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Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass

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Abstract

Establishing and implementing management practices that limit N leaching from agricultural and horticultural land is a priority internationally. Movement of N through soil to surface and ground waters can degrade aquatic systems and compromise water used for drinking, industry and recreation. Reported annual rates of N leaching from turfgrass range from 0 to 160 kg N ha^{-1} year^{-1}, representing up to 30% of applied N. Irrigation rate, fertiliser regime and turfgrass growth phase influence the amounts of N leached. Nitrogen losses tend to be low (<5% of applied fertiliser N) from established turfgrass that is not over-irrigated, and has received N fertiliser at 200–300 kg N ha^{-1} year^{-1}. Efficient irrigation management is critical for efficient N use. Irrigation scheduling that does not cause water to move beyond the active rooting zone decreases the amount of N leached from established turfgrass, without being detrimental to, and in some instances enhancing, turfgrass growth and quality. Applying N fertilisers at rates and frequencies that match N requirements decreases N leaching from established turfgrass. Soil disturbance, such as during preparation of areas for planting turfgrass, can increase N leaching. Therefore, the main strategies for minimising N leaching from turfgrass are (i) optimise irrigation regimes, and (ii) ensure N is applied at rates and frequencies that match turfgrass demand. These strategies are particularly important during turfgrass establishment. Further work is required on turfgrass-soil N cycling and partitioning of N applied to turfgrass. Research needs to be conducted for a broad range of turfgrass species, turfgrass ages, soil types and climates.
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Keywords: Growth; Mowing; Preferential flow; Soil amendment; Soil carbon sequestration; Turfgrass management; Turfgrass species

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1. Introduction

Nowadays people are more aware of the detrimental effects on the environment of improper use of N fertilisers. Poor N fertiliser management can cause N leaching, and increase the emissions of greenhouse and ozone depleting gases (i.e., N_2O, NO_x, NH_3). Nitrogen leaching is problematic as it can degrade surface- and ground-waters resulting in eutrophication and non-potable water supplies (OECD, 1982; Smith, 1998). In some countries N leaching is a significant source of water pollution (OECD, 1982; Carpenter et al., 1998), and is considered difficult to control as it is often derived from extensive areas of land. Managing N leaching is also difficult because losses are often intermittent, and linked with seasonal land management activities or irregular events such as rainfall or soil disturbance. Nitrogen leaching losses will only decrease when changes in land management practices improve N use efficiency (Carpenter et al., 1998).

The contribution of turfgrass systems to N leaching is increasingly being scrutinised by communities and environmental regulators. Turfgrass generally requires regular irrigation and fertiliser applications, and is often perceived to be a source of N leaching; especially on coarse textured soils. Leaching is best minimised by ensuring N is applied at a rate that the soil-crop system is able to assimilate or utilise N (Powlson, 1988; Carpenter et al., 1998). The approach taken to achieve this will vary depending on the crop N requirements, but also on the biological, chemical and physical attributes of the soil. Fertiliser N can either be taken up by turfgrass, denitrified or volatilised to gaseous N species by soil microbes, or immobilised into the soil organic matter (Petrovic, 1990). Any N not involved in these processes is likely to be leached. Additional N may also become available to the crop if management practises increase net soil N mineralisation rates (Macdonald et al., 1989; Whitmore et al., 1992; Shepherd et al., 1996), and if clippings are returned to the turfgrass (Starr and DeRoo, 1981; Qian et al., 2003). The ability of the turfgrass and soil microbes to utilise applied N will also be affected by the rate that dissolved N moves through the soil profile. Plant uptake and soil biological processes often occur at greater rates in the topsoil than the subsoil. So, fertiliser and irrigation management practices that increase the contact time between applied nutrients and the topsoil should increase plant uptake and soil 'retention', and decrease N leaching. The objective of this paper is to summarise irrigation and fertiliser management strategies that minimise N leaching from turfgrass. Specifically we will report annual rates of N leaching from turfgrass, discuss the effects of irrigation, fertiliser and other turfgrass management practices on N leaching, and examine how N leaching impacts on turfgrass growth and quality.

2. Annual rates of nitrogen leaching from turfgrass

Soil N leaching is best quantified directly, and throughout the year so that seasonal changes in soil N availability are included in the measurement (Addiscott, 1996). Measuring N leaching for an extended period will also account for any effects of establishing the experiment (e.g., soil disturbance) on N leaching. Techniques commonly used to measure N leaching from soils include porous (suction) cup lysimeters in combination with soil hydrological models, and soil lysimeters (Addiscott, 1996).

