

Soil Microbial Community Composition and Function in Turfgrass Ecosystems

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ABSTRACT

Turfgrasses are an integral component of the urban landscape. Their ecology is strongly influenced by the primary management practices of frequent mowing, fertilization, and irrigation. While much is known about turfgrass plant function, relatively little research has addressed the attending soil microbial community, especially when compared to counterparts in forests, grasslands, and arable soils. This paper reviews available information on soil microbial community composition and function, focusing on organic matter decomposition, nutrient cycling, and response to global environmental change. Consideration also is given to unfavorable conditions that commonly influence the soil microbial community in turfgrass systems (soil compaction, salinity, and use of pesticides). Areas for future research emphasis in turfgrass microbial ecology are discussed.

Keywords: decomposers, denitrifiers, microbial biomass, microbial community diversity, microbial activity, nitrifiers, nitrogen mineralization, turfgrass ecosystem

Abbreviations: CFU, colony forming unit; CLPP, community level physiological profile; DGGE, denaturing gradient gel electrophoresis; FAME, fatty acid methyl ester; FDA, fluorescein diacetate; MPN, most probable number; N₂O, nitrous oxide; PLFA, phospholipid fatty acids

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INTRODUCTION

Turfgrass has greatly increased in acreage during the latter half of the 20th century (Brown *et al.* 2005). It is used extensively for home lawns, roadsides, parks, sports fields, commercial landscapes, and golf courses. In the USA, turfgrass acreage has expanded from 16 million acres (i.e. 6.5 million hectares) in the 1960's to about 50 million acres (i.e. 20 million hectares) today, behind only corn and soybean in total land area (Falk 1976; Milesi *et al.* 2005).

Turfgrass systems are challenged with the contemporary environmental issues. Although most research indicates a low potential for NO₃⁻ leaching, with most fertilizer N being retained in the plant and soil organic matter (Petrovic 1990; Geron *et al.* 1993; Liu *et al.* 1997; Higby and Bell 1999; Lee *et al.* 2003), there are reports of relatively high

leaching losses (Frank *et al.* 2006), which could contribute to pollution of surface- and ground-waters. Turfgrass systems may also be an important source of global warming gases. In studies conducted in the U.S. Great Plains, turfgrass systems could account for 24% of soil CO₂ respiration and 30% of soil N₂O emission, while occupying only 6.4% of the land area (Kaye *et al.* 2004, 2005).

Because soil microorganisms are primary determinants of soil C and N ecology, it is important to understand their composition and function in turfgrass systems, particularly as related to soil C sequestration and N retention. Unfortunately, relatively little is known about the abundance, diversity and activity of the soil microbial community associated with turfgrasses, and it is often assumed that turfgrass monocultures, subjected to frequent chemical applications, have low microbial population size and diversity. In this

Table 1 Soil organic C in turfgrass systems of different ages.

Turf age ¹ (yr)	Turf type	Soil depth (cm)	Organic C (%)	Reference
10-51	Golf course	0-7.5	1.3-2. ²	Higby and Bell 1999
1.5-45	Putting green	0-11	0.6-3.4	Qian and Follett 2002
1.5-45	Fairway	0-11	1.8-4.2	Qian and Follett 2002
4-24	Golf course	0-15	0.6-1.2	Kerek <i>et al.</i> 2003
1-95	Golf course	0-5	1.0-7.2	Shi <i>et al.</i> 2006a
3-97	Golf course	0-7.5	0.8-4.8	Shi <i>et al.</i> 2006b

¹ Number represents the age from the youngest to the oldest turf in a turfgrass chronosequence.

² Values are calculated from soil organic matter by multiplying 0.58.

review, we integrate current knowledge on soil microbial community composition and function in turfgrass systems and discuss future research needs.

