

INFLUENCE OF EXCESS NITROGEN ON SOIL MICROBIAL COMMUNITIES IN TURFGRASS SYSTEMS

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ABSTRACT

As the main factor influencing plant growth with aesthetic quality and stress recovery, nitrogen inputs are essential to the management of turfgrass. The environmental effects of ineffective fertilization are significant due to the large amount of land devoted to managed turfgrass. The main pathways of nitrogen loss nitrate leaching, surface runoff and gaseous emissions (ammonia and nitrous oxide) as well as the ensuing ecological and public health effects such as groundwater contamination along with methemoglobinemia risk and aquatic eutrophication. Evidence suggests that nitrogen loss is not a natural defect of turfgrass systems, but rather a highly management-dependent phenomenon increased environmental risk arises when fertilizer application exceeds plant demand, coincides with excessive irrigation or is poorly matched to soil and turf conditions. Optimizing Nitrogen Use Efficiency (NUE) will lessen these effects.

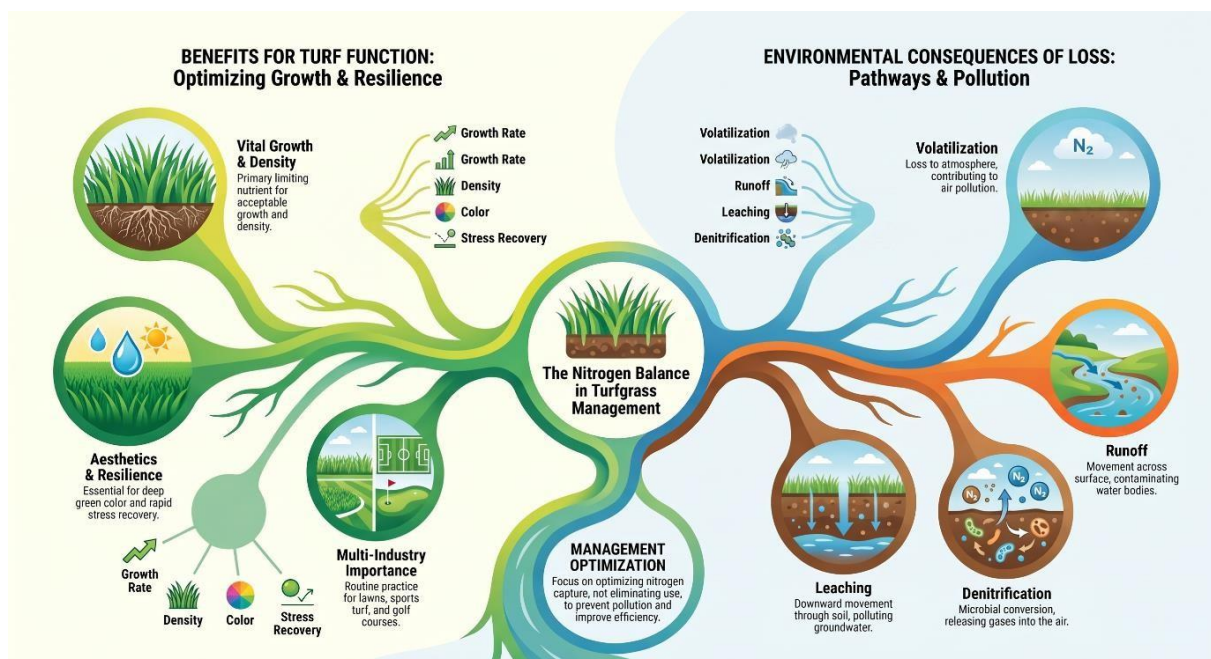
KEYWORDS: turfgrass, nitrogen fertilization, nitrate leaching, runoff, nitrous oxide, irrigation, environmental impact

INTRODUCTION

Turfgrass management relies heavily on nitrogen because nitrogen is the most limiting nutrient for turf growth and is necessary to maintain acceptable growth rate, density, color and stress recovery [1] [2]. Physiologically, nitrogen is a fundamental component of chlorophyll, amino acids and proteins which are driving the photosynthetic capacity and overall vigor of the plant. Turfgrass is maintained for aesthetics, recreation and soil stabilization, which makes nitrogen fertilization one of the most important routine practices in lawns, sports turf and golf courses [3]. Beyond visual appeal, well-fertilized dense turf provides critical functional benefits, including temperature moderation and carbon sequestration a safe playing surface for athletes and the mitigation of soil erosion in urban and suburban landscapes [4].

