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Mapping and Modeling the Biogeochemical Cycling of Turf Grasses in the United States

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ABSTRACT / Turf grasses are ubiquitous in the urban landscape of the United States and are often associated with various types of environmental impacts, especially on water resources, yet there have been limited efforts to quantify their total surface and ecosystem functioning, such as their total impact on the continental water budget and potential net ecosystem exchange (NEE). In this study, relating turf grass area to an estimate of fractional impervious surface area, it was calculated that potentially 163,800 km^2 (± 35,850 km^2) of land are cultivated with turf grasses in the continental United States, an area three times larger than that of any irrigated crop. Using the Biome-BGC ecosystem process model, the growth of warm-season and cool-season turf grasses was modeled at a number of sites across the 48 conterminous states under different management scenarios, simulating potential carbon and water fluxes as if the entire turf surface was to be managed like a well-maintained lawn. The results indicate that well-watered and fertilized turf grasses act as a carbon sink. The potential NEE that could derive from the total surface potentially under turf (up to 17 Tg C/yr with the simulated scenarios) would require up to 695 to 900 liters of water per person per day, depending on the modeled water irrigation practices, suggesting that outdoor water conservation practices such as xeriscaping and irrigation with recycled waste-water may need to be extended as many municipalities continue to face increasing pressures on freshwater.

Turf grasses are ubiquitous in the American urban landscape, in residential, commercial, and institutional lawns, parks, most athletic fields and golf courses, often as monocultures, independently of the local climate (Jenkins 1994). Existing estimates indicate that in the early 1990s, the surface cultivated with turf was up to three times larger than that of irrigated corn, the largest irrigated crop in the United States (DPRA, Incorporated 1992). As the construction of new homes, averaging 1.6 million per year in the late 1990s (U.S. Bureau of the Census 1999), continues to expand the American urban landscape, the total surface under turf is expected to further increase.

Turf grasses contribute to soil carbon (C) sequestration (Bandaranayake and others 2003, Qian and Follett 2002, Van Dersal 1936) and, as a component of urban vegetation, to the mitigation of the urban heat island effect (Spronken-Smith and others 2000) and to enhanced water infiltration compared to bare soil or impervious surfaces. However, turf has also been linked with a number of negative environmental impacts. Turf grasses often pose a neglected environmental hazard through the use of lawn chemicals and overfertilization (Robbins and Birkenholtz 2003, Robbins and others 2001), and, where used, irrigation of turf grasses sharply increases the summer water consumption for residential and commercial use, especially if grown in arid and semiarid regions, where it can account for 75% of the total household water consumption (Mayer and others 1999).

KEY WORDS: Turf grasses; BIOME-BGC; Impervious surface area; Carbon budget; Carbon sequestration potential; Water use

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In spite of the pervading presence of turf grass systems in the urban and suburban landscape and their considerable use of water resources, a national assessment of the ecological functioning of these systems is still missing. The fragmented distribution of residential and commercial lawns and the large variability in management practices adopted to grow the different types of turf surfaces certainly challenges the task of such an assessment.

In this study, we attempt a first estimate of the potential impact of turf grasses to the continental U.S. carbon and water budgets by producing a spatially explicit estimate of their distribution within the contiguous 48 states and simulating their growth with an ecosystem process model. Specific objectives of this study are (1) to compare a remote sensing-based estimate with other independent estimates of the total surface under turf grasses, and (2) to evaluate the impact of different turf management practices, such as removal versus on-site decomposition of the grass clippings, varying nitrogen fertilization regimes, and alternative irrigation schedules, on the continental carbon and water budgets.

Methods

Estimation of U.S. Turf Surface

A continental assessment of the carbon and water balances of turf grasses requires their spatial distribution to be mapped. With the exception of some golf courses, turf grasses are rarely cultivated on surfaces large enough to be identifiable with moderate resolution satellite data (~1 km). Due to excessive costs and time constraints, the use of high-resolution satellite images or aerial photography has been limited. Past efforts to estimate the continental surface of turf grasses used indirect approaches that provided measures of the total surface under lawn on a state-by-state basis, therefore lacking the spatial detail required to calculate spatially dependent biogeochemical cycles. Vinlove and Torla (1995), for example, estimated the national total home lawn area using methods based on adjusted Federal Housing Authority (FHA) average and median lot sizes by state, without accounting for the turf surfaces found in golf courses, parks, schools, roadsides, etc. DPRA, Incorporated (1992), in a report commissioned by the Environmental Protection Agency, estimated the total area under turf on the basis of direct surveys in 12 states, which were extrapolated to the remaining states in proportion to their population.

In our study, also adopting an indirect approach, we assumed the surface of turf grasses to be inversely related to the amount of impervious surface associated with urban development (roads, roofs, parking lots, sidewalks, etc.). We first calculated a fractional cover of Impervious Surface Area (ISA) for the 48 states at 1-km spatial resolution using 2001 radiance calibrated nighttime lights, a 1-km grid of road density and Landsat-derived urban landcover classes (Elvidge and others 2004). The road density was calculated as the length of road per square kilometer from 1998 TIGER (Topologically Integrated Geographic Encoding and Referencing System) road vector data from the U.S. Census Bureau. The nighttime lights were produced using cloud-free portions of DMSP/OLS (Defense Meteorological Satellite Program/Operational Linear Scanner) data using methods described by Elvidge and others (1999). We also used direct measurements of the proportion of constructed surface (roads, parking lots, buildings) versus the proportion of vegetated (turf grasses and/or trees) or other (undeveloped) surface calculated from 80 high-resolution aerial photographs collected along development transect distributed across 13 major urban centers. The transects extended from the urban cores out to the sparsely developed (or undeveloped) fringes of the urban centers of Atlanta, Boston, Chicago, Denver, Houston, Las Vegas, Miami, Minneapolis, New York, Phoenix, Portland, Sacramento, and Seattle. The aerial photographs were from year 2000 ± 1 year (see Figures 1 and 2 for an example of the aerial photographs over industrial and residential areas of Chicago, respectively). The measurements were done on square kilometer tiles extracted from the aerial photographs to match the coverage of specific cells in the satellite and road density grids, and were used to develop an empirical relationship between the fractional ISA and the radiance calibrated nighttime lights, road density, and Landsat-derived urban land cover classes. The highly significant regression model (P-value < 0.0001 and Root Mean Square Error (RMSE) of 13.4, Figure 3) was then applied to the conterminous United States to produce a 1-km grid depicting the spatial distribution of ISA in percentage terms. The total ISA for the conterminous United States calculated with this method was estimated to be 112,610 (±12,725) km^2 or 1.3% of the total area.