Although not completely without fault, these techniques are well-suited to soil types often used to grow turfgrass (i.e., sand and sandy-loam soils). For further information on techniques for measuring N leaching from soil, readers are referred to Addiscott (1990), Cameron et al. (1992), and Addiscott (1996).

Annual N leaching from turfgrass, where measurements have been taken in the field for at least 12 months using appropriate techniques, are summarised in Table 1. Only a small number of studies have reported annual N leaching rates from turfgrass, and most have been on cool-season grasses (mainly Kentucky bluegrass, *Poa pratensis*) grown in coarse (sand) to medium-textured (silt loam) soils (Petrovic, 1990). Nitrogen leaching has been measured using hydrologically isolated systems (e.g., lysimeters or plots) or suction cup lysimeters in conjunction with hydrological models to predict percolation rates through the soil. Most studies have only measured inorganic N leaching losses (nitrate plus ammonium, or nitrate only), rather than total N leached. Inorganic-N should not be the only form of N considered when measuring soil N leaching, as organic-N has represented up to 90% of N leached in some studies (Wang and Bettany, 1994; Singleton et al., 2001; Hood et al., 2003), albeit in situations not typical for turfgrasses.

Annual N leaching rates for turfgrass range from 0 to 160 kg N ha^{-1}, and represent up to 30% of the fertiliser applied N (Table 1). Irrigation rate, fertiliser regime and turfgrass growth phase all appear to affect the amount of N leached. Nitrogen losses tend to be low (i.e., <5% of applied fertiliser N) from established turfgrass that is not over-irrigated (i.e., rates equal to or less than potential evapo-transpiration) and has received moderate amounts of N fertiliser (i.e., 200–300 kg N ha^{-1} $year^{-1}$). Over-irrigating and practices that disturb the soil both increase the risk of N leaching. The following sections will further discuss the effects of irrigation, fertiliser regimes, turfgrass species and soil disturbance on N leaching from turfgrass.

3. Turfgrass management and nitrogen leaching

3.1. Irrigation management

Optimising irrigation management is crucial for minimising N leaching from turfgrass. Irrigation rates and frequencies that do not cause water to move beyond the active rooting zone will decrease N leaching (Brown et al., 1977; Snyder et al., 1984; Morton et al., 1988). In a 2-year field study, Morton et al. (1988) found that irrigation rates that caused water to percolate from the root zone of 4-year-old Kentucky bluegrass increased drainage and N leaching from a sandy-loam, in comparison to field plots that were irrigated to avoid drought stress, but prevent percolation. Nitrogen leaching was equivalent to 14% of the applied N from the over-watered treatment and <3% from the scheduled irrigation treatment, which was not different to losses from plots to which no fertiliser was added. Minimising soil water movement under established Bermudagrass (*Cynodon dactylon* × *Cynodon transvaalensis*) using a soil tensiometer-controlled irrigation system also decreased mineral-N leaching from 22% to 7.5% of applied N over 6 months (spring and summer) (Snyder et al., 1984). Optimum turfgrass irrigation requirements are site-specific and will vary depending on a turfgrass species, use of the surface (e.g., turfgrass for passive

Table 1
Annual nitrogen leaching losses from turfgrass

Turfgrass type and age	Soil texture and depth (mm)	Study length and method	Fertiliser type	Fertiliser rate (kg N ha^{-1} year^{-1})	Irrigation (mm week^{-1})	N leached (kg N ha^{-1} year^{-1})	Reference
Poa pratensis, *Festuca rubra*, 3 years old	Sandy loam, 300	3 years, suction cup lysimeter	None	0	None	0	Starr and DeRoo (1981)
			Inorganic[a]	180–195 (2, Sp, A)[b]	None	0	
Poa pratensis, *Festuca rubra*, 4 years old	Sandy loam, 200	2 years, ceramic lysimeter plates	None	0	Soil sensor[c]	1.88	Morton et al. (1988)
			None	0	37.5[c]	2.79	
			Urea & Fluf®	97 (2, S)	Soil sensor	3.04 (3.1)[d,e]	
			Urea & Fluf®	97 (2, S)	37.5	13.65 (14)[e]	
			Urea & Fluf®	244 (5, S, A)	Soil sensor	4.87 (2.0)[e]	
			Urea & Fluf®	244 (5, S, A)	37.5	31.94 (13)[e]	
Home lawn	Sandy loam, 200	2 years, lysimeter plate	None	0	Not given	1.3–1.4[e]	Gold et al. (1990)
			Inorganic[a]	244 (5, S, A)	Not given	1.9–9.3 (<1–4)[e]	
Poa pratensis established from seed	Silt loam, 800	1 year, lysimeter[f]	None	0	All treatments irrigated to prevent wilt & leaching, rate not given	38[e]	Geron et al. (1993)
			Urea & RCU[g]	218 (5, Sp, S, A)		59 (27)[e]	
Poa pratensis established from sod			None	0		43[e]	
			Urea & RCU	218 (5, Sp, S, A)		69 (30)[e]	
Poa pratensis, 6 months old	Sandy loam, 1200	2 years, lysimeter	Urea	196 (5, Sp, S, A)	Not given	1.65 (<1)[e]	Miltner et al. (1996)
			Urea	196 (5, S, A)	Not given	4.05 (2.0)[e]	