While nitrogen improves turf activity and nitrogen not captured by plants can be lost through volatilization, runoff, leaching and denitrification. These loss pathways not only lower fertilizer efficiency but also pose significant environmental and economic risks [5]. Nitrate leaching can contaminate local groundwater and drinking water supplies, while surface runoff into nearby water bodies frequently contributes to the eutrophication of aquatic ecosystems leading to harmful algal blooms and oxygen depletion. Furthermore, gaseous losses via denitrification can release nitrous oxide a highly potent greenhouse gas [6].

The turfgrass management is the frame of problem as one of optimizing nitrogen use rather than eliminating nitrogen altogether (Fig 1.) [7]. Because turfgrass systems are perennial and continually subjected to environmental and anthropogenic stresses, eliminating nitrogen would lead to rapid decline in turf health, weed encroachment and increased soil erosion [8]. Therefore, achieving optimal Nitrogen Use Efficiency (NUE) is a primary goal for modern turf science. This requires a multifaceted approach, integrating the use of slow- and controlled-release fertilizers, precision application timing based on plant uptake patterns, routine soil testing and the selection of turfgrass cultivars breed for lower nitrogen requirements. Ultimately, sustainable turfgrass management must balance the physiological demands of the plant with environmentally responsible application methods to mitigate its ecological footprint [9].



(Fig.1.) Benefits and Environmental Consequences

2.Plant Uptake and Nitrogen-Use Efficiency

Nitrogen-use efficiency is the effectiveness of nitrogen uptake and utilization by plants and improving it is the main route to lower environmental loss without sacrificing plant performance [10]. Reduced nitrogen-use efficiency is linked to higher nitrate leaching and higher gaseous losses including ammonia and nitrous oxide [11].

Nitrogen-use efficiency (NUE) refers to the ability of a plant to acquire nitrogen from the available nutrient pool and efficiently utilize that nitrogen to produce biomass, yield and desirable economic products [12]. Improving NUE is an important strategy for maintaining crop productivity while reducing excessive fertilizer application and associated environmental problems [13].

2.1Factors Influencing Nitrogen-Use Efficiency

Several biological and environmental variables analyse how efficiently turfgrass can capture applied nitrogen before it is lost to the atmosphere or groundwater. Turf species with deep, dense and fibrous root systems physically intercept a larger volume of soil water inherently increasing their NUE compared to shallow-rooted species [14]. Furthermore, soil microbes convert organic nitrogen and urea into plant-available forms. If fertilizers are applied when soils are too cold, microbial activity is sluggish, leaving nitrogen sitting in the soil where it is vulnerable to runoff [15].

Soil pH also plays a critical role in this process. The availability of nitrogen and other essential macronutrients is maximized when soil pH is maintained between 6.0 to 7.0. Outside this range nutrient lockout can occur causing applied nitrogen to be wasted. Finally, the plant's growth phase is vital [16]. Actively growing turf requires significantly more nitrogen than dormant or stressed turf, meaning fertilizer applications made during periods of heat stress, drought, or winter dormancy will drastically lower nitrogen-use efficiency [17].

2.2 Leaching, Runoff and Gaseous Loss

The main nitrogen loss pathways from turf are leaching, runoff, volatilization and denitrification. The amount lost depends on fertilizer source, timing, root density, soil moisture and precipitation or irrigation intensity, which is similar to nitrogen rates can lead to very different outcomes across sites [18].

