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Turfgrass Benefits and Issues

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Managed turfgrass accounts for an estimated 35,850 km^2 in the USA (Milesi et al., 2005). Turf areas can also be substantial in other developed countries; for example, turf comprises an estimated 6% of the federal land in Austria (Herndl et al., 2009). Turf management is a thriving industry, with professional landscaping services having had an annual growth rate of 15% between 1997 and 2002 in the United States, when 25 million households used professional landscaping services worth $28.9 billion (Des Rosiers et al., 2007). The sheer extent, growth and visibility of managed turf result in conflicting values and concerns for land use and ecosystem impacts, leading to increasing regulations regarding turf use and management (Blanco-Montero et al., 1995; Robbins and Birkenholtz, 2003; Rosen and Horgan, 2005).

Beard and Green (1994) published the first refereed summary of benefits from turfgrasses. Their paper described the ability of turfgrasses to control erosion and dust; recharge groundwater and protect surface water quality; ameliorate urban heating, noise, and glare; reduce noxious pests, allergens and human disease agents; diminish fire hazards; provide a low-cost security measure to discourage criminal activity and provide recreational, aesthetic, and health benefits to humans. A number of these benefits have received additional attention since 1994, and in some cases more benefits have been identified.

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Benefits

Atmospheric

Absorption of Pollutants

Vegetation, including turfgrass, plays an important role in reduction of atmospheric pollutants that are produced by anthropogenic activities. Sufficient vegetation to absorb atmospheric pollutants in urban environments is particularly important because of the high concentration of fossil fuel emissions from vehicles and because of the density of the human population.

The absorption and emission of carbon dioxide are currently of great interest as the global community seeks to understand and mitigate potential causes of climate change due to anthropogenic activities, including land-use change and fossil-fuel combustion (Lal, 2009). Managed turf areas are both a source and a sink for carbon dioxide, methane, nitrous oxide, and nitrogen oxides, as well as for non-greenhouse-gas pollutants. Kaye et al. (2004) measured gas exchange in urban, agricultural, and native grassland environments. Urban lawns composed approximately 6% of the study area, consuming 5% of the atmospheric methane while emitting 30% of the nitrous oxide.

Carbon dioxide flux is often reported in units of micromoles or moles for a given surface area over time because investigators are interested in photosynthesis or respiration, not carbon sequestration. Although these are standard international (SI) units, the actual amount of fixed carbon, which is important for regulatory purposes, is indeterminable by readers unless other information (e.g., pressure, temperature) is given. Su et al. (2007) provided one of the few measurements of actual carbon fixation by turf. Under relatively ideal conditions for C_3 turf growth, gross photosynthesis of tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort] and Kentucky bluegrass (*Poa pratensis* L.) consumed approximately 2000 g m^{-2} of carbon dioxide during a 14-h photoperiod; high-temperature and drought stress reduced the amount by about 50%. Milesi et al. (2005) used satellite imagery and modeling to estimate that the total potential carbon sequestration range of turf in the continental United States ranged from −0.2 Tg yr^{-1} to 16.7 Tg yr^{-1} of carbon depending on management. The CENTURY model has been used to determine that intensively managed golf-course turf can sequester approximately 0.9 Mg ha^{-1} yr^{-1} (Parton et al., 1987; Qian and Follett, 2002). Sequestration was estimated to peak at 23 to 32 Mg ha^{-1} carbon approximately 30 yr after establishment and comprised twice as much soil carbon than native prairie (Bandaranayake et al., 2003). Additional information is needed on the evolution of carbon dioxide from lawn-management equipment and turf respiration to more thoroughly assess the carbon dioxide flux from managed turf systems.

Turfgrasses can absorb various atmospheric pollutants, although the results are not always favorable for turf growth. In a calcareous soil, red fescue (*Festuca rubra* L.) was sensitive to ozone, and plant populations declined while populations of other plants, including some known turf weeds, such as *Plantago lanceolata* L., increased (Thwaites et al., 2006). Exposure to ozone may be toxic to turfgrasses in some instances (Ashenden et al., 1996) but in other situations has little to no significant effect, depending on factors such as the adapted varieties or species, environmental conditions, and time (Dueck et al., 1988; Bender et al., 2006). Some turfgrasses, such as *Agrostis capillaris* L., have adapted to air polluted with ozone, sulfur dioxide, nitrogen dioxide, and ammonia and show a positive growth response to increasing concentrations of these pollutants (Dueck et al., 1988). Perennial ryegrass (*Lolium perenne* L.) biomass was reduced in the presence of 40 μg L^{-1} sulfur dioxide plus nitrogen dioxide while the biomass of *A. capillaris* was only reduced when in the presence of sulfur dioxide plus nitrogen dioxide when misted with water at $pH \leq 3.5$ (Ashenden et al., 1996). Concentrations of nitrogen and sulfur in shoots and roots increased when sulfur dioxide–, nitrogen dioxide–, and ammonia–tolerant *Agrostis* populations were exposed to these gases but not when exposed to ozone or mixtures containing ozone. Other studies show that tremendous variation exists among cultivars within a species for tolerance to air pollution, with certain cultivars of Kentucky bluegrass and red fescue showing good adaptation for areas moderately polluted by ozone, sulfur dioxide, and nitrogen dioxide (Elkiey and Ormond, 1980). The ability of *L. perenne* to develop resistance to atmospheric sulfur dioxide is heritable and controlled by only a few genes; however, the tendency is toward susceptibility (Wilson and Bell, 1990).

Carbon monoxide is an air pollutant produced primarily by automobiles in urban environments, although biomass burning (e.g., leaves) can account for up to 37% of emissions (Khalil and Rasmussen, 1999). Tall fescue, Kentucky bluegrass, St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze], and manilagrass [*Zoysia matrella* (L.) Merr.] all emit and absorb carbon monoxide in both light and dark, although the variability over time was tremendous. Tall fescue was the only grass that appeared likely to effect a net absorption of carbon monoxide, although the results were not statistically significant at $P < 0.05$ (Gladon et al., 1993).

Controlled environmental conditions were used to show that annual ryegrass (given as *Lolium rigidum* there) absorbed only low amounts (~1%) of volatile organic compounds (VOCs) from air and soil (Cho et al., 2008). Transportation of VOCs between the roots and shoots appeared to be inhibited: atmospheric VOCs absorbed by the shoots were not readily transported to the roots, while root absorption of VOCs from the soil did not result in measurable concentrations of VOCs in the shoots. Polyaromatic hydrocarbons related to motor vehicle exhaust were readily absorbed by *L. perenne* along roadsides, with equilibrium attained in shoots after about 15 d at a concentration of approximately 150 ng g^{-1} dry weight (Tankari Dan-Badjo et al., 2007).

While some countries may still add lead to gasoline, even unleaded gasoline can still contain some lead (Singh et al., 1997). Common bermudagrass [*Cynodon dactylon* (L.) Pers.], along with other plant species, can accumulate lead from motor vehicle exhaust. Studies along two roadside pastures in India showed that *C. dactylon* leaves accumulated a peak of approximately 20 μg g^{-1} lead in leaves when the top 5 cm soil had a lead concentration of 45 of 55 μg g^{-1} (Singh et al., 1997). It is unknown if *C. dactylon* absorbed significant amounts of lead directly from air or if it only extracted lead from the polluted soil.

Cooling and Energy

Evapotranspiration (ET) from vegetation can modify local temperatures, reduce energy requirements, and improve human health. Dousset and Gourmelon (2003) documented the urban heat island effect using thermal and multispectral imaging to distinguish summer temperatures among different land uses in Los Angeles and in Paris, France. In Paris, the urban parks Bois de Boulogne and Bois de Vincennes averaged 19°C during the evening, which was comparable with that of rural areas (16°C), whereas downtown Paris temperatures were 21 to 22°C due to lack of ET and heat-trapping by buildings. Afternoon temperatures in downtown Los Angeles were 41.6°C compared with about 32°C at the city outskirts. Inside the city limits, temperatures at the Los Angeles Country Club and Wilshire Country Club averaged 3.8°C cooler than the city temperature. Clarke and Bach (1971) noted that an air temperature of 32.2°C was considered a critical threshold for human survival and provided evidence of a significant increase in deaths during a St. Louis, MO heat wave for every 1°C increase above 32.2°C. Since even temporary exposure to lower temperatures can reduce heat-related deaths, the authors suggested that urban planners provide green spaces in urban areas for residents to use. Oke (1982) explained the amelioration of the urban heat island effect from a thermal energy perspective as a function of evapotranspirational cooling from home lawns. Hardscapes surrounding grassed areas could raise the advective thermal loading to the lawn up to 30%, thereby increasing the ET rate, assuming the availability of sufficient soil moisture from natural sources or irrigation.

The ability of turf to moderate surface temperatures can have other direct human health benefits. Records from the Maricopa Medical Center in the American southwest (Arizona) show that 23 patients were admitted with pavement burns between 1986 and 1992 (Harrington et al., 1995). The critical temperature for pavement burns was 44°C during a 6 h period. Burn potential has an inverse logarithmic dependence on time as temperatures increase: at 48°C, second-degree burns occur in 15 min and within 45 s at 53°C. Harrington et al. (1995) reported that surface temperatures of asphalt and sand peaked at nearly 70°C on 20 June 1992 in Phoenix, AZ, and exceeded 44°C for 11 and 9 h, respectively. Lawn surface temperatures peaked at 49°C for less than 60 min and were normally within 1°C of air temperature. Data compiled from 1917 to 1990 in Athens, Greece, showed mean summer surface temperatures of bare soil averaged 38°C compared with 31°C for irrigated short-grass-covered landscapes (Jacovides et al., 1996). A study in southern Israel showed that a synergistic cooling effect was achieved when trees and turf were combined, compared with turf alone. The air temperature in midafternoon (1400 h) at a height of 1.5 m was 34.3°C for exposed bare ground, 33.8°C for exposed grass, 32.5°C for trees over bare ground, and 32.2°C for trees over turf (Shashua-Bar et al., 2009). Closer to the ground, transpirational cooling from the grass was more effective than from the trees. The cooler temperatures due to trees resulted from blockage of solar radiation because the transpirational cooling effects of trees occurred above, rather than below, the canopy.

