RESEARCH

Applying Biodiversity and Ecosystem Function Theory to Turfgrass Management

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ABSTRACT

In the United States, there is a growing need for turfgrass management practices that protect community and environmental health. The proportion of the developed landscape in the United States covered by turfgrass is significant and, at present, covers at least 1.9% of the total land area and comprises 60% in parts of the country. As urbanization progresses, there is a critical need to re-examine turf management practices that reduce reliance on pesticide and fertilizer inputs while contributing additional beneficial ecosystem services. In this review, we discuss the functional role of turfgrass in urban ecosystems. We identify key urban ecosystem processes associated with turfgrass and evaluate the potential to integrate biodiversity into their design and management. Specifically, we summarize research on the Biodiversity and Ecosystem Function theory that shows enhanced C storage, N retention, and weed suppression in natural and managed ecosystems, which are traits that are relevant to turfgrass systems. Enhancing biodiversity in turfgrass systems could increase ecosystem services in urban landscapes and should be considered a component of sustainable management practices.

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Abbreviations: BEF, biodiversity and ecosystem function; FD, functional diversity; SOC, soil organic C

Turfgrass landscapes have expanded rapidly in the United States in recent decades and will continue to become a dominant vegetation cover in urbanizing ecosystems. Within a 15-yr period (1982–1997), urban land cover expanded in the United States by 50% (Fulton et al., 2001). Although turfgrasses comprise only a portion of developed landscapes, collectively, they are estimated to cover 1.9% of the total terrestrial land area of the United States (Milesi et al., 2005). In fact, turfgrass in the United States covers an area three times larger than any irrigated crop (Milesi et al., 2005). The continuing expansion of developed lands suggests that turf establishment is a consequence of urbanization but it also reveals the potential to develop and manage turfgrass to increase ecosystem services in urban environments.

In 2010, the US Census Bureau found that over 80% of the nation lives in urban areas. Urbanization has increased by approximately 1.8% since 2000 (US Census Bureau, 2011). Remote sensing analysis of recently subdivided suburban parcels suggests between 25 and 90% of the landscape is pervious (Cappiella and Brown, 2001). Turfgrasses can be assumed to be the primary land cover of pervious landscapes within urban areas (Milesi et al., 2005). The dominance of turfgrass in developed landscapes is evidenced by a study conducted in an urbanized landscape in Ohio showing that 23% of the land area was covered with turfgrass lawns (Robbins and Birkenholtz, 2003). Similarly, an extensive study of the Chesapeake Bay watershed showed a 61% (3186 km^2) increase in urbanized land from 1990 through to

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2000, with much of the vegetated landscape containing turfgrasses (Jantz et al., 2005).

The replacement of natural habitats with turfgrass across the United States could reduce beneficial ecosystem functions. Expanding turfgrass coverage may increase the potential for non-point-source pollution stemming from improper turf management practices like overfertilization (Barth, 1995; Bormann et al., 2001; Guillard and Kopp, 2004; Raciti et al., 2011a; Townsend-Small and Czimczik, 2010). Although turfgrass landscapes pose several ecological concerns, multiple studies have indicated their potential to enhance N retention and C storage in soils underlying turfgrasses (Bandaranayake et al., 2003; Golubiewski, 2006; Groffman et al., 2009; Qian and Follett, 2002; Raciti et al., 2008; Townsend-Small and Czimczik, 2010). Although lawns offer more benefits than paved surfaces, there is great potential to enhance ecosystem performance by modifying management practices.

Common strategies for reducing pesticide and fertilizer inputs in turfgrass ecosystems have focused on plant breeding techniques or using native grass species (Simmons et al., 2011). Though such approaches are important, additional benefits of turfgrasses may be possible if ecological theory is applied to turf assemblage selection and design. Here, we discuss turfgrass systems in the context of urban grasslands, identify key ecosystem processes altered by turfgrass, and evaluate the potential to integrate biodiversity into designed landscapes. Specifically, we summarize the fundamental principles of biodiversity and ecosystem function (BEF) research that are relevant to C storage, N retention, and resistance to weed invasion in grasslands and prairies. Greater understanding of the benefits associated with increasing biodiversity in turfgrass systems may facilitate its incorporation into best management practices.