Nitrogen losses from turfgrass systems occur through several interconnected pathways, principally nitrate leaching, surface runoff, ammonia (NH_3) volatilization and microbial denitrification [19]. These losses represent a major reduction in nitrogen-use efficiency because nitrogen applied as fertilizer is not completely recovered by the turfgrass canopy and root system [20]. Globally, a substantial proportion of applied nitrogen can be lost to the environment, with leaching, volatilization, runoff and denitrification identified as major pathways responsible for reduced nitrogen-use efficiency [21].

2.2.1Expanding on Leaching, Runoff and Gaseous Loss

The dynamics of nitrogen in a turfgrass system are highly reactive meaning that any nitrogen not immediately absorbed by the plant becomes vulnerable to environmental escape [22]. Once applied, fertilizer enters the complex nitrogen cycle, where it can be lost through three primary physical trajectories like downward

movement through the soil, lateral movement across the surface, or upward diffusion into the atmosphere [23]. The dominance of any single pathway is rarely fixed instead, it is entirely dictated by a combination of soil properties, weather events and specific management decisions.

2.2.2 The Mechanics of Nitrate Leaching

Leaching represents the downward vertical movement of nitrogen, primarily in the form of nitrate, through the soil profile and beyond the reach of the turfgrass root system. Because nitrate molecules carry a negative electrical charge, they are repelled by the similarly charged soil particles, preventing them from anchoring securely in the soil matrix [24]. When irrigation or heavy rainfall exceeds the soil's water-holding capacity, this highly soluble nitrate is physically flushed downward. The risk of leaching is exceptionally high in sandy soils with large pore spaces and rapid drainage rates, ultimately serving as the primary pathway for groundwater contamination and drinking-water degradation [25].

2.2.3 Surface Runoff and Lateral Transport

In contrast to leaching, surface runoff involves the lateral movement of nitrogen across the top of the turf canopy and soil surface. This phenomenon occurs when precipitation or irrigation rates exceed the infiltration capacity of the soil [26]. When turf soils are heavily compacted and saturated from previous rains or situated on steep gradients, the excess water flows overland carrying both dissolved nitrogen and suspended particulate matter with it. Runoff is particularly problematic because it creates a direct transport mechanism to nearby municipal drainage systems, streams and lakes [27]. Once deposited into these surface waters, the exported nitrogen acts as a catalyst for severe algal blooms and aquatic eutrophication [28].

2.2.3 Ammonia volatilization

Ammonia volatilization is a gaseous nitrogen-loss pathway that is particularly associated with urea-based fertilizers. Following application of urea to the soil surface, urease-mediated hydrolysis converts urea into ammonium and can temporarily increase pH around the fertilizer granule [29]. Under favorable conditions, a portion of the resulting ammoniacal nitrogen can be converted to gaseous NH_3 and escape into the atmosphere [30].

The magnitude of ammonia volatilization is influenced by fertilizer type, soil pH, temperature, soil moisture, wind, surface residue and incorporation of fertilizer into the soil [31]. Surface-applied urea is generally more susceptible to volatilization than nitrogen sources that are less prone to rapid hydrolysis.

2.2.4 Denitrification and nitrous oxide emissions

Denitrification is a microbial process in which nitrate is sequentially reduced under low-oxygen or anaerobic conditions, ultimately producing gaseous nitrogen forms such as N_2O and N_2 [32]. It becomes particularly important in waterlogged, poorly drained or highly compacted soils, where oxygen availability is reduced.

A meta-analysis of nitrogen-management practices, emphasized that N_2O emissions are influenced by the interaction of N management, N balance and environmental conditions rather than by fertilizer rate alone [33]. Their findings support site-specific nutrient management instead of universally applying a single N-management strategy across different production environments.

3. Ecological and Human Health Impacts of Nitrogen Pollution

3.1 Atmospheric Losses via Volatilization

Gaseous losses occur through two distinct biological and chemical processes, the first being ammonia volatilization. This pathway is most active when urea-based fertilizers are broadcast across the turf surface and left exposed to the air without being watered into the soil [34]. Under conditions of warm temperatures, high wind and high soil pH, enzymes in the turf canopy rapidly break down the urea converting it into volatile ammonia gas before it can safely penetrate the soil profile. This atmospheric loss not only drastically reduces the agronomic efficiency of the fertilizer application but also contributes to localized air pollution and the formation of photochemical smog [35].