The cooling effects of vegetated landscapes can reduce energy usage. Parker (1983) studied the impact of various types of landscaping on energy usage in buildings of the hot, humid climate typical of Miami, FL, and concluded that landscaping could reduce the amount of energy used for air conditioning by 50%. McPherson et al. (1989) used one-quarter-scale models to estimate the energy used for cooling of residences with different types of landscaping in the hot, dry climate of the American Southwest. Both turf and shade reduced the amount of energy used for air conditioning by 20 to 30% between July and October compared with rock-based landscaping. The effects of landscaping type varied during the season. For instance, shade alone reduced energy use 24.3% and turf alone reduced use 19.8% from 25 August to 1 September, while shade reduced energy use 27.5% and turf reduced use by 30.1% from 1 to 8 October.

In Japan, the desire to have vegetation for human comfort in highly urbanized areas has led to research on "green roofs." Onmura et al. (2001) used synthetic fabric through which water was piped as a substrate to develop a lightweight, soilless lawn for rooftops in the hot, humid climate of Osaka. During a 3-wk period in August, the lawn reduced the heat loading of the simulated building by 50%. Neither management of the lawn nor water usage were addressed, both of which would be critical for practical use. Permpituck and Namprakai (2012) compared the cooling effects of various roof surfaces in the hot, humid climate of Thailand. Cooling a building with a bare concrete roof required 594 kWh yr^{-1}. Rooftops with 0.2 m of wet soil required 425 kWh yr^{-1}, while those with 0.2 m wet soil planted to manilagrass [*Zoysia matrella* (L.) Merr.] used 330 kWh and those planted with savannah grass [probably *Axonopus compressus* (Sw.) P. Beauv.] used only 279 kWh, a 53% reduction in energy usage compared with the bare roof.

The utility of grasses and other vegetation for cooling benefits has to be weighed against the use of irrigation water in areas where water scarcity is of concern. Bonan showed that irrigated residential lawns and parks had surface temperatures 2.4 and 3.0°C, respectively, lower than unirrigated native landscapes ($P < 0.05$). Shashua-Bar et al. (2009) showed that a combination of trees over turf in a hot, dry climate provided greater cooling efficiency than turf alone, and reduced water use by the turf more than 50% compared with turf without trees. However, in areas such as Arizona, irrigation for trees and turf can account for 30 to 50% of the total residential water consumption, and many municipalities in the southwestern USA have regulations or financial incentives to limit the amount of residential vegetation (McPherson et al., 1989).

Land Reclamation

Bioremediation

Bioremediation is the process of decontaminating soil or water by means of living organisms. Some plant species, including various grasses used for turf, are capable of growing in polluted soils that quell other types of plant growth. Phytoremediation is a specific type of bioremediation that uses plants to degrade or extract soil contaminants. Phytoremediation may be the most cost-effective option for remediating contaminated sites. While some soils are naturally contaminated (Presser et al., 1994), a growing number are contaminated through human activity and are typically known as brownfields (Yount, 2003). Over 400,000 brownfields exist in the United States (U.S. Conference of Mayors, 2008), and Europe has at least 900,000 (Thornton et al., 2007). Removal (ex situ) of contaminated soils is often prohibitively expensive, ranging from \$30 to \$300 m^{-3} (Watanabe, 1997). In situ clean-up costs may be less expensive, ranging from \$10 to \$100 m^{-3}, while phytoremediation costs can be as low as \$0.05 m^{-3} (Watanabe, 1997). The dense, overlapping root and rhizosphere systems of grasses provide more surface area for reactions than the tap root systems of trees and shrubs (Walton et al., 1994; Toal et al., 2000), which may enhance their ability as phytoremediators. Industry, particularly manufacturing, munitions, processing (e.g., dry cleaners, tanners), and spills or leaks (e.g., radiation from the Chernobyl plant) contaminates many of the soils found in urban environments. Synthetic products, such as batteries, paint, and pesticides, contaminate soils in urban and rural environments. Mine tailings, primarily in rural or natural areas, contain various heavy metals, which adversely affect most plant species.

Phytoremediation, or even biological stabilization, of sites contaminated by mine tailings is difficult due to the diversity and high concentrations of heavy metals and sometimes to the low pH. Heavy-metal contamination is problematic because elements do not decompose. Phytoremediation can reduce heavy-metal contamination problems by conjugating the metals to less toxic forms or by accumulating them in leaf tissues, which can then be harvested and removed for dispersal or metal extraction. Shahandeh and Hossner (2000) concluded that common bermudagrass was a better phytoremediator of chromium than most of the other 35 plant species examined. While its ability to accumulate the metals was relatively low, its tolerance level was high, making it among the most effective choices of the plant species investigated for land reclamation of chromium-contaminated sites. Tall fescue accumulated more zinc in shoots than the U.S. native *Andropogon gerardii* Vitman (big bluestem) and so would facilitate zinc removal from a site, although it would not be desirable if the area was subjected to grazing (Hetrick et al., 1994).

In a greenhouse study, red fescue had 100% seedling survival in unamended gold mine tailings compared with only 31% survival of alfalfa (*Medicago sativa* L.) and 90% survival of *Agropyron trachycaulum* (Link) Malte ex H.F. Lewis (Green and Renault, 2008). The addition of paper-mill sludge enhanced the biomass of all three species. The authors concluded that because of its highly fibrous root system, red fescue provided better erosion control than the other species, and that it had an inherent ability to grow despite low nitrogen and phosphorus. The fine, fibrous root systems of turfgrasses are beneficial because their roots will not likely penetrate subterranean linings used to contain toxic materials. Mine-tailing impoundments are sometimes sealed with fly ash, sewage sludge, or other materials to prevent contamination of water. Root-zone materials to support vegetation can be placed over sealing layers, but it is important that the plant roots not penetrate the sealing layer. Kentucky bluegrass was able to grow in a root-zone layer without penetrating a sealing layer, while the roots of three tree species demonstrated various amounts of penetration, depending on the sludge or ash content of the sealant (Neuschütz et al., 2006). In the United Kingdom, Tordoff et al. (2000) cited literature recognizing that sites contaminated with heavy metals are often naturally vegetated by *Agrostis capillaris* L. and sheep fescue (*Festuca ovina* L.), while *A. stolonifera*, *F. rubra* and *Deschampsia cespitosa* (L.) P. Beauv. grow on sites with alkaline pHs. Selections from such sites have yielded varieties such as 'Merlin' red fescue and 'Goginan' *A. capillaris* for sites contaminated by lead and zinc, and 'Parys' *A. capillaris* for sites contaminated by copper and zinc in Wales. Grass-legume mixtures can be beneficial for mine-site reclamation, because the legumes presumably provide nitrogen for the grasses (Tordoff et al., 2000). Insufficient soil nutrition can prevent the successful establishment of such grasses as tall fescue and their mycorrhizal relationships for reclaiming sites dominated by mine tailings (Hetrick et al., 1994).

In warm climates, common bermudagrass is often suitable for phytoremediation efforts. In Australia, common bermudagrass typically exhibited the greatest emergence rates from seed compared with 12 other grasses, trees, and shrubs across three former mine sites contaminated by copper, zinc, manganese, and arsenic (Grant et al., 2002). Mulching reduced the mortality rate of bermudagrass from 45 to 100% to 0 to 15%. Bermudagrass provided vastly superior ground cover, which was desirable to prevent wind-blown, asbestos-containing dust and sediment from contaminating surface waters. Bermudagrass also had the greatest biomass production on a per plant basis, producing approximately 4.5 Mg ha^{-1}.

Organic compounds, both synthetic and natural, are theoretically more amenable to phytoremediation than heavy metals. Tall fescue was among the grasses growing at a factory with soils contaminated with the explosive 2,4,6-trinitrotoluene (TNT; Krishnan et al., 2000). Seeds of 'Rebel Junior' tall fescue were planted in soils containing a range of TNT concentrations. Tall fescue germination was not as inhibited by TNT as big bluestem and smooth bromegrass (*Bromus inermis* Leyss.). But subsequent growth of tall fescue and smooth bromegrass was more inhibited than that of big bluestem or switchgrass (*Panicum virgatum* L.), with 50% shoot biomass reduction occurring at approximately 100 mg kg^{-1} soil-extractable TNT compared with approximately 250 mg kg^{-1} for the latter two grasses. Other research has identified tall fescue as a beneficial grass to incorporate into riparian areas for phytoremediation of the herbicides atrazine (1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine) and isoxaflutole (5-cyclopropylisoxazol-4-yl 2-mesyl-4-trifluoromethyl phenyl ketone) because of its ability to tolerate and degrade the chemicals (Lin et al., 2004).

Plant-microbe associations are often vital for phytoremediation efforts. In pyrene-contaminated soils, common bermudagrass doubled the pyrene degradation rate from 31 to 62% compared with nonvegetated soil (Thompson et al., 2008). Pyrene degradation, which occurred in the nonvegetated soil, was due to microbial activity. 'Hycrest' crested wheatgrass [*Agropyron desertorum* (Fischer ex Link) Schultes] accelerated the degradation of pentachlorophenol (PCP), a compound used to treat lumber to prevent rot, in contaminated soil with 36% of the PCP absorbed by the plants and 22% mineralized (Ferro et al., 1994). Subsequent research found that microbes in the rhizosphere were responsible for mineralizing the PCP (Miller and Dyer, 2002). While the specific microbes were not identified, experiments indicated that root exudates from the wheatgrass helped recruit PCP-degrading microbes and served as co-metabolites to enhance PCP degradation. Two C_4 grasses, seashore paspalum [*Paspalum vaginatum* S. (Walt.) Kuntze] and Korean velvet grass (*Zoysia tenuifolia* Willd. ex Thiele), were recovered from an oil-contaminated site in Kuwait. Later assays found a number of grass-species-specific and nonspecific microbes in the rhizospheres, with *Pseuodomonas boreopolis* Gray and Thornton 1928 and *Fusarium solani* (Mart.) Sacc. being the most effective hydrocarbon degraders (Yateem et al., 2007). At a former mine site in Poland contaminated with zinc and lead, inoculation of numerous grass species, including *Lolium perenne*, *Festuca ovina*, *F. rubra*, and *Poa pratensis* with arbuscular mycorrhizal fungi increased their initial growth rates (Ryszka and Turnau, 2007). However, over time, the planted turfgrasses were supplanted by other grasses, such as *F. trachyphylla* Tracey, which were also well colonized by mycorrhizal fungi (>90%). Colonization by mycorrhizal fungi was important for the growth of tall fescue in zinc-contaminated soil but had no growth effect in uncontaminated soil (Hetrick et al., 1994). Mycorrhizae can influence plant communities, for example, by enhancing the ability of white clover (*Trifolium repens* L.) to grow better than perennial ryegrass in arsenic-contaminated soils (Dong et al., 2008).