The proportions of impervious versus vegetated surfaces derived from the high-resolution aerial photography tiles were then used to develop a predictive relationship between the fractional ISA and the combined fraction of turf and tree surface, given that turf was present under the trees observed in the samples. For this model, only samples over areas with more than

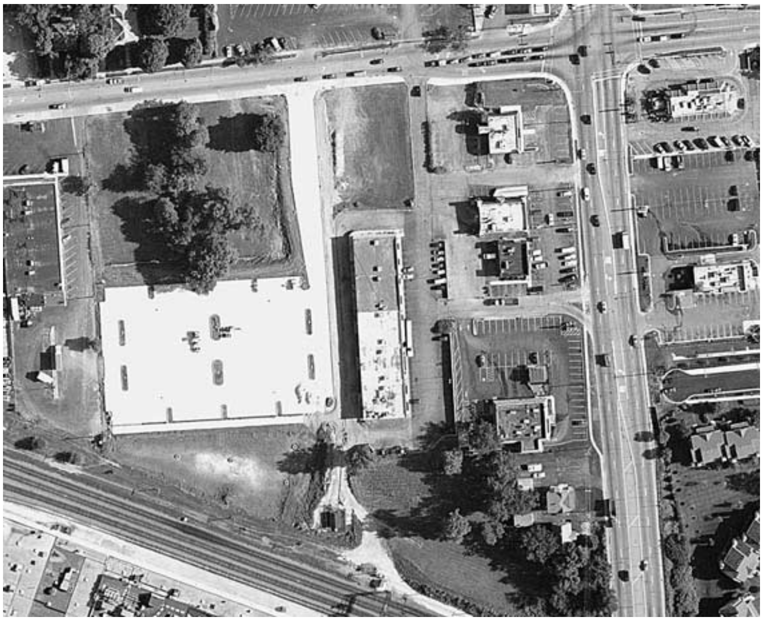

Figure 1. Detail of aerial photography used to measure fractional Impervious Surface Area over Chicago (infrastructure and commercial buildings).

Figure 2. Detail of aerial photography used to measure fractional impervious surface area over Chicago (residential area).

10% fractional ISA were used, leaving out the sparsely developed urban fringes, where the occurrence of very low development density is often associated with forested and other nonturf vegetated surfaces. The predictive model showed a moderately strong ($R^2 = 0.69$), highly significant ($P < .0001$, RMSE = 11.2) relationship between fractional ISA and fractional turf grass area (Figure 4) and was subsequently applied to the conterminous United States to produce a 1-km grid of fractional turf area (Figure 5).

Modeling of Turf Grasses Growth

Management of turf grasses is highly variable, in part because of the different uses for which these surfaces are dedicated. In order to withstand considerable wear, golf courses and athletic fields usually receive much higher doses of nitrogen (N) than residential lawns (up to 490 kg/ha/yr; Sartain 1998). For residential lawns, the recommended rates range between 98 and 195 kg/ha/yr (Schultz 1999) and are lower when the clippings are left to decompose on the turf

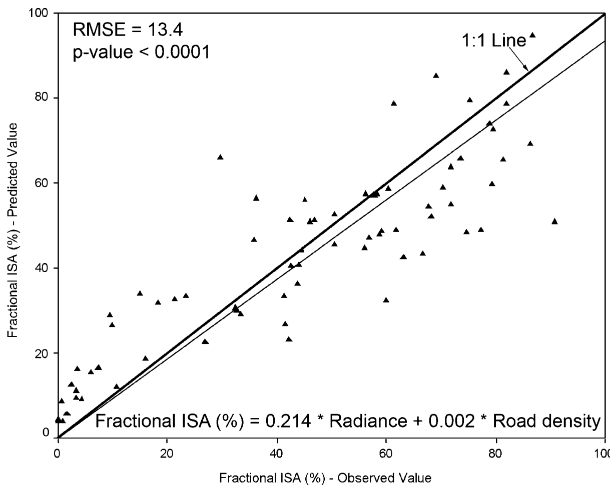

Figure 3. Scatter diagram of the observed values of fractional Impervious Surface Area (ISA) versus the values predicted from linear regression and equation for the predictive regression model used to estimate the 1-km grid of fractional ISA for the conterminous United States.

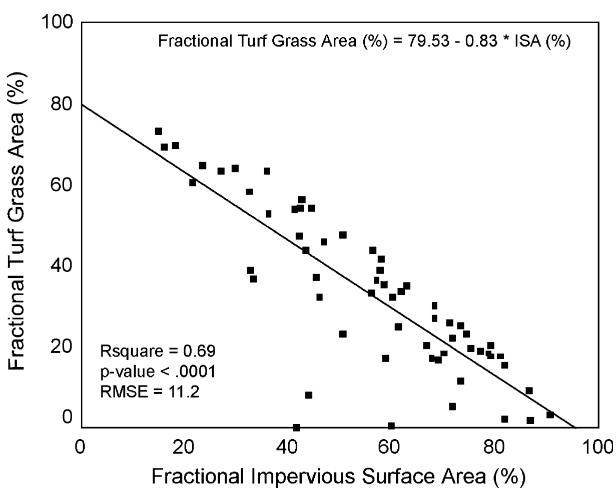

Figure 4. Scatter diagram of the direct measurements of fractional turf grass area and fractional Impervious Surface Area (ISA) and equation for the predictive regression model used to estimate the total U.S. surface under turf from the 1-km grid of fractional ISA.

surface rather than composted or bagged and sent to the landfill. Many residential lawns are managed by homeowners who pay little attention to the amount of resources invested for lawn maintenance and often receive excess water and fertilizer. On the other hand, there also are some areas cultivated with turf grasses that are not adequately watered and fertilized, spending part of the growing season in a dormant stage.