3.2 Denitrification and Greenhouse Gases

The second major atmospheric loss pathway is denitrification, a microbe-driven process that thrives under entirely different environmental conditions. When soils become waterlogged or saturated often due to poor drainage or excessive irrigation oxygen is driven out of the soil pores, creating an anaerobic environment [36]. In the absence of oxygen, specific soil bacteria strip oxygen atoms directly from the available nitrate to survive. This chemical reduction transforms the nitrate into nitrous oxide and inert nitrogen gas, which then vent into the atmosphere. Denitrification is a severe environmental concern because nitrous oxide is a remarkably potent and long-lived greenhouse gas that actively drives climate change [37].

3.3 The Public Health Implications

The infiltration of nitrate into groundwater elevates turfgrass management from an ecological issue to a significant public health concern. High concentrations of nitrate in drinking water are strictly regulated by

environmental and health agencies worldwide[38]. When consumed, particularly by infants, excessive nitrate interferes with the blood's ability to carry oxygen leading to a dangerous condition known as methemoglobinemia or "blue baby syndrome. Also, prolonged exposure to elevated nitrate levels in drinking water has been increasingly investigated for its potential links to broader chronic health conditions. Consequently, preventing downward nitrate migration is a paramount regulatory and agronomic priority [39].

3.4 Eutrophication and Aquatic Ecosystem Collapse

When runoff deposits excess nitrogen into surface waters, it triggers a destructive biological chain reaction known as eutrophication. The sudden influx of nutrients aggressively stimulates the growth of algae and aquatic weeds resulting in dense algal blooms that blanket the water's surface [40]. These blooms block vital sunlight from reaching submerged aquatic plants, disrupting the foundational food web. As the massive populations of algae eventually die and sink to the bottom, the bacteria that decompose them consume vast amounts of dissolved oxygen from the water [41]. This rapid oxygen depletion creates hypoxic "dead zones" where fish and other aquatic organisms suffocate, ultimately leading to severe losses of biodiversity and the degradation of recreational water resources [42].

3.5 Groundwater Contamination

Nitrate contamination of drinking water is a major environmental and human-health concern because nitrate pollution is linked to groundwater deterioration and contaminated water supplies [5]. Drinking-water nitrate contamination is associated with methemoglobinemia risk in infants and nitrate-contaminated water has also been linked to broader health concerns [43].

4. Quantifying Nitrogen Runoff and Gaseous Emissions

4.1 Golf Course Runoff

Golf course fairway research shows that turf species choice alone does not guarantee lower runoff losses. In one side-by-side study, fine fescue mixture produced 38% more ammonium-N transport and 56% more nitrate-N transport in runoff than creeping bentgrass [44]. Runoff volume in that study was most closely related to shoot density, thatch depth and soil moisture [4].

Beyond the physical architecture of the plants, the antecedent moisture of the soil is the ultimate governor of runoff volume. If a fairway is already heavily saturated from a previous rainstorm or overly aggressive irrigation, the soil matrix temporarily loses its capacity to absorb new moisture [45]. When the soil sponge is full, virtually all subsequent precipitation is forced to run off laterally, completely neutralizing the benefits of a dense canopy or deep thatch layer. This reality emphasizes the critical need for integrated fairway management. Golf course superintendents must balance species selection with deliberate cultural practices such as core aeration and sand topdressing to manage soil compaction and thatch buildup [46]. while carefully monitoring soil moisture to ensure irrigation is only applied when the ground has the physical capacity to absorb it. Managing golf course runoff is rarely about finding a perfect grass species, rather it is about constantly optimizing the physical and hydrological conditions of the entire turf system.

4.2 Watershed Relevance

Golf courses have been cited as significant sources of nutrient loading to groundwater and surface water, but the review evidence shows highly variable export rates rather than a single universal estimate [47]. That variability is watershed-scale best management practices focus not only on fertilizer rate but also on reducing opportunities for transport across the landscape [48].

