the 30 week study	Fine sandy loam	1”/week 1”/week+30 yr high prec 1”/week	Clipping return Clipping remove Clipping return Clipping remove Clipping return 17.2%	0.71 0.31 1.44 0.32 4.44	Koop & Guillard, 2005	Study looking at N rates, irrigation

	from a filed plot, 30 week study							Clipping remove 0.9%	0.40		and clipping mgt
							1”/week+30 yr high prec	Clipping return 39.2% Clipping remove 14.3%	4.03 1.34		
			0.75	4			1”/week	Clipping return 12.8% Clipping remove 2.8%	6.41 1.49		
							1”/week+30 yr high prec	Clipping return 41.8% Clipping remove 25.8%	6.87 3.78		
			2.7	8			1”/week	Clipping return 23.6% Clipping remove 7.6%	21.0 7.72		
							1”/week+30 yr high prec	Clipping return 62.9% Clipping remove 41.8%	16.8 11.8		
Creeping bentgrass, seeded at establishment	Fairway, 6ft by 8ft plots, 14 month field study	Not given	9 apps at 0.5 and 7 apps at 0.25	4.25 in 1st 12 months, 2.0 in 13th-14th month=6.25	Once or twice/month, Oct-Nov in 1st yr, Apr-Nov in 2nd yr	USGA sand profile, 4” of pea gravel under 12” sand root zone	Not reported, 25 rain events produced leachate	Not reported		Boniak & Chong, 2005	Root zone amendment, at establishment
						Sand			320 max in 1st yr, 4 max in 2nd yr		
						Sand-steer manure			160 max in 1st yr, 8 max in 2nd yr		
						Sand-bio/yd mix			125 max in 1st yr, 4 max in 2nd yr		
						Sand-sphagnum peat			10 max in 1st yr, 3 max in 2nd yr		
Land use study, suction lysimeters to collect percolate, 2”	Lawn with fertilizer	50% urea, 50% ureaform	1 0.5 2	5	June, Sept July, Aug Nov	Sandy loam	Not reported, 66 rain events produced leachate	3.8% 1st yr, LR of 0.19 0.8% 2nd yr, LR of 0.04	1.6 1st yr 0.3 2nd yr	Gold et al., 1990	3 yr field study, last 2 yrs
						Sandy loam		LR of 0.03 in 1st yr	0.2 1st yr		

in septic field area, 10.8” dia plates in other areas, Rhode Island	Unfertilized lawn Corn-rye cover Corn Corn-manure/fertilizer Forest Septic system	- Urea Urea Urea Dairy manure - -	- 0.7 3.4 0.7 3.4 0.7 4.1 - -	 4.1 4.1 4.8	 June July June July June June	 Silt loam Silt loam Sandy loam Silt loam Silt loam		LR of 0.03 in 2nd yr 39.9% 1st yr, LR of 1.6 21.0% 2nd yr, LR= 0.86 36.8% 1st yr, LR=1.5 39.7% 2nd yr, LR=1.6 8.7% 1st yr, LR=0.4 43.0% 2nd yr, LR=2.1 1st yr LR=0.02 2nd yr LR=0.03 LR=1.0	0.2 2nd yr 15.3 1st yr 8.1 2nd yr 14.9 1st yr 15.6 2nd yr 4.2 1st yr 17.5 2nd yr 0.2 1st yr 0.2 2nd yr 68.1 both yr		samples taken, lawn fert leaching occurred Jan-May (94%), conc. were yearly ave
Creeping bentgrass, 10 yr old field site before this 2 yr study, seeded , New York	Fairway, 12ft by 12 ft free draining lysimeters	Urea/methylene urea	1 1	2 3	Sept , Oct (1st yr) June, Sept, Oct (2nd yr)	16” of Sand Sandy loam Silt loam	Minimum 1”, more based on historic data	9.1%, LR=0.46 1.5%, LR=0.08 3.1%, LR=0.16	19.2 max, 1st yr, 4.8 max 2nd yr (0.5 max for unfertilized 3.5 max, 1st yr, 3.6 max 2nd yr (1.7 max for unfertilized 5.9 max, 1st yr, 6.6 max 2nd yr (1.1 max for unfertilized	Petrovic, 2004	Started at establishment
Kentucky bluegrass, Ithaca, NY, seeded 2 yrs before 2 yr field study	Lawn, 5” by 5” ion exchanged bags placed 16” deep in plots	Unfertilized control IBDU Urea Polymer coated urea	- 2 2 2	2	Oct-1st yr Nov-2nd yr	Fine sandy loam	None	LR= 0.4b 1.4%ab, LR=0.07ab 4.9%a, LR=0.14a 0.4%ab, LR=0.04ab		Petrovic, 2004	Late fall fertilizing study

