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REVIEWS AND ANALYSES

The Fate of Nitrogenous Fertilizers Applied to Turfgrass

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ABSTRACT

Maintaining high quality surface and groundwater supplies is a national concern. Nitrate is a widespread contaminant of groundwater. Nitrogenous fertilizer applied to turfgrass could pose a threat to groundwater quality. However, a review of the fate of N applied to turfgrass is lacking, but needed in developing management systems to minimize groundwater contamination. The discussion of the fate of N applied to turfgrass is developed around plant uptake, atmospheric loss, soil storage, leaching, and runoff. The proportion of the fertilizer N that is taken up by the turfgrass plant varied from 5 to 74% of applied N. Uptake was a function of N release rate, N rate and species of grass. Atmospheric loss, by either NH_3 volatilization or denitrification, varied from 0 to 93% of applied N. Volatilization was generally <36% of applied N and can be reduced substantially by irrigation after application. Denitrification was only found to be significant (93% of applied N) on fine-textured, saturated, warm soils. The amount of fertilizer N found in the soil plus thatch pool varied as a function of N source, release rate, age of site, and clipping management. With a soluble N source, fertilizer N found in the soil and thatch was 15 to 21% and 21 to 26% of applied N, respectively, with the higher values reflecting clippings being returned. Leaching losses for fertilizer N were highly influenced by fertilizer management practices (N rate, source, and timing), soil texture, and irrigation. Highest leaching losses were reported at 53% of applied N, but generally were far less than 10%. Runoff of N applied to turfgrass has been studied to a limited degree and has been found seldom to occur at concentrations above the federal drinking water standard for NO_3^-. Where turfgrass fertilization poses a threat to groundwater quality, management strategies can allow the turfgrass manager to minimize or eliminate NO_3^- leaching.

THE IMPORTANCE of maintaining high-quality surface and groundwater supplies cannot be overstated. Groundwater accounts for 86% of the total water resources in the contiguous USA and provides 24 to 95% of the drinking water supply for urban and rural areas, respectively (Scott, 1985). The dependence on groundwater supplies is increasing at a faster rate than for surface water (Solley et al., 1983). A wide range of contaminants are found in groundwater. Nitrate (NO_3) is considered one of the most widespread groundwater contaminants (Pye et al., 1983). Sources of NO_3^- contamination include effluent from cess pools and septic tanks, animal and human wastes, and fertilization of agricultural lands (Keeney, 1986). Nitrate leaching from fertilizers applied to turfgrass sites has been proposed as a major source of nitrate contamination of groundwaters in suburban areas where turfgrass is a major land use (Flipse et al., 1984).

To date, a comprehensive review of the effect of N applied to turfgrass on groundwater quality is lacking or has been ignored in another review (Keeney, 1986). The purpose of this paper is to provide a review and critical analysis of the current state of knowledge of the effect of nitrogenous fertilizers applied to turfgrass on groundwater quality. This review can be useful in providing information on the development of best management practices to minimize the impact of turfgrass fertilization on groundwater quality and to indicate gaps in the knowledge base, which can emphasize future research needs.

The discussion of the fate of N applied to turfgrass will cover the five major categories of the N cycle: plant uptake, atmospheric loss, soil storage, leaching, and runoff. As illustrated in Fig. 1, N can be found in both organic and inorganic forms in the turfgrass

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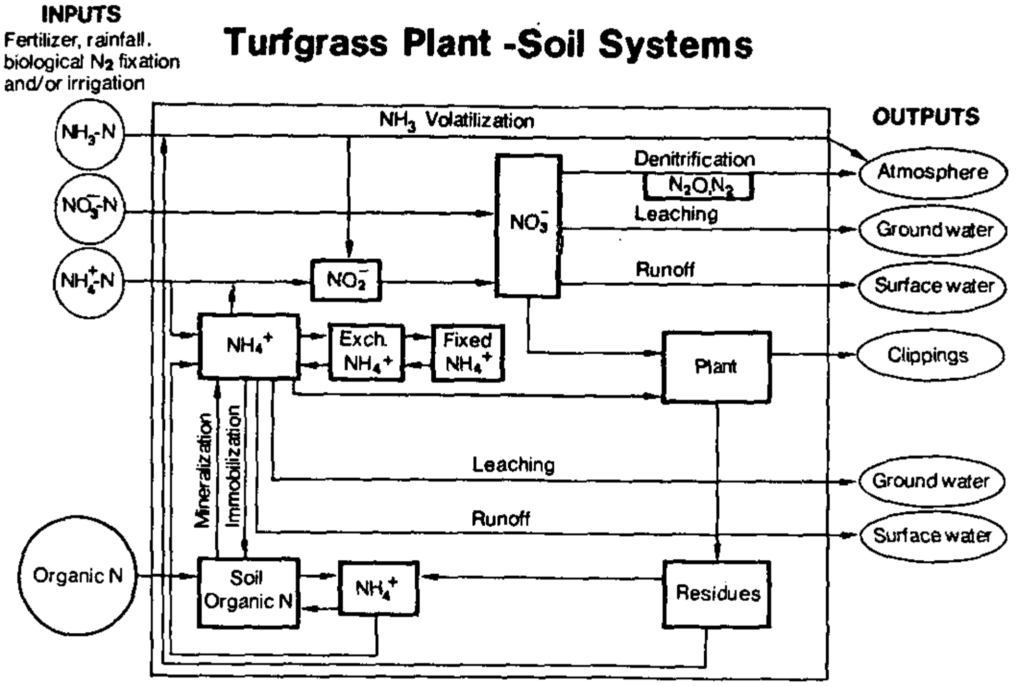

Fig. 1. The N cycle for the turfgrass ecosystem.

plant-soil system. Inputs of N into the system are primarily from fertilizers but to a lesser extent from rainfall, irrigation, and biological N_2 fixation. Once the N is in the turfgrass plant-soil system it may be found in one of the N pools of NO_3^-, NH_4^+, soil organic N or as part of the turfgrass plant. Nitrogen leaves the system via several routes: gaseous loss to the atmosphere (NH_3 volatilization and denitrification), leaching into groundwater, runoff into surface water, and removal in the clippings of the turfgrass plant.

Plant Uptake

The goal of an environmentally sensitive N management system is to optimize the amount of N uptake by the plant. However, the uptake of N is influenced by numerous factors including temperature and moisture that affect plant growth rate, available N pool, N source and rate, and the genetic potential differences between species and/or cultivars. With numerous factors influencing the amount of N taken up by a plant, direct comparisons of results of research from various experiments are somewhat difficult. However, this section summarizes and evaluates the results of numerous studies (Table 1) of the plant uptake of fertilizer N for grasses used for either turf and nonturf type situations.

Grass species and grass use patterns have a major impact on N recovered in clippings. Barraclough et al. (1985) observed that 99% of the fertilizer N, applied as ammonium nitrate (NH_4NO_3) at an N rate of 250 kg ha^{-1} yr^{-1} was recovered in the single harvest of the shoots of perennial ryegrass (*Lolium perenne* L.), whereas the N recovery in the clipping steadily declined with increased N rates to about 50% fertilizer N recovery at an N rate of 900 kg ha^{-1} yr^{-1}. In contrast, about 60% of the fertilizer N was recovered in the season long clippings yields of the 'Penncross' creeping bentgrass (*Agrostis palustris* Huds.) when fertilized at an N rate of 240 to 287 kg ha^{-1} yr^{-1} (Sheard et al., 1985). Cisar et al. (1985) found that 'Enmundi' Kentucky bluegrass (*Poa pratensis* L) had N uptake rates in the field of 4.6 g N m^{-2} d^{-1} compared with 3.1 g N m^{-2} d^{-1} for 'Yorktown II' perennial ryegrass.

Recovery of fertilizer N in the clippings of Kentucky bluegrass has been studied more thoroughly and found to be highly influenced by the rate at which N becomes available from various N sources during the growing season. Nitrogen recovery via clipping removal ranges from 25 to 60% from N sources from which most of the N is released during a single year. Over a 3-yr period, N recovery in the clippings averaged 46 to 59% of the 245 kg N ha^{-1} yr^{-1} supplied by sulfur-coated urea (SCU), isobutyldine diurea (IBDU), and NH_4NO_3 (Hummel and Waddington, 1981). Others have found similar (Hummel and Waddington, 1984) or slightly lower (Selleck et al., 1980; Starr and DeRoo, 1981) recovery with similar N sources and rates. However, with sources from which N is not entirely released in 1 yr, N recovery in the clippings is considerably less. Recovery of applied N in clippings was 22% from ureaformaldehyde, 29% from activated sewage sludge, 11% from ammeline, and 5% from melamine (Hummel and Waddington, 1981; Hummel and Waddington, 1984; Mosdell et al., 1987).