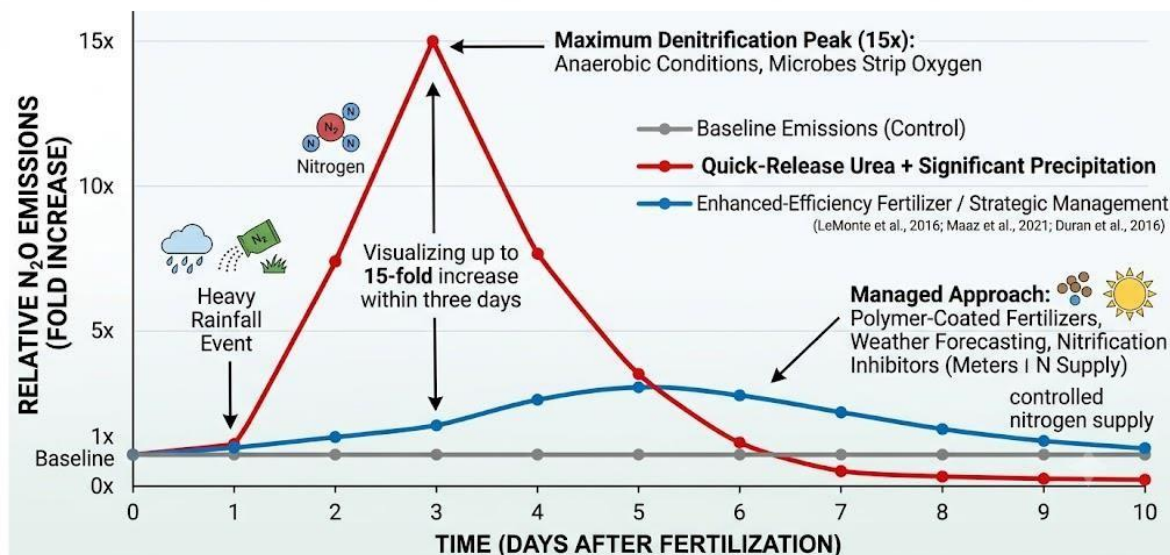
4.3 Nitrous Oxide Emissions

Nitrous oxide is especially important because it is a long-lived greenhouse gas with very high warming potential and it also contributes to ozone depletion. Fertilization can increase turfgrass N₂O emissions by up to 15-fold within three days after application and emission peaks are greater when significant precipitation follows fertilization [49].

This microbial activity, however, is heavily dictated by immediate weather patterns and soil moisture levels. The most extreme peaks in nitrous oxide emissions reliably occur when significant precipitation or heavy irrigation immediately follows a fertilizer application [50]. When soil becomes saturated, water completely fills the microscopic pore spaces between soil particles, aggressively pushing out the available oxygen. This sudden lack of oxygen creates an anaerobic environment. To survive in these suffocating conditions, specific denitrifying bacteria shift their metabolism, stripping the necessary oxygen atoms directly from the newly applied nitrate molecules [51]. As they tear the nitrate apart, nitrous oxide gas is formed as a byproduct and rapidly vents upward into the atmosphere. Mitigating these volatile atmospheric losses requires turf managers to act with exceptional precision regarding application timing and fertilizer selection. Broadcasting quick-release, highly soluble urea right before a forecasted rainstorm is a recipe for maximum greenhouse gas release, as the saturated soils will immediately trigger heavy denitrification [52]. To suppress these emission peaks, managers must utilize weather forecasting to avoid applying fertilizers prior to heavy rainfall. Furthermore, transitioning to enhanced-efficiency products, such as polymer-coated fertilizers or those containing nitrification inhibitors,

can slowly meter out the nitrogen supply. By preventing a sudden surplus of nitrogen in the soil, these technologies starve the microbes of the raw materials needed to generate massive nitrous oxide spikes, thereby protecting both the local environment and the broader climate[53].

COMPARATIVE N₂O EMISSIONS FOLLOWING TURFGRASS FERTILIZATION: MANAGEMENT IMPACTS AND WEATHER INTERACTIONS



5. Irrigation Practices and Eco-Physiological Responses

5.1 Irrigation Management

Irrigation is one of the clearest modifiers of nitrogen fate around 50%–60% of actual evapotranspiration, often maintains acceptable turf quality while using less water than irrigation back to field capacity. The same review found that irrigation beyond field capacity increases nutrient leaching risk [18].