DEFINING URBAN GRASSLANDS

Turfgrass landscapes differ from native grasslands or grazing pastures in species composition and management practices. We define urban grasslands as patches of turf-type grasses that coalesce spatially into a distinct vegetation type (Fig. 1), are semiregularly mown to a height of 10 cm (about 4 inches) or less, may be irrigated, may be fertilized, and are maintained as a ground cover for light traffic, playing surfaces, or aesthetic reasons (Groffman et al., 2009). This broad definition encompasses a range of management practices and turfgrass landscape types, including mown roadsides, residential and commercial lawns, sports fields, and golf courses. Furthermore, this definition is used in the urban ecology literature to signify that urban grasslands are novel ecosystems with impacts and interactions beyond parcel boundaries that can be systematically studied and managed (Durán et al., 2013; Klaus, 2013; Thompson and Kao-Kniffin, 2016). Preferences for the management intensity and aesthetics of turfgrass landscapes vary widely by use and by manager, thus making generalizations difficult and exceptions many. Examples of the most highly managed turf comprise a narrow range of species, most frequently graminaceous species, which are intensively mown, frequently fertilized, and irrigated and treated with pesticides. Highly managed turf include sports fields, golf courses, and intensively managed residential or institutional grounds. The majority of urban grasslands include lawns or fields that are less tightly controlled and may include desirable broad-leaf plants, have a moderate tolerance for weeds, are mown infrequently, and receive little fertilization, irrigation, or fewer pesticide applications. These lawn landscapes are typical of low-use-intensity municipal parks, corporate or college campuses, public right-of-ways, and most residential properties.

The typical urban grassland in the United States is dominated by one to three turfgrass species. In cooler climates, Kentucky bluegrass (*Poa pratensis* L.) is the most common species because it provides good traffic tolerance in a recreational or sport setting. It is also common to find *P. pratensis* growing with perennial ryegrass (*Lolium perenne* L.). More recently, tall (*Festuca arundinacea* Schreb.) and fine fescues (e.g., *Festuca ovina* L., *Festuca rubra* L., *Festuca rubra* subsp. *commutata*) have become common in residential and civic lawns. In warmer climates, bermudagrass (*Cynodon dactylon* (L.) Pers.), centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.), and St. Augustine grass (*Stenotaphrum secundatum* (Walter) Kuntze) are the most common turfgrasses. Urban grasslands are typically low in plant diversity, consisting of only a few species and possibly a mix of cultivars (Klaus, 2013).

Valuing Urban Grasslands in Terms of Ecosystem Services

In its simplest definition, ecosystem services refer to the benefits people obtain from ecosystems (Millennium Ecosystem Assessment, 2005). Within the framework of ecosystem services, there are multiple benefits that urban grasslands can provide (Fig. 2). To enhance the ecosystem services provided by turfgrass landscapes, key ecosystem functions and their drivers must be considered. Biogeochemical cycling, especially C and N, are widely affected by the cultivation of turfgrasses (Milesi et al., 2005; Pouyat et al., 2009; Pouyat et al., 2006; Qian and Follett, 2002; Raciti et al., 2011b). Additionally, a decrease in plant diversity reduces natural resistance to invasion, increasing management efforts to suppress weeds (Hector et al., 2002). Ecological theory derived from research in native prairie ecosystems can inform the establishment of urban grasslands and promote the desired ecosystem services.

Substantial research has examined the functional outcomes of biodiversity in ecosystems. Early work defined diversity as species richness, then as functional groups, and, more recently, in terms of phylogenetic distance.

Fig. 1. Spatial view of a typical urban ecosystem dominated by patches of turf grasses that form a distinct vegetation type, referred to as the urban grassland. The map shows a section of developed land ~24 km north of upper Manhattan in White Plains, NY, featuring components of the urban grassland—lawns, institutional grounds, cemetery, sports fields, and golf course. Image taken from Bing Maps.

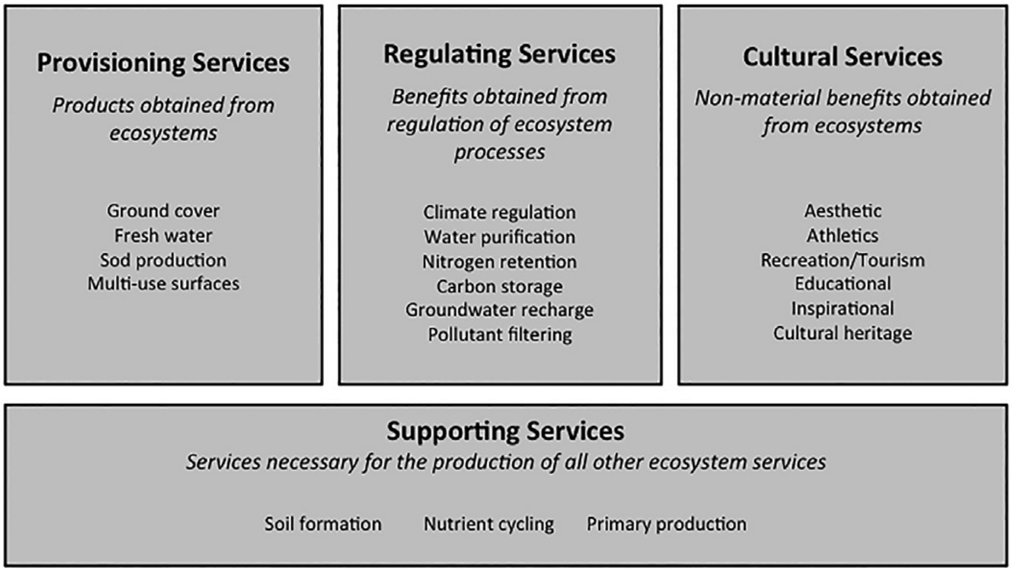

Fig. 2. Conceptualization of ecosystem services (benefits people obtain from ecosystems) specific to turfgrass. Examples of the different components of ecosystem services are listed and refer to services broadly covering turfgrasses in urban environments. The figure is reproduced and adapted from the Millennium Ecosystem Assessment (2005).