Table 1 (*Continued*)

Turfgrass type and age	Soil texture and depth (mm)	Study length and method	Fertiliser type	Fertiliser rate (kg N ha^{-1} $year^{-1}$)	Irrigation (mm $week^{-1}$)	N leached (kg N ha^{-1} $year^{-1}$)	Reference
Poa pratensis, 3–5 years old	Silt loam, 600	2 years, suction cup lysimeter	Inorganic[a]	149 (3, Sp, S, A)	Irrigated, rate not given	3.5–45 (2–30)[e]	Liu et al. (1997)
Lolium perenne, 3–5 years old						2.1–22 (1–15)[e]	
Festuca arundinacea, 3–5 years old						0.6–5.4 (0.4–4)[e]	
Maintained mixed sward[h], 12 years old	Silt loam, 600	1 year, suction cup lysimeter	None	0	Irrigated, rate not given	50[e]	Jiang et al. (2000a)
Killed mixed sward[h], 12 years old			None	0		161[e]	
Stenotaphrum secundatum, established from sod	Sand, 750	1 year, isolated plots	Inorganic[a]	300 (8, year)	20[i]	4.1 (1.4)[e]	Erickson et al. (2001)

[a] N:P:K (10:6:4) containing 50% of N as urea formaldehyde (years 1–2) or ammonium sulphate (year 3) (Starr and DeRoo, 1981); 50% urea and 50% urea formaldehyde (Gold et al., 1990); 50% NH_4NO_3 and 50% urea + methyl urea (Liu et al., 1997); N:P:K (26:3:11) where N derived from urea (58%), S-coated urea (37.5%) and ammonium phosphate (4.5%) (Erickson et al., 2001).

[b] Number of fertiliser applications, and timing in parentheses, Sp = spring, S = summer, A = autumn, year = all year.

[c] Irrigated mid-summer through to mid-autumn only; 37.5 mm^{-1} week represents mean maximum weekly evapotranspiration during summer months at the location of the study.

[d] Percentage of N applied that leached is given in parentheses.

[e] Only inorganic-N measured in leachate.

[f] Study conducted for 1.75 years, only 1st year results shown.

[g] RCU = resin coated urea.

[h] *Poa pratensis*, *Festuca rubra*, *Lolium perenne*, and *Festuca longifolia*.

[i] Calculated from a mean monthly irrigation rate of 80 mm. Mean monthly evaporation for one year at the location of the study = 74 mm $month^{-1}$ (approx. 18.5 mm $week^{-1}$).

areas or for sports), cultural practices (e.g., irrigation uniformity, salinity of irrigation water, mowing practices), soil type, and climate. For information on approaches to improve turfgrass irrigation efficiency, readers are referred to Carrow (2005).

In addition to application amount, irrigation rate and frequency can also influence N leaching from turfgrass. In some soil types, the irrigation rate and frequency may cause water and N to move unevenly through the top soil via large cracks, worm holes, root channels and water-repellent zones (i.e., preferential flow) (Bauters et al., 1998; McLeod et al., 2001). Preferential flow causes dissolved nutrients to move quickly through the top soil, minimising the opportunity for plant roots and soil microbes to utilise applied water and N. The irrigation rate and frequency required to minimise preferential flow will vary depending upon soil structure, and is often determined using dye or conservative tracers such as chloride or bromide (McLeod et al., 1998; McLeod et al., 2001; Nektarios et al., 2002). Generally speaking, soils that have uniformly porous structure can be irrigated at higher rates and less frequently than those soils that have large structural cracks (e.g., clays) or a tendency to develop water-repellent areas within the soil profile (e.g., 'finger-flow' in sands) (Starrett et al., 1995; McLeod et al., 1998; Nektarios et al., 2002). Applying surfactants to soil surfaces has been proposed as a method for minimising finger-flow in sandy soils, by mitigating localised dry spots (Wilkinson and Miller, 1978) and improving water infiltration (Zartman and Bartsch, 1990). However, Nektarios et al. (2002) concluded that surfactants only prevented finger-flow in a simulated United States Golf Association (USGA) putting green profile when there were no pre-existing preferential flow paths (i.e., soil irrigated frequently and never allowed to dry out). To date, decreasing irrigation rates per application, but with more frequent irrigation events, appears to be the most practical approach for preventing preferential flow in soils.