5.2 Deficit Irrigation and Evapotranspiration

To optimize both water conservation and nutrient retention, modern turf management relies heavily on measuring evapotranspiration. This evaluation calculates the exact amount of moisture lost to the atmosphere through soil evaporation and plant transpiration [54]. Research consistently demonstrates that replacing all of this lost water is biologically unnecessary. Instead of implementing a moderate deficit irrigation strategy replacing only 50 to 60 percent of actual evapotranspiration is often perfectly sufficient to maintain acceptable turf density, color and stress tolerance. By deliberately keeping the soil slightly drier than its maximum capacity managers leave vital pore space open to absorb unexpected rainfall preventing sudden runoff and creating a protective hydrological buffer [55].

5.3 Interaction of Water and Nitrogen

Water and fertilizer interact strongly rather than independently. Overwatering increases percolation and nitrogen loss, while high soil water content combined with high temperature can also increase gaseous losses through denitrification [56].

6. Species Dynamics in Sustainable Turfgrass Management

Species dynamics is an important component of sustainable turfgrass management because the composition, interaction and seasonal performance of turfgrass species directly influence turf quality, resource-use efficiency, environmental performance and long-term persistence [57]. Turfgrass systems are rarely static; changes in temperature, moisture availability, soil fertility, mowing intensity, traffic and management practices can alter the relative abundance and competitive ability of individual species over time [58]. Therefore, sustainable turf management requires consideration not only of the performance of a single species but also of species diversity, species replacement, interspecific competition and adaptation to changing environmental conditions [59].

6.1 Turf Species

Species choice also changes nitrogen outcomes. In Chinese urban turfgrasses, warm-season turf had lower annual N₂O and NO emissions than cool-season turf apparently because the stronger root system reduced inorganic nitrogen available for microbial nitrification and denitrification [50]. Species substitution can still create unexpected runoff tradeoffs as shown by higher runoff nutrient transport from fine fescue mixture than creeping bentgrass under fairway conditions [4].

6.2 The Complexity of Sustainable Species Selection

These inherent biological differences highlight the immense complexity of sustainable turfgrass management. There is no single "perfect" grass species that miraculously solves all environmental challenges [60]. Turf managers must carefully weigh the localized environmental risks before committing to a specific seed blend. Opting for a species that requires minimal fertilizer might inadvertently increase the risk of nutrient runoff if its canopy cannot physically slow down stormwater. Conversely, choosing a highly dense species to prevent runoff might require more frequent watering or chemical inputs to survive. Ultimately, sustainable species selection demands a holistic understanding of the site's hydrology, climate and specific ecological vulnerabilities to ensure that solving one environmental problem does not accidentally create another [61].

7. Mitigation Strategies

7.1 Improve Irrigation Scheduling

Irrigation should be scheduled to maintain turf quality while avoiding excessive drainage and denitrification. Moderate deficit irrigation appears to be the most evidence-supported general strategy where turf use intensity allows it [18].

7.2 Use Enhanced-Efficiency Fertilizers Carefully

Enhanced-efficiency fertilizers can reduce atmospheric nitrogen losses, but they are not universally effective across all soils and pathways. The broader meta-analytic evidence emphasizes that nutrient management has tradeoffs across loss pathways, so practices should be tailored rather than treated as universally prescriptive [6]. Urease inhibitors are particularly useful where ammonia volatilization is an important concern. They temporarily slow the conversion of urea to ammonium, providing more time for fertilizer nitrogen to move into the soil and become available to plants [62]. For example, meta-analytic evidence indicates that urease inhibitors can substantially reduce ammonia losses from urea compared with untreated urea. However, their effectiveness can decline when rainfall or irrigation is sufficient to rapidly incorporate urea into the soil, because incorporation itself reduces exposure of urea-derived ammonia to the atmosphere [63].