Plant-microbial associations are also important for mineralizing propylene glycol (1,2,-propanediol), a liquid widely used as an antifreeze in motor vehicles and as a deicing agent at airports. Shupack and Anderson (2000) found alfalfa grown in field soils provided superior rates of mineralization of propylene-glycol than Kentucky bluegrass, perennial ryegrass, tall fescue, or bare soil. Autoclaved soil provided the least mineralization, indicating a strong microbial effect.

Enhancing nutritional status of grasses can enhance phytoremediation. For example, nitrogen fertilization enhanced pyrene degradation in soils planted with bermudagrass (Thompson et al., 2008). Hetrick et al. (1994) found that nitrogen fertilization of tall fescue in zinc-contaminated soil significantly enhanced vegetative cover.

Revegetation of Landfills

The vegetation of closed landfills has become an important aspect of land development due to the closure of more than 6000 landfills in the United States alone since 1988 (USEPA, 2008). Closed landfills are sometimes viewed as net economic and social assets, because they are converted to parks, sports fields, or golf courses. Turfgrasses are often the vegetation of choice due to their ability to form dense, contiguous communities that inhibit erosion and have the ability to withstand the potential land shifts and methane emissions produced during decomposition of landfill waste. Converted areas provide green space, recreation, and economic benefits that accrue from methane reclamation for energy (Jacobs, 2000) and improved housing values (Parker, 2002). Approximately 70 U.S. golf courses have been constructed on former landfills or other brownfield-type areas (Gold, 2003). Development of former landfills for sports turf and recreational facilities are another benefit of grassing such sites (Town of Cedarburg, 2009).

Health, Aesthetics, and Recreation

Urban grasslands (i.e., sports fields and lawns in homesites and parks) provide a myriad of health benefits. Combinations of trees and grass foster human activities (e.g., recreation) and are important for children's development (Taylor et al., 1998). Many people favor landscapes with open grassy areas punctuated by trees (Parsons, 1995; Frumkin, 2001). Frumkin (2001) suggested that these settings relate to savannah-type settings under which humans may have evolved. People's preferences for the relative amounts of manicured grass versus tree density depends on a number of factors, including age, parenthood status and children's ages, education, gender, and the environment in which they live (Bixler and Floyd, 1997; Bjerke et al., 2006). In the Raisin River basin of southeast Michigan, long-term residents of rural areas preferred manicured landscapes, whereas new residents were more likely to prefer unmanaged landscapes (Ryan, 1998). Unmanicured vegetated sites provide a sense of tranquility when viewed from a distance yet positively correlate with perceived danger, while open vegetated areas provide tranquility without a perception of danger (Herzog and Chernick, 2000). Other studies cited by Frumkin (2001) indicated that looking at nature scenes increases one's sense of tranquility and may improve mental functioning. Kuo et al. (1998a) reported that spaced tree plantings and maintained grass improved the sense of safety and were preferred by inner-city residents. Surveys indicated the optimal tree density in public parks was about 2.5 trees ha^{-1} (Schroeder and Green, 1985). A follow-up study showed that impoverished inner-city residents experienced less stress and had better social networking than persons further removed from vegetated sites (Kuo et al., 1998b). Urban areas with grass and trees suffered less vandalism, graffiti, and litter than nonvegetated areas (Kuo and Sullivan, 2001). Urban parks, with their mixtures of mowed grass areas, trees, and other features, offer relief from city life. A recent survey of parkgoers in the Netherlands' most popular park, Vondelpark, showed that nearly 75% valued the park for relaxing in large part because of its vegetation (Chiesura, 2004). Memories of playing in the grass are often part of the idealized childhood experience recalled by adults (Sebba, 1991). The type of vegetation being viewed or used (e.g., unmanaged wooded areas, mowed lawns, flowers or shrubs) provides different types of satisfaction and comfort to persons. While all types of vegetation are commonly thought of as "nature" in sociological studies, manicured landscapes, such as "large mowed areas," provided a unique sense of satisfaction with many people (Kaplan, 2001).

Numerous studies have identified a relationship between the mental well-being related to green spaces and physical well-being. Prisoners with windows overlooking green space had 24% fewer sick-call visits than prisoners with windows looking onto a prison courtyard (Moore, 1981). In one survey, 50% of respondents stated that plants at public places enhanced their enjoyment, and nearly 100% of retirement-community residents indicated a desire to be surrounded by landscaped areas (Butterfield and Relf, 1992).

In low-income public areas, the right types of vegetation can act as a crime deterrent (Kuo and Sullivan, 2001). Vegetation relieves the mental fatigue that can lead to violence and encourages persons to interact in positive ways, and types that allow good sightlines (e.g., grass, trees properly spaced) reduce potential hiding spots (Kuo and Sullivan, 2001). Crime tends to be inversely related to the amount of greenery: burglaries, for example, are discouraged by well-maintained lawns and vegetation around buildings (Nassauer, 1988a; Kuo and Sullivan, 2001; Bedimo-Rung et al., 2005).

Mowing a lawn provides the physical activity necessary for improved health. A riding mower provides exercise equivalent to a leisurely stroll, operating a walk-behind power mower is equivalent to a brisk walk, and operating a non-motorized push mower is equivalent to a brisk uphill walk, burning more than 7 kcal min^{-1} (Pate et al., 1995). Mowing a lawn for 30 min once weekly with a non-motorized push mower provides the recommended daily exercise for an 18- to 65-yr-old person (Haskell et al., 2007).

Mowed grasslands are in many cases the areas best suited for recreational and leisure activities. People can readily lay and relax on mowed lawns but not on unmowed prairie or trees (Fig. 3-1). Mowed grasslands facilitate outdoor games related to physical activity, such as soccer, football, and baseball. Stress fracture injuries are more likely to occur if these games are played on paved surfaces rather than on grassed surfaces due to the reduced shock absorption of the harder surface (Coady and Micheli, 1997).

Mowed lawns can have direct health benefits by reducing disease-carrying organisms. During the early 20th century, the United States encouraged cutting of grass and brush as part of a greater, and successful, effort to virtually eradicate malaria (Klempner et al., 2007). Lyme disease–carrying tick populations are relatively well controlled by mowed lawns, because nymphs are subject to desiccation (Hayes and Piesman, 2003). Frank et al. (1998) studied 400 properties in

Figure 3-1. College students relaxing on Bascom Hill lawn, Univ. of Wisconsin–Madison, May 2009.

New York state and found that lawn area was negatively correlated with the tick population and positively correlated with wooded area.

Plant pollens often act as human allergens. Allergies to plant pollen appear to be worse in urban environments than in rural environments, perhaps due to confounding factors such as vehicle exhaust pollutants (D'Amato, 2000). Mowed lawns prevent most grass and weed pollen from being formed since seedheads are cut before maturity is possible. The act of mowing, however, can spread lawn allergens at least in the immediate vicinity, because allergens from fungal spores and soil-bound particles becomes airborne due to disturbance by gas-powered rotary mowers (Comtois et al., 1995). Pollen from some unmowed turfgrasses, such as Kentucky bluegrass and red fescue, was particularly allergenic, whereas pollen of common bermudagrass was substantially less so (van Ree et al., 1998). In some cases allergens from grass sap may cause adverse reactions, such as asthma, following chronic exposure (Subiza et al., 1995). Simply eliminating mowed turfgrasses from urban environments does not appear to be a reasonable solution for reducing allergens, because the diversity of nongrass plants in close conjunction with humans will also produce allergic responses in a proportion of the population (Thompson and Thompson, 2003). Thompson and Thompson theorized that nonnative plants increase the incidence of allergies in human populations in North America; however, since most of the North American human population is recently descended from areas where the nonnative plants originated, this thesis would need specific testing before being accepted. In reality, nonnative plants identified as being allergenic are likely highly allergenic in their home environments, such as common ragweed (*Ambrosia artemisifolia* L.) (Radauer and Breiteneder, 2006). Some researchers have promulgated the idea of "acceptable" species for use in urban environments in an effort to reduce urban allergens

(Lorenzoni-Chiesura et al., 2000). Grass and other plant allergens appear to be confined to a few groups of plant proteins (Radauer and Breiteneder, 2006), some of which are related to expansins, an important group of proteins in lawn grasses that accelerate cell and leaf expansion (Cosgrove et al., 1997). Genetic engineering methods have developed plants with reduced allergenic activity, although these are not currently available for use (Singh et al., 1999).

Property Values

A well-landscaped yard with a good-quality lawn increases residential values and the perception of a business or school. Yee (1990) reported that southern California developers who spent an average of 7% of their construction budget on landscaping were able to quickly lease their buildings, and such buildings were more acceptable in suburban communities. A study of 760 single-family-home sales between 1993 and 2000 in the Quebec (Canada) area showed that age demographics and house type affected the perception of a lawn's value. People aged 45 to 64 preferred properties with more lawn and fewer trees, while the value of smaller homes increased with nontree ground covers, such as lawns and flowerbeds (Des Rosiers et al., 2002). Landscape quality directly affects residential sales prices. Prices increased from 8.9 to 10.4% for homes with good landscaping compared with average or poor landscaping. Excellent landscaping increased home value an additional 4.0 to 4.6% compared with homes with good landscaping in a South Carolina study (Henry, 1994). The variation in the percentage increase depended directly on lot size. Behe et al. (2005) surveyed attendees at home and garden shows in seven states of the eastern and central USA for their perception of landscaping value. Participants were shown 16 photos of a newly constructed, two-story single-family home, with the base photo having only lawn and a driveway and the other 15 photos having various landscape plants digitally added. Participants indicated landscaping that included trees added the greatest value; overall, participants indicated the addition of nonlawn plants increased the home value 5 to 11%. The value of the lawn per se could not be determined because attendees were not shown the home with bare soil or weeds instead of a lawn. Most studies have focused on the effects of trees or overall landscaping quality. The effects of actual lawn quality on property value or perception are not well documented, although unmown lawns are generally deemed to depress values of surrounding properties and municipalities and homeowner associations often have regulations requiring mowing of residential lots (McKenzie, 2005).

