A STRATEGY FOR MAPPING AND MODELING THE ECOLOGICAL EFFECTS OF US LAWNS

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ABSTRACT:

Lawns are ubiquitous in the American urban landscapes. However, little is known about their impact on the carbon and water cycles at the national level. The limited information on the total extent and spatial distribution of these ecosystems and the variability in management practices are the major factors complicating this assessment. In this study, relating turf grass area to fractional impervious surface area, it was estimated that potentially 163,812 km^2 ($\pm$ 35,850 km^2) of land are cultivated with some form of lawn 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 turf grasses was modelled for 865 sites across the 48 conterminous states under different management scenarios, including either removal or recycling of the grass clippings, different nitrogen fertilization rates and two alternative water irrigation practices. The results indicate that well watered and fertilized turf grasses act as a carbon sink, even assuming removal and bagging of the grass clippings after mowing. The potential soil carbon accumulation that could derive from the total surface under turf (up to 25.7 Tg of 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, and a cost in carbon emissions due to fertilization and operation of mowing equipment ranging from 15 to 35% of the sequestration.

1. INTRODUCTION

Lawns are ubiquitous in the American urban landscapes, as they can be found on most residential lots, parks, institutional and commercial landscapes, and golf courses, often as monocultures of turf grasses, independently of the local climate (Jenkins 1994). Existing estimates indicate that in the early 1990's the surface cultivated with turf was up to three times larger than that of irrigated corn, the largest irrigated crop in the U.S. (DPRA, Incorporated 1992).

Turf grasses contribute to soil carbon (C) sequestration (Bandaranayake et al., 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 et al., 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 over-fertilization (Robbins and Sharp, 2003; Robbins et al., 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 et al., 1999).

In spite of the pervading presence of turf grass systems in the urban and suburban landscape and their considerable use of water resources, there continues to be little knowledge about the ecological functioning of these systems at the national level. If turf grasses are to be considered carbon sequestering components of the urban ecosystems, what is their contribution to the national carbon sequestration potential? And what is the estimated water use to sustain this sequestration potential? 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 answering these questions.

In this study we present an estimate of the carbon sequestration potential of U.S. lawns and the implied water use by producing a spatially explicit estimate of their distribution within the contiguous 48 states and simulating their growth with an ecosystem process model.

2. METHODS

2.1 Estimation of U.S. turf surface

Due to its high level of fragmentation, direct mapping of the total surface under turf in the U.S. is impractical. 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, road sides, etc. DPRA, Incorporated (1992), 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 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 used the 1-km gridded fractional cover of Impervious Surface Area (ISA) for the continental U.S. derived by Elvidge et al. (2004). Ground calibration for the creation of this dataset was provided by 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 from 80 high-resolution aerial photographs collected along development transect distributed across thirteen major urban centres distributed across the U.S.

The proportions of impervious versus vegetated surfaces derived from the high-resolution aerial photography tiles were 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 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 non-turf vegetated surfaces. The predictive model showed a moderately strong (R-square=0.69), highly significant (p-value < .0001, RMSE = 11.2) relationship between fractional ISA and fractional turf grass area and was subsequently applied to the conterminous U.S. to produce a 1-km grid of fractional turf area (Figure 1). For full details on the estimation of the continental area under turf refer to Milesi et al. (2005).

2.2 Modelling of turf grasses growth

Management of turf grasses is highly variable, and can range from high maintenance golf courses and athletic fields, which require high doses of fertilizer, to some residential lawns that are not adequately watered and fertilized, spending part of the growing season in a dormant stage. Many residential lawns, on the other hand, are managed by homeowners who pay little attention to the amount of resources invested for lawn maintenance and often receive excess water and fertilizer. Variability exists also in the fate of the clippings, which are either mulched and left decompose on the grass (recycling part of the nitrogen fertilizer) or removed, and composted or bagged and sent to the landfill. In this study the simulation of the impact of different turf grass management practices on the continental C sequestration potential 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.

We adapted the Biome-BGC ecosystems process model (Thornton et al., 2002; White et al., 2000) to predict C and water fluxes of cool season (C3) and warm season (C4) grasses turf ecosystems at 865 sites distributed across the U.S. Mowing activities were simulated as mortality processes that would remove 20% of the leaf area index (LAI) and of the fine roots every time the LAI reached a critical value of 1.5. Removal of the clippings was simulated by removing the portion of C and N associated with the cut leaves from the ecosystem process. In the cycling scenario, the C and N associated with the cut leaves were left on the site to decompose as litter. 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 18-year 1-km gridded climate data obtained from the Daymet dataset (Thornton et al., 1997). We assumed that the sprinkling season of a certain location would start when the minimum temperatures remained above 5 °C for seven consecutive days in the spring, and end when minimum temperatures decreased below 5 °C for seven consecutive days in the fall, as plants growth requires temperatures above freezing to take place. Two watering management scenarios were simulated. 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. 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, in this case 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. The simulation sites were assumed to grow either C3 (cool season) or C4 (warm season) turf grasses, or an equal mix of the two in the transitional region, based on adaptation zones (Beard 1973).