A comparison of two highly water-soluble N sources showed that 53% of the applied N from NH_4NO_3 was recovered in the clippings of an infrequently harvested perennial ryegrass compared with 31% recovery from urea (Watson, 1987). Although, little difference in turfgrass quality has been shown between turfgrasses treated with either urea or NH_4NO_3 (Rieke and Bay, 1978), one would expect a difference in quality due to a difference in uptake substantial as that reported by Watson (1987). The rate of N applied has a variable effect on N recovery in the clippings. At N rates less

Table 1. Uptake of fertilizer N by turfgrasses.

		Clipping		Nitrogen				Plant uptake		
Grass	Use	Frequency	Placement	Source	Rate	Season	Soil texture¶	Clippings	Other†	Reference
		days			kg N ha^{-1}			% of applied		
Agrostis palustris Huds 'Penncross'	Putting green	4–13	removed	Urea	287	Year	Sand	60	–	Sheard et al. (1985)
Lolium perenne L. 'Melle'	Forage	5 yr^{-1}	removed	NH_4NO_3	250	Year	Sandy loam	99	–	Barraclough et al. (1985)
					500			76	–	
					900			50	–	
Lolium perenne L. 'Melle'	Forage	once, 7 wks		Urea	90		Sandy loam	31	16	Watson (1987)
				NH_4NO_3	90			53	25	
Poa pratensis L. 'Merion'	Lawn	7	removed	SCU-11‡	245	Fall	Hagerstown silt loam	32	1.9	Hummel and Waddington (1984)
					245	Spring		37	2.3	
					245	Spring/fall		33	2.1	
					147	Spring/fall		25	2.7	
				Ureaformaldehyde	245	Spring/fall		22	2.2	
				IBDU	245	Spring/fall		46	2.0	
				NH_4NO_3	245	Spring/fall		59	2.1	
					147	Spring/fall		53	3.1	
Poa pratensis L.	Lawn	7	removed	Not stated	100	Year	Haven-Riverhead sandy loam	36	39	Selleck et al. (1980)
					200			36	31	
					400			35	20	
Poa pratensis L. and *Festuca rubra* L.	Lawn	7	removed	$(NH_4)_2SO_4$	180	Spring/fall	Merrimac sandy loam	29	–	Starr and DeRoo (1981)
			returned					30	–	
Poa pratensis L. 'Baron'	Lawn	7	removed	IBDU-course	197	Spring/fall	Hagerstown silt loam	37	–	Hummel and Waddington (1981)
				IBDU-fine				47	–	
				Ureaformaldehyde				22	–	
				Activated sewage sludge				29	–	
				Methylene urea				42	–	
				$(NH_4)_2SO_4$				48	–	
Poa pratensis L. 'Wabash'	Lawn	12–15	removed	Melanie	98	Summer	Chalmers silt loam	5	–	Mosdell et al. (1987)
				Ammeline				11	–	

Table 1 (cont.)

than optimum for shoot growth, increasing the rate of N will result in an increase in the percentage N recovered in the clippings (Selleck et al., 1980; Wesely et al., 1988). When rates are near optimum for shoot growth, the recovery was not influenced by the increase in the rate of N applied (Hummel and Waddington, 1984; Selleck et al., 1980; Wesely et al., 1988). Furthermore, at higher than optimum rates, percentage of N recovered generally declined (Barraclough et al., 1985; Halevy, 1987; Selleck et al., 1980).

Limited information exists on the percentage of fertilizer N recovery in the clippings as influenced by soil type. In one study 9% more of the fertilizer N was found in the clippings from plants grown on a silt loam soil than a clay loam soil (Webster and Dowdell, 1986). The difference was found to relate to greater amounts of leaching, denitrification, and/or storage of N in the clay loam soil.

Season, temperature, and irrigation also have some effect on fertilizer N recovery in clippings. Spring-applied SCU was found to enhance total N recovery in the clippings over fall-applied material (Hummel and Waddington, 1984). In a growth chamber, Mosdell and Schmidt (1985) observed that at day/night temperatures of 16 °C/4 °C from 26 to 39% of fertilizer N was recovered in the clippings of Kentucky bluegrass. However, at temperatures of 30 °C/24 °C, N removal in the clipping was no greater in pots fertilized with either NH_4NO_3 or IBDU at a N rate of 74 kg ha^{-1} than on the unfertilized pots.

Clipping management should be expected to influence fertilizer N recovery in the clippings (Rieke and Bay, 1976), but Starr and DeRoo (1981) found almost identical amounts of fertilizer N (29%) in the clippings on plots either having the clippings returned or removed.

The amount of fertilizer N found in other plant parts (roots, crowns, stems) has been studied to a lesser extent. Selleck et al. (1980) observed that the percentage of fertilizer N found in verdure, crowns, roots, and

Table 1. (Continued).

		Clipping		Nitrogen			Soil	Plant uptake		
Grass	Use	Frequency	Placement	Source	Rate	Season	texture¶	Clippings	Other†	Reference
		days			kg N ha^{-1}			% of applied		
Poa pratensis L. 'Park'	Lawn	7	removed	Urea	9	Spring	Sharpsburg silty clay loam	49	–	Wesely et al. (1988)
					18			60	–	
					27			59	–	
					36			59	–	
Lolium perenne L. 'Engels'	Forage	21	removed	IBDU	1120	Glasshouse	Sand	71	–	Halevy (1987)
					2240			41	–	
					3360			22	–	
					4480			12	–	
				SCU	1120			64	–	
					2240			42	–	
					3360			25	–	
					4480			15	–	
				Urea	373			71	–	
					746			70	–	
					1307			64	–	
					2053			44	–	
Unspecified	Forage	7	removed	$Ca(NO_3)_2$	400	Year	Clay loam	52	–	Webster and Dowdell (1986)
					400		Silt loam	63	–	
Poa pratensis L. 'Adelphi'	Lawn	Once, 70	removed	NH_4NO_3	74		Lodi silt loam			Mosdell and Schmidt (1985)
						16 °C/4c L§		12	–	
						H		39	–	
						30 °C/24c L		0	–	
						H	0	–		
				IBDU		16 °C/4c L		26	–	
						H		43	–	
						30 °C/24c L		0	–	
						H		0	–	

† Other plant parts including roots, stems, and verdure.

‡ Sulfur-coated urea, 36% N with 11% 7-d dissolution rate.

§ Growth chamber study, day and night T; L and H refer to 2.5 and 5.0 cm of irrigation wk^{-1}, respectively.

¶ Hagerstown, fine, mixed, mesic Typic Hapludalfs; Haven-Riverhead, mixed, mesic Typic Dystrochrepts; Merrimac, sandy, mixed, mesic Typic Dystrochrepts; Chalmers, fine-silty, mixed, mesic Typic Haplaquolls; Sharpsburg, Typic Argiudolls; Lodi, clayey, kaolinitic, mesic Typic Hapludults.

debris (possibly thatch) was 39, 31, and 20% of applied N at N rates of 100, 200, and 400 kg N ha^{-1} yr^{-1}, respectively. Hummel and Waddington (1984) observed only 1.5 to 3% of the applied fertilizer N recovered in the unmowed portions of the plant (top, roots, and debris). The different results may be a function of the amount of thatch present as suggested by the results of Starr and DeRoo (1981). They found that 14 to 21% of the fertilizer N was found in the thatch layer. Neither Selleck et al. (1980) nor Hummel and Waddington (1984) provided thatch data; therefore, this explanation is only speculative.

Uptake of N from $(NH_4)_2SO_4$, as measured in the clippings of Kentucky bluegrass-red fescue (*Festuca rubra* L.) turf, occurred primarily within the first 3 wk after application (Starr and DeRoo, 1981). During the period from 3 to 9 wk after application, most of the N uptake was derived from the soil N pool and occurred at a rate (0.24 kg ha^{-1} d^{-1}) five times faster than that from fertilizer N. Clipping management during the 3 yr of this study had a major impact on total N uptake. About 9% of the total N found in the clippings was derived from the current year's returned clippings; whereas the N found in the clippings from the previous 2yr returned clippings accounted for 20% of the N in the clippings during the third year of the study.