Environmental and Social Issues

Water

Consumption

Global concerns regarding the availability of fresh water for humans and the environment are resulting in increased scrutiny of water for all purposes, particularly those perceived as amenities. Turf irrigation is typically considered an amenity use. In the late 2000s, the USEPA developed a voluntary initiative called WaterSense, which was designed to conserve fresh water. The goal was to reduce residential water use by 20%, in part by limiting turf to no more than 40% of the landscapable area of residences (USEPA, 2009b). Such a goal may make sense for arid regions but may result in additional runoff and reduced groundwater recharge if over-utilized in areas with abundant rainfall, particularly if hardscapes replace turf areas. Surveys indicate that residential outdoor water use depends on the location, with an annual mean of over 757 kL home^{-1} in warm arid climates and a low of 29.5 kL in cool humid climates (Fender, 2008). Information on the final use of water for outdoor purposes, such as landscaping, gardening, and vehicle washing, is not well documented.

Plant selection and landscape design are key factors in urban landscape water conservation because ET rates vary by species and cultivars. Qian et al. (1996) ranked the ET rates of four turfgrasses under field conditions in a semi-arid region: 'Mustang' tall fescue (6.8 mm d^{-1}), 'Meyer' zoysiagrass (*Zoysia japonica* Steud., 5.6 mm d^{-1}), 'Prairie' buffalograss [*Buchloe dactyloides* (Nutt.) Engelm., 5.1 mm d^{-1}], and 'Midlawn' hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *transvaalensis* Burtt Davy, 5.0 mm d^{-1}]. Using a controlled environment setting, Ebdon et al. (1998) showed that ET rates varied up to 60% among 61 Kentucky bluegrass cultivars in relation to temperature and vapor pressure deficit, which ranged from 1.13 to 3.16 mm d^{-1} kPa^{-1}. Fernandez and Love (1993) identified low-water use cultivars representing Kentucky bluegrass, red fescue, and hard fescue (*F. ovina* var. *duriuscula* L. Koch) by evaluating cumulative ET rates under conditions of water stress. Although water usage rates for turfgrasses have been extensively reported, far less is known about the actual water use of ornamental plants, especially large trees, and even less about that of other shrubs and species used in mixed landscape designs. There are perhaps 12 major turfgrass species used extensively in urban landscapes, whereas the number of ornamental species may exceed several thousand. It may be this paucity of research on ornamentals and total landscape water use, compared with research that has enabled the precision irrigation of turfgrass, that has led to restrictions on turfgrass or its removal in many water-conservation programs. A study in the dry climate of Colorado showed certain annual bedding plants required less irrigation during the summer than a perennial turf of Kentucky bluegrass when irrigated to maintain maximum quality (Henson et al., 2006); however, simply replacing turfgrasses with other species may not reduce irrigation needs or enhance groundwater recharge. Park et al. (2005) documented that the irrigation requirements for an ornamental mixed-species Florida landscape increased over time and used more water than a St. Augustinegrass turf. In Texas, Pannkuk et al. (2010) showed that crop coefficients for water use were similar among mowed St. Augustinegrass turf, unmowed native prairie grasses [*Schizachyrium scoparium* (Michx.) Nash and *Muhlenbergia capillaries* (Lam.) Trin.], and Shumard red oak (*Quercus shumardii* Buckl.) over a 2-yr period at two locations. A paucity of data exist for determining relative water use by turf compared with other landscape plants, particularly outside of arid climates. Minimizing irrigation can conserve water because at least some turfgrasses display luxury consumption of water, a characteristic that may also extend to some native grasses (Kneebone and Pepper, 1984; Pannkuk et al., 2010). Deficit irrigation, which applies less water than the estimated loss by ET, can provide suitable quality while conserving significant amounts of water and may reduce mowing needs (Fu et al., 2007).

The relative influence of turf management practices on water use is not well documented. The dynamics of ET appear to be complex and have not been well investigated in the past 20 yr. Kneebone et al. (1992) cited numerous projects showing that water use increased with mowing height and frequency. Mowing with dull blades reduced water use 20 to 30% because shoot density and growth decreased, resulting in less leaf surface area. Likewise, the effects of irrigation timing are not well known. Irrigating during periods of low evaporative potential (e.g., night, early morning) is routinely recommended, but data on the actual amount of water conserved using this practice in turf management are not readily available in the refereed literature (LSU AgCenter, 2008; Soldat and Stier, 2011). Fertility and mowing affect water use rates, although the data do not always agree on their effects. In a greenhouse study (Wherley and Sinclair, 2009), low rates of nitrogen (0.3 g m^{-2} wk^{-1}) did not reduce the water use of creeping bentgrass (*Agrostis stolonifera* L.) or hybrid bermudagrass compared with a high nitrogen rate (1.2 g m^{-2} wk^{-1} nitrogen). The ET rates of Kentucky bluegrass and kikuyugrass (*Pennisetum clandestinum* Hochst. ex Chiov) increased with the nitrogen fertilization rate in field studies (Ebdon et al., 1999; Barton et al., 2009). Studies with the older classes of growth retardants yielded mixed results regarding water use, as summarized by Kneebone et al. (1992). McCann and Huang (2007) showed the currently popular growth retardant trinexapac-ethyl [4-(cyclopropylhydroxymethylene)-3,5-dioxo-, ethyl ester] reduced the ET of creeping bentgrass approximately 0.4 mmol m^{-2} s^{-1} 10 d after application during drought and heat stress, yet increased ET by 2 mm at 21 d after application. In nonstress conditions, trinexapac-ethyl did not affect the ET of Kentucky bluegrass, creeping bentgrass, or hybrid bermudagrass (Ervin and Koski, 2001; Wherley and Sinclair, 2009).

Pollution

Sediment and Nutrients

The USEPA has identified runoff from urban areas as an important source of nutrient pollution contributing to the impairment of over 41,000 bodies of surface water (USEPA, 2012a). Sediment and phosphorus are the primary concerns in runoff water pollution, while nitrogen is typically associated with leaching to groundwater. Nitrogen tends to be primarily a groundwater issue because surface-water nitrogen rapidly converts to atmospheric forms of nitrogen and nitrate forms are more stable belowground, where levels can rise above regulatory allowances over time. Concerns about non-point-source pollution within urban bodies of water have caused local and state governments to pursue the regulation of turfgrass management practices and pollutant sources (Rosen and Horgan, 2005).

Despite seemingly favorable conditions (fertilization, irrigation, and disturbed soils) for nutrient loss from turfgrass ecosystems, very little nutrient and sediment runoff has been measured from properly maintained, correctly fertilized turfgrass (Gross et. al., 1990; Miltner et al., 1996; Erickson et. al., 2001, 2005). The thatch-forming capabilities of turfgrass in combination with a permanent and dense plant structure provide a more circuitous, less channelized pathway for water movement, which increases resistance, horizontal spread, and infiltration of surface runoff (Gross et al., 1990; Linde et al., 1995). This effect was demonstrated by Krenitsky et al. (1998), who observed turfgrass sod to be more effective than synthetic erosion-control materials in reducing both runoff and sediment losses through the delay of runoff initiation. Data from turf and other perennial systems indicate that the development of macropores from grass roots and edaphic organisms may improve infiltration rates over time (Linde et al., 1998;

Hamilton and Waddington, 1999). Easton and Petrovic (2004) showed that infiltration rates improved as turfgrass shoot density increased during establishment ($R^2 = 0.62$, $P = 0.004$). In disturbed sites typical of urban development, turf systems may inhibit runoff as well or better than any other anthropogenic ecosystem. Erickson et al. (2001) found no significant differences in runoff water quantity when comparing a native Florida woody perennial landscape to a St. Augustinegrass landscape. Steinke et al. (2007) evaluated mowed Kentucky bluegrass and a nascent prairie planting (2 to 3 yr in age) as buffer strips to mitigate runoff from concrete pavement. Most runoff occurred during winter over frozen ground and was not affected by vegetation type. When runoff occurred during the growing season, runoff volumes were less from Kentucky bluegrass buffers than from the prairie vegetation ($P \leq 0.10$).

Sediment losses from turfed areas are negligible compared with situations in which bare soil is exposed, such as in row-crop agriculture or construction sites. Daniel et al. (1979) found urban construction sites yielded 20 times the amount of sediment compared with agricultural runoff waters. Although simultaneous studies of sediment losses from row-crop agriculture and maintained turf have not been published, data are available on the amounts of both types of soil loss from separate studies. In row-crop agriculture, soil loss has been shown to be on the order of 11 Mg ha^{-1} yr^{-1} (Uri and Lewis, 1999), whereas sediment losses from dense, managed turf have been shown to be on the order of 3.0×10^{-4} to 0.02 Mg ha^{-1} yr^{-1} (Gross et al., 1990; Kauffman and Watschke, 2007). Sediment losses can be much greater as a turf is establishing due to the lack of vegetative cover compared with fully established turf. Sediment losses from buffer strips receiving runoff from concrete pavement declined from 1.7×10^{-2} Mg ha^{-1} yr^{-1} as Kentucky bluegrass was establishing to 3.5×10^{-3} Mg ha^{-1} yr^{-1} in the second year after seeding (Steinke et al., 2008). Burwell et al. (2011) showed that sediment losses from embankments declined from approximately 2 Mg ha^{-1} to less than 0.2 Mg ha^{-1} during the first 70 d of bermudagrass establishment. The establishment rate was unaffected by nitrogen fertilizer, although soluble nitrogen sources contributed to nitrogen loading in the runoff.