However, many studies continue to use species richness as the primary diversity metric, since it is easy to manipulate and measure. Experimental and observational studies in native grasslands, drylands, forests, and aquatic ecosystems represent the majority of BEF research to date (Balvanera et al., 2006; Cadotte et al., 2008; Cardinale et al., 2011; Maestre et al., 2012; Worm et al., 2006). However, relatively little BEF research has been conducted within urban grassland ecosystems. In a study of native vs. non-native turfgrasses, Simmons et al. (2011) measured diversity, but only among native turf treatments, hence biodiversity effects were not fully explored. The next section provides an overview of the conceptual origins, current thinking, and mechanisms by which biodiversity has been studied in relation to ecosystem functions.

Underlying Principles of BEF Research

Decades of scientific debate have attempted to conceptualize, experientially determine, and model the role biodiversity plays in determining ecosystem functioning. The dramatic surge in BEF research resulted from an early international conference on biodiversity held in Bayreuth, Germany in 1991 (Schulze and Mooney, 1994). The meeting catalyzed much research, resulting in the second conference in Paris, France in 2000 to summarize a decade of data (Loreau et al., 2002). Subsequent research has attempted to reconcile theoretical and experimental findings, by determining the effects of biodiversity in various ecosystems and the mechanisms underlying those effects, and refining the spatial and biological scales at which diversity is measured. A more complete review of the theoretical foundations, historic discourse, and current directions in BEF research can be found in the following: (Cadotte et al., 2008; Cardinale et al., 2006; Hooper et al., 2005, 2012; Loreau and Mazancourt, 2013).

Early hypotheses suggested linear, redundant, keystone, or rivet response models to explain the relationship between a biodiversity gradient and a given ecosystem process (Fig. 3) (Naeem et al., 2002; Vitousek and Hooper, 1993). Although the field has moved beyond these simplified models, they are still archetypes referenced during analyses of contemporary findings (Naeem et al., 2002). Generally, each model depicts the effect on a specific ecosystem process for each addition or subtraction of a species. A linear response indicates that there is a direct relationship between the total number of species and the process of interest. Redundant models assume species have similar effects on ecosystem processes; therefore, increasing species richness produces a diminishing response, causing an asymptotic function (Lawton and Brown, 1993). Keystone and rivet response models are related and suggest a tipping point where if a critical species is lost (keystone) or if a diversity threshold is crossed (rivet), there will be a sharp decline in an ecosystem process (Ehrlich and Ehrlich, 1981; Mills et al., 1993). Most early research focused on a readily quantifiable ecosystem process, such as aboveground plant biomass production.

To understand why diversity would produce different response models and under what conditions, researchers have focused on plant traits that might influence productivity. Initial BEF theory assumed that plant species possess different inherent traits with regards to nutrient acquisition, growth, and other life history traits. These differences should result in a single species occupying a distinct role (niche) within an ecosystem. As species diversity increases, the theory suggests a greater degree of niche partitioning occurs, allowing multiple species to coexist and more efficiently use a finite set of environmental resources (e.g., nutrients, water, space, light, etc.). (Fig. 4) (Tilman, 1999, Tilman et al., 1997a). An extension of the niche partitioning theory is species complementarity, which occurs when (i) resources used by multiple species occur in complementary ways in space or time, or (ii) when interspecific interactions between two coexisting species use resources more efficiently (Cardinale et al., 2007). An alternative explanation for the increased productivity associated with high-diversity communities is the sampling effect. This framework proposes that polycultures have a greater likelihood of including highly-productive species than monocultures (Aarssen, 1997). Parsing out the mechanisms driving the effects of biodiversity is difficult and they may vary between ecosystems or be interpreted differently among researchers (Naeem et al., 2002). Regardless of the mechanism, a majority of studies have found that diversity increases the average productivity of an ecosystem (Cardinale et al., 2013; Pasari et al., 2013).

Biological diversity creates a stabilizing effect, moderating fluctuations in ecosystem functioning caused by biotic and abiotic stresses (Hooper et al., 2005, Tilman et al., 2006). Ecosystem stability occurs when a community can sustain a process at an average level under fluctuating environmental conditions, though species-level population fluctuations may occur. Long-term studies of a native prairie diversity gradient in Minnesota, which compared replicated plots of 1–16 species, exhibit some of the strongest evidence coupling diversity and stability (Tilman et al., 2006). Tilman and colleagues found greater ecosystem stability with regards to biomass in 70% of high-diversity plots compared to monocultures. However, individual species stability within a polyculture was inversely related to species richness (Tilman et al., 2006). The authors concluded this was an example of the biodiversity portfolio effect, a generalized form of ecosystem stability. It should be noted that productivity and stability are not inherently linked and may vary independently in diverse ecosystems (Cardinale et al., 2013).