CHARACTERISTICS AND MANAGEMENT OF TURFGRASS SYSTEMS

Turf, which consists of closely-spaced turfgrass plants and the subtending soil, is a unique ecosystem subjected to intense management. Frequent mowing maintains high shoot density, uniform height and constant composition of grass species. It also limits reproductive development, thus enhancing vegetative growth (Falk 1976). A mature turf consists of millions or even billions of shoots per hectare and a liter of topsoil can contain more than 100,000 roots and 1,000,000 root hairs (Beard and Green 1994). Although managed for visual quality as opposed to high growth rate, turf can be a highly productive ecosystem. It has been estimated, for example, that primary productivity of turfgrass systems is about 1,000 g m⁻² year⁻¹, comparable to that of corn and tallgrass prairie (Falk 1976). Similar estimates have been made by others (Herte *et al.* 1971; Madison 1971; Jo and Mcpherson 1995). One of the differences between turf and cropping systems is the degree to which fixed C is partitioned to below-ground tissues. Carbon allocation to roots and other subsurface tissues was 2.5- to 5-fold greater in turfgrasses than in corn, wheat and shortgrass prairie (Kaye *et al.* 2005). This, together with the return of mowed clippings to the turf system, contributes to the rapid accretion of organic matter in the topsoil.

Accumulation of soil organic matter is substantial during the first few decades after turfgrass establishment (Qian *et al.* 2002; Bandaranayake *et al.* 2003). Approximately 23 to 32 Mg soil organic C ha⁻¹ could be accrued in the top 20-cm of soil beneath a 30-year-old turf (Bandaranayake *et al.* 2003). Soil organic C from 690 samples, mainly from northern Colorado USA, indicated that organic matter accumulated at a rate of about 1.0 Mg C ha⁻¹ year⁻¹ during the first 30 years of culture (Qian and Follett 2002). Obviously, soil organic matter accumulation is finite and in different environmental conditions approaches a maximum or 'equilibrium' approximately 20 to 50 years after turfgrass establishment (Petrovic 1990; Qian and Follett 2002; Bandaranayake *et al.* 2003).

The time required for particular soils to reach equilibrium is influenced by soil texture, previous land use, grass species, fertilization rate, irrigation, and other management practices (Qian and Follett 2002; Bandaranayake *et al.* 2003). But, the dominant factor controlling soil organic matter content in turfgrass systems is age. In one study, approximately 81% of the variance in soil organic matter sampled from various turfgrass systems could be explained by turf age (Higby and Bell 1999), and in another 47 to 70% (Qian and Follett 2002). In newly established turf, soil organic C in the top 15 cm is comparable to that in arable soils, i.e. 0.5-4.0% (**Table 1**). By contrast, older turf soils often accumulate higher levels of organic C. Soil organic C in an urban lawn, for example, was 1.7- to 2.8-fold greater than that in native or agricultural soils (Kaye *et al.* 2005). About a 6-fold difference in soil organic C was reported for a 95-year-old turf compared to native pines adjacent to the turf (Shi *et al.* 2006a). However, as with other managed and natural ecosystems, soil organic C in turf declines with in-

creasing soil depth. Soil organic C in the topsoil was about 2- to 4-fold greater than that in the lower soil depth (Kaye *et al.* 2005; Shi *et al.* 2006a).

ABUNDANCE, DIVERSITY, AND ACTIVITY OF MICROBIAL FUNCTIONAL GROUPS

As with any plant-soil ecosystem, turfgrass soils support abundant and diverse microbial populations (**Table 2**). The somewhat limited published data indicate that microbial biomass increases with turf age to relatively high levels in a mature turf, in parallel with soil organic matter. Soil microbial biomass increased from 249 µg C g⁻¹ in a 4-year-old turf to 1119 µg C g⁻¹ soil in a 21-year-old turf, for example, and this increase was positively correlated with the increase in soil organic matter (Kerek *et al.* 2002). Urban lawns had about 2 times greater biomass than agricultural (corn and wheat) and natural (shortgrass steppe) ecosystems, and the differences were positively correlated with soil organic matter content (Kaye *et al.* 2005). A recent examination of soils from golf courses ranging in age from 1 to 95 years revealed that increasing organic matter was paralleled by high microbial biomass (Shi *et al.* 2006a).