Phosphorus in runoff is problematic because it is often the limiting nutrient for algal blooms in surface waters (Carpenter et al., 1998). Phosphorus movement in runoff from turf areas tends to be soluble rather than sediment-bound due to the vegetative cover, which inhibits sediment loss (Steinke et al., 2007; Soldat and Petrovic, 2008). Repeated fertilization of crops and urban landscapes has resulted in progressive increases in soil-test phosphorus (STP). Once the STP rises above the crop phosphorus requirement, no further agronomic benefits are obtained, and the risk of environmental contamination is increased when surface runoff and erosion occur (Sharpley et al., 1994). The rise in STP concentrations appears to be a regional issue affecting states containing, or in close proximity to, bodies of freshwater (Sharpley et al., 1994). The increase in STP has probably come from surface application of organic and inorganic fertilizers in urban ecosystems. A lack of soil inversion can create surface STP levels two to three times higher than those just a few centimeters beneath the surface (Guertal et al., 1991). Since 2000, several U.S. states have restricted phosphorus fertilization of turf based on STP (Rosen and Horgan, 2005; Stier and Soldat, 2011; Miller, 2012; WDNR, 2012; Wisconsin Statutes Database, 2009). However, Soldat et al. (2009) assessed the utility of three commonly used soil phosphorus test procedures and concluded that STP did not accurately predict the phosphorus in forced runoff from seven turf sites in New York state, showing $r^2 = 0.02–0.23$ of STP and phosphorus concentration in runoff. Correlations were strong in samples from unfertilized turf ($r^2 = 0.9$), presumably because the lack of applied fertilizer resulted in less turf cover that allowed phosphorus-carrying sediment into the runoff.

Fertilizer can in some cases contribute to phosphorus in runoff depending on the phosphorus carrier, amount of phosphorus, time between applications, and amount of precipitation or irrigation (Soldat and Petrovic, 2008; Bierman et al., 2010). However, Gross et al. (1990) found no significant differences in total phosphorus in runoff between granular versus liquid fertilizer or between fertilized versus unfertilized turfgrass. Bierman et al. (2010) found that unfertilized Kentucky bluegrass turf had larger phosphorus losses (1.7×10^{-4} Mg ha^{-1} yr^{-1}) than fertilized turf in one of 3 yr (approximately 4.0×10^{-5} Mg ha^{-1} yr^{-1}) and attributed the difference to a reduction in turf cover caused by the lack of nutrition. Easton and Petrovic (2004) demonstrated larger phosphorus and nitrogen runoff losses from unfertilized control plots of Kentucky bluegrass and perennial ryegrass (post establishment) than plots receiving organic or synthetic organic complete fertilizers.

Replacement of turf with other vegetation may not necessarily reduce the phosphorus in urban runoff. Erickson et al. (2005) evaluated phosphorus losses from a perennial landscape using plants native to the Florida environment and a St. Augustinegrass turf. While runoff losses were negligible due to the high percolation rates of the sandy soil, phosphorus losses in the leachate were greater in the native plant landscape, due to a less extensive root system, than in the turf. Steinke et al. (2007) showed that phosphorus loading in runoff was similar in prairie vegetation and mowed Kentucky bluegrass used as buffer strips, approximately 0.002 Mg ha^{-1} yr^{-1}. Replacing turf with trees may not necessarily decrease phosphorus in urban runoff due to phosphorus leaching from leaves onto pavement. Waschbusch et al. (1999) revealed a linear relationship between both total and soluble phosphorus from streets and the percentage of tree canopy. These data suggest that even a moderate tree canopy (<35%) may serve as a potential primary source of phosphorus within urban watersheds, especially when channeled to surface waters via impervious surfaces and storm sewers (Bannerman et al., 1993).

Petrovic (1990) published a compilation of data regarding the fate of nitrogen fertilizers applied to turfgrass. The nitrogen concentrations in groundwater below turf and urban surfaces tended to be substantially below those in agricultural fields and were usually below drinking water standards (Petrovic and Easton, 2005). Additional information has been generated, and it is largely in agreement with Petrovic's reviews. Nitrogen from turf is most likely to occur in leachate during establishment, when turf roots and plant density are sparse and unable to absorb the nitrogen, or when soils are sandy or excessive irrigation or precipitation occurs. Soil disturbance itself releases a fair amount of nitrogen although nitrate leaching declines as the vegetation develops. Steinke et al. (2009) reported nitrate nitrogen concentrations of approximately 35 mg L^{-1} in leachate from a silt loam soil during the spring following tillage and planting of prairie and turfgrasses the previous fall, but concentrations declined to below 5 mg L^{-1} by summer. Geron et al. (1993) reported that nitrate levels in percolate from a silt loam soil averaged as high as 31.7 mg L^{-1} in the autumn following spring seeding and that concentrations declined to below 2 mg L^{-1} the following year. In fully established turf, relatively little nitrogen leaches from silt or clay soils due to slower percolation, so there is more time for the nitrogen to interact with the soil ecosystem, where it is absorbed by microbes or plant roots or converted to gaseous forms through denitrification (Young and Briggs, 2007). Miltner et al. (1996) used ^{15}N-labeled urea fertilizer to determine the nitrogen rate in a 6-yr-old Kentucky bluegrass turf growing in a fine sandy loam. Monolith lysimeters were installed in such a way that soil was not disturbed. During a 2-yr period, only 0.23% of the labeled nitrogen was recovered in leachate, with the majority recovered in clippings or remaining in thatch and smaller amounts in verdure and soil. A large-scale urban watershed study of the peri-urban Baltimore area indicated that urban environments, for example, lawns, were “surprisingly” good at retaining nitrogen (Groffman et al., 2004). Turfgrasses with greater root biomass or deeper root systems reduce nitrate leaching better than shorter-rooted types (Bowman et al., 1998). Nitrogen leaching in sand-based root zones, such as those used for putting greens and athletic fields, can be reduced by employing a layer of crumb rubber under the root zone. Lisi et al. (2004) showed that crumb-rubber layers of 5 and 10 cm reduced the total nitrate nitrogen in leachate from a sand-based putting green by 18 and 22% during a 33-d period.

Slow-release nitrogen sources are less likely to allow nitrogen leaching than water-soluble sources in rapidly draining soils (e.g., sand) subject to high precipitation or reduced plant uptake rates. In nonsandy soils, however, water-soluble nitrogen sources do not necessarily result in more leaching than slow-release sources or unfertilized situations. During a 2-yr establishment and postestablishment study, Geron et al. (1993) found that nitrate nitrogen from urea fertilizer was significantly greater than from a slow-release source (3.7 vs. 2.1 mg L^{-1} nitrogen) only during one winter period, when turfgrass growth was restricted, while all other quarterly periods and annual amounts had similar amounts. In years of normal or below-normal precipitation, Petrovic (2004) reported similar nitrogen leachate concentrations on a sandy soil for water-soluble and slow-release carriers, ranging from 0.9 to 5% of applied nitrogen from water-soluble sources and from 0.5 to 7.4% from slow-release sources. During an above-normal precipitation year, losses from water-soluble forms ranged from 12 to 29% of applied nitrogen compared with 2 to 7% from slow-release forms.

As a turf ages, excessive nitrogen fertilization can overwhelm the ability of the turf ecosystem (including microbes and soil) to immobilize the element, and increasing amounts of nitrate can occur in leachates. When 10-yr-old Kentucky bluegrass turf was fertilized with 245 kg ha^{-1} yr^{-1} nitrogen from urea, the concentrations of nitrate-nitrogen in the leachate were frequently greater than 20 mg L^{-1} (Frank et al., 2006). Annual nitrogen application rates of 98 kg ha^{-1} yr^{-1} consistently produced nitrate-nitrogen values below 10 mg L^{-1}, which is the USEPA notification limit for drinking water (USEPA, 2011). Nitrate leaching is also more likely to occur when fertilization corresponds to periods of low or inactive growth and nutrient uptake such as late autumn. Lloyd et al. (2011) used a controlled environment to evaluate ^{15}N-labeled uptake of ammonium sulfate fertilizer by turfgrasses under various simulated climatic periods. Nitrogen uptake increased linearly with the rate for creeping bentgrass, Kentucky bluegrass, and annual bluegrass until cooler conditions typical of late autumn set in, at which point nitrogen uptake plateaued at approximately 40 kg ha^{-1}. Based on a field study comparing nitrogen leachate of fall-applied nitrogen to a cool-season turfgrass mixture, Mangiafico and Guillard (2006) suggested that the cosmetic benefits of fall-applied nitrogen may be unfavorable for maintaining groundwater quality.

Pesticides

The ability of pesticides to sorb to organic matter (i.e., the organic carbon partition coefficient, K_{OC}) is inversely proportional to their ability to move in runoff and groundwater percolate, absent any particulate movement such as with soil and grass clippings (Rice et al., 2010). Most of the time pesticide movement is minimal. Carroll (2008) showed that turfgrass thatch bound much of the applied pesticide that was not absorbed into the turf plant, with absorption correlated to the K_{OC}, which ranged from approximately 0.2 to over 0.8 (Carroll, 2008). A review of 44 studies involving 80 golf courses during a 20-yr period showed that of 161 pesticides and their metabolites, toxicity reference points were exceeded 0.15 and 0.56% of the time, respectively, based on 38,827 analyses (Baris et al., 2010). None of the studies concluded that pesticides caused widespread biological or human health concerns. King and Balogh (2006) summarized the results of 14 field studies published between 1989 and 2004. Turf pesticides in surface waters, such as golf course ponds and turf runoff, usually had concentrations less than 1 $\mu g\ L^{-1}$. Greater amounts were found with water-soluble products in worst-case scenarios, such as excessive irrigation immediately following application. Pesticide movement is most likely if sufficient irrigation or precipitation occurs immediately after application, with the greatest losses occurring from the first major runoff or leaching event (King and Balogh, 2006). Cole et al. (1997) used a portable rainfall simulator to instigate runoff from bermudagrass turf within 24 h of pesticide application. Up to 15% of applied 2,4-D was captured in runoff, with the highest concentrations ranging from 174 to 314 $\mu g\ L^{-1}$.