		biosolid	2					0.2%b, LR=0.03ab			
Kentucky Bluegrass, seeded 5 yrs before field study, 2 Long Island,NY sites		unfertilized control	-		Nov	Sandy loam	None	LR=0.13c LR=0.17z			late fall study
		ureaformaldehyde	2	2				0%c, LR=0.13c 3.9%c, LR=0.25z			
		sulfur coated urea	2					11.6%b, LR=0.36b 10.8%y, LR=0.39y			
		urea	2					29.4%a, LR=0.72a 46.5%x, LR=1.10x			
		polymer coated urea	2					0%c, LR=0.13c 0%z, LR=0.12z			
		biosolid	2					0%c, LR=0.13c 2.6%z, LR=0.22z			
Kentucky bluegrass, seeded 9 yrs before the 3 yr field study, Long Island, NY		unfertilized control	- 1 &2	- 4	May, June, July, Sept.	Sandy loam	To prevent wilt	Yr 1, LR=0.11 Yr 2, LR=0.16 Yr 3, LR=0.03c Ave LR=0.10d			Considered long term effects, 3 yrs with contrasting rainfall (below, normal & above normal)
		ureaformaldehyde						Yr 1, 4.0%, LR=0.16 Yr 2, 4.2%, LR=0.20 Yr 3, 2.9%b LR=0.16bc Ave 3.7%b 0.17bc			
		methylene urea						Yr 1, 1.7%, LR=0.13 Yr 2, 4.6%, LR=0.16 Yr 3, 6.7%b LR=0.21bc Ave 4.6%b 0.17bc			
		IBDU						Yr 1, 1.9%, LR=0.13 Yr 2, 6.9%, LR=0.18 Yr 3, 4.1%b LR=0.22bc Ave 4.9%b 0.18bc			
		sulfur coated urea-no wax						Yr 1, 4.9%, LR=0.11 Yr 2, 4.8%, LR=0.20 Yr 3, 4.8%b LR=0.22bc Ave 4.8%b 0.18bc			

		sulfur coated urea-wax						Yr 1, 1.7%, LR=0.11 Yr 2, 7.4%, LR=0.19 Yr 3, 5.8%b LR=0.25bc Ave 5.4%b 0.18bc			
		urea						Yr 1, 1.6%, LR=0.12 Yr 2, 4.1%, LR=0.17 Yr 3,12.1%bLR=0.38ab Ave 6.1%b 0.21ab			
		calcium nitrate						Yr 1, 0.9%, LR=0.12 Yr 2, 5.0%, LR=0.19 Yr 3,29.7%aLR=0.85bc Ave 12.5%a 0.37a			
		polymer coated urea (100 day)						Yr 1, 2.4%, LR=0.12 Yr 2, 6.4%, LR=0.17 Yr 3, 4.1%b LR=0.16bc Ave 4.2%b 0.14cd			
		Polymer coated urea (200 day)						Yr 1, 0.5%, LR=0.09 Yr 2, 3.1%, LR=0.17 Yr 3, 2.5%b LR=0.07bc Ave 2.0%b 0.12cd			
		biosolid						Yr 1, 5.6%, LR=0.11 Yr 2, 3.9%, LR=0.18 Yr 3, 2.2%b LR=0.14bc Ave 3.7%b 0.15bc			
Kentucky bluegrass, long term study, collected data for yrs 10-12 after establishment, Michigan	Lawn, 8” dia by 18” deep lysimeters place in plots	urea	0.5 as ^{15}N 1.0	2 as regular N 5	Oct of ^{15}N of 1st yr May, June , July, Oct, in 2nd & 3rd yr Oct of ^{15}N of 1st yr May, June, July, Sept., Oct	Fine sandy loam	80% of potential ET	1.2%, LR=0.06 10.3%, LR=0.10	Flow weighted mean of 4, high of 10, low of 2 Flow weighted mean of 21, high of 42, low of 8	Frank et al., 2006	2nd set of data on a long term study
Kentucky bluegrass,	Lawn, 8” dia by 18”	urea			Oct of ^{15}N of 1st yr	Fine sandy loam	80% of potential		Flow weighted	Frank , 2008	