In this study, the simulation of the impact of different turf grass management practices on the continental C and water budget was based on the simplifying assumption that, under a given scenario, the entire turf surface is managed homogeneously, such as irrigated with the same criteria, fertilized with the same amount of N, and mowed at the same height, whether it would be part of a residential lawn or a golf course. Although this assumption largely simplifies reality, it allows developing a first estimate of the potential national impacts of turf grasses on ecosystem functioning by asking: how would the continental C and water budgets be affected if all the surface currently under turf was to be managed like a well-maintained lawn?

We adapted the Biome-BGC ecosystems process model to predict C and water fluxes of turf ecosystems at 865 sites distributed across the United States, corresponding to populated places that, according to the 2000 U.S. Census, had a population of at least 40,000 people (the list of populated places is available online at: http://www.census.gov/geo/www/gazetteer/places2k.html). Biome-BGC has been extensively documented and validated (Thornton and others 2002, White and others 2000, Kimball and others 1997, Hunt and others 1996, Running 1994, Running and Hunt 1993, Running and Gower 1991, Running and Coughlan 1988). Biome-BGC uses prescribed site conditions, meteorology, and parameter values to simulate daily fluxes and states of C, water, and N for coarsely defined biomes, at areas ranging from 1 m^2 to the entire globe. Biome-BGC can be used to simulate these fluxes for more specifically defined ecosystems when appropriately parameterized. Adapting Biome-BGC for simulating the ecosystem processes of turf grasses required modifying the default parameterization for C3 (cool season) and C4 (warm season) grasses to reflect the higher specific leaf area as well as the lower C:N ratio of leaf, litter, and fine roots of fertilized and watered turf grasses. Leaf C:N ratio was assigned to 20 and litter C:N ratio was assigned to 40, as suggested by Bandaranayake and others (2003). We also modified the lignin, cellulose, and labile portions of fine roots to, respectively, 12%, 52%, and 36% (Bandaranayake and others 2003), while the canopy average specific leaf area (SLA) was increased to the upper range of SLA values observed for grasses (White and others 2000) and set to 70 m^2/kg C.

Mowing activities were simulated as mortality processes that would take place every time the leaf area index (LAI) reached a critical value of 1.5. The mortality event was assumed to remove 20% of LAI and the corresponding amount of fine roots. Removal of the clippings was simulated by removing the portion of C and N associated with the cut leaves from the ecosys-

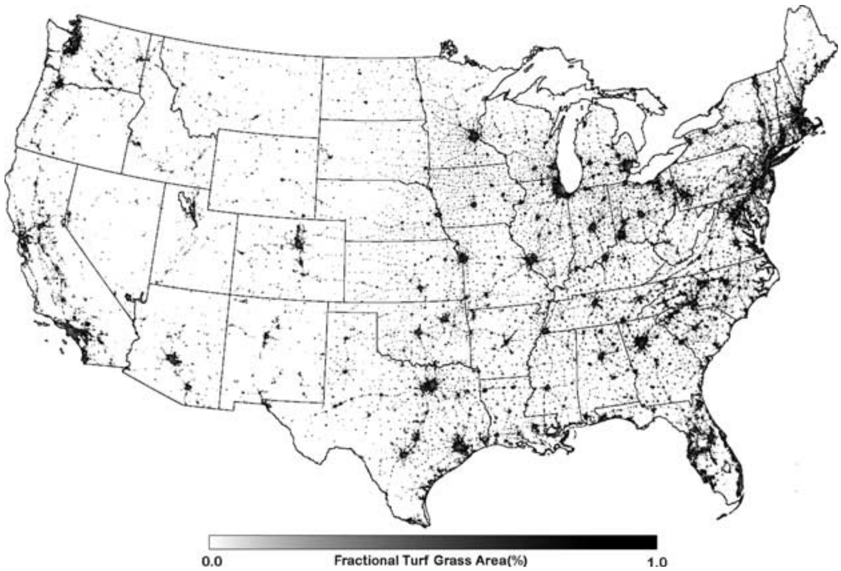

Figure 5. Distribution of the fractional turf grass area in the conterminous United States.

tem process. In the cycling scenario, the C and N associated with the cut leaves were left on the site to decompose as litter.

N was added to the system at a constant rate, simulating a slow-release fertilizer. To evaluate the effect of clipping cycling on grasses N availability, N was applied at two different rates in contrasting simulation runs. Clippings were either removed or cycled in scenarios simulating an application of 146 kg N/ha/yr and cycled in scenarios with an application of 73 kg N/ha/yr.

Irrigation during the growing season was simulated by adding water to the precipitation field in the climate parameterization. We assumed that the sprinkling season of a certain location would start when the minimum temperatures remained above 5°C for 7 consecutive days in the spring, and end when minimum temperatures decreased below 5°C for 7 consecutive days in the fall. Although the start and end of the sprinkling season are generally determined arbitrarily and may incorporate other climatic factors, we found the chosen temperature threshold to represent an acceptable approximation of the growing season and, consequently, of the evapotranspirational season of turf grasses. The simulations assumed water to be sprinkled following two different watering management types. In one type of watering management, we followed the common recommendation that during the growing season, turf grasses require about 2.54 cm (1 inch) of water per week (Schultz 1999). In the simulations, in the case of rainfall, rain made up for part of this amount. In the real world, it is common that sprinklers, especially if automated, run also on rainy days. The alternative watering management scenario, rather than providing a fixed weekly amount of water, modulated the irrigation based on the potential evapotranspiration (PET) and precipitation, the former calculated according to Priestly and Taylor (1972). In this case, irrigation was simulated to be triggered when the PET minus precipitation, accumulated since the last watering event, exceeded 60% of the added water. Irrigation then replaced 20% of the PET, bringing the water availability to nearly 80% of PET. The effect of the two different water management practices on the C and water balance was evaluated comparing scenarios in which N added through fertilization was constant and irrigation was either fixed at 2.54 cm of water/week or modulated according to PET.