7.3 Consider Nitrification Inhibitors

Nitrification inhibitors reduced dissolved inorganic nitrogen leaching by 48% and N₂O emissions by 44%, while improving plant nitrogen recovery by 58%. However, they also increased ammonia emissions by 20%, highlighting that their use involves important trade-offs rather than being an entirely beneficial [64].

Theme	Main Finding	Evidence
Nitrogen necessity	Turf needs nitrogen for quality and persistence	[2]
Water quality	Leaching and runoff are the main aquatic risks	[4]
Atmospheric loss	N ₂ O and NH ₃ increase after fertilization	[65]
Management dependence	Rate, soil, source and species	[20]

8. Nitrogen Use in Turfgrass Systems

8.1 Agronomic Importance of Nitrogen in Turfgrass

Nitrogen is the most limiting nutrient in turfgrass and is applied to sustain growth density recovery and visual quality [66]. Turfgrass fertilization is therefore a core maintenance practice in lawns, sports turf and golf courses rather than an optional input. The scale of this issue is large because turfgrass covers about 1.68% of U.S. land and includes more than 80 million residential lawns. Balanced fertility matters because nitrogen interacts with other nutrients and stress responses, so excess nitrogen is not equivalent to better management [67].

8.2 Nitrogen Uptake, Use Efficiency & Loss Pathways

Nitrogen use efficiency is the central concept linking turf performance to environmental protection because nitrogen not recovered by plants is vulnerable to loss. Across agriculture broadly, about 50% of applied nitrogen is lost to the environment and higher nitrogen fertilization has often produced low agronomic benefit with higher environmental risk [68]. The main loss pathways are volatilization, runoff, leaching and denitrification. These losses are influenced by fertilizer type, application timing, root density, soil moisture, and rainfall or irrigation intensity. As a result, the same fertilizer rate can produce very different outcomes under different site conditions [69].

8.3 Nitrate Leaching to Groundwater

Nitrate leaching is the most established water-quality concern in turfgrass fertilization research. When fertilization is well managed nitrate losses through leaching are often less than 10% of applied nitrogen and leachate concentrations generally remain below 10 mg L⁻¹ [70]. In a greenhouse lawn study acceptable turf quality was generally reached at rates of 100 kg N ha⁻¹ or more, while coated urea sources were more effective at reducing leaching [71]. Sand rootzones were more vulnerable to high nitrate losses from some products with urea UFLEXX and XCU at high rates producing 8.5 to 23.7 mg L⁻¹ nitrate in leachate [72]. Coarser soils generally carry higher leaching risk than medium or fine soils which aligns with broader meta-analytic evidence across fertilizer studies [73].

8.4 Surface Runoff and Eutrophication Risk

Nitrogen can also leave turf laterally in runoff, especially where hydrologic connectivity carries water rapidly to nearby streams or ponds or drainage systems. In golf fairway runoff experiments fine fescue mixture produced 38% more ammonium-N and 56% more nitrate-N transport than creeping bentgrass, showing that alternative species do not automatically reduce off-site nutrient movement [74]. Runoff volume in that study was most closely linked to shoot density, thatch depth and soil moisture, which means plant structure and surface hydrology strongly mediate nitrogen export [75]. At golf-course scale, typical inorganic nitrogen losses via leaching and runoff are on the order of 2–12 kg ha⁻¹ yr⁻¹, but rates vary across 2–3 orders of magnitude, so local conditions matter greatly [76].

9. Atmospheric Consequences

9.1 Nitrous Oxide Emissions From Fertilized Turf

Nitrous oxide is the main gaseous nitrogen loss of concern because it is a potent greenhouse gas and contributes to ozone depletion [77]. In turfgrass, fertilization increased N₂O emissions by up to 15-fold within three days after application and fluxes ranged from winter uptake to peaks of 407 µg N₂O-N m⁻² h⁻¹ after fall fertilization [49]. Annual cumulative emissions reached 1.65 kg N ha⁻¹ under high-rate urea and 1.01 kg N ha⁻¹ under low-rate urea, a 63% increase with the higher rate. In zoysia grass, the 200 and 250 kg N ha⁻¹ treatments produced the highest CO₂ and N₂O fluxes and the greatest global warming potential [78].