In coarse-textured soils, optimising irrigation regimes may not be sufficient to minimise N leaching. Retaining water and nutrients in the topsoil of sandy soils can be particularly difficult as these soils often have high hydraulic conductivities and low cation exchange capacities (CEC). Instead, amending these soils with inorganic or organic materials may improve soil water and nutrient retention. Engelsjord and Singh (1997) found addition of peat to sand significantly decreased the amount of N leached over 6 months from lysimeters planted with Kentucky bluegrass; with total N leaching representing 3–12% of applied N (8.9–35 kg N ha^{-1}) for the 80:20 (sand:peat) mixture and 1.8–3.3% of applied N (5.4–9.8 kg N ha^{-1}) for the 60:40 mixture. Increasing the proportion of peat in the sand decreased N leaching more from turfgrass fertilised monthly than from turfgrass fertilised biweekly with a soluble N fertiliser (Engelsjord and Singh, 1997). Huang and Petrovic (1994) found adding clinoptilolite zeolite (9:1, w/w, soil:zeolite) decreased N leaching from creeping bentgrass by 50–87% when ammonium sulphate was applied to lysimeters at 196 and 293 kg N ha^{-1}. In the absence of turfgrass, the effectiveness of both inorganic and organic amendments to increase soil water holding capacity and decrease ammonium leaching from coarse-textured soils has been shown to depend on the CEC of the amendment, rate of incorporation and the depth of incorporation (Adriano et al., 1980; Adriano and Weber, 2001; Bigelow et al., 2001; Pathan et al., 2002, 2003, 2004). In cases that soil amendments have decreased N leaching from turfgrass, effects on turfgrass growth have been mixed (Huang and Petrovic, 1994; Bigelow et al., 2001). While clinoptilolite zeolite increased N uptake of creeping bentgrass by up to 22% (Huang and Petrovic, 1994), increasing the proportion of peat:sand decreased Kentucky bluegrass growth (5–26% depending upon fertiliser type) and colour (Engelsjord and Singh, 1997). Adding relatively large quantities of materials to soils, as described in the studies cited above, presents practical challenges for incorporation to reasonable depths and can be costly.

3.2. Nitrogen fertiliser management

Once turfgrass irrigation management has been optimised, further decreases in N leaching may be achieved via improved N fertiliser management. Ideally, N should be applied at a rate and frequency that matches turfgrass demand, and if possible should not be applied immediately before heavy rainfall (Brown et al., 1977; Snyder et al., 1981; Snyder et al., 1984; Morton et al., 1988; Miltner et al., 1996; Engelsjord and Singh, 1997).

The amounts of N applied to established turfgrasses varies depending upon turfgrass species (Beard, 1973), but typically ranges from 100 to 300 kg N ha^{-1} $year^{-1}$ (Petrovic, 1990; Turner and Hummel, 1992). At these application rates, N leaching is not significant from established turfgrass when irrigated at a rate that maintains the soil water in the rooting zone (Table 1)(Petrovic, 1990). However, most turfgrass studies investigating the effects of turfgrass management on N leaching have been conducted on relatively young stands (Table 1), and the effects of fertiliser application rates on N leaching from more mature stands has not been reported. It has been suggested that turfgrass N requirements decrease with time after establishment (Petrovic, 1990; Qian et al., 2003). Estimates based on historical data and simulation modeling suggest that N requirements for cool-season turfgrass will be maintained for the first 10 years after establishment, and then continue to decline for up to 60 years (Petrovic, 1990; Qian et al., 2003). Adjusting the fertiliser regimes to match N removal rates (plus atmospheric losses) has been proposed as an approach to minimise N leaching from older turfgrass stands (Petrovic, 1990).

The amounts of N applied to turfgrasses might also need to be modified if clippings are returned. Turfgrass produces a large amount of clippings annually, representing a major pool of N. Returning clippings has been shown to reduce fertiliser N requirements by 30% (Starr and DeRoo, 1981), 50% (Heckman et al., 2000) and 75% (Kopp and Guillard, 2002). The effects of clipping management on N leaching have not been studied in the field. However, model simulations found that N leaching was low for 20–30 years after Kentucky bluegrass establishment under low N inputs (75 kg N ha^{-1} $year^{-1}$) and when clippings were returned (Qian and Follett, 2002). Returning clippings in combination with moderately high N inputs (150 kg N ha^{-1} $year^{-1}$) increased N leaching, with predicted losses reaching 50–60 kg N ha^{-1} $year^{-1}$ by the time the turfgrass is 100 years old (Qian and Follett, 2002).