long term study, collected data for yrs 8-12 after establishment, Michigan	deep lysimeters place in plots		0.5 as ^{15}N 1.0	2 as regular N 5	May, June , July, Oct, in 2nd & 3rd yr Oct of ^{15}N of 1st yr May, June, July, Sept., Oct		ET, amount not given		yearly mean: Yr 8= 2.6 Yr 9= 2.0 Yr 10= 2.1 Yr 11= 3.7 Yr 12= 4.8 Yr 8= 5.0 Yr 9= 8.5 Yr 10= 14.7 Yr 11= 18.9 Yr 12= 25.3		
Kentucky bluegrass, 25 yr old turf site before a 7 yr field study, Rhode Island	Lawn, plots with 0.8 inch dia suction lysimeter in each plot 24 inches deep in the last 19 months of the study	Urea Unfertilized control	0.42 0.75 1 -	2.1 3.7 5.25 -	Apr, June, July, Sept, Oct	Fine silty loam	Not given	Yr 6, 4.8%, LR=0.10b Yr 7, 18.4%, LR=0.39y Yr 6, 8.9%, LR=0.33a Yr 7, 20.0%, LR=0.73x Yr 6, 7.0%, LR=0.37a Yr 7, 19.5%, LR=1.02w Yr 6, LR=0.08c Yr 7, LR=10z	Yr 6, max 4 Yr 7, max 6 Yr 6, max 8 Yr 7, max 9 Yr 6, max 6 Yr 7,max 16 Yr 6, max 3 Yr 7, max 2	Duff et al., 1997	
Kentucky bluegrass, sodded 2 yrs before treatment, Guelph, Ontario	Lawn, 17" dia, 32" long packed lysimeters	Ammonium nitrate	3	9	May, July, Sept	10" of sandy loam, over 10" of loamy sand, over 12" of sand	0.4" once in Aug, 0.25: once in Sept.	21%, LR=1.89 (all occurred between Dec-Feb	Max 800 in Dec.	Roy et al., 2000	Wors e case scena rio study, applie d 3X N rate 3 times
Guelph, Ontario, greenhouse, 3.5 month old turf, 57 day study Annual bluegrass	Simulated sand green, 4" dia by 16" long lysimeters	Ammonium nitrate	0.5	2	14 day intervals	80-20 sand/peat, 4" of pea gravel under 12" of sand root zone	0.75" per day			Pare et al., 2006	Green house study of differ ent annul a blueg

Canada Ontario 1 2 3 Quebec 1 2 3 USA 1 2 3 4 5 Vesper Velvet bentgrass Highland dryland bentgrass Penn A-4 creeping bentgrass Penncross creeping bentgrass Unplanted-fertilized control								 40% LR=0.8 57 % LR=1.2 36 % LR=0.7 68% LR=1.4 71% LR=1.5 61% LR=1.2 34% LR=0.7 41% LR=0.8 28% LR=0.6 44% LR=0.8 36% LR=0.7 Ave 47% LR=1.0 6% LR=0.1 11% LR=0.2 10% LR=0.2 11% LR=0.2 116% LR=2.3	 28 max 40 max 23 max 8 max 17 max 12 max 56 max		rass ecotypes compared to bentgrass species. Very high daily irrigation, worse case scenario
Kentucky bluegrass, greenhouse 7 day study, Iowa	Lawn, intact soil columns (8” dia by 20 “ long) taken from a 11 yr old field site	urea	1	1	once	Fine sandy loam, 2.3% om, pH=7.4	0.25”/application, 4 in 7 day period 1.0”/ application, 4 in 7 day period	<0.1% as nitrate 0.1% (0.6% total N)		Starrett et al., 1995	Intact soil columns with macropores
Kentucky bluegrass, greenhouse 2 yr study,	Lawn intact soil columns (8” dia,	Ammonium nitrate	0 0.1	0 0.6	Monthly May-Oct	Fine sandy loam	1”/wk May - Nov	0 1% LR=0.006	Flow wt mean 2 3	Mangiafico & Guilla	Study that determined