For the 865 selected populated places, soil texture information was extracted from the STATSGO database (Miller and White 1998) and 18 years of climate data were obtained from the Daymet dataset (Thornton and others 1997). The simulation sites were assumed to grow C3 (cool season) or C4 (warm season) turf grasses based on adaptation zones (Beard 1973, Time-Life Books 2000). In cities located in the C3-C4 transitional region, the grasses were assumed to be a mixture of both photosynthetic models and the simulation was run twice, once for each type of grass. The resulting C and water fluxes in the transitional region were determined to be an average of the two runs, assuming that half of the surface was growing C3 grasses and half C4 grasses. All the C and water fluxes are reported as an average of the 18-year model simulation results.

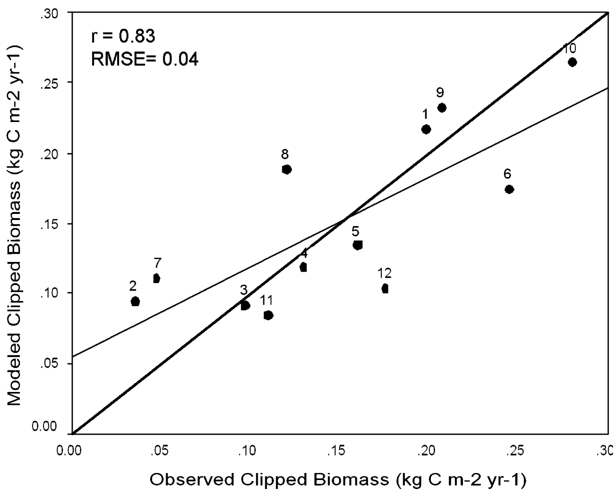

Figure 6. Scatter diagram of the modeled versus observed grass clipping yields expressed in C biomass (kg/m^2/yr). 1*–Observed and modeled data at Santa Clara, CA, clippings removed, N rate 146.5 kg/ha/yr (Harivandi and others 1996); 2–Observed at Spring Manor Farm (SM), Storrs, CT, clippings removed (bagged), N rate 0 kg/ha/yr, modeled at Hartford, CT (Kopp and Guillard 2002); 3–Observed at SM, Storrs, CT, clippings removed, N rate 98 kg/ha/yr, modeled at Hartford, CT (Kopp and Guillard 2002); 4–Observed at SM, Storrs, CT, clippings removed, N rate 146.5 kg/ha/yr, modeled at Hartford, CT (Kopp and Guillard 2002); 5–Observed at SM, Storrs, CT, clippings removed, N rate 196 kg/ha/yr, modeled at Hartford, CT (Kopp and Guillard 2002); 6–Observed at SM, Storrs, CT, clippings removed, N rate 392 kg/ha/yr, modeled at Hartford, CT (Kopp and Guillard 2002); 7–Observed at SM, Storrs, CT, clippings cycled, N rate 0 kg/ha/yr, modeled at Hartford, CT (Kopp and Guillard 2002); 8–Observed at SM, Storrs, CT, clippings cycled, N rate 98 kg/ha/yr, modeled at Hartford, CT (Kopp and Guillard 2002); 9–Observed at SM, Storrs, CT, clippings cycled, N rate 196 kg/ha/yr, modeled at Hartford, CT (Kopp and Guillard 2002); 10–Observed at SM, Storrs, CT, clippings cycled, N rate 392 kg/ha/yr, modeled at Hartford, CT (Kopp and Guillard 2002); 11–Observed at Rutgers, NJ, clippings removed, N rate 97.6 kg/ha/yr, modeled at Edison, NJ (Heckman and others 2000); 12–Observed at Rutgers, NJ, clippings removed, N rate 195.2 kg/ha/yr, modeled at Edison, NJ (Heckman and others, 2000). *Only C4 grass site. Points 2–12 refer to sites growing C3 grasses.

The growth of turf grasses at the 865 sites was simulated for the following five different scenarios:

- Control: Turf grasses growth was simulated with no management (no irrigation and no N fertilization) except for cycling of the clippings;
- Removed-146N: The grass was irrigated during the growing season so that a total of 2.54 cm of water per week, rainfall included, was provided, fertilized with 146 kg N/ha/yr, and the clippings were removed from the system after each mowing event;
- Cycled-146N: same as Removed-146N, except for the clippings, which were left on the site after each mowing event;
- Cycled-73N: same as Cycled-146N, except for the amount of fertilizer, which was halved to 73 kg N/ha/yr;
- Cycled-73N-PET: same as Cycled-73N, except for the irrigation management, which was calculated based on Priestly-Taylor PET.

Mann-Whitney *U*-test for differences was used to evaluate whether model results under the five scenarios differed significantly from each other.

The net accumulation of C in the ecosystem was estimated by calculating the Net Ecosystem Exchange (NEE), where NEE = Net Primary Productivity (NPP) – heterotrophic respiration – fluxes of C out of the ecosystem. Fluxes of C out of the ecosystem refer here to the C removed with the clippings.

The simulation results were extrapolated to the continental surface, assuming that turf areas in the vicinity of a simulation site displayed similar C and water fluxes. The continental United States was divided into Thiessen polygons centered on the simulation sites to identify individual ''regions of influence'' around each of the 865 simulation localities. The output results at each simulation site were then multiplied by the total turf area estimated within the respective polygon.