The frequency (or timing) of fertiliser applications needed to achieve quality turfgrass and minimise N leaching varies with fertiliser type. For more water-soluble N fertilisers, lower rates and more frequent applications should be used to minimise N leaching. For example, applying ammonium nitrate weekly, rather than bi-monthly, decreased N leaching from 17 to 2.5% of the N applied to established Bermudagrass irrigated using soil moisture sensors (Snyder et al., 1984). Less water-soluble fertilisers, such as slow- or control-release fertilizers, can be applied at higher, less frequent rates than water-soluble fertilisers, without increasing N leaching (Snyder et al., 1984; Geron et al., 1993;

Engelsjord and Singh, 1997). Bermudagrass fertilised bi-monthly with a slow-release fertiliser (sulfur-coated urea) leached a similar amount of N (<5% of N applied) as turfgrass fertilised with ammonium nitrate applied weekly via fertigation (Snyder et al., 1984). Similarly, Kentucky bluegrass fertilised with a single application of sulfur-coated urea in spring leached a similar amount of N (<3% of N applied) to that fertilised bi-weekly with soluble NPK when both treatments were irrigated at a rate that prevented wilt and percolation (Engelsjord and Singh, 1997). Nitrogen losses should be low from all fertiliser types as long as the N provided matches turfgrass requirements, and irrigation does not cause nutrients to move beyond the rooting zone.

The timing of fertiliser applications required to minimise N leaching also varies between 'warm'-season and 'cool'-season grasses. Applying fertilisers at times when the turfgrass is actively growing will minimise N leaching. Warm-season grasses grow best during the warmer months and at temperatures ranging from 26 to 35 °C, while cool-season grasses have an optimum temperature range of 16–24 °C (Hartley, 1950; Beard, 1973; Hull, 1992). Consequently, it is recommended that fertilisers should be applied to established warm-season grasses from late spring through to early autumn, when growth is greatest (Turner and Hummel, 1992). Applying fertiliser to warm-season grasses at cooler times of the year can increase N leaching (Brown et al., 1977; Snyder et al., 1984). For cool-season grasses, fertilising in spring and autumn is recommended (Turner and Hummel, 1992) and generally results in low leaching losses under irrigation regimes designed to minimise percolation (Morton et al., 1988; Miltner et al., 1996). In some parts of the world, fertilisers are applied to cool-season grasses in late autumn, as this enhances turfgrass growth and colour the following spring (Turner and Hummel, 1992). There is concern that this practice may increase the risk of N leaching during winter. However, Miltner et al. (1996) found applying fertiliser to a 6-year-old Kentucky bluegrass in late autumn resulted in low N losses (<0.2% of applied ^{15}N) that were similar to those after a spring application. After 2 years, 20% of ^{15}N applied in spring was recovered from the thatch, 35% from harvested clippings and 20% from the soil. For the late autumn application, 35% of ^{15}N was recovered in the thatch, 38% in the clippings and 25% from the soil. Miltner et al. (1996) attributed the low leachate losses from both spring and autumn applications to the rapid N uptake by the turfgrass (78–109% within first 18 days). Furthermore, accumulation of applied ^{15}N in the thatch after the autumn application reduced the risk of N leaching the following winter. The authors concluded fertiliser applied in late autumn to established Kentucky bluegrass does not increase the risk of N leaching when the turfgrass density and soil organic matter content are high. However, these findings do indicate that if the turfgrass density is not high and if thatch is not present (e.g., during turfgrass establishment, or periods after harvesting sod) the seasonal timing of fertiliser applications can influence N leaching (see Section 3.4 below).

Plant testing has been suggested as an approach for better synchronizing N fertiliser applications with turfgrass N uptake (Sanchez and Doerge, 1999). Traditionally, total N concentration in plant material has been used to determine if a plant contains adequate or deficient amounts for growth; however, plant sap 'quick tests' have also been developed to provide a more rapid assessment of plant N status (Handson and Shelley, 1993; Lewis et al., 1993; Smith and Loneragan, 1997). A basic requirement for interpretation of plant and sap analyses is the availability of reliable critical values. Critical values are often based on experimental findings or surveys of ‘healthy’ plants that have compared the total N concentrations in selected plant tissues with some yield parameter (Lewis et al., 1993; Reuter and Robinson, 1997; Smith and Loneragan, 1997). However, the development and use of critical values can be hindered by a wide range of factors including the plant part analysed, plant age, seasonal trends, nutrient interactions, and genotype (Lewis et al., 1993). Lewis et al. (1993) consider changes in critical nutrient concentrations with plant age and plant part to be one of the biggest problems limiting interpretation of plant analyses, which is particularly relevant to turfgrass management given that turfgrass stands can vary widely in age. The effectiveness of plant tissue testing as an approach for improving the timing of fertiliser applications to turfgrass and decreasing N leaching appears to be poorly documented, despite the development of critical values for total N concentrations in shoots of turfgrass species (Turner and Hummel, 1992; Reuter and Robinson, 1997), and the availability of sap tests.