Watershed-scale studies indicate that urban pesticides are readily found in surface, and to a lesser degree, in groundwater (Blanchoud et al., 2007; Gilliom, 2007). While small-plot and sub-watershed-scale studies have generally determined turf pesticide movement to be minimal, their residues at the watershed-scale remain an issue. Most pesticides used in turf management are also applied to agricultural settings. Since most studies indicate that pesticide runoff from turf is relatively minor, the interconnectedness of impervious surfaces to surface waters in the urban environment is probably an important contributor of pesticides in water pollution. Blanchoud et al. (2007) studied pesticide contamination of the Marne watershed in France and found that pesticide contributions were nearly equivalent between urban and agricultural areas, although agricultural sites had nearly 100 times the amount of active ingredients applied. Various models have been developed to estimate the movement of pesticides in runoff and groundwater following application to lawns (Haith et al., 2008; USEPA, 2012b). Pesticides are typically more likely to occur in runoff when they are inadvertently applied to pavement rather than to turf. Stier et al. (2005) applied granular formulations of pendimethalin (3,4-dimethyl-2,6-dinitro-*N*-pentan-3-yl-aniline) and prodiamine (5-dipropylamino-α, α, α-trifluoro-4,6-dinitro-o-toluidine) herbicides to turf with a 6% slope and paved areas followed by irrigation (1.25 cm) 24 h after herbicide application. The greatest losses were observed during the first runoff event. During a 28-d period after application, the pesticide amounts in runoff from the paved area totaled 1.0×10^{-3} % of the pesticide applied compared

Figure 3-2. Impervious surfaces collect and channel runoff from irrigation or precipitation to storm drains and surface waters, Madison, WI, 2007.

with 5.1×10^{-8} % from turf applications (198 vs. 8.7×10^{-3} μg m^{-2}). Dry (granular) formulations of pesticides are much more likely to wash off from concrete surfaces than are liquid forms, much of which is retained in micropores (Jiang et al., 2010). Atmospheric deposition of pesticides transported from agricultural or other uses may also result in inequitable amounts of pesticide residues in urban surface waters due to the concentrating and funneling effect of runoff caused by pavement and hardscapes (Arnold and Gibbons, 1996; Brun et al., 2008; Fig. 3-2).

Pesticide Perception, Exposure, and Risk

Public concerns about pesticides have remained relatively high since public awareness began to increase following the publication of *Silent Spring* in 1962. Technological advances have increased society's ability to identify compounds at extremely low levels that are often, if not mostly, below any measurable consequence to humans or the environment (Kamrin, 2003). Pesticides pose the greatest risk to those closely involved with their handling, whereas the majority of public exposure is insufficient to elicit a response (Kamrin, 2003). Even so, reports of low levels of pesticides in households following lawn application cause concern and are exacerbated by human and pet movement from lawn and house. A case study of six dogs and homes found diazinon {*O*,*O*-diethyl *O*-[4-methyl-6(propan-2-yl) pyrimidin-2-yl] phosphorothioate} residues of 88 ng cm^{-2} on paws 1 d following application of a granular formulation (5% a.i.) to the lawns by the homeowners (Morgan et al., 2008). Urine samples of the diazinon metabolite

2-isopropyl-4-methyl-6-hydroxypyrimidine in children and adults showed no significant change pre- and post-application (<0.3–5.5 ng mL^{-1} versus <0.3–12.5 ng mL^{-1}; $p > 0.05$) even though children and dogs played outside in the yard 1 to 6 h d^{-1} each day following application. Nishioka et al. (2001) found that 2,4-D herbicide residues inside 11 houses rose from undetectable to as high as 228 μg m^{-2} following application to the lawns. The authors concluded the majority was brought into the home by children and dogs, and substantial reductions could be attained by not wearing shoes in the home.

Fears of pesticides causing cancer remain high, with some pesticides identified as known or probable carcinogens while others are not. The herbicide 2,4-D is one of the most commonly used lawn herbicides in the USA. It is often perceived as a carcinogen, and various groups have at times sought a ban on its use (USEPA, 2012c). The USEPA, charged with overseeing the responsible use of pesticides, has reviewed hundreds of studies in the past several decades, each time determining there are no indications of 2,4-D being classifiable as a human carcinogen (USEPA, 2005).

Tests on human exposure to pesticides are sometimes used to estimate risk. Harris and Solomon (1992) calculated the dermal exposure of persons working or laying on turf, sometimes in shorts and tee shirts, within 1 and 24 h after 2,4-D was applied. Following a liquid application to turf, 8% of the 2,4-D was dislodgeable, and only 1% after 24 h. Ten adults, some wearing only shorts, tee shirts, and no shoes, walked, sat, or lay on the turf for 1 h at 1 and 24 h after treatment. No 2,4-D was detected in urine of persons contacting turf 24 h after treatment, and only minimal amounts were detected in persons contacting the turf at 1 h after treatment. Such exposure studies form the basis for label requirements for persons and pets to stay off turf for certain time periods following application. Murphy and Haith (2007) used models to estimate the long-term health risks from inhalation of turf pesticides by daily golfers in the northeastern USA. Using information such as pesticide application rates, pesticide properties, atmospheric data, reference dosages, and carcinogenicity, the authors concluded that the long-term health risks from 15 types of pesticides possibly used on golf courses was inconsequential. Hazard quotients for potential carcinogenicity ranged from 1.1×10^{-12} to 2.4×10^{-8}, well below the acceptable level of 10^{-6}. The cutoff for chronic, noncarcinogenic health risks is 1.0; calculated risks for the pesticides ranged from 6.4×10^{-8} to 3.6×10^{-3}.

However, even low levels of pesticides may affect other organisms in our environment, and there is a paucity of knowledge in this area (Berrill et al., 1993). Fears of pesticide impacts on human health and the environment have led to calls for their reduction or elimination for use on turf (Robbins et al., 2001; Robbins and Sharp, 2003; USEPA, 2012c). Public policies increasingly appear to be based on politics as influenced by advocacy groups, resulting in divergent outcomes depending on the public venue rather than being based on logical, science-based decisions (Pralle, 2006).

Mowing

Fossil-Fuel Use

Fuel Demand and Economics

Fuel usage data for turf mowing is not readily available. Instead, such data must be gleaned from a broader dataset of fuel estimates from both on- and off-road populations. In the United States, on-road fuel use was approximately 150 billion gallons in 1997 (Davis and Truett, 2004). On-road fuel usage for transporting mowing equipment by commercial operators between turf sites is unknown. Off-road fuel use was approximately 11% of that used on-road, or 17 billion gallons. In 2001, nearly 60% of the off-road fuel usage was diesel; consequently about 5.5 billion gallons of gasoline were used off-road, nearly all for personal and recreational or industrial and commercial vehicles. An estimated 3 billion gallons of gasoline was used in the United States during 2001 by lawn mowers (1.7 billion), commercial turf equipment (1 billion), and lawn and garden tractors (0.3 billion; Davis and Truett, 2004). The number of turf-related vehicles that could presumably use gasoline in the United States during 2001 was approximately 38 million lawn mowers, 13 million lawn and garden tractors, and 178,000 golf cars. Most residential lawn mower engines are gasoline powered (Davis and Truett, 2004). Davis and Truett (2004) point out that all gasoline sold for off-road, non-public use is inappropriately taxed as if it was to be used for on-highway use.

Air Pollution

The burning of fossil fuels in lawn maintenance equipment produces a number of pollutants that may have adverse human or environmental impacts. An Australian study estimated lawn mowers contributed approximately 5% of carbon monoxide and 12% of nonmethane hydrocarbons (Priest et al., 2000). Two-stroke engines, which are used primarily on hand-held equipment, burn a mixture of oil and gasoline. While two-stroke engines produce more smoke than four-stroke engines (most lawn mowers), pollutant emissions are relatively similar for the two engine types, except that two-stroke engines can emit more of certain polyaromatic hydrocarbons (Volckens et al., 2008). Two-stroke engines emit approximately 1560 g kW-hr^{-1} of pollutants, approximately 55% as carbon dioxide, 34% as carbon monoxide, 11% as hydrocarbons, and 0.2% as particulates (Volckens et al., 2008). Four-stroke engines produce 1000 to 1500 g kW-hr^{-1} carbon dioxide , 280 to 600 g kW-hr^{-1} carbon monoxide, 14 to 30 g kW-hr^{-1} hydrocarbons, and 2 to 4 g kW-h^{-1} nitrogen oxides, depending on the engine age and model and load conditions (e.g., wet versus dry grass; Gabele, 1997). The USEPA estimates that approximately 8.9 Mg of ozone-forming VOCs are emitted for every 1000 gasoline-powered lawn mowers each year (USEPA, 2009a). Hydrocarbon emissions from 1 h of a lawn mower's operation is equivalent to that from a car driven for 320 km (USEPA, 2009a) partially because lawn mowers do not have the air-pollution-prevention equipment mandated for automobiles. Newer engines, coupled with different fuels and catalysts, can significantly reduce emissions, although certain pollutants, such as nitric oxide, can be increased by reformulated gasoline (Gabele, 1997; Christensen et al., 2001). Corded electric mowers have lower negative environmental impacts than battery or gasoline-powered mowers; corded electric mowers do not emit the carbon monoxide, hydrocarbons, nitrogen oxides, and carbon dioxide that gasoline mowers do and do not emit the lead that battery-powered mowers do (Sivaraman and Lindner, 2004). Solar-powered mowers, which use no fossil fuels, have been developed but are not commonly used (Paytas, 1991). Nonmotorized reel mowers offer the simplest option for low- or no-emission mowers.

Safety

Estimates of injuries from lawn mower accidents each year in the United States alone range from approximately 20,000 to 100,000 (Smith, 1988; Letton and Chwals, 1994). Most mower injuries are due to contact with the blades of powered rotary mowers, causing severe trauma and sometimes resulting in amputations (Letton and Chwals, 1994; Chopra et al., 2000). Other injuries occur when objects are flung from rotary mowers and injure others in the area, particularly children playing in the yard (Letton and Chwals, 1994). Burns, and occasional deaths, occur occasionally during fueling or other maintenance and storage operations (Still et al., 2000). Riding mowers are associated with more of the severe injuries than walk-behind mowers (Vosburgh et al., 1995). In Canada, 354 patients required hospital treatment for mower-related injuries between 1990 and 1995 (Chopra et al., 2000). Sixty percent of the patients were 19 years old or younger. No fatalities occurred, although 12% of the injuries involved amputations, and lacerations accounted for about half of all injuries. Burns and fractures accounted for most of the other mower-related injuries. In the United States, an estimated 75 deaths occur annually due to mowing-related accidents (Smith, 1988).

Many of these injuries are preventable. Recommendations include mowing when others are not nearby (Chopra et al., 2000), not having children ride double on mowers (Chopra et al., 2000), installing engine cut-off switches on mowers (Still et al., 2000), keeping guards in place, and generally following mower manufacturer directions for safe operation. The potential for automated mowers, which do not require a hands-on operator, may further decrease injury potential (Nelson, 1999). Automated mowers powered by photovoltaic or hydrogen fuel cells offer the additional benefits of reduced air pollutant emissions and no reliance on fossil fuel supplies (Colen, 1995; Colella et al., 2005).