Model Validation

There are only a few studies on the effect of turf grass management on the C budget. The adaptation of Biome-BGC to simulate the growth of turf grasses was validated by comparing the simulated clipping yield with published clipping yield data (C was assumed to represent 48% of the dry yield). Two studies (Kopp and Guillard 2002, Heckman and others 2000) presented clipping yields under different N fertilization rates for C3 grasses. Kopp and Guillard (2002) present yields both for removed clippings and for recycled clippings. Only one value of clipping yield was available for C4 grasses (Harivandi and others 1996). The measured versus modeled yield data showed a strong and highly significant correlation ($r = 0.83$, $P < 0.0001$) (Figure 6).

Results and Discussion

Estimation of Turf Grass Area

The total turf grass area estimated in this study summed up to 163,800 km^2 (± 35,850 km^2 for the upper and lower 95% confidence interval bounds) (Table 1). This estimate, intended to include all residential, commercial, and institutional lawns, parks, golf courses, and athletic fields, accounts for approximately 1.9% of the total continental U.S. area, which compares with 3.5–4.9% of the total surface estimated to be devoted to urban development (Nowak and others 2001, National Association of Realtors 2001). Although it is difficult to validate the estimate of total turf grass area derived from this analysis, it reasonably compares to the estimates of the other studies, in particular when considering the recent growth in population and urban areas in the United States (Fulton and others 2001). DPRA, Incorporated (1992), assuming turf surface to be directly related to the population, estimated a total surface of 188,180 km^2, among which 94,090 km^2 were of home lawns (Grounds Maintenance 1996). A 1987 study by Roberts and Roberts (1987) estimated a total surface of 100,000–120,000 km^2. Another study, focusing only on residential lawns, analyzing state-based average lot sizes of single family homes, estimated a total home lawn area ranging between 58,000 km^2 and 71,680 km^2, considerably downsizing DPRA's estimate of home lawns (Vinlove and Torla 1995). One of the earliest estimates of total turf surface dates back to the late 1960s, when it was reported that 67,000 km^2 of lawn existed nationally (Falk 1976).

Even when the estimate of total surface is considered to be closer to the lower bound of the 95% confidence interval (128,000 km^2), it appears that turf grasses would represent the single largest irrigated "crop" in the United States, occupying a total area three times larger than the surface of irrigated corn (43,000 km^2 according to the 1997 Census of Agriculture, out of 202,000 km^2 of total irrigated cropland area).

Water Budget

The two alternate irrigation methods produced watering requirements that varied widely across the climatic regions of the 48 states, with the yearly total amount of water that needed to be provided through irrigation at each site depending both on the total rainfall and its distribution during the growing season and the length of the sprinkling season. In general, a fixed irrigation management based on turf requirements of 2.54 cm of water per week, including rainfall, resulted in a minimum of no irrigation in Lincoln Park, Michigan (meaning that here rainfall alone is able to satisfy the watering requirements of the turf throughout the growing season) to a maximum of 125 cm of water per year to be added through irrigation in Yuma, Arizona. In contrast, the irrigation management based on PET tended to decrease the amount of water supplied through irrigation in wet regions and increase it in arid and semiarid regions of the United States, where it was by far larger than 2.54 cm/week. Modulating irrigation according to PET required a minimum of 17 cm/yr of water to be added through irrigation in Pensacola, Florida, to a maximum of 197 cm/yr in Yuma, Arizona. The Mann-Whitney *U*-test for differences indicated that the two irrigation methods would provide significantly different annual amounts of water at 77% of the 865 sites. The sites with no significant difference between the two irrigation methods were all but three located just east of the Great Plains. The spatially interpolated differences in irrigation water use between the two irrigation managements (Figure 7) indicates that adopting the PET-based method versus applying constantly 2.54 cm/week would result in a larger amount of water sprinkled in the West, with a maximum difference of up to 72 cm/yr in the Southwest, and less water in the southeastern United States, with a reduction in water use of up to 38 cm/yr in southern Florida, where the high relative humidity reduces the evapotranspirational demand.

Extrapolating the water use for irrigation with the two methods at each of the 865 sites to the surface of turf grasses contained in the respective Thiessen polygons yields an average total of 73,560 Mm^3 (Mega cubic meters) of water with the constant 2.54 cm/week method and 95,100 Mm^3 of water with the PET method, while rain contribution during the sprinkling season to the watering of the total estimated turf grass area would amount to 99,130 Mm^3 (Figure 8).

These estimates indicate that, in the scenario that the entire turf surface in the United States was to be irrigated to satisfy the 2.54 cm/week water supply or at 80% of PET, domestic and commercial consumptive water use would be, respectively, 695 to 900 liters of water per person per day. Noteworthy is that in spite of the elevated irrigation requirements, there appears to be a considerable amount of water leaving the soil layer as outflow (water in excess of field capacity) rather than evapotranspiration (56,620 to 57,670 Mm^3 of water, depending on the irrigation management scenarios). Ninety percent of the estimated outflow takes place in the eastern and southern United States, where it is related to rainfall rather than sprinkling events. On occasions of abundant rainfall, precipitation is larger than the soil water-holding capacity and leaves the soil before the grass can use it for evapotranspiration. In spite of a surplus of available water during the rainy periods, sprinkling is still required during the drier periods.