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 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.

More details on the simulation methods can be found in Milesi et al. (2005).

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 U.S. was divided into Thiessen polygons centered on the simulation

sites and the output results at each simulation site were then multiplied by the total turf area estimated within the respective polygon.

3. RESULTS AND DISCUSSION

3.1 Estimation of turf grass area

The total turf grass area estimated in this analysis summed up to 163,812 km^2 (± 35,850 km^2 for the upper and lower 95% confidence interval bounds). 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 et al., 2001; National Association of Realtors, 2001). Our estimate is compatible with the results from other studies, in particular when considering the recent growth in population and urban areas in the U.S. (Fulton et al., 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 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 1960's, 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 (127,962 km^2), it appears that turf grasses would represent the single largest irrigated "crop" in the U.S., 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).
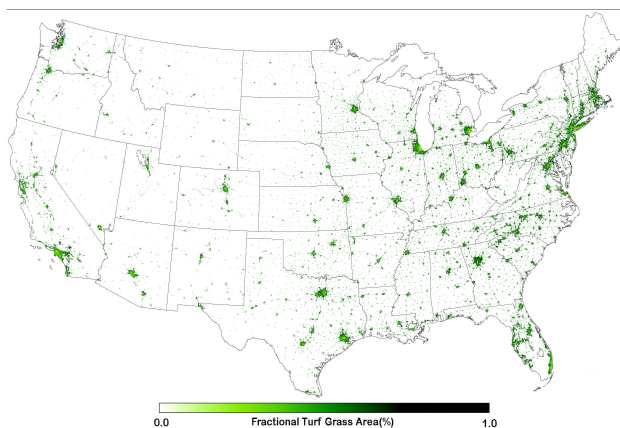

Figure 1. Distribution of the fractional turf grass area (%) in the conterminous U.S.

3.2 Water budget

The two alternate irrigation methods produced watering requirements that varied widely across the climatic regions of the 48 states. 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 U.S., 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. A 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, with a larger amount of water sprinkled in the West and less water in the humid southeastern US.

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 2).

These estimates indicate that, in the scenario that the entire turf surface in the U.S. 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). 90% of the estimated outflow takes place in the eastern and southern U.S., where it is related to rainfall rather than sprinkling events. In occasion 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.

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 increase in the water requirements with the PET-based method has to be attributed to the arid western U.S., 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 leave the soil layer as outflow.
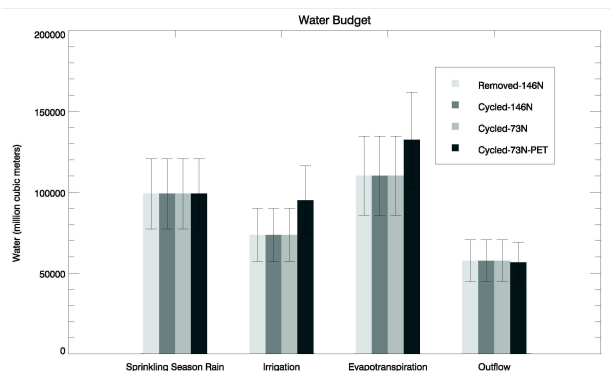
Figure 2. Water budgets of the total U.S. surface for the forus management scenarios. Error bars indicate budget values calculated for 95% confidence interval lower and upper buond estimate of total turf surface.

3.3 Soil carbon sequestration potential

The model simulation results referring to the C accumulating in soils in the five different management scenarios are reported in Table 1. The values represent the range in simulated soil C accumulation over the 18-year period of climate data for the 865 locations.

A comparison of the results under the 5 management scenarios reflects the notion that N fertilization increases the accumulation of carbon in the soil. For a certain amount of N input through fertilization, the C accumulations 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 range were related mainly to the growing season length.

The control scenario produced the lowest carbon accumulation (an average of 88 g C/m^2 over 18 years). The low number of mowing counts produced by the model in this scenario suggests that in most locations (most of the simulation sites except a few in the northeastern US) it would be impossible to grow a lawn as a monoculture of turf grasses with no irrigation and fertilization. If turf grasses reach an LAI of 1.5 only 6-7 times in areas where the growing season is as long as 300-360 days, then it is probable that between subsequent cuts there would be several opportunities for non-turf species to invade the surface and prosper over time.

The largest C accumulation was simulated for scenario Cycled-146N. Abundant fertilization (146 kg N/ha/yr) and the recycling of the N contained in the clippings left to decompose on the site produced an average C accumulation potential of 1978 g C/m^2 over 18 years.

The second largest soil C accumulations were simulated for scenarios Cycled-73N and Cycled-73N-PET, with an average reduction of 43% in C accumulation when compared with that simulated for Cycled-146N but with 50% less fertilizer. For Cycled-73N and Cycled-73N-PET the different water management had no significant effect on the carbon cycle.