The conceptual framework describing trade-offs in polycultures explained above, is derived from stock trading analogies in economics and is referred to as a portfolio effect (Figge, 2004). For example, under the most favorable conditions, a monoculture could be highly functional but under stressed conditions (such as drought, disease, pests, etc.), the community could decline, losing functionality. In a multiple species scenario, one species may thrive while another declines under a given set of stresses. However, if environmental conditions change, the relative success of each species may be altered. Thus a diversified community (or stock portfolio) can more adequately buffer changing stresses but cannot capitalize on potentially large gains should conditions favor one species as compared to a monoculture of the favored species.

Current BEF research tends to focus on the multifunctionality of diverse ecosystems and alternative ways to consider diversity. Reassessments of long-term grassland studies have found that plot-scale species richness (α-diversity) and landscape-scale heterogeneity (β-diversity) are necessary for ecosystems to simultaneously enhance multiple ecosystem functions (Pasari et al., 2013; Zavaleta et al., 2010). In addition to assessing diversity within and between sites, a shifting focus of BEF research is emphasizing the predictive power of functional diversity (FD) and phylogenetic diversity (Cadotte et al., 2008, 2009; Flynn et al., 2011). Plant species vary with regards to functional traits, such as photosynthetic pathway (C_3, C_4, and crassulacean acid metabolism) and their ability to associate with N-fixing bacteria (e.g., legumes). Therefore, combinations of FD have been suggested as being more relevant than species richness as a predictor of ecosystem function. Similarly, distantly related species (larger phylogenetic diversity) are thought to be less similar in their functional traits, ecological niches, and life history strategies and are therefore more complementary than two closely related species (Cadotte et al., 2008, 2009).

The value of biodiversity, measured in species, traits, and phylogeny and at various scales, is strongly supported by the body of BEF research. Although the mechanisms, strengths, and conditions under which biodiversity affects ecosystem processes remain unresolved, the consensus of the field is that diversity matters. Preserving or enhancing biodiversity within managed ecosystems is critical to sustaining the services they provide to human populations. To date, the design of urban grasslands has not included BEF theory to increase the multifunctionality of these landscapes.

Ecosystem Services Provided by Urban Grasslands

Urban grasslands have impacts on multiple ecosystem services in developed landscapes, especially in the context of rapid urbanization. With regards to BEF theory, we examine three services altered by turfgrass landscapes: C storage, N retention, and plant invasion resistance. The following examples discuss how these services are impacted in urban grasslands, the applicable BEF theory, and how increasing diversity in turfgrass landscapes might enhance these ecosystem services.

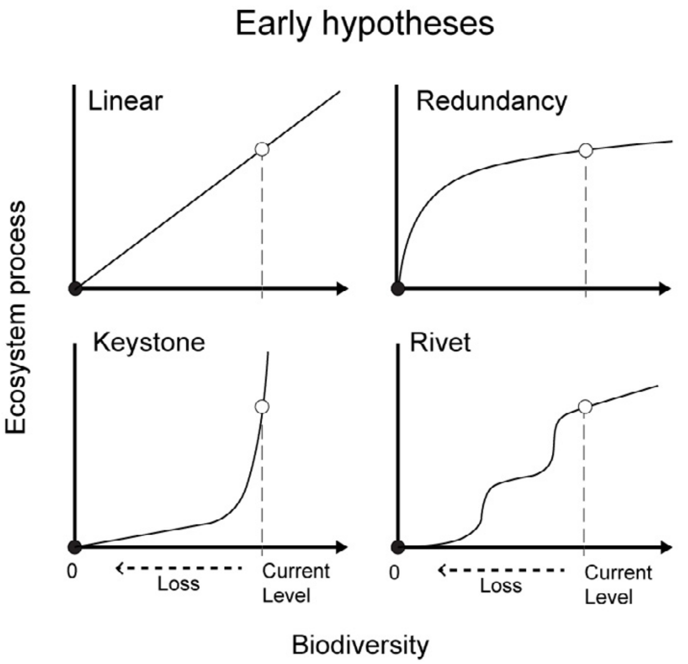

Fig. 3. Early hypotheses in Biodiversity and Ecosystem Function (BEF) research postulated linear, redundancy, keystone, and rivet responses in ecosystem processes to declining biodiversity. Contemporary BEF research refers to these archetypal responses, but now considers functional responses to biodiversity loss to be more nuanced. The figure is reproduced and adapted from Naeem et al. (2002).