ATMOSPHERIC LOSS OF FERTILIZER NITROGEN

Nitrogen applied as a fertilizer to turfgrass can be lost to the atmosphere as either ammonia (NH_3 volatilization) or as one of several nitrous oxide compounds (denitrification). Numerous factors influence the degree of NH_3 volatilization and denitrification as summarized in Table 2.

Ammonia volatilization can occur very rapidly following an application of N fertilizer such as urea. Factors that influence the amount of NH_3 volatilization include N source/form (liquid vs. dry) and rate, soil pH, amount of water (irrigation or precipitation) received after application and thatch. In addition, when urea was applied to bare soil and to turfgrass, the amount of NH_3 volatilization was higher in the turfgrass system than from bare soil (Volk, 1959). Thus, some other factor(s) related to the presence of turfgrass resulted in the acceleration of the NH_3 volatilization process.

Studies of NH_3 volatilization can be divided into field and nonfield studies. Results from the nonfield and/or closed system monitoring field studies are highly quantitative, and are useful for comparing treatment effects. Aerodynamic or other open system techniques can give results more typical of field conditions.

Table 2. Atmosphere loss of fertilizer nitrogen applied to turfgrass.

Grass	Location of study	Sampling period	Nitrogen		Soil moisture % saturation	Irrigation or rainfall	Temperature (relative humidity)	Soil texture§	NH_3 volatilization	Denitrification	Reference
			Source	Single/total application rate							
				kg N ha^{-1}		cm	C (%)		% applied N	% applied N	
Poa pratensis L. 'Benson'	Field	3 d	Urea	58	–	0	27–39	Yolo loam	3–36	–	Bowman et al. (1987)
					–	0.5			2–21	–	
					–	1.0			1–8	–	
					–	2.0			1–5	–	
					–	4.0			0–3	–	
Poa pratensis L. 'Baron'	Growth chamber	10 d	KNO_3	52	75	–	22	*Hadley silt*	–	0.02	Mancino et al. (1988)
					75	–	>30		–	0.11	
					75	–	22	Hadley silt loam	–	0.4	
					75	–	>30		–	–	
					100	–	22	Hadley silt	–	5.4	
					100	–	>30		–	94	
					100	–	22	Hadley silt loan	–	2.2	
					100	–	>30		–	46	
Poa pratensis L.	Growth chamber	8 d	Urea	253	–	2.27 d^{-1}		Flanagan silt loam	5	–	Nelson et al. (1980)
								Thatch	39	–	
			IBDU		–			Flanagan silt loam	2	–	
								Thatch	4	–	
Poa pratensis L. and *Festuca rubra* L.	Field	8 d (July)	Urea	100	–	0			15.1	–	Sheard and Beauchamp (1985)
		5 d (August)			–	0.19			6.7	–	
Poa pratensis L. and *Festuca rubra* L.	Field	Growing season	$(^{15}NH_4)_2SO_4$	90/180	–	–		Merrimac sandy loam		24 36‡	Starr and DeRoo (1981)
Poa pratensis L. 'Merion'	Growth chamber	84 h	Urea (granular)	73	–	–	10	Crosby silt loam	18	–	Titko et al. (1987)
						–	22		43	–	
						–	32		61	–	
						–	(31)		39	–	
						–	(68)		61	–	
						0	–		51	–	
						2.5	–		2	–	
			Urea (dissolved)	73		–	10		3	–	
						–	22		17	–	
						–	32		12	–	
						–	(31)		2	–	
						–	(68)		12	–	
						0	–		16	–	
						2.5			5		
Poa pratensis L.	Growth chamber	21 d	Urea	293	–	–	24	Flanagan silt loam	10	–	Torello et al. (1983
			SCU						2		
		10 d	Urea (granular)	49	–	–	24		2		
			Urea (dissolved)						5		
		4 d	Ureaformaldehyde	49	–	–	24		3		
			Methyol urea						5		

† Values are a combination of NH_3 volatilization and denitrification for plots where clippings were returned.

‡ Values are a combination of NH_3 volatilization and denitrification for plots where clippings were removed.

§ Yolo, Typic Xerorthents; Hadley, coarse-silty, mixed, nonacid, mesic Typic Udifluvents; Flanagan, Aquic Argiudolls; Merrimac, fine, mixed, mesic Aeric Ochraqualfs.

Examining the results of studies from nonfield or closed systems field experiments, several important concepts can be put forth. An aspect of the turfgrass ecosystem that has a dramatic impact on NH_3 volatilization is the absence or presence of thatch. Nelson et al. (1980) observed that within 8 d after application of urea, 39% of the applied N volatilized as NH_3 from cores of Kentucky Bluegrass containing ≈5 cm of thatch but only 5% volatilized from cores having 5 cm of soil and no thatch below the sod. It should be noted that urea was applied at an extremely high N rate in this study (253 kg ha^{-1}). Substantial urease activity has been noted in the thatch layer, which is needed to convert urea to NH_3, and this activity serves to explain the role thatch plays in NH_3 volatilization (Bowman et al., 1987).

The source, rate, and form of N influences the pool of NH_3 available for volatilization. Torello et al. (1983) noted that 10% of the applied urea volatilized as NH_3 within 21 d after a single N application of 293 kg ha^{-1}, whereas only 1 to 2% of SCU N was volatilized as NH_3. At a lower rate of urea (49 kg ha^{-1}) only about 2% was volatilized. In general, Titko et al. (1987) observed more NH_3 volatilization with granular than dissolved urea. However, Torello et al. (1983) noted the opposite.

An estimate of NH_3 volatilization under field condition was observed by Sheard and Beauchamp (1985). Using an aerodynamic procedure they found that 15% of urea was lost by NH_3 volatilization from a bluegrass–red fescue sod fertilized at 100 kg N ha^{-1}.

Ammonia volatilization is influenced by the position of the N in the turfgrass system after application. The position is highly influenced by rainfall or irrigation. Bowman et al. (1987) studied the influence of irrigation on NH_3 volatilization after an application of liquid urea (49 kg N ha^{-1}). They observed a maximum of 36% NH_3 volatilization when no irrigation was supplied, whereas applying 1 and 4 cm of water within 5 min after application reduced NH_3 volatilization to 8 and 1%, respectively. Titko et al. (1987) also noted a significant reduction in NH_3 volatilization from either dry or dissolved urea applied to turfgrass that received 2.5 cm of irrigation. Irrigation after application dramatically affects the position of the urea. Without irrigation 68% of the urea was located in the shoots and thatch (Bowman et al., 1987). Irrigation at 0.5 and 1.0 cm reduced the percentage of urea found in the shoot and thatch to 31 and 26%, respectively. Urease activity was highly confined to the shoot and thatch region (97% on a dry wt. bases.). Sheard and Beauchamp (1985) also noted that NH_3 volatilization was reduced from 15 to 7% when a 1.2-cm rainfall occurred within 72 h after the urea application.

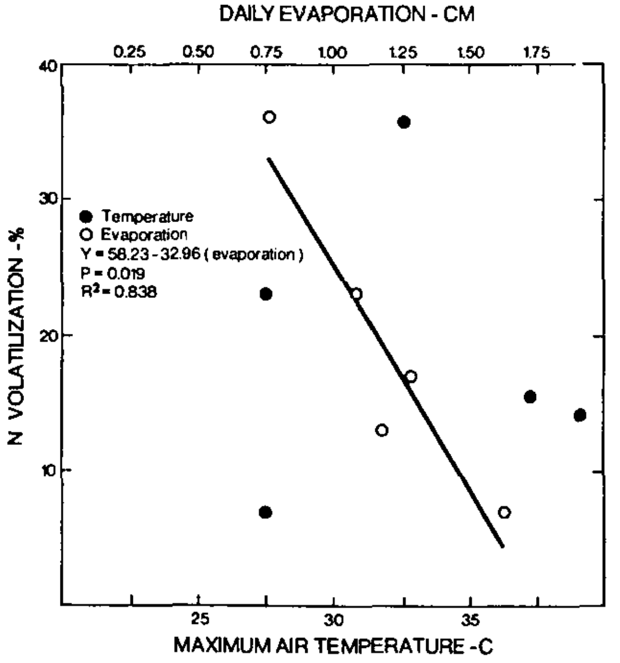

Fig. 2. Ammonia volatilization as influenced by maximum air temperature (●) and evaporation (O) the first 24 h after a liquid urea application (data from Bowman et al., 1987).