Nitrification inhibitors have been proposed as an approach to improving fertiliser use efficiency, and thus minimise N leaching from soil (Amberger, 1989). By decreasing nitrification, soil and fertiliser N is retained in the ammonium form for longer, reducing the risk of nitrate leaching. Both nitrate and ammonium can be absorbed by roots, so N maintained in the ammonium form is available for plant uptake. A number of nitrification inhibitors are available; however, the literature mainly contains information on the use of dicyandiamide (DCD) on turfgrass. Dicyandiamide has been shown to have either no benefit (Spangenberg et al., 1986; Fox and Bandel, 1989; Waddington et al., 1989), or only a short-term benefit (Mosdell et al., 1986) to turfgrass growth or colour when added with urea or ammonium-based fertilisers. Unfortunately, neither the effect of DCD on N leaching from fertiliser applied to turfgrass, nor the effectiveness of other nitrification inhibitors for use on turfgrass, have been reported. Ultimately, nitrification inhibitors can only be expected to improve fertiliser use efficiency if increased plant available N coincides with plant demand. Similar gains may be achieved by improving irrigation management and timing of fertiliser applications.

3.3. *Choice of turfgrass species*

Turfgrass species has been shown to directly influence nitrate leaching in a limited number of studies and generally under conditions designed to maximise leaching potential. For cool-season turfgrass species, Liu et al. (1997) ranked nitrate leaching from soil as Kentucky bluegrass > perennial ryegrass (*Lolium perenne*) > tall fescue (*Festuca arundinacea*), after measuring field losses from a silt loam for 26 months. Nitrate leaching also varied amongst cultivars within a species, with the amounts leached ranging from 3 to 45 kg NO_3–N ha^{-1} for 10 Kentucky bluegrass cultivars, 2–22 kg NO_3–N ha^{-1} for 10 perennial ryegrass cultivars, and 0.6–5 kg NO_3–N ha^{-1} for 10 tall fescue cultivars (Liu et al., 1997). In a study comparing nitrate leaching from under six warm-season turfgrasses, nitrate leaching was greatest for Meyer’ zoysiagrass (*Zoysia japonica*; 55 kg NO_3–N ha^{-1} $year^{-1}$) and lowest from St Augustinegrass (*Stenotaphrum secundatum*; 3 kg NO_3–N ha^{-1} $year^{-1}$) (Bowman et al., 2002). Differences between these two warm-season grasses were attributed to differences in root length density at soil depths >300 mm, with greater root length densities improving N uptake. Root length density, rather than plant N-use efficiency (NUE), also explained differences in nitrate leaching under two genotypes of creeping Bentgrass (Bowman et al., 1998). Under high leaching conditions, 38% of applied N leached under a shallow-rooting genotype in comparison to 18% under a deeper-rooting genotype. Losses from the shallow-rooting genotype were partly mitigated by lowering the irrigation rate and delaying irrigation after applications of fertiliser (Bowman et al., 1998).

Choosing turfgrass species that require less N per unit of biomass produced may be another approach to decreasing the amounts of fertiliser applied and thus potential for leaching of N. Nitrogen-use efficiency has been shown to vary amongst turfgrass species (Liu et al., 1993) and cultivars (Jiang and Hull, 1998; Jiang et al., 2000b). The physiological and metabolic basis for differences in NUE of turfgrass has not been extensively studied. For Kentucky bluegrass cultivars, NUE was negatively correlated with root-zone nitrate levels, nitrate uptake rate and nitrate reductase activity (Jiang and Hull, 1998; Jiang et al., 2000b).