Turfgrass establishment usually involves considerable soil disturbance, or even the complete replacement of the native soil with sand, as is common with athletic fields and golf course putting greens. As a result, soil organic matter may be expected to be low or almost non-existent in new turfgrass systems, suggesting a small microbial community. Surprisingly, microbial population density in recently planted turf is comparable to that in arable soils. Abundant and diverse microbes were found in sand-based putting greens of creeping bentgrass (*Agrostis stolonifera*) six months after seeding (Bigelow *et al.* 2002). Culturable bacteria, fungi, and actinomycetes were present, and aerobic spore forming populations (i.e. *Bacillus* spp.) numbered about 10⁸ colony forming units (CFU) g⁻¹ soil. Variations in the microbial population occurred during the course of the first year but not in subsequent years, indicating microbial population stability despite seasonal changes in the soil environment. In another study with newly constructed golf course putting greens of creeping bentgrass, there were about 10⁵ to 10⁸ CFU g⁻¹ soil of various microbes including fluorescent pseudomonads, Gram-positive bacteria, Gram-negative bacteria, *Stenotrophomonas*, maltophilia-like bacteria, actinomycetes, and heat-tolerant bacteria (Elliott *et al.* 2003). Again, microbial population densities were only slightly affected by temporal and spatial changes in the soil environment (Elliott and des Jardin 1999; Elliott *et al.* 2004).

Microbial community composition and diversity have also been addressed using more sensitive methodologies. Using phospholipid fatty acid (PLFA) analyses, the soil microbial community composition and diversity was examined in a turfgrass chronosequence of bermudagrass (*Cynodon dactylon* X *transvaalensis*) (1 to 95 years old) and compared with those in adjacent native pines (Yao *et al.* 2006). The microbial community composition differed mainly between the turfgrass and pine ecosystems, and to a lesser extent among the turf of different ages. Microbial community composition in urban lawns dominated by Kentucky bluegrass (*Poa pratensis* L.), identified using PLFA techniques, was also similar to that in arable soils and in the shortgrass prairie ecosystem (Kaye *et al.* 2005). Few changes were ob-

Table 2 Microbial community abundance, composition, and activity in turfgrass systems.

Turfs	Abundance, composition or activity	Reference
Abundance		
Putting green	10 ⁸ CFU bacteria g ⁻¹ soil	Bigelow <i>et al.</i> 2002
Golf course	249-1119 µg biomass C g ⁻¹ soil	Kerek <i>et al.</i> 2002
Turf	10 ⁵ -10 ⁸ CFU bacteria g ⁻¹ soil	Elliott <i>et al.</i> 2003
Lawn	76.4 µmol PLFA g ⁻¹ soil	Kaye <i>et al.</i> 2005
Golf course	300-1400 µg biomass C g ⁻¹ soil	Shi <i>et al.</i> 2006
Composition		
Turf	Diverse, unaffected by turf management	Acosta Martinez <i>et al.</i> 1999
Turf	Diverse, unaffected by turf management	Feng <i>et al.</i> 2002
Lawn	Diverse, similar to agricultural and natural lands	Kaye <i>et al.</i> 2005
Golf course	Diverse, slightly shifts with turf age	Yao <i>et al.</i> 2006
C and N mineralization		
Lawn	31.6 µg C g ⁻¹ soil d ⁻¹	Kaye <i>et al.</i> 2005
Turf	31-922 C µg m ⁻² y ⁻¹	Milesi <i>et al.</i> 2005
Golf course	13-35 µg C g ⁻¹ soil d ⁻¹	Shi <i>et al.</i> 2006a
Turf	12-30 kg N ha ⁻¹ mo ⁻¹	Lee <i>et al.</i> 2003
Lawn	1.8 µg N g ⁻¹ d ⁻¹	Kaye <i>et al.</i> 2005
Golf course	0.2-1.2 µg N g ⁻¹ d ⁻¹	Shi <i>et al.</i> 2006a

served in microbial community composition with resource additions to a turfgrass soil, in the form of N fertilizer and leaf tissue (Acosta-Martinez *et al.* 1999), or with the management practices of subsurface aeration and plant growth regulation with trinexapac-ethyl (Feng *et al.* 2002). It has been postulated that turfgrass management practices are secondary factors influencing the microbial community compared to soil pH, plant species and/or land uses (Yao *et al.* 2006).

Although typically grown as a monoculture, turfgrasses produce a highly diverse soil environment for microorganisms. Both spatial and temporal gradients can exist for organic C and N, moisture, pH, temperature, and soil gases. While recognizing that such heterogeneity may support numerous microbial functional groups, we will focus only on those critical to decomposition, nitrification and denitrification.