The rate at which liquid urea dries influences NH_3 volatilization. Ammonia volatilization from urea on nonirrigated sites is shown in Fig. 2. Ammonia volatilization appears independent of the maximum temperature recorded in the first 24 h after application. However, NH_3 volatilization was inversely related to the daily open pan evaporation rate. Furthermore, Titko et al. (1987) noted more NH_3 volatilization at 68% relative humidity than at 31% with either granular or dissolved urea.

Information regarding direct measurements of the magnitude of denitrification under turfgrass conditions is limited. Mancino et al. (1988) used the acetylene inhibition technique under laboratory conditions to measure the denitrification rate of KNO_3 applied to Kentucky bluegrass. They observed that when the soil was at a moisture content 75% of saturation, less than 1% of the N from KNO_3 was denitrified. Soil type and temperature had no effect on denitrification. However, when the soil was saturated, denitrification became significant. When temperatures were 22 °C or less, 2 and 5% of the N from KNO_3 was denitrified on a silt loam and silt soil, respectively. When temperatures were 30 °C or above, denitrification was substantial: 45 to 93% of applied N for the silt loam and silt soil, respectively. Thus, during periods of high temperatures, substantial losses of N by denitrification could occur in wet soils.

Starr and DeRoo (1981) studied the fate of N in turfgrass. Using a ^{15}N-labeled $(NH_4)_2SO_4$ to calculate a mass balance, they concluded that between 24 and 36% of the fertilizer N applied to Kentucky bluegrass–red fescue turf site was lost to the atmosphere by NH_3 volatilization and/or denitrification. The higher amount reflects clipping removal. When clippings were removed, less fertilizer N was found in the soil and thatch; thus, reducing the total amount of N accounted for and a higher calculated value of gaseous loss.

FERTILIZER NITROGEN STORED IN THE SOIL

When N in fertilizers, rainfall, or irrigation reaches the turfgrass-soil system, it may enter the inorganic pool (NH_4^+, NO_3^-), the organic pool, or be taken up by the plant.

Organic N must be converted through microbial activity to an inorganic form before it can be taken up

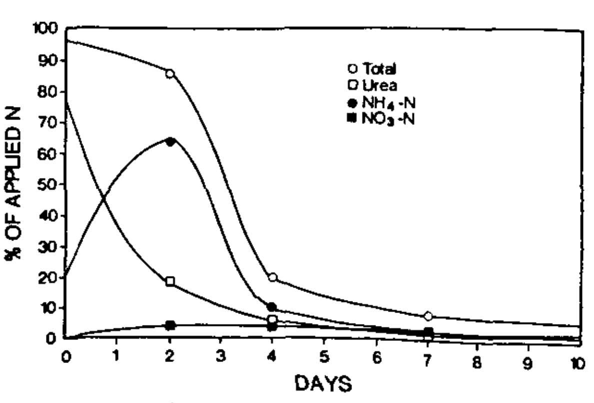

Fig. 3. Percentage of urea applied N recovered as urea, NH_4^+-N, and NO_3^--N as a function of time (data from Mosdell et al., 1987).

by the turfgrass plant. The rate of conversion is highly influenced by the form of the N, temperature, and moisture. At low temperatures or when soils are very dry, urea will not be converted to an inorganic form. However, in warm, moist soils, urea conversion is very rapid. Mosdell et al. (1987) followed the transformation process for urea (98 kg N ha^{-1}) applied to Kentucky bluegrass (Fig. 3). They observed that 76% of free urea was still present the day of treatment but little urea was found 4 d after treatment (DAT). Ammonium accumulation peaked at 2 DAT. The amount of NO_3-N never exceeded 4% of the applied N.

The conversion of other N sources often takes a slightly different pathway than that for urea. Urea in SCU must escape the S coating before conversion. Urea is liberated by hydrolysis from IBDU. Organic N forms (e.g., activated sewage sludge), like any other component of the soil organic matter pool, must be mineralized to NH_4^+ then can be nitrified to NO_3^-.

The amount of fertilizer N stored in the soil is influenced by the release rate of different N source, clippings management and organic matter content as reflected in the age of the turfgrass site (Table 3). The source of N is important when considering sources that have delayed N release. Waddington and Turner (1980) determined the amount of undissolved SCU pellets at selected time intervals after the application (Table 4). They noted that SCUs with lower dissolution rates (% N dissolved after 7 d) and more S coating had a larger amount of residual SCU pellets recovered. In a short-term control environmental chamber study using Kentucky bluegrass, Nelson et al. (1980) determined the percent of residual fertilizer N in a 5.3-cm deep core, containing either soil or thatch, treated at an extremely high single N application rate of 253 kg ha^{-1}. Fifteen days after treatment, only 2% of the urea-N was left in cores with thatch compared with 58% without thatch. For IBDU, the amounts recovery of IBDU-N was 96% from cores with thatch and 67% from cores without thatch.

Determining the amount of fertilizer N that is eventually incorporated into soil organic matter is difficult, thus only a few studies have been done. Nitrogen stored in the soil is not all from fertilizer N; therefore, a tracer for the N in the fertilizer is necessary. Commonly, a ^{15}N source is used for this purpose. Starr and DeRoo (1981) fertilized a Kentucky bluegrass–red fescue turf with $(NH_4)_2SO_4$ containing ^{15}N. They found at the end of the year (4 months after last application) that 15 to 21% of the fertilizer N was stored in the soil. The lower value was from treatments from which clippings were removed. Also, they noted that 21 to 26% of the fertilizer N was found immobilized in the thatch layer, again the lower number is from treatment with clippings removed. Other studies using ^{15}N applied to perennial ryegrass have shown similar results. Watson (1987) noted that 13 and 17% of the applied N was found in the soil organic N pool 7 wk following an application with urea and NH_4NO_3, respectively. Webster and Dowdell (1986) found between 20 and 24% of the fertilizer N remained in the organic N pool soil 4 yr after the final appliction.

The results of the research cited above indicate that 15 to 26% of the N applied by urea, NH_4NO_3, and $(NH_4)_2SO_4$ is present as organic soil N within 4 months to 4 yr after application. If N in thatch (Starr and

Table 3. Soil storage of fertilizer N applied to turfgrass.

Grass	Soil texture	Nitrogen		Days from last treatment	Clipping management	Thatch N	Soil N	References
		Source	Rate					
			kg N ha^{-1}			—— % of applied N ——		
Poa pratensis L.	Flanagan silt loam	Urea	253	15	Removed	–	58	Nelson et al. (1980)
		IBDU				–	67	
	Thatch	Urea				–	2	
		IBDU				–	96	
Poa pratensis L. and *Festuca rubra* L.	Merrimac sandy loam	$(NH_4)_2SO_4$	195	120	Returned	26	21	Starr and DeRoo (1981)
					Removed	21	15	
Lolium perenne	Sandy loam	Urea	90	49	Removed (once)	–	13	Watson (1987)
		$(NH_4)_2NO_3$				–	17	
Perennial grasses	Clay loam	$Ca(NO_3)_2$	400	1460	Removed	–	24	Webster and Dowdell (1986)
	Silt loam					–	20	

Table 4. Residual undissolved pellets on turfgrass fertilized with S-coated urea.

Source	Fertilizer characteristic†			Months after last application				
	N	Sulfur coating	7-day dissolution rate	0	6	13	23	30
	——— % ———			——— % of applied N ———				
SCU-16w‡	37	21	15	15c*	17bc	6cd	3d	0d
SCU-17	34	27	17	37a	37a	21a	26a	13a
SCU-26w	37	19	27	3c	3c	1d	1d	0d
SCU-26	35	24	27	26b	23b	15b	17b	9b
SCU-35	36	22	35	14c	14cd	8c	8c	4c
Gold-N	30	34	37	3d	10de	3cd	4cd	1cd

* Values within columns followed by the same letter are not significantly different. (LSD Walker-Duncan, $k = 100$).

† Each material was applied on 16 May 1974, 20 May 1975, and May 1976 at a rate of 195 kg N ha^{-1} (from Waddington and Turner, 1980).