3.4. Turfgrass management and soil nitrogen storage

The majority of soil N is present in organic matter, in forms unavailable for plant uptake. Although organic-N can be mineralised to plant available forms (e.g., NO_3^-, NH_4^+), the amount of inorganic-N generally represents a small proportion of the organic N pool. Soil N mineralisation and immobilisation rates are influenced by soil C contents. Turfgrass management practices that increase soil C sequestration would be expected to increase soil N storage, and reduce the risk of soil N leaching. Studies of soil C cycling in turfgrass systems are scant, as long-term field studies are required (i.e., years and decades) to fully evaluate the effects of management regimes on soil C and N dynamics. Historic soil testing data suggests that cool-season turfgrass systems can sequester significant amounts of C (i.e., 1 t ha^{-1} $year^{-1}$) and for up to 45 years after establishment (Qian and Follett, 2002). The amount of C sequestration depends on the intensity of use of the surface, N application rate, clipping management, past land use, soil pH and soil CEC (Qian and Follett, 2002; Qian et al., 2003). Model simulations predict that while C sequestration continues in a soil under turfgrass, it also continues to be a sink for applied N. However, as the rate of soil C accumulation decreases with time, the rate of soil N storage also decreases, increasing the risk of N leaching if fertiliser N applications are not adjusted (Qian et al., 2003).

Turfgrass management practices that decrease soil C sequestration would be expected to increase N mineralisation and N leaching potential. Soil C storage may decline if the turfgrass system is physically disturbed (Macdonald et al., 1989; Whitmore et al., 1992; Shepherd et al., 1996), such as during re-establishment of turfgrass areas. Establishing turfgrass has been shown to increase N leaching for up to seven months (Geron et al., 1993; Engelsjord and Singh, 1997). Geron et al. (1993) measured N leaching from establishing Kentucky bluegrass for 95 weeks, and found 74–84% (66–83 kg NO_3–N ha^{-1}) of nitrate leaching occurred during the first 39 weeks following planting as seed or sod. The untreated seed control and untreated sod control also leached up to 29–45 kg NO_3–N ha^{-1} over the same period. The authors attributed greater N leaching during turfgrass establishment to increased soil mineralisation rates resulting from soil disturbance during planting. However, as N leaching was also greater from lysimeters with fertiliser applied when compared to those without fertiliser throughout the study, part of the increased loss may also have been due to applying N fertiliser. Soil C and N cycling may also change after the sudden death of turfgrass; for example, resulting from prolonged drought, herbicide misapplication, inappropriate renovation practices, and pests or diseases. Jiang et al. (2000a) reported almost 161 kg NO_3–N ha^{-1} year^{-1} leached from 12-year-old cool-season turfgrass plots killed using glyophosphate in early spring. In comparison, healthy plots (without fertiliser) leached 50 kg N ha^{-1} year^{-1} during the same period. Increased nitrate leaching from the killed plots was attributed to the absence of turfgrass to utilise mineralised N, rather than enhanced mineralisation rates. Furthermore, nitrate leaching following the death of turfgrass can be partly mitigated by prompt re-seeding of such sites (Bushoven et al., 2000). Soil N mineralisation may, therefore, be an additional source of N during turfgrass establishment, and if mineralised N plus fertiliser N exceeds turfgrass requirements, then high N leaching losses can occur.

Knowledge on the fate of N applied to turfgrasses, and the influence of turfgrass management on soil N and C cycling is limited. Thatch, clippings and soil organic matter are known to be significant sinks for N in turfgrass systems (Petrovic, 1990). However, the mechanism(s) by which thatch retains N and influences soil N cycling is not clear. In particular, what management factors influence how much N is retained by the thatch, and does N stored in thatch become a source of N leaching when a turfgrass dies or is renovated? Returning clippings to the turfgrass system provides an additional source of N that needs to be accounted for when designing fertiliser management regimes. Approaches for managing clipping N need to be developed from an understanding of the effects of clipping management on soil N and C cycling. Information on the factors that influence soil N storage under turfgrass is also needed. Research suggests soil C sequestration can influence the magnitude of soil N storage under turfgrass (Qian et al., 2003). Qian et al. (2003) recommend further studies investigating the effects on soil C sequestration of fertiliser regimes, mowing height and frequency, species, irrigation management, climate, and soil type.

4. Nitrogen leaching, turfgrass growth and quality

Recommended irrigation and fertiliser management strategies for minimising N leaching are unlikely to be adopted by turfgrass managers, unless it is also demonstrated that these practices do not have a detrimental effect on turfgrass growth and quality. Turfgrass managers are required to produce a surface with good cover, colour and strength; although not necessarily high biomass production, as disposal of mowing clippings and thatch is an additional expense. While it is intuitive that turfgrass management practices that reduce N leaching and maintain N within the rooting zone will also benefit turfgrass quality, the effects of irrigation and fertiliser management on both N leaching and turfgrass growth and quality are rarely reported in the same study. Notably, Snyder et al. (1984) demonstrated that optimising irrigation regimes benefited turfgrass quality and minimised N leaching. Soil-sensor controlled irrigation improved N uptake, growth and colour of Bermudagrass fertilised bi-monthly with a water-soluble fertiliser; and at the same time nitrate leaching was decreased. Matching fertiliser application frequencies to seasonal turfgrass requirements has also been shown to improve the consistency of turfgrass growth and colour, when irrigation regimes used minimised percolation (Snyder et al., 1984; Engelsjord and Singh, 1997). Although single, large applications of water-soluble fertilisers initially tend to give higher turfgrass growth and colour than smaller, less frequent applications, these results are often short-lived and increase N leaching. Using slow-release fertilisers, or water-soluble fertilisers more sparingly and frequently, appears to provide more consistent growth and colour for both warm- and cool-season grasses, while minimising N leaching (Snyder et al., 1984; Engelsjord and Singh, 1997).