Carbon Storage

Since land use conversion to urban conditions is long-lasting (Pouyat et al., 2002), potential soil C storage gains from urban grasslands is a low-risk payoff. Urbanization causes a shift in terrestrial C cycling as land is converted from forest or agricultural uses (Pataki et al., 2006). Carbon cycling in managed turfgrass is also substantially different than that in natural environments because of human management practices, such as irrigation, fertilization, and mowing (Zhang et al., 2013). However, C cycling in urban environments remains poorly quantified, though research in turfgrass landscapes suggests there is great potential for C sequestration, especially belowground (Pouyat et al., 2002; Zhang et al., 2013). Historical land uses affect the potential for urban grassland soil C accumulation, with C-poor agricultural soils having greater potential to accumulate soil C stocks than forest soils beginning with moderate soil C levels when converted to urban uses (Pataki et al., 2006). Soil C stocks in turfgrass landscapes are typically greater than agricultural systems and can approach levels observed in native forests (Raciti et al., 2011b). However, C emissions from maintenance practices (e.g., fossil fuel consumed by mowing, embodied energy in fertilizers, and

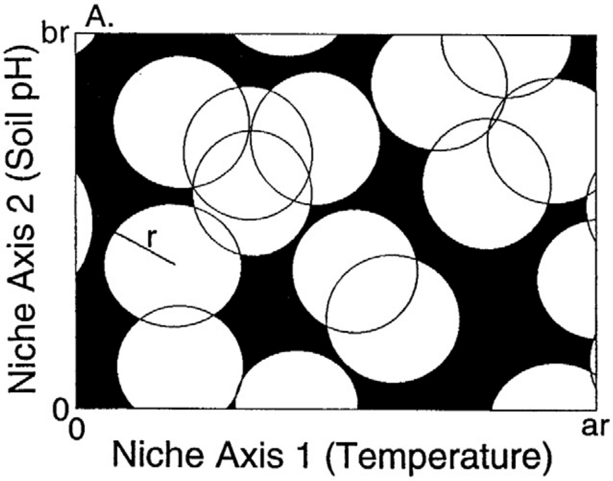

Fig. 4. Niche partitioning explains how a single species captures environmental resources within an ecosystem. However, no species is optimally suited to fully exploit the entire range of an ecosystem. Here, this is illustrated at all temperature and soil pH combinations. As biodiversity increases, the entire niche space of an ecosystem is more fully used. The figure is reproduced from Tilman et al. (1997b) Copyright (1997) National Academy of Sciences.

energy for irrigation) may decrease or completely offset belowground urban grassland C storage (Townsend-Small and Czimczik, 2010; Zhang et al., 2013).

Carbon storage may be significant in turfgrass systems where disturbance is minimized, sufficient water (natural or irrigated) exists, and fertilization allows soil organic matter to increase. Since soil organic matter is approximately 57% C, increasing soil organic matter is necessary to sequester more C (Follett et al., 1987). In one study, low annual disturbance, fertilization, irrigation, and more pervious surfaces caused increases of 44 and 38% in soil C densities in low density residential and institutional land uses, respectively, compared with commercial developments (Pouyat et al., 2002). Soils in a golf course in New York City were found to have the highest soil organic C (SOC) density (28.5 kg m^{-2}) of samples taken from six US cities and Moscow, Russia (Pouyat et al., 2002). Soil organic C was found to increase at the rate of 0.1 kg m^{-2} yr^{-1} over a 25- to 30-yr period in golf course greens and fairways (Qian and Follett, 2002) which is similar to SOC accumulation rates observed in lawns (0.14 kg C m^{-2} yr^{-1}) (Townsend-Small and Czimczik, 2010). Modeling efforts predict accumulation rates of 2.3 to 3.2 kg m^{-2} SOC in the top 20 cm over 30 yr for the conversion of native grasslands to golf turf in Colorado (Bandaranayake et al., 2003). In each of these instances, C emissions from urban grassland establishment and maintenance are not accounted for, so the net effect on global greenhouse gas concentrations remains unknown. More studies are needed to show the incremental SOC increases for mow-only, irrigated or fertilized areas and turfgrass landscapes that receive both irrigation and fertilization.

Increasing urban grassland diversity has the potential to increase C sequestration in urban landscapes. There is substantial evidence suggesting that plant species richness increases the efficiency of an ecosystem to use and convert assimilated resources into plant biomass (Cadotte et al., 2008; Cardinale et al., 2011, 2007; Hooper et al., 2005). These analyses summarize and parse over 20 yr of plot, greenhouse, and mesocosm studies in which species diversity was directly manipulated to determine how ecosystem functions, including productivity, were affected. Aboveground biomass accumulation is not always representative of C sequestration, as greater than 70% of terrestrial C is retained in soil stocks (Catovsky et al., 2002). This is of particular importance in turfgrass systems where mowing regularly removes aboveground biomass. Enhancing the productivity of urban grasslands by increasing assemblage diversity could increase belowground productivity and deposition of C compounds, potentially contributing to higher SOC accumulation rates, but additional research in turfgrass systems is needed to test this hypothesis.