In scenario Removed-146N, where the clippings are removed, the soil C accumulation was 60% less than in scenario Cycled-146N, although the same amount of external N was applied but no internal N recycling was allowed to take place because of the removal of the clippings.

	Control	Removed-146N	Cycled-146N	Cycled-73N	Cycled-73N-PET
Soil C (g C m^{-2} yr^{-1})	-8 – 7	27 – 60	64 – 149	37 – 67	37 – 67
(g C m^2 18-yr)	88	783	1978	1122	1119
Mowing counts	0 – 7	16 – 52	22 – 98	14 – 55	16 – 56

Table 1. Minimum and maximum values of the modelled annual gross soil C accumulation, 18-year increment in soil C, and mowing counts.

In the managed scenarios turf grasses present average annual increments in soil carbon comparable to the rates observed for crops cultivated with no-till practices (Ismail et al., 1994). Large differences in total C sequestration 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 2). 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.

Extrapolating the simulation results from the 865 sites to the total surface potentially under turf continental U.S., the total gross soil carbon sequestration ranged from 10.4 Tg C/yr in the Removed-146N scenario to 25.7 Tg C/yr in the Cycled-146N scenario (Figure 3). A modest 1.2 Tg C/yr was obtained from the unmanaged control scenario, since in most of the country turf grasses would not be able to survive without irrigation and fertilization. While the highest availability of N in the Cycled-146N scenario also produces the highest gross C sequestration potential, halving the input of external fertilizer to 73 kg N/ha/yr and recycling the clippings appears to be a more efficient approach to soil C accumulation than fertilizing with 146 kg N/ha/yr and removing the clippings.
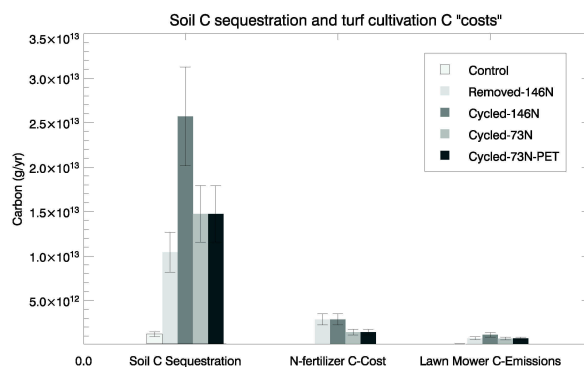

Figure 3. Annual gross soil carbon sequestration and C costs due to N fertilizer and lawn mower operation emissions.

From the perspective of evaluating the ecological effects of lawns in the U.S., the gross soil C sequestration potential values estimated from the model runs have to be discounted by the C emissions involved. At least two sources of emissions implied in the assumptions of this analysis can be quantified here. For example, there are emissions associated with N fertilization. While the input of N increases the soil C

accumulation potential, there is a linear increase in C emissions attributable to the synthesis, transport and commercialisation of the fertilizer, which is estimated around 1.4 moles of C per mole of N (Schlesinger, 2000). In scenarios Removed-146N and Cycled-146N, where 2.4 Tg N/yr would be distributed over the entire area potentially under turf, fertilization would contribute to 2.9 Tg C/yr, or 28% to 11% of the soil C sequestration respectively (Figure 3). In scenarios Cycled-73N and Cycled-73N-PET, the N fertilizer C "cost" would amount to 10% of the soil C sequestration potential.

A conservative estimate of the C emissions deriving from the operation of lawn mowers can be attempted using data from Christensen at al. (2001), reporting the emissions from a small engine 4-stroke lawn mower. Considering an emission rate of 250 g C/h and assuming an average mowing speed of 2000 m^2/hr, lawn mower emissions for the entire surface potentially under turf would range from 0.7 to 1.1 Tg C/yr depending on the management scenario, and only 0.1g TgC/yr in the control scenario (Figure 3). Adding the lawn mower C emissions to the N fertilizer related emissions would reduce the total gross C sequestration potential of lawns by 35% in the Removed-146N scenario and by about 15% in the other management scenarios. Further reductions in the C sequestration potential that cannot be accounted for with the available data are possibly connected with irrigation practices, especially were pumping is involved, and with the disposal of lawn clippings in landfills.

4. CONCLUSIONS

In this study we mapped the total surface of turf grasses in the continental U.S. and simulated its water use and C sequestration potential under different management practices for irrigation, fertilization and 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 while modeling turf grasses growth.

The analysis indicates that turf grasses, occupying about 2% of the surface of the continental U.S., 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 discounted for the hidden costs associated with N-fertilizer and the operation of lawn mowers comes at the expense of a very large use of water, 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 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.

If the entire turf surface was well watered following commonly recommended schedules there would also be an enormous pressure on the 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. 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, 1993), on site decomposition of the grass clippings and extending the practice of irrigating with waste water rather than with drinking water.

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