5. Future work

Much remains to be learnt about plant-soil N cycling under turfgrasses. Our understanding of N leaching is based mainly on data from relatively young plantings of cool-season turfgrasses receiving inorganic fertilisers (Table 1) (Petrovic, 1990), and would benefit from longer-term studies of a range of species, ages, management regimes, climates and soils. Studies during the establishment phase are also needed. Turfgrass growth and quality, in addition to N leaching, should be evaluated in all future work.

Optimised irrigation regimes are crucial to control of N leaching, and technological advances have improved irrigation management (Carrow, 2005). However, much of the literature on N leaching in turfgrasses has not expressed irrigation applied relative to evaporative demand, so that comparisons between sites and studies are difficult. Approaches for maintaining soil water in the rooting zone are also needed for situations where irrigation management can not be optimal, due to site (e.g., very free-draining soils, slopes, preferential flows), climate (e.g., locations prone to sudden, heavy rainfall) or cost constraints. Use of amendments to improve soil water-holding capacity, and using species that require less N, should be explored.

Quantifying N leaching is expensive and requires intensive sampling strategies over extended periods. Simulation models that predict N leaching and turfgrass performance from easily measurable parameters would assist with designing strategies for minimising N leaching from turfgrass. The success of simulation models will depend upon understanding the fates of applied N, and the effects of management regimes on soil N and C cycling. Thatch, clippings and soil organic matter are significant sinks for N in turfgrass systems (Petrovic, 1990). However, the dynamics and mechanisms of N entry, storage, and release from these pools have rarely been quantified. Furthermore, the fates of thatch and soil N pools following perturbations (e.g., turfgrass renovation practices) should be elucidated. The effect of 'catching' or 'returning' clippings to turfgrass warrants additional study. Soil C sequestration can influence the magnitude of soil N storage under turfgrass; however the extent and rate of C sequestration, factors influencing C sequestration, and the relationship between soil C sequestration and N leaching needs further study (cf. Qian et al., 2003).

Improved knowledge of N and C cycles in turfgrass systems should guide the development of future management strategies aimed at minimising N leaching. Inexpensive and simple techniques for determining site-specific timings of fertiliser applications are needed by turfgrass managers. Research findings will only impact on N leaching in the field when management strategies developed for practitioners are shown to have minimal, if any, impact on turfgrass quality.

6. Conclusions

Turfgrass areas need not pose a risk to the environment if appropriate management strategies are undertaken. Irrigation scheduling that does not cause water to move beyond the rooting zone has been repeatedly shown to successfully decrease the amount of nitrate and ammonium leached from established turfgrass in temperate climates, without being detrimental to turfgrass growth or quality. The amount of water applied needs to match turfgrass requirements, but rates and frequencies should be chosen to avoid preferential flow. Irrigation scheduling can be optimised by using either soil sensor-controlled irrigation systems, or by calculating irrigation rates based on potential evapo-transpiration. Further strategies may be required to optimise irrigation regimes for turfgrass grown on coarse-textured soils, such as use of soil amendments to decrease hydraulic conductivity and increase water-holding capacity, and in turn reduce leaching. Soil amendments that increase the CEC of coarse-textured soils might decrease the leaching of ammonium, but not of nitrate.

Applying N fertilisers at rates and frequencies that match turfgrass requirements can also decrease N leaching from established turfgrass, although the benefits may be less marked under optimised irrigation regimes. Smaller, more frequent applications of water-soluble fertilisers reduce N leaching, as does the use of slow-release fertilisers. Turfgrass growth and quality are often also more consistent when water-soluble fertilisers are applied sparingly and frequently. Healthy turfgrass, free from other nutrient deficiencies and free of disease and pests, should also ensure that uptake of applied N is maximised. Turfgrass appears to be more susceptible to N leaching during site establishment, and optimising both irrigation and fertiliser regimes while the turfgrass develops roots is particularly important for reducing N leaching.

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