Decomposers

Soil microorganisms in turf have two major C sources: fresh leaf clippings and senescing root and shoot tissues, and soil organic matter. The former are probably more important in young turf due to relatively low soil organic matter, while the latter plays the more significant role in older turf. Eliminating the source of fresh organic matter by killing a 12-year-old turfgrass had no effect on the soil microbial biomass one year later (Jiang *et al.* 2000). This suggests that a stable microbial biomass was supported by the soil organic matter, independent of other labile sources of C. This relationship also was indicated by the work of Shi *et al.* (2006b). The soil microbial biomass increased quickly and peaked 7 days after turfgrass clipping additions to the soil, but after 28 days, microbial biomass had declined to the pretreatment level. The labile C source had only a transient stimulatory effect. It is logical to think that microbial biomass would remain elevated with repeated clipping additions generated by frequent mowing.

There is little doubt that microorganisms in turfgrass systems can respond quickly to additions of organic matter. About 30% of the C and N in turfgrass clippings were released as CO₂ or inorganic N within two weeks of clipping additions, regardless of microbial population size and community composition (Shi *et al.* 2006a, 2006b; Yao *et al.* 2006). Heterotrophic soil microbes acquire their C and nutrients after extracellular digestion. Accordingly, it was found that soil enzymes involved in organic matter decomposition and N acquisition were abundant even in newly established turf (Shi *et al.* 2006c).

Heterotrophic respiration in turfgrass systems is governed by management practices. Heterotrophic respiration was estimated to range from 31 g C m⁻² year⁻¹ in unman-

aged turfgrass systems to ~922 C m⁻² year⁻¹ with fertilization, mowing, and on-site recycling of clippings (Milesi *et al.* 2005). Turf may release more CO₂ than arable and natural ecosystems since they often contain higher soil organic matter (Kaye *et al.* 2005).

Nitrogen mineralization rate in turf soils is also considerable (Table 2). The rate of N cycling from urban lawn clippings was about 120 to 150 kg N ha⁻¹ year⁻¹ (Kaye *et al.* 2005). During the active growing season of May to October, mineralized N in a bermudagrass (*Cynodon dactylon* L.) turf was estimated at 60 to 154 kg N ha⁻¹ (Lee *et al.* 2003). Nitrogen mineralization is the net result of gross N mineralization and microbial N assimilation. Experiments using ¹⁵N tracing and pool dilution techniques indicated that gross N mineralization and immobilization in turfgrass systems were tightly coupled, both increasing with turf age (Shi *et al.* 2006a, 2006b). Mineralization amounted to about 5% and 2% of soil organic N in newly established and mature turf soils (Shi *et al.* 2006a). The soil microbial community, in addition to living grass roots, could assimilate soil NO₃⁻, contributing to N capture and minimizing N losses via leaching (Jiang *et al.* 2000). In their study examining NO₃⁻ leaching from killed turf, leaching losses were 3 times greater than from healthy, living turfgrass. But the amount was <10% of total available N present in the soil. This indicates significant immobilization by soil microorganisms. By monitoring soil NO₃⁻ concentrations in the turfgrass soil profile over two years, Lee *et al.* (2003) also concluded that the potential for NO₃⁻ leaching from turfgrass systems was similar to that of adjacent natural ecosystems.

Nitrifiers

Soil ammonia oxidizing- and nitrite oxidizing bacteria are key functional groups producing nitrate. As such, they are at least indirectly responsible for N losses via leaching and denitrification. Turf systems support abundant nitrifiers, and the rates of nitrification are comparable to those in arable soils. Potential rates of nitrification in topsoil (0 to 5 cm) ranged from 8 mg N kg⁻¹ day⁻¹ in a 1-year-old turf to 25 mg N kg⁻¹ day⁻¹ in a 95-year-old turf (Shi *et al.* 2006a). When the same turf sites were sampled two years later (0 to 7.5 cm), potential rates of nitrification was about 4 mg N kg⁻¹ soil day⁻¹ in the younger and 15 mg N kg⁻¹ soil day⁻¹ in the older turf (Shi *et al.* 2006b). Similarly, potential rates of nitrification in the top 10 cm were about 1 mg N kg⁻¹ day⁻¹ in a 6-year-old turf and about 6 mg N kg⁻¹ day⁻¹ in an 18-year-old turf (Cantera *et al.* 2006). Clearly, the potential rates of nitrification increase with turf age. However, unlike the heterotrophic microbes, nitrifiers in old turf systems apparently express their maximum activity as potential rates of nitrification in a 99-year-old turf were unaffected by the

addition of turfgrass clippings (Shi *et al.* 2000b). This contrasted with the 3-fold increases that occurred in a 3-year-old turf after clipping additions.