As suggested by the portfolio effect and diversity–stability (discussed above), evidence suggests that polycultures are frequently more productive than monocultures, but exceptions may exist. Cardinale et al. (2007) analyzed 44 experiments manipulating diversity and found that 79% of polycultures were more productive than average monoculture treatments. However, in 88% of these cases, the most productive individual species included in the polyculture, when grown in monoculture, accumulated more biomass than the polyculture (Cardinale et al., 2007). Upon further analyses of diversity experiments, Cardinale et al. (2011) found that the highest diversity polycultures only accumulated 87% of the biomass of the highest yielding monoculture. Thus a diverse community would be expected to be more functional on average than an average monoculture but less functional than the best-suited monoculture. However, in application, we rarely know the best monoculture species, what environmental conditions it is most suited for, or its ecosystem functional traits.

Given these constraints and the desire to increase C storage, more research is needed to determine how diversity can enhance turfgrass ecosystem productivity. This is particularly critical where environmental conditions (spatially and temporally) are variable, multiple functions are desired from the landscape, and the ideal turfgrass selection is unknown. Although urban C storage represents a small portion of total soil C storage, diversifying urban grasslands is a low-risk opportunity to increase soil C in developed landscapes.

Nitrogen Retention

Nitrogen cycling is complex, highly variable, and subject to extensive human influence in urban grasslands. A study conducted by the National Gardening Association (2000) found that 89.3% of American homes used fertilizers on their lawns or gardens. Lawn chemical and fertilizer users tend to be more highly educated and affluent and to self-identify as environmentally knowledgeable (Robbins et al., 2001). Despite this higher level of education, improper fertilization is commonplace. A study in the Minneapolis, MN, metropolitan area found fertilizer N inputs to be on average 78.9 kg N ha^{-1} yr^{-1} (Fissore et al., 2012). The level exceeded the estimated net primary productivity and N storage potential of urban landscapes by over 50%, resulting in increased N losses. Increased N fertilizer applications on urban grasslands has resulted in higher N exports compared with forest ecosystems (Groffman et al., 2009). Turfgrass fertilizers, especially synthetic formulations, have been implicated in non-point-source water pollution, resulting in eutrophication of urban watersheds and contributing to algal blooms in coastal waters and estuaries (Barth, 1995; Easton and Petrovic, 2004; Petrovic, 1990). Furthermore, turf fertilization may contribute to atmospheric N_2O concentrations, which have nearly 300 times the global warming potential of CO_2 on a per molecule basis, although this is minimal compared to CO_2 concentrations in terms of climate forcing (Raciti et al., 2011a, Zhang et al., 2013).

Under proper management practices, turfgrasses have displayed high capacities for N retention. In a review, Petrovic (1990) found greater than 90% of N was retained in turfgrass systems, which prevented N from leaching into groundwater. Similarly, several studies found unfertilized or minimally fertilized turfgrass could retain as much as 95% of N on an annual basis (Gold et al., 1990, Guillard and Kopp, 2004). In a long-term study, NO_3^- leachate concentrations from turfgrass plots showed that N retention from applied fertilizer was near 100% in dry years and >60% in wet years. Nitrogen removal through denitrification occurs at variable, but low rates, in turfgrass landscapes (Raciti et al., 2011a). Multiple studies suggest the worst-case scenarios for high N leaching from turfgrasses occur in recently established lawns, turfgrass planted on heavily compacted soils, over watered lawns, and fertilized lawns (Cheng et al., 2013; Easton and Petrovic, 2004; Guillard and Kopp, 2004; Morton et al., 1988).

Application of BEF theory to urban grasslands would suggest that increasing turf species diversity within lawns will enhance N retention, as a result of more complete resource use (Loreau, 1998). Indeed, Tilman et al. (1996) found soil NO_3^- to be a negative saturating function of species richness within and below the rooting zone of native prairie grassland field mesocosms. A >50% decrease in soil NO_3^- was observed in their diverse polycultures that included six or more species. However, soil NO_3^- content only implies N leaching potential. Another native grassland study found that increasing both species richness and functional group richness caused a reduction in measured NO_3^- leaching, but leaching differences were only observed when an N-fixing legume was included in the plot (Scherer-Lorenzen et al., 2003). Where legumes were not present, virtually no NO_3^- leached from plots, suggesting that regardless of the number of species present, non-N-fixers will efficiently use available soil NO_3^- (Scherer-Lorenzen et al., 2003). A mesocosm study featuring different levels of turfgrass diversity also showed reduced NO_3^- losses in the more diverse turfgrass assemblages, regardless of whether a legume was added to the mix (Thompson and Kao-Kniffin, 2016). The study compared a common pool of seven species and five cultivars of typical turfgrass species and one cover species in 1-, 3-, 6-, and 12-part mixtures (Thompson and Kao-Kniffin, 2016). In each case, increasing turfgrass mesocosm diversity from one to three components enhanced the ecosystem service measured (Thompson and Kao-Kniffin, 2016). In an effort to determine the effects of biodiversity under future elevated atmospheric CO_2 concentrations, one study used free air C enrichment in combination with N-fertilized and unfertilized native grassland plots (Mueller et al., 2013). Results from 13 yr of the experiment show soil NO_3^- decreased both in response to species richness and functional group regardless of N fertilization. Fine root biomass leading to N uptake was suggested as the primary driver of the observed diversity differences in soil NO_3^- (Mueller et al., 2013). This study suggests that grassland biodiversity will continue to provide benefits under elevated atmospheric CO_2 concentrations.