‡ SCU sources with a w have a 2% sealant; all other sources have a S coating only.

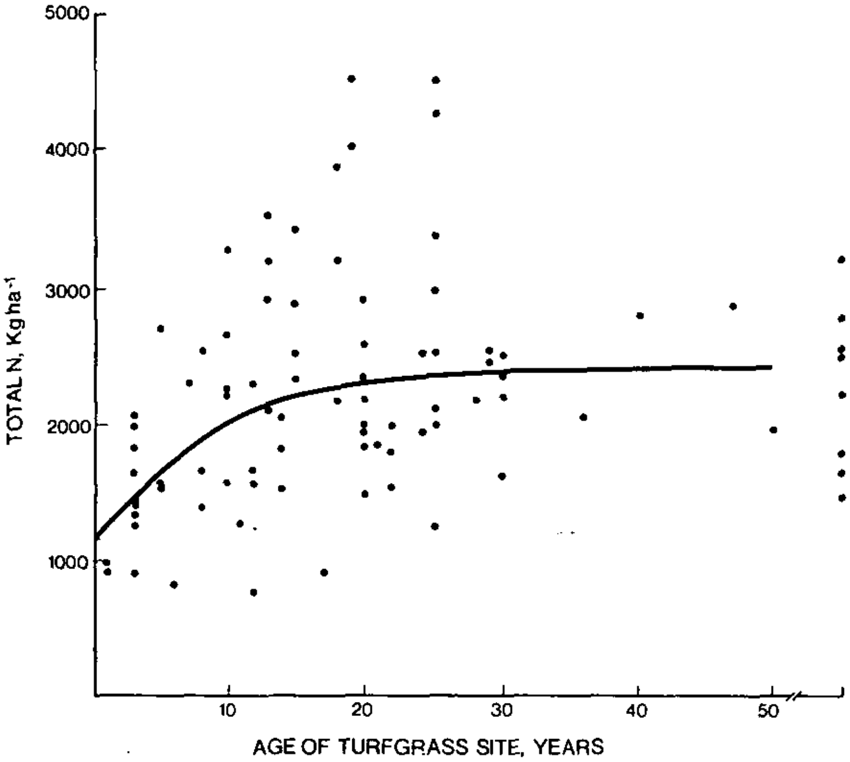

Fig. 4. Total N in surface layer of soil (0–10 cm) as a function of the age of the turfgrass site. Bulk density, 1.4 Mg m^{-3} (with permission from Porter et al., 1980).

DeRoo, 1981) is added to that in soil, then 36 to 47% of the fertilizer N becomes part of the organic N in the soil-thatch system.

Generally, when turfgrass is established on an area, the soil organic matter will increase for several years because of the increased input of organic matter to the soil (thatch, roots) and the lack of soil disturbance. During this period of increasing soil organic matter, some of the fertilizer N applied to the turf will be stored in the organic matter. Eventually, a new equilibrium will be established, and soil organic matter content will remain relatively constant. Therefore, the capacity of a turfgrass to store fertilizer N in the soil is a function of the age of the turfgrass. However, an exception would be when turfgrass is established on a soil that already has a relatively high organic matter content. Turfgrass would not increase organic matter, and consequently, little of the applied fertilizer N would be stored in the soil organic matter.

Only one attempt has been made to study soil N accumulation as a function of age of turfgrass sites. Porter et al. (1980) sampled 100 turfgrass sites ranging in age from 1 to 125 yr on Long Island, NY. Sites were chosen that had received somewhat uniform maintenance over a long period of time and from an array of turfgrass sites including residential lawns, golf course, church yards, and cemeteries. The level of maintenance was recorded and soil samples to a depth of 40 cm were collected and analyzed for total N. Figure 4 graphically depicts their results. Total N accumulation is very rapid in the first 10 yr and changes little after 25 yr. Thus, on younger sites (<10 yr in this example) the rate of N applied should match the rate at which N is stored in the soil, used by the plant and lost to the atmosphere. Older turf sites (>25 yr in this example) should be fertilized at a rate equal to the rate of removal by the plant and by loss to the atmosphere. Thus, old turf sites should be fertilized less to reduce the potential for NO_3^- leaching. Even though other cultural information was obtained in this survey (i.e., grass type, N rate, irrigation practices), only age influenced the storage of N in the soil. These factors could be important but due to the relative small sample population (100) the influence of these factors could not be determined.

LEACHING OF FERTILIZER NITROGEN APPLIED TO TURFGRASS

Several methods have been utilized in studying the leaching of fertilizer N. These include collection of drainage water, soil sampling, sampling of soil water above the saturated zone, trapping NO_3^- on ion exchange resins and sampling shallow groundwater. In most of these studies the assumption made was that once NO_3^- leaches past the root zone, it will eventually move into groundwater. This is true assuming little upward movement of water from below the root zone. A majority of the studies determined the degree of fertilizer N leaching by adjusting the values for background leaching from unfertilized plots. Starr and DeRoo (1981) used ^{15}N to more closely determine the fate of applied N.

The degree of NO_3^- leaching from a N fertilization of a turfgrass site is highly variable (Table 5). Some researchers reported little or no leaching, whereas others suggest that as high as 80% of the fertilizer N was leached as NO_3^-. Factors that influence the degree

Table 5. Summary of nitrate leaching from fertilizers applied to turfgrass.

	Nitrogen								
Grass	Source	Single N application rate	Total yearly N rate	Season applied	Soil texture‡	Irrigation	% of Applied N leached	Concentrate of NO_3-N in water	References
		—— kg ha^{-1} ——				mm d^{-1}		mg L^{-1}	
Cynodon dactylon L.	Ureaformaldehyde	224	224	June	Sand/peat	6–8	–	0	Brown et al. (1977)
						8–10	–	<1	
						10–12	–	<1	
	NH_4NO_3	163	163	Feb.		6–8†	–	<1	
						8–10†	–	>10 for 20 d	
						10–12	–	>10 for 28 d	
	Milorganite	146	146	Oct.		6–8	–	<3	
						8–10	–	<6	
						10–12	–	<5	
	$(NH_4)SO_4$	24	24	Summer		12	37	<10	
		49	49			12	25	<10	
		73	73			12	22	>10 on 3 d	
		98	98			12	16	>10 on 3 d	
Cynodon dactylon L.	IBDU	146	146	June	Sand/peat	12	0.9	0	Brown et al. (1982)
					Sand/soil/peat	12	0.7	<2	
					Sandy loam soil	12	0.1	<1	
	Milorganite	146	146	Oct.	Sand/peat	12	7.7	0	
					Sand/soil/peat	12	2.4	<2.2	
					Sandy loam soil	12	0.5	0	
	Ureaformaldehyde	224	224	June	Sand/peat	12	0.2	0	
					Sand/soil/peat	12	0.3	0	
					Sandy loam soil	12	0.1	0	
	NH_4NO_3	163	163	Feb.	Sand/peat	12†	22	>10 for 25 d	
					Sand/soil/peat	12†	22	>10 for 25 d	
					Sandy loam soil	12†	8.6	>10 for 25 d	
Poa pratensis L. and *Festuca rubra*	Urea + fluf	49	98	June, Nov.	Merrimac sandy loam	1.8	–	0.87	Morton et al. (1988)
		49	98	June, Nov.		5.4	–	1.77*	
		49	245	June, July, Aug., Nov.		1.8	–	1.24	
		49	245	June, July, Aug., Nov.		5.4	–	4.02*	
		0	0			1.8	–	0.51	
		0	0			5.4	–	0.36	
Poa pratensis L. 'Adelphi'	NH_4NO_3	74	74	Cool	Lodi silt loam	3.6	0	–	Mosdell and Schmidt (1985)
				Cool		7.2	0	–	
				Warm		3.6	1.2	–	
				Warm		7.2	2.6	–	
	IBDU	74	74	Cool		3.6	2.7	–	
				Cool		7.2	0	–	
				Warm		3.6	0	–	
				Warm		7.0	0		
Poa pratensis L.	IBDU	245	245		Flanagan silt loam	2.3	26	–	Nelson et al. (1980)
					thatch	–	7	–	
	Urea			Warm	Flanagan silt loam	–	32	–	
					thatch	–	84	–	
Poa pratensis L.	Ureaformaldehyde	98	98	Nov.	Riverhead sandy loam	None	0–4	–	Petrovic et al. (1986)
	PCU (150D)						0–0	–	
	Milorganite						0–3	–	
	Urea						29–47	–	
	SCU						11–12	–	
Agrostis palustris Huds.	Urea	24	294	Whole year	Sand	Not given	2.0	<1.3	Sheard et al. (1985)
	SCU						1.2	<1.3	
Poa pratensis L. and *Festuca rubra*	Ammonium sulfate	88	176	May/Sept.	Merrimac sandy loam	None	0	0	Starr and DeRoo (1981)
Cynodon × *magenissii* H.	Check	0	0	Year	Pompano sand	As needed	0	–	Synder et al. (1981)

Table 5 (cont.)