9.2 Effects of Climate, Temperature and Moisture on Gaseous Losses

Nitrous oxide emissions are strongly controlled by soil temperature and water status rather than by fertilizer rate alone. In urban turfgrass in Beijing, annual N₂O emissions ranged from 0.75 to 1.27 kg N ha⁻¹ yr⁻¹ and 17%–37% of annual N₂O budgets occurred outside the growing season [79]. Warm-season turf emitted less N₂O and NO than cool-season turf apparently because stronger root systems limited inorganic nitrogen available to microbial nitrification and denitrification. Precipitation shortly after fertilization further increases N₂O peaks, so timing relative to weather is a critical practical variable [80].

10. Management Factors Controlling Environmental Impact

The environmental impact of turfgrass systems is largely determined by management practices rather than the inherent characteristics of the turfgrass itself. While turfgrass has the potential to provide numerous ecosystem services, including carbon sequestration, soil stabilization, erosion control and urban cooling, inappropriate management can increase nutrient losses, greenhouse gas emissions and water consumption [81]. Therefore, the sustainability of turfgrass depends on adopting management strategies that maximize resource-use efficiency while minimizing adverse environmental effects. Numerous studies have concluded that nitrogen losses from turfgrass are management-dependent rather than fixed properties of turf systems [82].

10.1 Effects of Nitrogen Rate Timing & Irrigation

Irrigation beyond field capacity increases nutrient leaching risk, while moderate deficit irrigation around 50%–60% of evapotranspiration often maintains acceptable turf quality with lower water use [81]. It is found that nitrogen rate, soil, species and growth rate often influence leaching more than irrigation alone [18]. In home lawns, overwatering combined with fertilization produced the highest annual nitrogen losses, up to 32 kg ha⁻¹, whereas scheduled irrigation treatments did not differ significantly from unfertilized controls [83]. Light and frequent irrigation can slightly increase nitrate leaching in some species and stressed turf with poor visual quality can also show more nitrate leaching [84].

10.2 Effects of Fertilizer Source, Soil Type and Turf Species

Fertilizer source changes the timing and magnitude of nitrogen release and therefore changes environmental loss profiles. Polymer-coated urea reduced ammonia emissions by 41%–49% and nitrous oxide emissions by 45%–73% compared with urea while maintaining turf vigor [8] (LeMonte et al., 2016). Differences in nitrate leaching between urea and polymer-coated urea were less consistent, showing stronger evidence for reducing atmospheric than aqueous losses. Soil texture remains a primary control because coarser soils increase leaching vulnerability. Species also matter, since warm-season turf retained nitrogen more effectively in one annual flux study but species substitutions can still create runoff tradeoffs under fairway conditions [85].

CONCLUSION

Nitrogen is essential for the health and function of turfgrass; however, its significant potential for environmental harm requires a change in how it's managed in today's landscapes. This review underscores that the ecological and public health impacts of nitrogen mismanagement, which include nitrate-polluted groundwater, eutrophic water bodies, and the release of powerful greenhouse gases such as nitrous oxide, are significant and widespread. The literature consistently shows that these environmental impacts are not unavoidable results of turfgrass farming; instead, they are greatly influenced by particular agronomic methods and local site conditions.

The data highlights that enhancing Nitrogen Use Efficiency (NUE) is essential for sustainable turfgrass systems. Accomplishing this necessitates progressing from fixed timetable-based application rates to dynamic unified management frameworks.

In the end, turfgrass management's future must align seamlessly with the larger goals of landscape architecture and urban climate resilience. Shifting from reactive, high-input maintenance to precision-focused, eco-physiological approaches guarantees that turfgrass maintains crucial functional advantages including soil stabilization, urban heat island reduction, and carbon sequestration, while protecting local watersheds and the global climate. Advancing to sustainable turf systems will rely on the ongoing enhancement of plant-soil-water interactions and the implementation of technologies that harmonize the plant's physiological needs with the critical requirement of environmental care.

DECLARATIONS

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