Land Use

Alternative and Edible Landscapes

Feagan and Ripmeester (1999) surveyed homeowners in suburban Canada to determine their perceptions about the evolution and continued use of manicured lawns. The authors discussed the historic development of a lawn as an entity of elitism possessed by wealthy landowners before the mid-19th century. Urban parks were developed in the latter part of the 19th century from a desire to provide naturalistic yet manicured settings for city dwellers. As Western society flourished in the 20th century, particularly after WWII, a manicured lawn became associated with success and orderliness. The authors concluded that manicured turf has now become an ingrained aspect of North American civilization. In a study designed to inform officials about the design, construction, and management of roadways, a survey showed that motorists preferred mowed landscapes as opposed to unmowed landscapes (Nassauer and Larson, 2004). However, mowed lawns are not always viewed as desirable. Jackson (2003) discussed the importance of green space in urban environments but made a special point that lawns are overrepresented at a "staggering cost in terms of water, energy, toxic exposures, and wildlife habitat." Options to mowed turf in urban environments include paved or otherwise developed areas, bodies of water, urban forest, unmanaged vegetation or soil, food or ornamental gardens, or other planted vegetation, most or all of which requires some degree of management. While high-rise and multiple-unit dwellings are undoubtedly a more efficient use of space than single-family homes, research finds that single-family homes promote better individual and social health, leading to less juvenile delinquency (Gillis, 1974; Wells, 2000). Health benefits accrue with single-family homes, as Wells (2000) reported previous research that found less respiratory illness among children living in homes surrounded by individual (British) "gardens" compared with children living in multiunit dwellings. However, as agricultural land areas in developed countries have diminished in relation to urban areas, with concomitant concerns about the environmental impact of managed lawn areas, the appropriateness of land use for turf has been increasingly questioned (Howe, 2002; Robbins and Birkenholtz, 2003; Domene et al., 2005; Ghosh et al., 2008).

Several alternatives to the traditional mowed lawn have been suggested, for rationales ranging from a desire to have more natural settings to maximizing food production for sustainable societies, but there remain reasons for maintaining the traditional mowed lawns in place of alternative landscaping or use, including a desire to have manicured vegetation congruent with the neighborhood culture. Homeowner surveys by Nassauer (1988a, 1988b), primarily in rural and semirural communities, showed that people favored well-maintained landscapes over less-maintained landscapes. In one Canadian study, less than 2% of nearly 20,000 single-family homes were defined as "alternative landscapes," that is, less than 20% mowed turf (Henderson et al., 1998). The alternative landscapes were most commonly found in the older sections of a city, where the absence of modern building codes led to a diversity of housing structures and small lots with little distance between buildings or road setbacks. Nonnative ornamental plants were the preferred vegetation in the alternative landscapes. The use of nonnative ornamental plants is increasingly at odds with local and federal regulations in the United States that seek to eliminate invasive plant species, which include many ornamental plants, and economic stress combined with the public acceptance of unmanaged sites pressure property owners, including businesses and municipalities, to reduce management inputs (Grant, 1997).

Alternative landscapes are sometimes touted for their putative ability to reduce urban runoff and enhance groundwater recharge, but such outcomes are not necessarily certain. Erickson et al. (2001) showed that a mowed and fertilized St. Augustinegrass lawn had similarly low runoff as an alternative landscape of trees, shrubs, and mulch. While both landscapes yielded relatively similar amounts of percolate, the alternative landscape resulted in 10 times more nitrogen leachate than the St. Augustinegrass turf due to differences in the root systems between the plantings. Steinke et al. (2007) showed that managed Kentucky bluegrass turf was as effective a buffer for runoff from paved surfaces as a planting of native prairie and yielded no more nutrient or sediment pollution despite fertilization. Kentucky bluegrass turf had similar water infiltration capacity and nitrate levels as the prairie plantings (Steinke et al., 2009). Enhanced use of alternative landscapes instead of mowed turf may in the future be driven by a lack of irrigation water in areas where irrigation is necessary to maintain turf (Postel, 2000). Erickson et al. (2001) found that landscapes of trees, shrubs, and mulch required 10% less irrigation than mowed St. Augustinegrass turf.

Concerns about sustainability, which are driven in part by broader concerns about population growth, urban sprawl, and transportation costs for food, are prompting more urban planners and social scientists to encourage urban food production (Martin and Marsden, 1999; Brown and Jameton, 2000; Howe, 2002; Ghosh et al., 2008). The conversion of both single-family and public turf spaces may be considered for local food production (Langdon, 2009). Books such as *Food Not Lawns: How to Turn Your Yard into a Garden and Your Neighborhood into a Community* are published for the general public (Flores, 2006). Ghosh et al. (2008) estimated that local food production could reduce fossil fuel emissions from food transportation by 96%. A designed community in northern California incorporated "edible landscapes," often in shared spaces, allowing residents to grow about 25% of their fruit and vegetable needs (Francis, 2002). Brown and Jameton (2000) reported estimates that a 100-m^2 plot could produce a household's annual vegetable needs during a 130-d growing season. Other researchers indicate that 240 m^2 would be needed, leading to the conclusion that low-density neighborhoods surrounding high-density neighborhoods could allow more sustainable communities (Ghosh et al., 2008). "Edible landscaping" is a concept that incorporates food-producing plants into an ornamental landscape. Beck et al. (2001) compared "emergy" (energy used to develop a product or service) values of a conventional lawn-based landscape, an edible landscape, an organic garden, and a forest garden. The conventional lawn-based landscape had the lowest labor input (39 h yr^{-1}), almost three times less than required for the organic garden. All systems had extremely low emergy values for sustainability. In addition, the soil loss was greatest from the organic garden and edible landscape plots. In some cases, unfavorable soil conditions (e.g., pollutants) impair or preclude the utility of urban soils for food production (DeKimpe and Morel, 2000). Areas with contaminated soils may benefit from phytoremediation by grasses, which may perhaps double as biofuel sources.

A broader social realization of solving urban stormwater issues and providing human-to-nature contact in suburban environments while limiting sprawl has led to the idea of conservation subdivisions. Conservation subdivisions seek to preserve land and provide interconnected greenways utilizing areas including farm fields, steep slopes, and floodplains (Arendt, 2004; Carter 2009). As much as 40 to 70% of the buildable land may be preserved in conservation subdivisions (Arendt, 2004). Lawns and homes would be kept to those areas with the least significant resources, minimizing home sites to 50% of the potential building sites. While conservation subdivisions may reduce stormwater pollution issues and enhance wildlife activity (Carter, 2009), other goals, such as preserving natural features, are not necessarily achieved (Taylor et al., 2007).

Urban Habitat for Wildlife

Urbanization results in the loss of large, contiguous areas of wildlife habitat. As the areas mature, however, some generalist species adapt to urban and suburban environments due in large part to "fringe" areas of diverse, unmanaged vegetation (Adams, 1994). Mowed lawns surrounding buildings generally do not provide a desirable habitat for most wildlife due to lack of cover and diversity in plant species, surface roughness, and moisture. Mowing can reduce arthropod populations by destroying eggs and larvae of both pests and nonpests (Williamson and Potter, 1997; Johst et al., 2006). Some researchers have termed mowed lawns an "ecological disaster" and encourage urban planners and homeowners to discourage lawns on public property and minimize lawn use on private property (Marzluff and Ewing, 2001). While discouraging most wildlife, mowed landscapes can have desirable effects for building owners and occupants, because wildlife is less likely to invade living space. Human health effects may accrue due to fewer human pathogens and pests, for example, ticks (Frank et al., 1998; Hayes and Piesman, 2003). Some animal species are not deterred by the relatively monocultured surfaces of lawns. The Canada goose is one species that is an increasingly frequent inhabitant of mowed turfs (Conover and Chasko, 1985). Problems from their presence include large deposits of feces, which pollute water with phosphorus and potentially carry human pathogens such as *Escherichia coli* (Kullas et al., 2002). A high density of geese reduces groundcover (Conover, 1991), which could increase runoff and surface-water pollution. Management of Canada geese may depend on biological principles, because they favor grasses with lower ash and fiber content, such as Kentucky bluegrass, and not grasses with tougher leaves, such as tall fescue or nongrass plants (Conover, 1991).

Some urban and suburban residents are interested in the development of more wildlife-friendly neighborhoods. Public focus on inner-city renewal includes restoring habitat for wildlife rather than managed turf areas (Callander and Power, 1992). Benefits of "conservation subdivisions," which provide linked green spaces for wildlife habitat, include positive wildlife–human interactions, increased home values, reduced construction costs, and faster resell time (Thompson, 2004; Mohamed, 2006). Mahan and O'Connell (2005) reported that mowed park areas housed only one or two species of small mammals compared with four species in forested areas. A key component of wildlife-friendly neighborhoods is a reduction in the amount of turf area, which is instead relegated to trees, brush piles, and other unmanaged vegetation (Adams, 1994). Wildlife corridors that connect nonturf wildlife habitat are being increasingly promulgated for wildlife preservation (Marzluff and Ewing, 2001; Evans, 2007). Increased use of wildlife-containing areas in urban environments will probably increase negative human–wildlife interactions, which include wildlife digging in lawns and serving as potential disease vectors (FitzGibbon and Jones, 2006).

Invasive Species

An emerging issue with unmanaged areas involves new and pending regulations developed to thwart the ingress of invasive plant and animal species. The issue has become politically important because the costs associated with invasive species damage and control exceeded $300 billion annually in the United States alone (Pimentel et al., 2001). In 2009, the state of Massachusetts banned more than 130 plant species (MDAR, 2012). The state of Wisconsin has developed a tiered system for classifying plants and animals for their invasive potential and impact, with some turfgrasses still awaiting final classification (WDNR, 2009). Mowing has been used to control a number of invasive plants, including woody species such as *Lespedeza cuneata* (Dum. Cours.) G. Don., grasses such as *Arrhenatherum* spp., and numerous other unwanted plants (DiTomaso, 2000; Wilson and Clark, 2001; Brandon et al., 2004), but mowing is less relevant if turfgrasses are considered as invasive.