Table 5. (Continued).

Grass	Nitrogen								
	Source	Single N application rate	Total yearly N rate	Season applied	Soil texture‡	Irrigation	% of Applied N leached	Concentrate of NO_3-N in water	References
		kg ha^{-1}	kg ha^{-1}			mm d^{-1}		mg L^{-1}	
	Methylene Urea	39	245				<1	<1	
	Ureaformaldehyde						<1	<1	
	SCU						0	<1	
	IBDU						0.5	<1	
	Urea						0	<1	
	$Ca(NO_3)_2$						4.7	<1	
	Methylene Urea	78	490				2.0	<1	
	Ureaformaldehyde						0.1	1	
	SCU						0.8	<1	
	IBDU						5.5	1.4	
Cynodon × *magenissii* H.	Urea				Pompano sand		0.9	<1	Synder et al. (1981)
	$Ca(NO_3)_2$						9.3	2.4	
Cynodon × *magenissii* H.	NH_4NO_3	49	98	Feb.–Mar.	Pompano sand	6 (daily)	54.6	9.4	Synder et al. (1984)
	SCU						33.1	6.5	
	Fertigation						7.0	1.2	
	NH_4NO_3					1.5 (sensor)	40.5	14.4	
	SCU						11.2	4.0	
Fertigation							6.3	2.2	
	NH_4NO_3			June–July		3 (sensor)	8.3	3.2	
	SCU						1.6	0.8	
	Fertigation						0.8	0.1	
	NH_4NO_3					12 (daily)	22.2	3.2	
	SCU						10.1	1.4	
	Fertigation						15.3	2.1	
	NH_4NO_3			Apr.–May		3 (sensor)	1.9	6.2	
	SCU						0.3	1.0	
	Fertigation						0.3	1.0	
	NH_4NO_3					8 (daily)	56.1	18.9	
	SCU						14.4	4.8	
	Fertigation						3.5	1.2	

* Values significantly higher than unfertilized control plots ($P = 0.05$).

† Irrigation applied every other day.

‡ Riverhead, mixed, mesic Typic Dystrochrepts; Pompano, Typic Psammaquents.

of leaching were found to be soil type, irrigation, N source, N rates, and season of application.

Soil texture can have a dramatic effect on the leachability of N from turfgrass sites, because of its influence on the rate and total amount of percolating water, extent of denitrification, and to some degree ability of soil to retain NH_4^+. On an irrigated site in upper Michigan, Rieke and Ellis (1974) followed the movement of NO_3^- in a sandy soil (91% sand) to a depth of 60 cm by periodic soil sampling. Applying 290 kg N ha^{-1} as NH_4NO_3 each spring (six times the normal N single application rate), significantly elevated the NO_3^- concentration over that in the unfertilized plots in the 45- to 60-cm soil depth on only two of the 20 sampling during the 2 yr of the study. The results suggest only limited potential for NO_3^-. As expected, soil NO_3^- concentrations were highly elevated most of the 2 yr of the study in the surface 30 cm of the soil. Applying the same total amount of N in three applications revealed a similar trend. Sheard et al. (1985) observed that creeping bentgrass sand greens lost only 1.2 to 2.0% of applied N in the drainage water (N rate of 242–390 kg ha^{-1} yr^{-1}). The results on NO_3^- leaching from a U.S. Golf Association specification putting green were somewhat higher. The U.S. Golf Association specification putting greens have a minimum of 93% sand, a maximum of 3% silt and 5% clay, and an infiltration rate of at least 5 cm hr^{-1}. Brown et al. (1982) noted that 22% of NH_4NO_3-N leached as NO_3-N in the drainage water when N was applied in February at 163 kg ha^{-1} (three times the normal rate from bermudagrass (*Cynodon dactylon* L.) greens in Texas). However, the results from a Florida study (Synder et al., 1981) with bermudagrass sand greens revealed that average NO_3 leaching loss from urea over a 2-yr period was only 1% of applied N (78 kg ha^{-1} bimonthly). The mean NO_3-N concentration in the drainage water from this treatment was about 0.2 mg L^{-1}, well below the drinking water standard of 10 mg L^{-1}.

The information on NO_3 leaching from cool and warm season grasses grown on sandy loam soils is much more extensive. Brown et al. (1982), studying NO_3 leaching in bermudagrass greens built with a sandy loam soil, found that 9% of NH_4NO_3-N leached as NO_3 from a single application of NH_4NO_3 at 163 kg N ha^{-1} (three times the normal N application rate). Significant NO_3 leaching occurred from 10 to 40 DAT. Rieke and Ellis (1974) conducted a study in lower Michigan on a sandy loam soil identical to the one they conducted in upper Michigan on sand. Even though N was applied at six times the normal single N application rate (290 kg ha^{-1}), none of the treatments increased soil NO_3-N concentrations in the 45- to 60-cm soil depth over concentrations measured in the unfertilized Kentucky bluegrass plots. As before, soil NO_3-N concentrations in the surface soils were elevated but deeper movement of NO_3 appeared not to occur. Several others also have observed limited NO_3 leaching and on sandy loam soils, especially at normal N fertilization rates. Starr and DeRoo (1981) studied the fate of ^{15}N-$(NH_4)_2SO_4$ applied to Kentucky bluegrass–red fescue turf. They observed NO_3^--N concentration in the saturated soil zone (1.8–2.4 m deep) to range from 0.3 to 10 mg L^{-1} over the 3 yr of this field study. In only one sample did they find any ^{15}N and concluded that $(NH_4)_2SO_4$ applied at a yearly N rate of 180 kg ha^{-1} to a sandy loam soil in Connecticut did not result in NO_3^- contamination of groundwater.

Information on NO_3^- leaching from fertilizer N applied to turfgrasses grown on finer-textured soil is limited. Furthermore, the studies were conducted as short-term growth chamber experiments; thus, long-term field data are lacking. Nelson et al. (1980) studied the leaching potential of urea and IBDU applied to Kentucky bluegrass underlaid with either 5 cm of a silt loam soil or thatch. Applying 253 kg ha^{-1} (five times the normal rate) and collecting leachate for 15 DAT, they found that 32 and 81% of the applied urea leached as NO_3^- from the silt loam soil and thatch, respectively. Only 5 to 23% of the applied IBDU-N was leached from the thatch and silt loam soil cores, respectively. Nitrogen leaching losses with IBDU from the thatch were lower than from soil. Thatch has been shown to have a lower moisture retention capacity than soil (Hurto et al., 1980); thus, thatch could have dried between waterings and may not have been as favorable an environment for IBDU hydrolysis as soil. A conclusion one can draw from this work is that if NO_3^- is present in a soluble form above a concentration that can be used by the plant and if water moves through thatch or a silt loam soil (or any soil), then NO_3^- leaching can occur. If the N is not readily available, as in the case for IBDU, NO_3^- leaching losses were significantly less.

The impact of the source and rate of N on the leachability of N has received considerable attention. Most of the studies were conducted under the "worst case scenario," namely, sandy soils that were heavily irrigated and fertilized at several times the normal use rate. Others studies were conducted under less extreme conditions.