Table 1. Estimates of turf grass area by state

	Turf grass area (km^2)		
State	Mean	Upper 95% C.I.	Lower 95% C.I.
Alabama	3130	3741	2520
Arizona	2559	3178	1941
Arkansas	2098	2519	1679
California	11159	13890	8434
Colorado	2478	3047	1910
Connecticut	2429	2946	1913
Delaware	533	644	422
District of Columbia	57	86	28
Florida	11570	14221	8925
Georgia	5688	6848	4530
Idaho	942	1133	751
Illinois	5729	7102	4359
Indiana	3843	4679	3008
Iowa	2227	2772	1822
Kansas	2004	2453	1555
Kentucky	2446	2935	1958
Louisiana	3377	4099	2656
Maine	975	1157	793
Maryland	2471	3013	1929
Massachusetts	4183	5054	3314
Michigan	4538	5598	3480
Minnesota	3176	3866	2487
Mississippi	1969	2362	1578
Missouri	3442	4217	2669
Montana	735	884	585
Nebraska	1149	1401	898
Nevada	928	1162	694
New Hampshire	1126	1339	913
New Jersey	3942	4885	3002
New Mexico	1545	1860	1231
New York	6320	7770	4873
North Carolina	8112	9715	6512
North Dakota	572	693	452
Ohio	6733	8213	5257
Oklahoma	2689	3294	2086
Oregon	1977	2406	1549
Pennsylvania	7293	8789	5799
Rhode Island	506	622	390
South Carolina	4034	4822	3248
South Dakota	692	829	555
Tennessee	4201	5064	3339
Texas	13187	16242	10138
Utah	1207	1493	922
Vermont	524	621	427
Virginia	4544	5510	3581
Washington	3579	4345	2814
West Virginia	1459	1731	1189
Wisconsin	3110	3764	2457
Wyoming	554	665	444
Total U.S.	163,812	199,679	128,016

If irrigation could just replace actual evapotranspirational losses, the water to be added through sprinkling would amount to 11,070 Mm^3 in the case of the 2.54 cm/week method and 33,300 Mm^3 with the PET-based method. The large increase in water requirements with the PET-based method has to be attributed to the arid western United States, where grasses can evaporate much more than 2.54 cm of water per week if more irrigation is supplied. Still, part of the water reaching the surface during the growing season, either from precipitation when abundant rainfall occurs, or from the sprinkler, due to Priestly-Taylor PET overestimating actual evapotranspiration, would not be used by the grass and would leave the soil layer as outflow.

Carbon Budget

Table 2 reports the ranges in C fluxes and mowing counts for the control and the four management scenarios. In general, the simulation results indicate that the C fluxes of a well-watered grass increase with the amount of available N. For a certain amount of N input through fertilization, the C fluxes were larger when cycling of the grass clippings was simulated, since the onsite decomposition of the mowed grass clippings returned a consistent amount of N to the soil. For each scenario, differences in the maximum–minimum ranges are related mainly to the growing season length.

Unsurprisingly, the control scenario displays the lowest range of C fluxes, and the lowest range of mowing counts, which are both significantly different from all the other scenarios at all 865 sites. The low number of mowing counts simulated in the control scenario let us infer the obvious: in the absence of irrigation and fertilization, turf grasses would not be able to grow in most of the United States. A general guess of where turf grasses could grow with no added resources of N and water can be inferred by calculating the number of days between successive mowings (ratio of yearly mowing counts to growing season length). Assuming that turf grasses should grow back to an LAI of 1.5 in at least 30–35 days in order not to be outcompeted by weeds, Figure 9 shows that monocultures of turf could probably grow without managed inputs of water and fertilizer only in a few of the modeling sites, all but one located in the northeastern portion of the country (the site in the western United States corresponds to Flagstaff, AZ). If turf grasses reach an LAI of 1.5 only six to seven times in areas where the growing season is as long as 300–360 days, then it is probable that between subsequent cuts there are several opportunities for nonturf species to invade the surface and prosper over time. Because the LAI is reduced by 20% every time the LAI would reach the value of 1.5, the NPP of an unmanaged turf would be considerably lower than that of natural grasslands, which in tem-

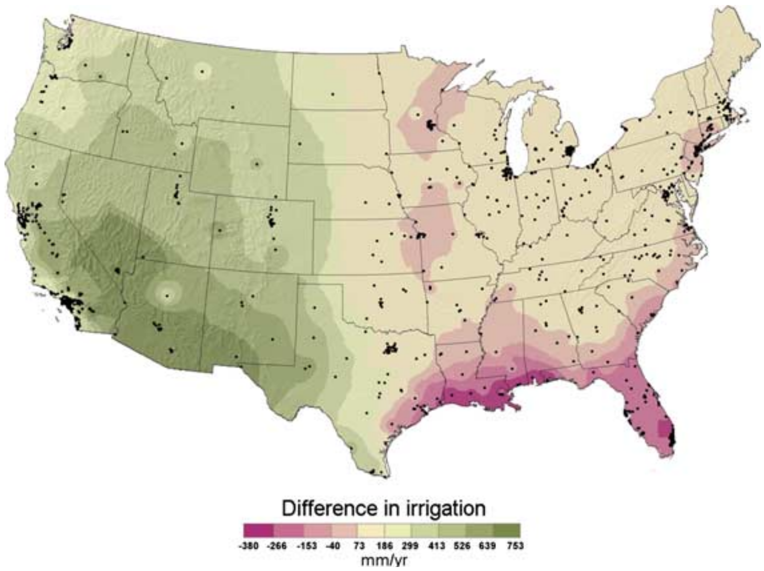

Figure 7. Spatially interpolated differences in irrigation water use between the two irrigation methods.

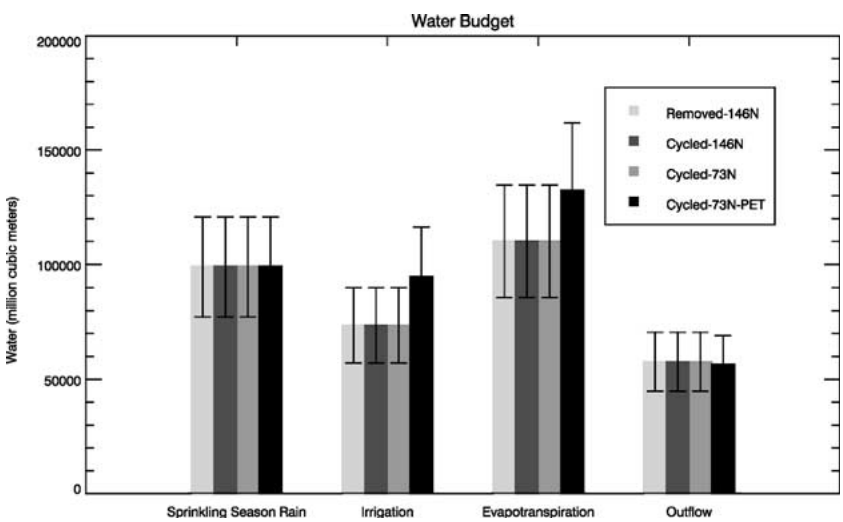

Figure 8. Water budgets of the total U.S. turf surface for the four management scenarios. Error bars indicate budget values calculated for the 95% confidence interval lower and upper bound estimate of total turf surface.

perate ecosystems ranges between 320 and 750 $g/m^2/yr$ (Saugier and others 2001, Schlesinger 1997).