Using most probable number (MPN) techniques, the number of ammonia oxidizing bacteria in a turfgrass system was estimated to be about 10^4 g⁻¹ soil (Bigelow *et al.* 2002), which was similar to values in arable soils (Phillips *et al.* 2000). It is well known that culture-based techniques such as MPN underestimate the abundance of microorganisms due to selective media or conditions that do not favor all microbes. Values may be 1 to 3 orders of magnitude lower than those determined using molecular biology techniques (Phillips *et al.* 2000). Using quantitative PCR, for example, ammonia oxidizing bacteria in turfgrass systems were estimated at 10^5 to 10^6 g⁻¹ soil (Cantera *et al.* 2006). This was equivalent to those in agricultural soils determined by the same method (Phillips *et al.* 2000).

Denitrifiers

Subject to frequent irrigation and N fertilization, turfgrass systems are likely to support abundant denitrifiers, the key functional group responsible for denitrification. However, less is known about denitrification compared to other aspects of turfgrass soil biology. Denitrification rates varied seasonally, with N₂O fluxes ranging from near zero in winter to about 400 µg N m⁻² hour⁻¹ in fall after fertilization (Bremer 2006). Nitrogen fertilization increased N₂O emission by about 15-fold within 3 days when followed by significant precipitation (Bremer 2006). Heavy fertilization (250 kg N ha⁻¹ year⁻¹) resulted in 63% more N₂O than light fertilization (50 kg N ha⁻¹ year⁻¹); however, the annual N₂O emission was <1.7 kg N ha⁻¹ year⁻¹ (Bremer 2006). Denitrifiers in turfgrass soils reportedly produce more N₂ than N₂O gas, with measured N losses as high as 27% of applied N (Horgan *et al.* 2002a, 2002b).

Denitrifiers are abundant in turfgrass systems (Mancino and Torello 1986; Bigelow *et al.* 2002; Wang and Skipper 2004). Denitrifiers up to 10^7 g⁻¹ soil were detected in soil under irrigated and fertilized turf (Mancino and Torello 1986), which is comparable to populations in arable soils. Using bacterial isolation and subsequent identification via 16S rDNA or gas chromatography-fatty acid methyl ester (GC-FAME), it was found that denitrifiers accounted for 17% of isolates in the turfgrass rhizosphere, with *Bacillus* and *Pseudomonas* being dominant (Wang and Skipper 2004). Additionally, soil texture and moisture content were found to be more important than fertilization in determining denitrifier population size (Mancino and Torello 1986).

MICROBIAL COMMUNITY UNDER UNFAVORABLE CONDITIONS

Pesticides

Pesticides, including herbicides, insecticides, fungicides, and nematicides, are applied to turfgrass to maintain a healthy and attractive groundcover. While pesticides are designed to target weeds, insects, or pathogens, they may adversely affect non-target soil microorganisms. In general, some evidence suggests that fungicides may have greater effects on soil organisms than insecticides or herbicides (Bünemann *et al.* 2006). The role of pesticides on the soil microbial community in turfgrass systems, however, has not been extensively evaluated.

Bioavailability of pesticides, which determines their impact on soil microorganisms, is dependent on various interactions with soil organic matter. These include ionic-, hydrogen-, and covalent bonding, ligand exchange, and Van der Waals forces (Gevao *et al.* 2000). Reduced bioavailability is associated with both solid phase and dissolved organic matter (Chen *et al.* 2006). Surface soil in turfgrass systems contain high concentrations of solid and dissolved organic matter due to the extensive turfgrass root system and frequent leaf clipping deposition. Consequently, one

might think that the impact of pesticides on soil microorganisms may be moderate compared to their effects in agricultural soils.

There is indeed evidence that the soil microbial community abundance beneath turfgrasses, determined as the number of total culturable bacteria, fungi, or actinomycetes, is little affected by the use of pesticides. In an 8-year-old Kentucky bluegrass turf treated with herbicides for 3 years, the number of total bacteria or fungi was similar to untreated controls (Cole and Turgeon 1977). Assessments on the effects of 14 individual fungicides and 5 fungicide mixtures on soil microorganisms in a 2-year-old Kentucky bluegrass also indicated that fungicides only slightly affected the number of total culturable bacteria, fungi, and actinomycetes (Smiley and Craven 1979). A recent study examining the number of total culturable bacteria and fungi in a newly constructed turf repeatedly treated with fungicides indicated little effect on the abundance of soil microorganisms (Harman *et al.* 2006). However, individual microbes within bacteria, actinomycetes, or fungi evidently can be affected by pesticide use (Smiley and Craven 1979).