Connecticut	30" long)		0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.2 1.4 1.6 1.8 2.0	1.2 1.8 2.4 3.0 3.6 4.2 4.8 5.4 6.0 7.2 8.4 9.6 10.8 12.0				9% LR=0.11 13% LR=0.23 6% LR=0.14 8% LR=0.24 7% LR=0.25 14% LR=0.59 9% LR=0.43 8% LR=0.43 10% LR=0.60 14% LR=1.01 16% LR=1.34 17 % LR=1.63 18% LR=1.94 27% LR=3.24	4 6 5 8 9 11 12 13 18 22 24 27 31 49	rd, 2007	the useful ness of anion excha nge memb ranes to predic t nitrat e leachi ng
Mixture of 4 lane grasses (Kentucky bluegrass, chewing fescue, hard fescue and perennial ryegrass, 12 yrs old) site in turf for 31 yrs before study, 12 month field study, Rhode Island	Lawn, suction lysimeter at 24" deep	Prior to study, 7 yrs of a fertilizer trial (2.5 lbs N in either early of late fall, 5 sources- soluble to slow release, 1 lb N in June) ½ plots kill in Sept. with no fall fertilizer Killed alive	2.5	3.5	June & early or late fall	Silt loam	Yes. ,but amount not given	46 lbs of total N in profile 7.2% of tot N, LR=3.3 2.2% of Tot N,LR=1.13	Max 38 in Dec Max of 10 in Jan, June Aug	Jiang et al., 2000	Studi ed what if turf sudde nly dies, much more N leachi ng
Kentucky bluegrass, seeded, 6 month field study in Norway	Athletic field- lawn, lysimeters (1.7 sq.ft by 10" deep)	Sulfur coated urea(SCU) Ureaformalde hyde Resin coated	6.2 "	6.2 "	May "	Sand: sphagnum peat 80:20 "	As needed but amount not give, several at high events to cause leaching	2.7%, LR=0.17 2.7%, LR=0.17 5.0%, LR=0.31	Max of 5 in May Max of 32 in May Max of 25 in	Engel sjord & Singh ,	Colle cted N from April -Nov

		ammonium nitrate	“	“	“	“			May		
		Water sol. NPK	1	“	6 X, May-Oct	“		11.7%, LR=0.72	Max of 63 in June		
		“	0.52	“	12 X, May-Oct	“		2.7%, LR=0.17	Max of 10 in June		
		Sulfur coated urea(SCU)	6.2	6.2	May	Sand: sphagnum peat 60:40		2.3%, LR-0.14	Max of 2		
		Ureaformaldehyde	“	“	“	“		1.7%, LR=0.10	Max of 3		
		Resin coated ammonium nitrate	“	“	“	“		3.0%, LR=0.19	Max of 4		
		Water sol. NPK	1	“	6 X, May-Oct	“		2.7%, LR=0.17	Max of 4		
		“	0.52	“	12 X, May-Oct	“		2.0%, LR=0.12	Max of 5		
		Sulfur coated urea(SCU)	6.2	6.2	May	Sand: sphagnum peat 80:20	Amount controlled by soil moisture tension (0.1 MPa), only precip causing leaching	1.5%, LR=0.09	Max of 3		
		SCU	9.3	9.3	May	“		1.1%, LR=0.10	Max of 3		
		SCU	3.1	6.2	May , July			1.5%, LR=0.09	Max of 5		
		SCU	4.6	9.3	May, July	“		1.1%, LR=0.10	Max of 6		
		Urea-ammonium nitrate (UAN)	6.2	6.2	May	“		2.5%, LR=0.15	Max of 43 in June		
		UAN	9.3	9.3	May	“		2.9%, LR=0.27	Max of 36		
		UAN	3.1	6.2	May , July	“		2.5%, LR=0.15	Max of 31		
		UAN	4.6	9.3	May, July	“		2.0%, LR=0.19	Max of 32		
		Water sol. NPK	0. 61	6.2	10X, May-Sept	“		2.5%, LR=0.15	Max of 2		
		“	0.93	9.3	10 X, May-Sept	“		2.0%, LR=0.19	Max of 1		