Given the evidence suggesting that native grassland polycultures reduce soil NO_3^- and decrease N leaching potential, it seems logical to diversify urban grasslands. Complementarity effects in fine root biomass, N uptake, and N fixation have been used to explain the observed results from BEF research in native grasslands. Though legumes are known to increase the amount of soil NO_3^- greatly and thus potentially increase N leaching, evidence suggests that this can reduce in diverse grassland polycultures (Mueller et al., 2013; Scherer-Lorenzen et al., 2003). Clover (*Trifolium* spp.) is a common weed in turf systems and fixes N (Turgeon, 2005). Clover genotypes have recently been developed to achieve dwarf forms for use as a more sustainable alternative to N fertilizer dependency on turfgrass lawns (Wagner et al., 2010). More research is needed to determine if this unintended or deliberate N-fixation has an effect on ground water quality and if introducing diverse turfgrass landscapes uses additional fixed N.

Invasion Resistance (Weed Suppression)

Weed invasion is a common issue in urban grasslands, requiring significant monetary and environmental inputs. Historically, pesticides were used to control disease, weed, and pest problems in turf; however, as environmental and human health concerns have increased, many landscape managers are reducing pesticide use. Nationally, consumer attitudes are shifting away from intensive pesticide and fertilizer application. For example, pesticide use dropped from 63.0 to 57.6 million kg annually between 1988 and 2007, while the cost rose from $1.27 to $2.66 billion dollars during the same period (USEPA, 2011). States such as California and New York, as well as some Canadian provinces, are adopting pesticide restrictions or bans for lawns (Bélair et al., 2010). With current chemical weed control options being limited, effective alternatives for weed suppression are in high demand.

Urban water quality can be negatively impacted by the mismanagement of turfgrass landscapes. Pesticides, including 2,4-D (2,4-dichlorophenoxyacetic acid), atrazine (6-chloro-*N*-ethyl-*N*'-isopropyl-1,3,5-triazine-2,4-diamine), glyphosate [([phosphonomethyl]amino)acetic acid], diazinon [*O*,*O*-diethyl O-(2-isopropyl-4-methyl-6-pyrimidinyl) phosphorothioate], and dicamba (3,6-dichloro-2-methoxybenzoic acid), have been detected in 25 to 90% of water samples taken after storm events in residential watersheds, though pesticide concentrations often go unreported (Robbins et al., 2001; Schueler, 1995; Wotzka et al., 1994). Common turf pesticides including 2,4-D, dicamba, mecoprop [2-(4-chloro-2-methylphenoxy)propanoic acid], (4-chloro-2-methylphenoxy)acetic acid, and glyphosate are found in urban runoff (Schueler, 1995). In experimental manipulations, pendimethalin [3,4-dimethyl-2,6-dinitro-*N*-(3-pentanyl)anilin], 2,4-D, and mecoprop [2-(4-chloro-2-methylphenoxy)propanoic acid] have been measured above US safety standards in runoff or leachate from bluegrass lawns under both irrigated and nonirrigated conditions (Slavens and Petrovic, 2012). Increasing turfgrass diversity may provide an effective tool for reducing weed invasion and the need to apply herbicides, thereby reducing risk exposure concerns.

Exploring the role of biodiversity in determining an ecosystem's resistance to invasion has been a long studied area within BEF research. The work of Elton (1958) is an early example posing a theoretical framework linking diversity and invasion resistance. More than 50 yr of research in this area has come to a few conclusions: (i) the species composition of a plant community has an effect on invasion resistance (Crawley et al., 1999); (ii) resource availability, partly influenced by community composition, has an effect on invasion resistance (Davis et al., 2000); (iii) high niche partitioning in diverse plant communities results in invasion resistance as a result of complementarity and more complete resource use (Knops et al., 1999; Shea and Chesson, 2002; Tilman et al., 1997a). Because of the inherent correlation of these mechanisms (for example, changing the species composition of a community may alter the species richness of the community), determining the contribution of biodiversity alone is frequently confounded (Davis et al., 2000; Levine and D'Antonio, 1999). Diversity–invasion resistance studies suggest that in general, higher species richness results in a higher probability of a community to resist weedy invasion, if all other factors are constant (Hector et al., 2002; Hooper et al., 2005). Experimental studies are needed to determine the degree to which turfgrass diversity confers invasion resistance.