Generally, worst case scenario studies have shown that as the rate of N increased, the percent of the fertilizer N that leaches decreases; however, the amount of NO_3 leaching on an area basis was found to increase with increasing rates. Brown et al. (1977) observed that on putting greens containing root zone mixes of 80 to 85% sand, 5 to 10% clay, and up to 10% peat, the percent of N from $(NH_4)_2SO_4$ that leached as NO_3 in the drainage water decreased from 38 to 16% as the rate of N increased from 24 to 98 kg ha^{-1}. However, the amount of NO_3 leached increased from 9 to 15 kg ha^{-1}, which is important in terms of the concentration of NO_3-N in the drainage water. They noted, however, that when a fine sandy loam soil was used as the rooting zone media, the percent of fertilizer N that leached as NO_3 was reduced from 15 to 5% as the N rate increased. More importantly, the amount of NO_3-N that leached (4 to 5 kg ha^{-}) on an area basis was essentially unchanged as the N rate increased. Thus, increasing the rate of N applied to highly sandy greens would lead to a deterioration in the drainage water quality; whereas, on sandy loam greens, increased N fertilization would not further reduce the drainage water quality. Even at the high N rate of 98 kg ha^{-1} the drainage water exceeded drinking water standards for NO_3-N only 4 d. Furthermore, they observed considerably less NO_3 leaching from activated sewage sludge (Milorganite) or ureaformaldehyde, even when these materials were applied at very high single N application rates of 146 to 244 kg ha^{-1}.

Synder et al. (1981) also studied the N-leaching potential from sand as influenced by the source and rate of N. At a low rate of 39 kg N ha^{-1} applied bimonthly, they noted very little leaching with any N source. The highest leaching of inorganic N ($NO_3^- + NH_4^+$) was for $CaNO_3$, where 2.9% of applied N leached over 2 yr of the study. However, at a higher N rate of 78 kg ha^{-1} applied bimonthly, leaching occurred, in the order of 9.3 and 5% of applied N was leached from for $CaNO_3$ and IBDU, respectively. At the higher N rate, it appears that the amount of N for these two sources was applied in excess of that used by the plant, stored in soil, or lost to the atmosphere; thus, more leaching occurred. Less than 1% of the applied N was leached from ureaformaldehyde, SCU, and urea. The mean concentration of N in the leachate for $CaNO_3$ and IBDU-treated areas was 2.4 and 1.4 mg N L^{-1}, respectively, far below the safe drinking water standard of 10 mg L^{-1}.

Sheard et al. (1985) monitored N in the drainage water from creeping bentgrass sand greens. They observed that only 1.2 and 2.0% of the applied N (293 kg N ha^{-1} yr^{-1}) was collected as NO_3^- in the drainage water for an entire year on greens fertilized with either SCU or urea, respectively. They also noted very little difference between N leaching on acid (1.8%) on alkaline (1.4%) greens, from urea. Synder et al. (1981) found a big difference in N leaching between the soluble nitrate source ($CaNO_3$) and urea. They attributed the lower leaching from urea to greater NH_3 volatilization on the slightly alkaline sands. However, neither reported their post-irrigation irrigation practice, which has a major impact on the degree of NH_3 volatilization (Bowman et al., 1987).

The last example of studies on sandy soils with high N rates was from Rieke and Ellis (1974). In the upper Michigan site, a sandy soil (91% sand) received 122 cm of rainfall plus irrigation the first year and 83 cm the second, four N sources were applied in the spring at 378 kg ha^{-1}, a rate of eight times the normal single N application rate. As one would expect, NO_3^--N concentrations were significantly higher in the surface 30 cm of the soil most of the growing season. From their deepest sample (45 to 60 cm), NO_3^--N concentrations were significantly higher than those in the unfertilized plots one sampling date only. In this case more NO_3^- leaching was noted from NH_4NO_3, ureaformaldehyde, and IBDU than from activated sewage sludge.

Brown et al. (1982) studied the interaction of N source and soil texture on NO_3^- leaching from U.S. Golf Association specification greens of bermudagrass. Irrigation was provided to encourage some leaching into the drainage water. With root zone mixtures containing greater than 80% sand, leaching losses were 22% from NH_4NO_3, 9% from activated sewage sludge, and <2% from either ureaformaldehyde or IBDU. On greens constructed with a sandy loam soil, the losses were 9% from NH_4NO_3, 1.7% from activated sewage sludge, and <1% from either ureaformaldehyde or IBDU.

There are several reports on the effect irrigation has on the leaching potential of fertilizer applied to turfgrass. Morton et al. (1988) studied the effect of two N rates and two irrigation regimes on the leaching of N from a Kentucky bluegrass–red fescue lawn. The N rate was typical of a moderate to high lawn fertility program, of 50 urea and 50% flowable ureaformaldehyde (Fluf) applied at 98 and 244 kg N ha^{-1} yr^{-1}. Two irrigation regimes were used; one applied 1.2 cm of water when the tensiometer readings reached −0.05 MPa and the second was 3.75 cm water wk^{-1}. The former did not result in water draining out of the root zone, but the latter did. Drainage water was collected and analyzed for NH_4^+ and NO_3^-. Irrigation based on tensiometer reading did not cause a significantly ($P \leq 0.05$) higher mean annual N concentration in the drainage water at either rate of N applied than was found in the unfertilized control plots. However, irrigating at a higher rate resulted in significantly higher N concentrations in the drainage water (1.8 and 4.0 mg L^{-1} for the low and high N rates, respectively). These values are still well below safe drinking water standards of 10 mg NO_3^--N L^{-1}.

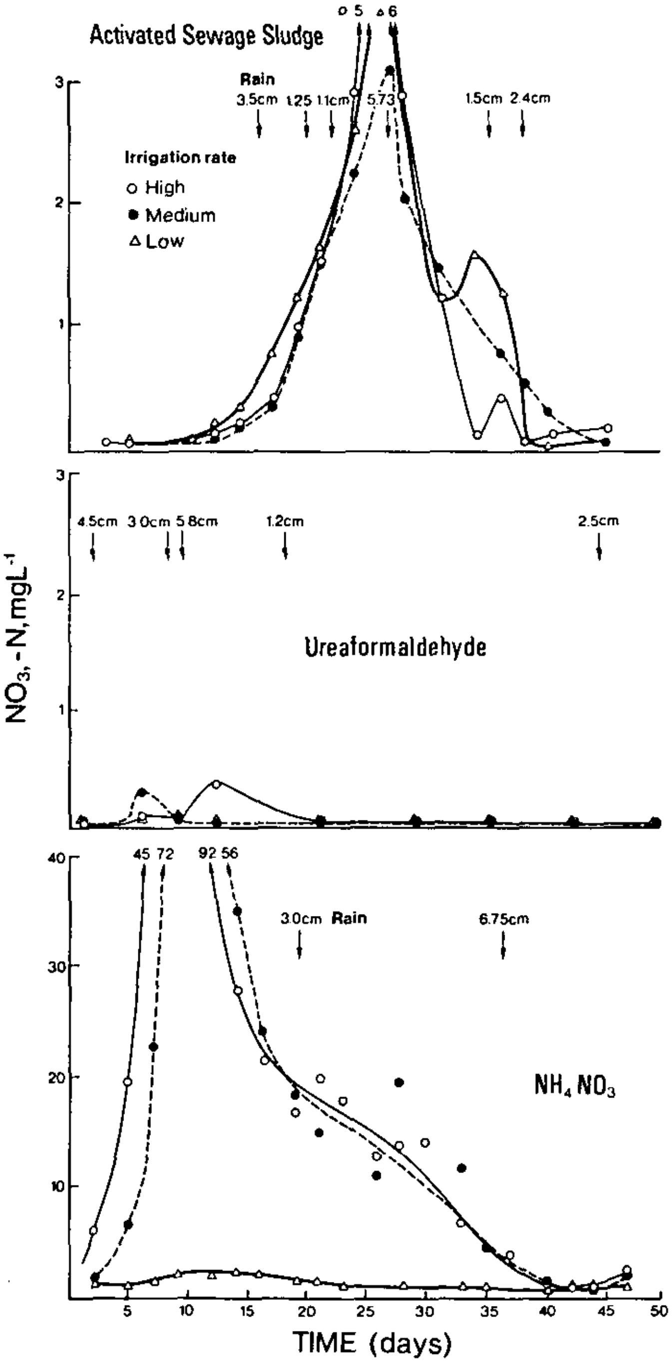

Fig. 5. Leachate concentration of NO_3-N as a function of N source and irrigation (low, medium, high): Milorganite applied on 17 Oct. 1973 at a rate of 146 kg N ha^{-1}, ureaformaldehyde applied on 6 June 1973 at a rate of 244 kg N ha^{-1}; NH_4NO_3 applied on 16 Feb. 1973 at a rate of 163 kg N ha^{-1} (with permission from Brown et al., 1977).