Kentucky bluegrass-perennial ryegrass (80/20), seeded 2 yr field study, Ithaca NY from establishment	Lawn, ion exchange resin strips placed below the rootzone for month long periods	Swine compost	1	4	July, Aug, Sept, Oct July, Sept	Sandy loam-silt loam	none	Yr 1, 14.4%, LR=1.0 Yr 2, 1.2%, LR=0.13	Not given due to collection technique	Easton & Petrovic, 2004	Leached as nitrate, first year considered worse case scenario, part of a runoff study
			2					Yr 1, 14.5%, LR=1.0 Yr 2, 4.0%, LR=0.24			
		Dairy compost	1					Yr 1, 0%, LR=0.32 Yr2, 0.4%, LR=0.09			
			2					Yr 1, 11.9%, LR=0.91 Yr 2, 4.8%, LR=0.28			
		Biosolid	1					Yr 1, 36.6%, LR=1.92 Yr 2, 1.3%, LR=0.13			
			2					Yr 1, 56.1%, LR=2.73 Yr 2, 3.6%, LR=0.23			
		Urea/DAP	1					Yr 1, 30.8%, LR=1.69 Yr 2, 7.2%, LR=0.38			
			2					Yr 1, 83.1%, LR=3.85 Yr 2, 9.1%, LR=0.45			
		SCU	1					Yr 1, 43.9%, LR=2.23 Yr 2, 6.8%, LR=0.36			
			2					Yr 1, 80.8%, LR=3.75 Yr 2, 8.8%, LR=0.44			
		Unfertilized control						Yr 1, LR=0.42 Yr 2, LR=0.08			
Creeping bentgrass, greenhouse pot study, 14 days to 10 weeks, started 10 months after seeding	Tee or fairways of sand, drainage from 12" dia pots					Sand/sphagnum peat 80:20	0.5"for 3X/week	<u>10 week study</u>	Not reported	Mancino & Troll, 1990	Amount leached contained both nitrate and ammonium
		Urea	0.20 0.40	2.0 2.0	Every 7 days Every 14 days			0%, LR=0.02 0.02%, LR=0.05			
		Calcium nitrate	0.20 0.40	2.0 2.0	Every 7 days Every 14 days			0.20%, LR=0.13 0.27%, LR=0.17			
		Ammonium nitrate	0.20 0.40	2.0 2.0	Every 7 days Every 14 days			0.12%, LR=0.09 0.32%, LR=0.19			
		Ammonium	0.20	2.0	Every 7 days			0%, LR=0.03			

		sulfate	0.40	2.0	Every 14 days			0%, LR=0.03			
			0.20	2.0	Every 7 days			0%, LR=0.03			
		Ureaformaldehyde	0.40	2.0	Every 14 days			0%, LR=0.03			
			0.20	2.0	Every 7 days			0.02%, LR=0.04			
		IBDU	0.40	2.0	Every 14 days			0.01%, LR=0.04			
		Unfertilized control						LR=0.03			
								<u>14 day study</u>			
		Urea	1	1	once			0.00%, LR=0.0009	Max of 0.6		
		Calcium nitrate	1	1				2.80%, LR=0.03	Max of 40.5		
		Ammonium nitrate	1	1				4.13%, LR=0.04	Max of 68.8		
		Ammonium sulfate	1	1				0.09%, LR=0.001	Max of 0.6		
		Ureaformaldehyde	1	1				0.01%, LR=0.0001	Max of 1.0		
		IBDU	1	1				0.26%, LR=0.003	Max of 6.0		
		Unfertilized control	0	0				LR=0..001	Max of 0.9		
Cool season lawn grasses, 2.5 yr field study, PA	Lawn, 9-14% slope runoff plots, 10" dia by 6" long lysimeters placed 6 " deep in soil	Urea mostly, once a yr with urea/ammonium nitrate	0.75	1.5-2.25	Aug & Oct, June, July, Sept	Slit loam with karst topography	6" in 1 hr, 4 X in 1st yr, 8 X each in yrs 2 &3	Not given	Range in yr 1 was 1-3, yr 2 was 0-4 and yr 3 was 0-5 Irrigation water was 2.1	Harrison et al., (ch 17)	
Kentucky bluegrass,	Lawn, 45" dia by 47"	Urea (^{15}N)	0.8	0.8	April	Fine sandy loam	As needed to prevent	0.1%, LR=0.001	Not given	Branham et	Amountleac