Ecosystem scale matters when considering diversity and invasion resistance. Specifically, the point at which local biotic interactions are supplanted by landscape-level abiotic interactions determines whether diversity suppresses or facilitates invasion (Fridley et al., 2007). The invasion paradox, articulated by Fridley et al. (2007) explores the transition from small scales (1 m^2) to large scales (10^7 ha), whereby increasing environmental heterogeneity causes a shift in diversity–invasion likelihood relationships from negative to positive.

Managers of turfgrass landscapes frequently attempt to reduce site heterogeneity through maintenance practices, which increases the potential for weed invasion. Increasing turfgrass diversity may be one means of reducing weeds in managed landscapes. Furthermore, complementarity in spatial and temporal resource use may improve a diverse lawn's resistance to invasion.

Uncertainties about BEF Effects Applied to Urban Grasslands

The field of BEF research has advanced greatly from initial theoretical models through to manipulated diversity experiments in mesocosms and small field plots. Though much has been learned from dryland, forest, native prairie, and aquatic ecosystems, translating such findings and applying them to urban grasslands poses some uncertainties.

Biodiversity effects tend to be smaller in magnitude in less-controlled experimental systems (Balvanera et al., 2006; Hooper et al., 2005; Loreau et al., 2001). Laboratory microcosm and greenhouse microcosm studies do not experience the unpredictable biotic and abiotic fluctuations that field experiments or real-world applications do (Balvanera et al., 2006). Urban grassland biodiversity research should rely on findings from native grassland field experiments as a starting point for hypothesis generation.

Small experimental field plots tend not to capture the heterogeneity of environmental conditions, which affect the outcome of biodiversity effects (Balvanera et al., 2006). Furthermore, the scale of managed landscapes tends to be negatively correlated with the homogeneity of environmental variables (Fridley et al., 2007). As the size of urban grasslands expands, increasing management inputs are needed to overcome environmental heterogeneity. Such relationships should inform the experimental design of diverse urban grassland experimental trials.

The historical emphasis of BEF research on productivity may be less relevant to turfgrass systems, where such increases may require more frequent mowing. Diversity may increase biomass and plant productivity, resulting in greater management requirements such as mowing, potentially reducing the benefits of diversity. However if turfgrass diversity increases stand density, enhances resource use complementarity, and reduces weed invasion, then increased productivity may remain a beneficial biodiversity effect in urban grasslands. Given the unique constraints facing turfgrass managers in terms of producing a high quality turf crop while minimizing inputs and detrimental environmental effects, the emphasis of BEF research in urban grasslands may be different from previous BEF research in other ecosystems.

Since the latter half of the twentieth century, a shrinking number of turfgrass species have been considered desirable, whereas formerly acceptable species such as clovers, are now considered weedy. Each turfgrass manager must determine what is acceptable within the context of the site and the expectations of users under the state or municipal laws regulating turf management. However, increasing turf diversity by including a wider range of species—graminaceous or broad-leaf—may yield ecosystem service benefits. Initial efforts to increase turfgrass diversity may be best targeted in areas with lower turfgrass aesthetic or performance requirements until potential ecosystem service benefits are better quantified.

CONCLUSION

Turfgrass landscapes are presently an integral part of developed areas across the United States and the world. As native and agricultural ecosystems are converted to turfgrass, changes in ecosystem processes should be considered. We suggest applying the fundamental principles of biodiversity and ecosystem function theory to urban grasslands to improve ecosystem functioning. Specifically, we suggest including stand diversity as a key criterion in evaluating turfgrass landscapes, beneficial ecosystem services, and reduced management inputs. Such research hypotheses generated by including diversity in turfgrass landscape evaluation might include: How much diversity is needed to provide additional ecosystem functions? What is the best way to diversify existing lawns? How can we establish and maintain diverse urban grasslands? What species could increase ecosystem services in turfgrass landscapes that are not traditionally considered desirable in urban grasslands?

Given that the body of BEF research supports the importance of biodiversity and its role in increasing ecosystem functioning, applying BEF theory to turfgrass management is a logical step to enhance the ecosystem services provided by these landscapes. More *in situ* research is required to determine the extent to which the positive effects of biodiversity can be realized in turfgrass landscapes. Future research should focus on appropriate measures of grassland diversity, which may include measures of genetic diversity or FD, depending on the ecosystem's services of interest. Ecosystem services such as C storage, NO_3^- leaching, invasion resistance can be explicitly studied and monitored in turfgrass landscapes. Additionally, studies should be designed to simultaneously measure multiple ecosystem services of interest to increase the multifunctionality of turfgrass polycultures.

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