Many state and national organizations list some or virtually all grasses used for turf as invasive, including Kentucky bluegrass, tall fescue, several fine fescues (*Festuca* spp.), several bentgrasses (*Agrostis* spp.), bermudagrass, and seashore paspalum (Bureau of Invasive Plant Management, 2003; U.S. Natl. Park Serv. and Univ. of Georgia, 2009; Univ. of Georgia, 2009; WDNR, 2009; USDA-NRCS, 2010). Most of the turfgrasses used in much of the developed areas of the world have origins in another country or continent. Bermudagrass has African and Middle Eastern origins (Taliaferro, 2003) while bahiagrass (*Paspalum notatum* Flüggé) is native to South America (Burton, 1967). Seashore paspalum's origin is typically given as South America, but genetic analysis suggests a South African origin (Tischler et al., 1990; Chen et al., 2005). Zoysiagrass is native to Southeast Asia (Qian et al., 2000), perennial ryegrass is native to the British Isles (Balfourier et al., 2000), and tall fescue is native to Eurasia and the Mediterranean region (Meyer and Watkins, 2003). Kentucky bluegrass probably originated in Eurasia yet uncertainty exists, and the USDA-NRCS (2009) lists it as both introduced and native to the United States (Soreng, 1990; Huff, 2003). Wipff (2002) suggested that the hybridization ability of Kentucky bluegrass, combined with the disappearance of its progenitor species, may not enable its origins to be accurately identified. Before 2012, all of the commonly used fine fescue species—hard [*Festuca trachyphylla* (Hackel) Krajina], red, sheep, and Chewings [*F. rubra* (L.) ssp. *fallax* (Thuill.) Nyman]—could be found on various U.S. invasive species lists, although red fescue, sheep fescue, and possibly others may be native to the continental United States (Ruemmele et al., 1995; USDA-NRCS, 2012). Red fescue and hard fescue still remain on at least one list supported by groups such as the U.S. Park Service, the U.S. Forest Service, and the University of Georgia. In fact, with most turfgrasses, the high degree of complexity, genetic relatedness, and hybridization within genera complicate attempts to truly identify one species as native but not another (Ruemmele et al., 1995; Gillespie and Soreng, 2005; Casler, 2006).

Levine (2000) documented the occurrence of creeping bentgrass in sedge (*Carex nudata* W. Boott) tussocks along a riparian zone in California. When bentgrass seeds were added to tussocks, their establishment success was inversely proportional to the inherent species richness and other plant cover of the tussock systems. Gremmen et al. (1998) noted that creeping bentgrass had spread across about 50% of the sub-Antarctic Marion Island, replacing the native herb *Acaena magellanica* (Lam.) Vahl. It spread primarily by stolon dispersal along waterways. Human trampling increased the amount of ground covered by *A. stolonifera* (Gremmen et al., 2003). Human trampling and ground disturbance are consistent with the evolutionary concepts on the origin of turfgrasses and select other species, as evidenced by the ingress of nonnative *Agrostis capillaris*, annual bluegrass (*Poa annua* L.), and other species at remote Alpine sites in association with hiker's huts (Casler, 2006; Morgan and Carnegie, 2009). Tall fescue, bahiagrass, and bermudagrass can be problematic weeds in old fields during attempts to restore native warm-season grasses (Barnes, 2004). Combinations of burning, herbicide application, and seeding of native grasses are useful for reducing or eliminating turfgrasses during prairie restorations (Barnes, 2004).

The ability of some turfgrasses to invade natural areas without assistance is questionable, because their presence is often associated with site disturbance, roads, or old fields (Tyser and Worley, 1992; Larson, 2003; Tunnell et al., 2004). Tunnell et al. (2004) concluded that tall fescue could be a "transformer species" because its abundance did not decline during a 3-yr period after disturbance ceased in an old field. Kentucky bluegrass has been reported to exist at low levels (<6% cover) in forested ecosystems (Klinger et al., 2006; Wiegmann and Waller, 2006). Wiegmann and Waller (2006) suggested that the presence of Kentucky bluegrass and other exotics may have depended on one or more anthropogenically driven factors, including soil disturbance by nonnative earthworms to an overly abundant deer population. Wedin and Tilman (1993) showed the competitive ability of Kentucky bluegrass depended on the availability of nitrogen; at low nitrogen, native species such as little bluestem [*Schizachyrium scoparium* (Michx.) Nash-Gould] outcompeted the bluegrass. As old fields convert to forest, light-limited Kentucky bluegrass becomes relegated to open areas (Howard and Lee, 2002). Garrison et al. (2009) found that populations of *A. stolonifera*, Kentucky bluegrass, and *Festuca* spp. on defunct golf courses declined substantially within 7 yr after management ceased. The ability of turfgrasses to be outcompeted may depend on the surrounding species and other factors. Vegetative plugs of 10 C_3 turfgrass species failed to thrive when placed in two prairie ecosystems due to herbivory, environmental stress, and competition from the larger prairie plants (Garrison and Stier, 2010). Surveys of natural areas surrounding 12 largely rural golf courses ranging in age from 4 to 112 yr showed a relative lack of turfgrass ingress (Garrison, 2009). Of 2433 survey quadrats, only 1% contained creeping bentgrass, 9% contained fine fescue, and 15% contained Kentucky bluegrass. The vast majority, and all of the creeping bentgrass, was confined to within 12 m of the edge of the golf-course turf. When turfgrasses were found, they generally composed less than 5% of the quadrat area, indicating that they were not outcompeting other plant species.

The ability to transfer genes across species into turfgrasses for enhancing stress tolerance, herbicide resistance, and other features through genetic engineering has accelerated the concern about the potential for turfgrasses to be considered invasive species (Luo et al., 2005; Bae et al., 2008; Zapiola et al., 2008). A number of turfgrass species have been genetically modified: tall fescue, redtop (*Agrostis alba* L.), velvet bentgrass (*Agrostis canina* L.) red fescue, creeping bentgrass, Italian ryegrass (*Lolium multiflorum* Lam.), zoysiagrass (*Zoysia japonica* Steudel), colonial bentgrass (*Agrostis tenuis* Sibth.; syn. *A. capillaris* L.), Kentucky bluegrass, bahiagrass, bermudagrass, and perennial ryegrass (Wipff, 2002; Wang and Ge, 2006); however, as of 2011 none had been deregulated for commercial use due in part to concerns about their environmental impact.

Several studies have been conducted to determine the environmental impact of genetically modified turfgrasses. Wipff and Fricker (2001) reported that pollen flow from creeping bentgrass modified for resistance to glufosinate {2-amino-4[hydroxyl(methyl)phosphoryl] butanoic acid} herbicide occurred for distances of about 1300 m and that cross-pollination occurred with several closely related *Agrostis* spp. Watrud et al. (2004) performed a similar study and reported that pollen spread was mostly limited to within 2 km but could occur up to 21 km. Zapiola et al. (2008) reported that more than 60% of the creeping bentgrass plants within 4.6 km of a former glyphosate-tolerant creeping bentgrass production field carried the gene for glyphosate resistance. While the gene was not found in any of the related grass species that could potentially hybridize with *A. stolonifera*, five putative hybrid plants were identified that carried the transgene. Reichman et al. (2006) concluded that both pollen movement and seed dispersal resulted in spread of glyphosate-resistant transgene products into nonagronomic areas, including the USDA Crooked River National Grassland. Fei and Nelson (2004) used a greenhouse study to determine the environmental fitness of glyphosate-resistant creeping bentgrass, finding that inflorescence and seed-set characteristics were similar to those of nontransgenic bentgrass. Bae et al. (2008) compared zoysiagrass engineered for glufosinate resistance to wild-type zoysiagrass. Their data showed that flowering time, cross-pollination events, morphology, seed composition, effect on pathogenic soil fungi populations, and production of human allergens were similar for the modified and wild-type plants. No gene flow occurred to 14 cohabitant weed species. Wang et al. (2004) reported that the pollen viability of transgenic tall fescue was similar to that of pollen from nontransgenic plants.

Other research has focused on the impact of genetically modified turfgrasses in maintained turf areas. Gardner et al. (2004) reported that the lateral spread of glyphosate-resistant creeping bentgrass in mowed swards of perennial ryegrass, bermudagrass, and St. Augustinegrass was similar to that of nontransgenic bentgrass. Blume et al. (2008) found that Kentucky bluegrass lines expressing both glyphosate-resistance and overexpressing GA-20 oxidase (for dwarfing) had either shorter or longer rhizomes than the reference cultivars, depending on the line and location of the study, but the lengths were always shorter than those from tissue-culture lines.

While the implantation of genes to enhance tolerance to environmental stresses such as salt or drought may improve environmental fitness, single-gene additions do not necessarily translate to improved environmental fitness compared with that of wild-type plants (Wang and Ge, 2006). Some types of genetic modification could actually reduce the fitness of turfgrasses. Several gene constructs have been shown to reduce lignin production in tall fescue (Wang and Ge, 2006), which could reduce its traffic tolerance and enhance herbivory. Part of the debate surrounding use of genetically modified turfgrasses has focused on a perception that glyphosate is the only reliable and relatively benign herbicide for controlling species such as creeping bentgrass. In fact, several herbicides exist that can also control creeping bentgrass, including mesotrione {2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione}, an analog developed from the bottlebrush plant, which is selective for creeping bentgrass (Hart et al., 2005; Beam et al., 2006). Another concern is the potential for gene flow into nontransgenic grass-seed production areas, where it may not be wanted. The use of male sterility genes in conjunction with transgenic outcrossing grasses may reduce, if not eliminate, outcrossing events (Luo et al., 2005). A consortium of scientists determined that release of genetically modified perennial grasses would need to be considered on a case-by-case basis (Kenna et al., 2004).

Conclusion

Turfgrasses have become an integral component of society due to their multiple uses, including erosion control, aesthetics, and recreation, and relative ease and cost. Turfgrasses have a proven ability to mitigate runoff from urban environments, absorb atmospheric pollutants, provide evaporative cooling that translates into energy savings and improved comfort, remediate contaminated soils, increase property values, deter pests, repress criminal activity, and enhance mental health.

Management of turf relies on routine mowing and sometimes irrigation and pest control. Turf management practices result in concerns about water consumption and pollution, human and environmental risks from pesticide application, fossil fuel use and emissions, mowing injuries, lack of suitable habitat for most wildlife species, lack of land application for crop production, and potential of turfgrasses to invade natural areas. Research continues to identify benefits and issues. In the past 20 yr, the focus of turf research has changed from improving aesthetic quality to improving the environmental impact of turf management.

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