The largest C fluxes are realized for scenario Cycled-146N, in which Mann-Whitney *U*-test for differences in C fluxes and mowing count indicates that this scenario is significantly different from the other scenarios for all the variables measured at the 865 sites ($P < 0.01$). Abundant fertilization (146 kg N/ha/yr) and the recycling of the N contained in the leaves left to decompose on the site boosts both the productivity as well as the heterotrophic respiration. As a consequence of the higher productivity of turf grasses in this scenario, there is also an increase in mowing frequency, which can reach 98 cuts per year in those sites where climatic conditions favor year-round growing season, resulting in about two cuts per week.

Scenario Removed-146N produces the second highest NPP and clipped biomass ranges. Because the clipped biomass is assumed to be removed from the turf surface, very low on-site decomposition activity results in the smallest C fluxes from heterotrophic respiration.

In scenario Cycled-73N, the C fluxes are significantly lower ($P < 0.01$) at all sites when compared to those of Removed-146N and lower in 88–92% of the sites when compared to Cycled-146N.

Scenario Cycled-73N-PET, which differs from Cycled-73N only for the type of water management, modulating irrigation according to PET rather than supplying a weekly fixed amount of water, does not produce significantly different C fluxes from Cycled-73N at any of the 865 sites. Mann-Whitney *U*-test at 5%

Table 2. Minimum and maximum values of the modeled C fluxes and mowing counts

Carbon fluxes (g C m^{-2} yr^{-1})	Control	Removed-146N	Cycled-146N	Cycled-73N	Cycled-73N-PET
NPP	22–121	257–641	281–1063	184–604	195–613
Clippings	0–34	79–207	87–348	55–195	58–198
Heterotrophic respiration	31–121	138–392	210–922	140–533	150–542
Mowing counts (cuts yr^{-1})	0–7	16–52	22–98	14–55	16–56

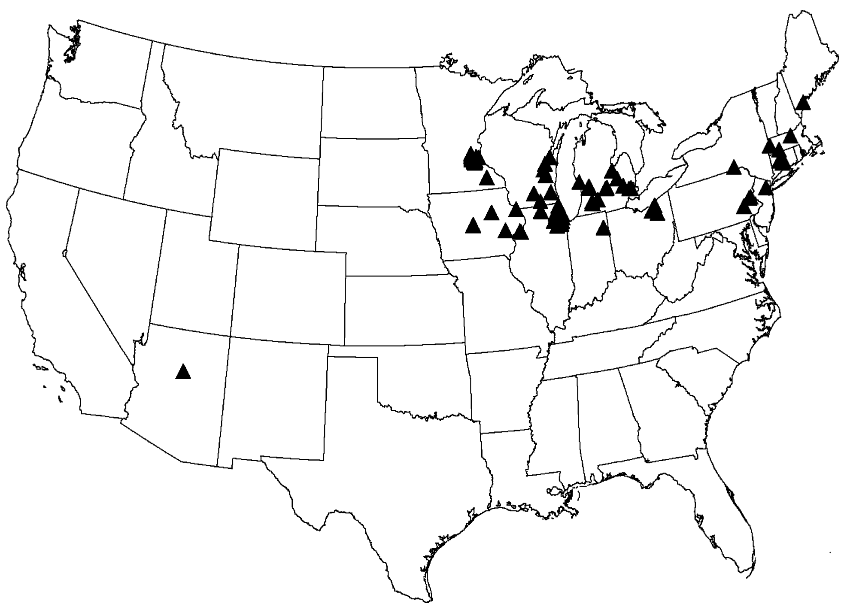

Figure 9. Modeling sites where growth of turf grasses appears to be possible without irrigation or fertilization.

significance level indicates a water effect on NPP and clipped C at 7% of the sites, and an effect on heterotrophic respiration at 5% of the sites.

Large differences in total C fluxes can be realized under the same irrigation management of 2.54 cm of water per week, all resulting in very large losses of water through outflow (Figure 8). This result is most probably explained by the fact that in all the simulated management scenarios water is not limiting growth, which responds rather to increases in N availability. The large increase in water application observed when modulating irrigation according to PET, on the other hand, results in an insignificant change in C fluxes, indicating that the water is lost in luxury evapotranspiration.

The estimation of the total C budget for the continental U.S. turf surface under the five scenarios examined (Figure 10) indicates that the highest NEE is recorded for the Cycled-146N scenario, amounting to 16.7 Tg C/year. The lowest NEE is recorded for the Removed-146N scenario, for which the removal of the clippings from onsite decomposition reduces the C sink to just 5.9 Tg C/yr, in spite of the fact that the same amount of N as in Cycled-146N is added through fertilization (a total of 2.39 Tg N/yr for the total estimated surface under turf). Offsite composting of the clippings allows recuperating part of the C. On the other hand, the practice, nowadays less common, of sending the clippings in trash bags to the landfill leads, through anaerobic decomposition, to the production of methane, a powerful greenhouse gas. Reducing the N fertilization by half in scenarios that recycle the clippings (Cycled-73N and Cycled-73N-PET) lowers the NPP by 36–37% and the NEE by 45% compared to the Cycled-146N scenario but also considerably lowers the number of times the grass needs to be cut throughout the growing season. The C budget for the control scenario, on the other hand, results in a small source of carbon, since the total heterotrophic respiration (15.5 Tg C/yr) slightly surpasses the total NPP (15.3 Tg C/yr), bringing the NEE for the control scenario to –0.2 Tg C/yr.