Traditional plate culture methods may lack adequate resolution to measure more subtle effects of pesticides on soil microbial community. Nonetheless, the results of studies with more specific methods have been mixed. Using denaturing gradient gel electrophoresis (DGGE, a DNA fingerprinting technique), it was determined that a single application of the fungicide to turf either enhanced or inhibited a variety of dominant organisms present in the soil (Sigler and Turco 2003). While in another study using PLFA and CLPP techniques, no effects of fungicides on microbial community composition were observed (Harman *et al.* 2006).

There are few studies describing pesticide effects on soil microbial activity in turfgrass systems. Reductions in microbial degradation of glucose, nitrification, and amylase activity were documented in a turfgrass system subjected to herbicides (Cole and Turgeon 1977). In contrast, application of pesticides did not alter soil microbial activity, measured as hydrolysis of fluorescein diacetate (FDA) (Harman *et al.* 2006).

While pesticides could exert direct biocidal effects on soil microorganisms, they may also alter soil properties such as pH and thus indirectly alter soil microbial community composition and activity. Furthermore, and perhaps most importantly, sorption of pesticides by organic compounds in solid and liquid phases could substantially reduce their bioavailability and subsequent biocidal effects, and this may be an overriding factor in mature turf systems. A comprehensive understanding of abundance, diversity, composition, and activity of soil microbial community in turfgrass rhizosphere would seem to necessitate consideration of the quantity and physical and chemical characteristics of soil organic matter.

Salinity

It is known that salinity-based ion toxicity and osmotic stress limit microbial growth and activity (Low *et al.* 1997; Rietz and Haynes 2003). To conserve potable water, turfgrasses in arid regions are often irrigated with reclaimed municipal wastewater containing elevated salt levels. Absent sufficient leaching, this inevitably leads to salt accumulation, possibly to toxic levels (Miyamoto and Chacon 2006). Irrigating turfgrass with wastewater for 5 years increased soil salinity by 187%, extractable sodium by 200%, sodium absorption ratio by 481%, and soil pH by 0.3 units (Qian and Mecham 2005). Soil electrical conductivity (EC) was as high as 15 dS m⁻¹ years after wastewater irrigation (Miyamoto and Chacon 2006). The abundance, diversity and activity of soil microorganisms, such as ammonia oxidizing bacteria could be reduced in turf irrigated with saline water (Cantera *et al.* 2006). An earlier study showed that bacteria counts were unaffected in a turf irrigated with treated sewage effluent for 3 years (Mancino and Pepper 1992). The different treatments, however, had only a moderate ef-

fect on soil salinity, which may have been below the microbial response threshold.

Soil compaction

Most turfgrass soils are prone to compaction due to heavy foot and machinery traffic (Shearman 2006). But, to our knowledge, no information is available that relates compaction with effects on soil microorganisms. Evidence is limited with other plant systems as well. In forest and arable soils, total soil microbial community biomass and activity were little affected by soil compaction (Vanveen and Kuikman 1990; Jensen *et al.* 1996; Shestak and Busse 2005). In another study with forest soils, however, compaction favored prokaryotes over eukaryotes (Schnurr-Putz *et al.* 2006). More specifically, facultative and anaerobic bacteria, including N₂O-producing denitrifiers, acetate- and lactate-utilizing iron and sulfate reducers, and methanogens, were enhanced by soil compaction. And compaction-related oxygen deficiency caused a reduction in nitrification and increased denitrification in crop and grassland soils (de Neve and Hofman 2000; Yamulki and Jarvis 2002; Batey and Mckenzie 2006). It should also be recognized that compaction might alter the relative availability of NH₄⁺ versus NO₃⁻ for absorption by the turfgrass roots (Pengthamkeerati *et al.* 2006). Such observations are consistent with compaction reducing soil porosity and, importantly, soil aeration.