sodded, 3 yr field study, MI	deep lysimeters		0.8	0.8	Nov		wilt, amount not given	0.2%, LR=0.002		al., (ch 4)	hed contained both nitrate and ammonium
Kentucky bluegrass & perennial ryegrass, mature stand- 3 month field study, CA	Lawn, 36” deep suction lysimeters in 4’ X 6’ plots	Urea SCU Blood meal Unfertilized control	2.5	5.0	May & July	Fine sandy loam	Based on ET, 50% soil moisture depletion, amounts not given	Not reported	Max of 10, 14 days after treatment Max of 3, 3 days after treatment Max of 0.5, 22 days after treatment Max of 1, 22 days into the study	Gibeault et al., 1998	Soil water samples collected twice per week
Kentucky bluegrass- (90:10) as sod, 2 yr field study in CT	Lawn, leachate collected in buried lysimeters (22” dia by 33” deep) placed in 4.6’ by 8’ plots	Urea (74%) and water insoluble N (17%)	1 1 1 1 1	2 3 3 3 3	May, June May, June, September May, June, October May, June, November May, June, December	Loamy sand top soil, lysimeters in subsoil containing loamy sand	1”/wk May-Sept	Yr 1, 2.4%, LR=0.03 Yr 2, 9.6%, LR=0.48 Yr 1, 2.3%, LR=0.07 Yr 2, 16.1%, LR=0.48 Yr 1, 2.6%, LR=0.08 Yr 2, 25.2%, LR=0.76 Yr 1, 2.1%, LR=0.06 Yr 2, 27.8%, LR=0.83 Yr 1, 7.2%, LR=0.22 YR 2, 28.4%, LR=0.85	2 yr ave of 0.4 2 yr ave of 1.5 2 yr ave of 2.0 2 yr ave of 1.8 2 yr ave of 3.0	Mangiafico & Guillard, 2006	At treatments made in Sept-Dec were on the 15th of the month
Creeping bentgrass, sodded 8 yrs before a 2 yr field study, ID	Actual golf green, all drainage water collected from a	Urea + ammonium nitrate Urea	0.1 0.6	Every 7-10day during growing season both yrs	Over all amount applied 3.6 to 4.1	14” sand rootzone over 4” of gravel	Not reported	13.2%, LR=0.50	Ave 0.9 with a max of 2.7	Johnson et al., 2001	The higher N rates were done for

	14,000 sq. ft. green	Urea + ammonium nitrate 38% urea+45% water soluble organic N, +17% water insoluble N 41% urea+23% water soluble organic N, +17% water insoluble N+ 19% N as DAP	0.3 0.6 0.92 0.72	Aug, yr 1 Sept, yr 1 Apr, yr 2 Sept, yr 2							research, superintendent used only lower rates, highest loses during Nov-Feb with large amounts of drainage
Creeping bentgrass, sodded 15 wks before 4 month greenhouse study	Green, 12” dia by 16 long lysimeters	Ammonium sulfate Ammonium sulfate	0.25, 0.25 0.50 1.0 0.50 0.50 1.0 2.0 0.75 0.75 1.50 3.00 0.25, 0.25 0.50 1.0 0.50 0.50 1.0	2 4 6 2 4	Wk 1 Wk 6 Wk 12 Wk 15 Wk 1 Wk 6 Wk 12 Wk 15 Wk 1 Wk 6 Wk 12 Wk 15 Wk 1 Wk 6 Wk 12 Wk 15 Wk 1 Wk 6 Wk 12	12” of sand over 4” of gravel “ “ 12” sand to clinoptilolite (90:10) over 4” of gravel “	Weekly to container capacity plus 0.27” to cause leaching, 18 events	2.8%, LR=0.06 2.3%, LR=0.09 6.6%, LR=0.40 2.5%, LR=0.05 1.1%, LR=0.04	Ave of 3.7, max of 115 Ave of 4.8, max 78 Ave of 23.1, max of 413 Ave of 2.2, max of 6 Ave of 2.5, max of 14	Huang & Petrovic, 2004	Less nitrate leaching from sand amended by clinoptilolite due to great N in clippings

			2.0 0.75 0.75 1.50 3.00	 6	Wk 15 Wk 1 Wk 6 Wk 12 Wk 15	“		0.9%, LR=0.05	Ave of 2.2, max of 8		
Kentucky bluegrass & red fescue, 34 day field study, NE	Outfield of a sports field, 20 ft deep soil cores extracted at the end of the study	Ammonium nitrate Unfertilized control	2 3 4 5 0	2 3 4 5 0	Aug	Sandy loam soil in upper 16”, then loamy sand over sand and gravel	2” (3 X the ET rate)at fertilization and every 3 day for a total of 25” + 1.25” of rainfall (0.77”/day of rain + irrigation)	90%, LR=1.8 93%, LR=2.8 95%, LR=3.8 83%, LR=4.2	Max of 45 Max of 105 Max of 120 Max of 92 Max of 10	Exner et al., 1991	High rates of application (2 to 5 X0 and excessive irrigation, worse that worse case

LR= loading rate in lbs of nitrogen/1,000 sq. ft. /yr