Snyder et al. (1984) studied the interactive effect of irrigation and N source on seasonal N leaching from sand under bermudagrass. Ammonium nitrate and SCU were applied at a rate of 98 kg N ha^{-1} to plots that were irrigated either on a fixed daily schedule or by tensiometer-activated irrigation (sensor). In addition, N was also applied in the irrigation water (fertigation). Soil water samples were extracted daily to determine the amount of N (NH_4^+ + NO_3^-) leaching past the root zone. The percent of applied N leached ranged from 0.3 to 56% and was highly influenced by N source, irrigation schedule, and season of the year. The greatest leaching occurred in the February and March period, less in April and May, and the least in the June and July. The decline in leaching loss was probably due to both increased plant growth and increased evapotranspiration. In every case, N leached from the daily-irrigated plots was 2 to 28 times greater than that leached from the sensor-irrigated plots. Generally, N leached from plots treated with NH_4NO_3 was from 2 to 3.6 times greater than that leached from ones treated with SCU. Generally, fertigation resulted in lowest N leaching losses, except for the June and July period.

Brown et al. (1977) also evaluated the effect of N source and rate of irrigation on NO_3^- leaching. Irrigation had little effect on NO_3^- leaching from plots treated with very high rates of N (146–244 kg ha^{-1}) from either activated sewage sludge or ureaformaldehyde (Fig. 5). In fact, NO_3^- concentration in the drainage water never exceeded the safe drinking water standard. However, when NH_4NO_3 was applied at the extremely high single application rate of 163 kg N ha^{-1}, medium to heavy irrigation (0.8–1.2 cm d^{-1}) resulted in substantial increases in NO_3^- concentration in the drainage water 5 to 30 DAT. Drainage water from greens irrigated with less than 0.8 cm d^{-1} (low) did not have elevated NO_3^- concentrations.

In a 10-wk growth chamber study, Mosdell and Schmidt (1985) determined the N leaching by collecting drainage water from pots of Kentucky bluegrass containing a silt loam soil. They applied 74 kg N ha^{-1} as either NH_4NO_3 or IBDU and irrigated the pots at 2.5 and 5.0 cm wk^{-1}. At cool temperatures, (16 °C/4 °C), the only treatment with high N concentration in the drainage water was IBDU irrigated at 2.5 cm wk^{-1}. Correcting for the leaching from the unfertilized check, this would amount to 2.7% of the applied N being leached. At a higher temperature regime (30 °C/24 °C), leaching of N from the NH_4NO_3 and IBDU pots occurred, but never in excess of 2.5% of applied N. Leaching was not influenced by irrigation amount.

The season at which the N is applied can have a direct effect on the amount of N that is leached. Leaching is significant during periods when temperature is low and precipitation (minus potential evapotranspiration) is high, e.g., November through April in northern climates. The cool temperatures reduce denitrification and NH_3 volatilization, limit microbial immobilization of N in the soil and limit plant uptake. However, low temperatures also reduce the rate of nitrification. With low evapotranspiration by plants and relatively high precipitation, more water drains out of the root zone.

The late fall has become an important time for N fertilization of cool-season grasses (Street, 1988). However, as stated above, this period may lead to a greater potential of NO_3^- leaching. This concept was tested in a cool season turfgrass study on Long Island, NY. Nitrogen was applied at 97 kg ha^{-1} in November (Petrovic et al., 1986). The amount of N leached out of the root zone (30 cm deep) was determined by trapping the NO_3^- with an anion exchange resin. The researchers found, as expected, that significant NO_3^- leaching can occur when a soluble N source like urea is used. Nitrate leaching ranged from 21 to 47% of applied N for urea depending on the site characterics. On the site with a gravely sand B horizon, there was more NO_3^- leaching from urea. Losses from activated sewage sludge (Milorganite), ureaformaldehyde, and a resin coated urea, were less than 2% of applied N, whereas, NO_3^- leaching from plots treated with a nonsealed SCU was 12% of applied N. Even though the late fall N fertilization principle has many good agronomic benefits, the environmental impact may overshadow the positive factors in groundwater sensitive areas. Nitrate losses were also greater on warm-season grasses fertilized in the cooler periods of the year (February or March) compared with warmer seasons (Brown et al., 1977; Synder et al., 1984).

Runoff

When fertilizer N is applied to any site, there is a potential for some of it to run off into surface waters. A limited number of studies have been conducted to determine the quantity of fertilizer containing N that will run off a turfgrass site. In a 2-yr field study in Rhode Island, Morton et al. (1988) observed only two natural events that lead to runoff of any water. One was from frozen ground and the other occurred from wet soils receiving 12.5 cm of precipitation in one wk. The concentration of inorganic N (NH_4^+ + NO_3^-) in the runoff water from the two events ranged from 1.1 to 4.2 mg L^{-1}, far below the 10 mg L^{-1} drinking water standard. This amount, regardless of the treatment, accounted for less than 7% of the total N lost by leaching and run off.

Brown et al. (1977), studying the impact of N source, rate and soil texture, only found in one case (1-d period) that runoff water had NO_3^- concentrations in excess of 10 mg NO_3^--N L^{-1}.

Watschke (personal communication 1988), studying runoff from turf sites on a 9 to 12% slope, silt loam soil, also observed only one natural precipitation event that led to runoff over 2 yr of the study. Results of these studies suggest that the turfgrass ecosystem results in soils with high infiltration capacity; thus, runoff seldom occurs.

SUMMARY AND CONCLUSION

The distribution of fertilizer N applied to turfgrass has generally been studied as a series of components rather than a complete system. Only Starr and DeRoo (1981) attempted to study the entire system of the fate of N applied to turfgrass. However, their findings are limited to a small set of conditions (i.e., cool-season turfgrass, unirrigated, sandy loam soil). Thus, more information of this nature is needed on a wide range of conditions.

Generally, the amount of fertilizer N recovered in the turfgrass plant (clippings, shoots, and roots) varied from 5 to 74%, depending on factors such as N source, rate and timing, species of grass, and other site-specific conditions. The highest recovery of total fertilizer N was noted for Kentucky bluegrass fertilized with a soluble N source at a moderate rate (102 kg ha^{-1} yr^{-1}) (Selleck et al., 1980). In contrast, the lowest recovery also occurred on Kentucky bluegrass fertilized with a very slowly available N source (Mosdell et al., 1987). When accounting for recycled fertilizer N in the returned clippings, Starr and DeRoo (1981) observed that about 29% of the fertilizer N was found in the turfgrass plant. Information on N recovery from warm-season grasses is lacking but very necessary to develop models that predict the fate of N applied to warm-season turfgrasses.

Atmospheric loss of fertilizer N can occur by NH_3 volatilization or denitrification. Ammonium volatilization losses can range from 0 to 36% of the applied N. Reducing NH_3 volatilization can be accomplished by irrigating the fertilizer into the soil (Bowman et al., 1987), by using slowly available N sources and reducing the amount of thatch present (Nelson et al., 1980).

Information on denitrification is limited. Losses can be substantial (93% of applied N) under conditions of a saturated silt soil at high temperatures (Mancino et al., 1988). However, more information is needed on a wider variety of site conditions (soil) and turfgrasses to more thoroughly understand the impact that denitrification has on the fate of N.

The storage of fertilizer N in the soil generally occurs in the soil organic matter phase or as undissolved fertilizer pellets of slow-release N sources (Hummel and Waddingtion, 1981). The actual amount of fertilizer found in the soil was determined by Starr and DeRoo (1981). They found that between 36 to 47% of the fertilizer N was in the soil-thatch pool.

Leaching of fertilizer N applied to turfgrass has been shown to be highly influenced by soil texture, N source, rate and timing, and irrigation/rainfall. Obviously, if a significantly higher than normal rate of a soluble N source is applied to a sandy turfgrass site that is highly irrigated, significant NO_3^- leaching could occur (Brown et al., 1977). However, limiting irrigation to only replace moisture used by the plant (Morton et al., 1988; Synder et al., 1984), using slow-release N sources (Brown et al., 1982; Petrovic et al., 1986; Synder et al., 1984) and using less sandy soils (Brown et al., 1977) will significantly reduce or eliminate

NO_3^- leaching from turfgrass sites. If turfgrass fertilization does pose a threat to groundwater quality, several management options are available to minimize or eliminate the problem.

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