Therefore, if the entire area was well watered and fertilized, we would have a positive NEE, even when assuming the bagging and removal of the grass clippings. A positive NEE means that more carbon is

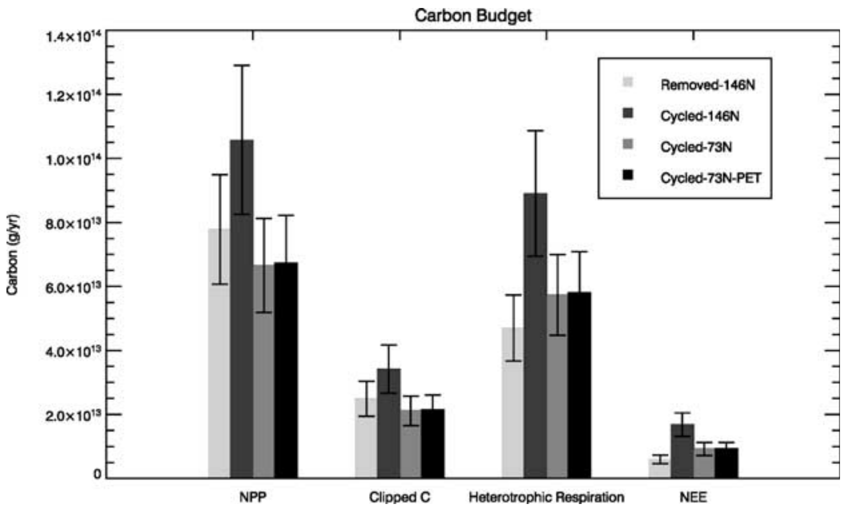

Figure 10. Carbon budgets of the total U.S. turf surface for the different simulations. Error bars indicate budget values calculated for the 95% confidence interval lower and upper bound estimate of total turf surface. The carbon budget for the control scenario is negligible and therefore not displayed. NPP, Net Primary Productivity; NEE, Net Ecosystem Exchange.

accumulated in the turf grass system than is released through respiration processes and, eventually, removed with the clippings, indicating that the soils of lawns and golf courses that are left undisturbed for a few decades have the potential to sequester a consistent amount of C in their soils. The sink is generally stronger when more N is available. N availability can be increased both through increased fertilization or, more efficiently, by leaving the clippings to decompose on the site after mowing. Merely applying a larger amount of N through the use of synthetic fertilizer without recycling the clippings would reduce the potential gain in C sequestration because of increased discounts due to the C costs of manufacturing, transporting, and commercializing the fertilizer (Schlesinger 1999). These C costs are in addition to the ones deriving from the operation of lawn mower equipment, distributing water for irrigation, and from transporting and decomposing the clippings in the landfill.

In addition to the associated C costs, the current high-input choices made by consumers and professional turf managers for maintaining monocultures of turf grasses typical of many lawns and play fields comes at the risk, not analyzed here, of watershed pollution due to improper fertilization and use of pesticides (Petrovic 1990). The input levels of herbicide and insecticide per unit area of turf are often several times larger than in their agricultural counterparts, independently from the consumer's knowledge and understanding of personal health risks and negative environmental effects associated with the use of these products (Robbins and Sharp 2003a, 2003b).

Beneficial effects of turf grasses, such as a carbon sequestration but also recreation, storm runoff reduction due to increased soil infiltration in occasion of intense rainfall, and removal of impurities and chemicals during percolation of the water through the root zone, could be sought by minimizing the application of fertilizers and pesticides, introduction of lower input species mixes such as clover and other so-called weeds (Bormann and others 1993), on-site decomposition of the grass clippings, and extending the practice of irrigating with waste water rather than with drinking water.

Conclusions

In this study, we mapped the total surface of turf grasses in the continental United States and simulated its potential C and water budgets. We also provided a description of how the C and water budgets can be affected by adopting different management practices for irrigation, fertilization, and the fate of the clippings. Rather than trying to accurately quantify the existing fluxes, we simulated scenarios in which the entire surface was to be managed like a well-maintained lawn, a thick green carpet of turf grasses, watered, fertilized, and kept regularly mown. The accuracy of the results is therefore limited by both the uncertainty in the mapping of the total lawn area and by the simplifying assumptions made in the modeling of the growth of turf grasses.

The analysis indicates that turf grasses, occupying 1.9% of the surface of the continental United States, would be the single largest irrigated crop in the country. The scenarios described in this study also indicate that a well-maintained lawn is a C sequestering system, although the positive C balance has to be discounted for a very large use of water and N and, not quantified in this study, pesticides. The model simulations have assumed a conservative amount of fertilization (a maximum of 146 kg N/ha/yr). In general, the rates of N applications are similar to those used for row crops, and N losses from turf surfaces can contribute to non-point source pollution when fertilization takes place improperly.

If the entire turf surface was well watered following commonly recommended schedules, there would be very large pressure on U.S. water resources, especially when considering that drinking water is usually sprinkled. At the time of this writing, in most regions outdoor water use already reaches 50–75% of the total residential use. Because of demographic growth and because more and more people are moving towards the warmer regions of the country, the potential exists for the amount of water used for turf grasses to increase. Several counties in the arid and semiarid regions of the United States have already implemented lawn watering restrictions, the recycling of wastewater to replace drinking water for outdoor sprinkling, and incentives to increase the use of xeriscaping. Although turf grasses also provide important ecological benefits such as slower storm runoff, improved water infiltration, and holding soil in place on sloping terrains, to protect our water resources as further urban growth takes place other regions will probably need to extend the practice of recycling wastewater for outdoor use while continuing to educate the population on the value of water resources.

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