APPLICATIONS OF SOIL MICROBIAL COMMUNITY

Bioremediation

Turfgrasses have long been recognized for their ability to remediate agricultural, industrial, and urban wastes (Anderson *et al.* 1981a, 1981b; Bradshaw 1987; Beard and Green 1994). Applications of composted municipal and agricultural sewage to turf are common, with cities sometimes marketing their product as a fertilizer. Historically, the turfgrass plant has been given most of the credit for successful remediation (Beard and Green 1994), although the focus is now also being directed at the soil microbial community. A recent study demonstrated that a turfgrass system could remove high amounts of NH₄⁺ from landfill leachate through the coupled processes of nitrification and denitrification (Bowman *et al.* 2002). Following applications of leachate to the turf, nitrifiers apparently oxidized NH₄⁺ to NO₃⁻ and, subsequently, NO₃⁻ was reduced by denitrifiers and lost as gases. The result was that nearly 50% of the N was removed from the leachate.

The soil microbial community in turf can be efficient in degrading toxic compounds. For example, N-nitrosodimethylamine (NDMA), a toxic material often found in wastewater, was degraded faster in landscapes planted with turfgrasses than with trees, and the difference was mainly attributed to soil microbial community function (Yang *et al.* 2005). Similarly, 2,4-dichlorophenoxyacetic acid (2,4-D) was found to be less persistent in turfgrass systems than in landscapes dominated by trees, and its rapid degradation in turf was due to abundant 2,4-D degrading bacteria (Gan *et al.* 2003). Although comprehensive reviews have detailed the enhanced degradation of pesticides in turfgrass systems (Branham *et al.* 1993; Sigler *et al.* 2000), limited information is available on remediation of pollutants in wastewater and runoff.

C and N sequestration

Several studies have addressed the contribution of turfgrass systems to soil C sequestration (Qian and Follett 2002; Bandanayake *et al.* 2003; Millesi *et al.* 2005). Net accumulation of C in an ecosystem represents the difference between net primary production and heterotrophic respiration, so soil microbial activity substantially controls C seques-

tration. Soil heterotrophic respiration varied with turfgrass management practices including fertilization and clipping use (Millesi *et al.* 2005). With the aid of the CENTURY model, it was estimated that clipping return, combined with a high N fertility (150 kg N ha⁻¹ year⁻¹) for 10 to 50 years, would increase soil C sequestration by 11 to 25% and soil N sequestration by 11 to 28% (Qian *et al.* 2003). If fertilization rate were reduced to 75 kg N ha⁻¹ year⁻¹, soil C sequestration would be increased by 11 to 59% and soil N sequestration by 14 to 78%.

Turfgrass systems function as a strong sink for N (Petrovic 1990; Higby and Bell 1999), and the N resource is highly conserved. Fertilized soils had about 1900 kg ha⁻¹ more N than unfertilized soils in the 0-30 cm depth (Higby and Bell 1999). This amount was equivalent to that applied over 10-year period. Soil N retention is thought to be associated with soil microbial community biomass and activity. Nitrogen mineralization and microbial N assimilation in a turf system were tightly coupled such that plant available N (i.e. N mineralization potential) amounted to <2% of total soil N (Shi *et al.* 2006a, 2006b). *In-situ* measurement of soil inorganic N in the soil profile up to 120 cm in old turf (>50 years old) also showed that soil inorganic N was low (<4 mg N kg⁻¹ soil) and similar to an adjacent natural area (Lee *et al.* 2003). Given that N losses from the turfgrass system are controlled through a small but very active pool, it is perhaps not too surprising that turfgrasses sequester N efficiently and in large amounts.

FUTURE RESEARCH

Turfgrass systems are being recognized for enhancing land restoration and for protecting soil, air and water in urban, suburban, and rural communities. A variety of research has examined the ability of turfgrass systems to mitigate environmental pollution and reduce leaching and runoff of pesticides and fertilizers. However, the focus has often been on the turfgrass plant rather than on the broader soil ecology. Based on this review of the literature, it is apparent that our knowledge of turfgrass soil ecology is lagging that of arable soils, grasslands, and forests. There is a need for basic information on soil microbial community in turfgrass systems including, but not limited to C and N cycling processes and the fate of pesticides. A detailed understanding of N fertilization on soil microbial community composition, enzyme activity, and soil microbial activity is central to improving C sequestration and N retention in turfgrass systems. The roles of turfgrass age and species should be examined. With the shortage of fresh water in arid regions, microbial community composition and function in response to water deficit and saline conditions need to be understood to better manage the turfgrass ecosystem.

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