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The Effects Of Household Management Practices On The Global Warming Potential Of Urban Lawns

1. Introduction

Urban residential lawns comprise the majority of intensely managed turfgrass systems, covering 1.9% of land in the continental United States (Milesi et al., 2005) and increasing at an annual rate of 800,000 ha (U.S. Depart. of Housing and Urban Development, 2000). Typical lawn maintenance involves mowing, management of lawn clippings, fertilization, irrigation, etc. Maintaining an aesthetically appealing lawn is a common driver for lawn irrigation and fertilization (Nielson and Smith, 2005). Currently, turfgrass is the most irrigated crop in the U.S. (Milesi et al., 2005) and fertilization rates are close to agronomic row crops and golf courses (Barthe, 1995). Between 50 and 70% of homeowners throughout the U.S. fertilize their lawns regularly, but only a few homeowners base their application rates on soil test recommendations (Barthe, 1995; Fissore et al., 2011; Law et al., 2004; Robbins et al., 2001).

Urban lawn management practices such as no-till, irrigation and fertilization enhance net primary production and soil organic carbon (SOC) storage in turfgrass systems (Bandaranayake et al., 2003; Qian and Follett, 2002; Selhorst and Lal, 2013). Furthermore, turfgrasses are a perennial plant and have capability of long-term SOC storage (Pouyat et al., 2006). Turfgrass soils have a 2-fold higher SOC density than rural forest soils in southeast US (Pouyat et al., 2006). The carbon sequestration rates in golf fairways in Colorado can sequester SOC at a rate of 1.0 Mg ha^{-1} yr^{-1} during the first 25 years after conversion from crop land or native grassland (Qian and Follett, 2002). Conversion of arable lands to perennial grasses sequestered 1.1 Mg C ha yr^{-1} with fertilizer and irrigation (Post and Kwon, 2000). Increased fertilizer and irrigation management in a golf courses converted from farmlands sequesters an average of 3.1 Mg C ha^{-1} yr^{-1} (Selhorst and Lal, 2011).

Lawn management can also increase soil emissions of other greenhouse gases (GHGs), such as nitrous oxide (N_2O) (Groffman et al., 2009; Kaye et al., 2004; Townsend-Small and Czimczik, 2010). Lawn care practices can provide optimum conditions for N gaseous losses as N_2O, especially lawns receiving sufficient N and water. N_2O is a GHG with 310 times greater global warming po-tential (GWP) than CO_2 on a per molecular basis over a 100-yr time frame (IPCC, 2007). Rainfall or irrigation, especially right after fer-tilizer N applications, enhances N_2O emission, because the water inputs provide soil moisture contents essential for enhancing the nitrification and denitrification processes (Horgan et al., 2002). In addition, soil N_2O emission in turfgrass ecosystems might be enhanced by the increased SOC pools, thus increased supply of substrates for nitrification and denitrificaiton (Bouwman et al., 2002). N_2O emission has been found to overcompensate for car-bon sequestration in arable lands (Robertson et al., 2000) and urban turfgrass (Townsend-Small and Czimczik, 2010). Nevertheless, the impacts of turfgrass management practices of mowing, irrigating, fertilizing, and clipping placement on N_2O emissions and carbon sequestration in turfgrass ecosystems remain unclear. A complete turfgrass carbon and nitrogen cycle must be understood to develop best management practices (BMPs) for turfgrass to promote healthy turfgrass ecosystem and mitigate greenhouse gases emissions. In addition to the biogeochemical processes, it is important to un-derstand typical lawn management practices and the motivations for these practices. This information will provide a baseline against which to estimate GHG emissions reductions if lawn management practices were changed. In addition, this information can help de-cision makers select behaviors to target in outreach effort as well as strategies for changing those behaviors (Carrico et al., 2011; Dietz et al., 2009). Together this information can help inform the devel-opment of more effective BMP guidelines and communications.

To understand global warming contributions of turfgrass eco-systems, a full budget of all greenhouse gases and SOC sequestra-tion, as well as CO_2 emitted from energy use in lawn management is warranted. Nevertheless, it is impractical to make multi-decadal simultaneous measurements of SOC, N_2O, and CH_4 emissions. To address this issue, a process-based model was adopted io assess the impacts of turfgrass management practices on SOC sequestration, N_2O and CH_4 emissions, and net global warming potentials (GWP). The objectives of this study were: 1) to measure the impacts of common lawn care management regimes on N_2O fluxes at resi-dential lawn sites at Nashville, TN; 2) to investigate the N_2O and net GWP mitigation measures including variations of fertilizer appli-cation, irrigation, clipping placement, and mowing; and 3) to determine the net GWP of turfgrasses over time for three levels of lawn management intensity; 4) to examine the relation between lawn management practices and lawn appearance concerns and environmental concerns. The results can provide crucial insights into the potential role turfgrasses play in climate change and help develop BMPs for minimizing the global warming potential of turfgrasses.

2. Materials and methods

2.1. Study sites

Much of the data used in these analyses were collected as part of the Nashville Yard Project, an interdisciplinary project examining the environmental impacts of lawn care, as well as the psycho-logical, social, and legal influences on lawn management behavior. The study site is the Richland Creek Watershed (RCW), which en-compasses an area of 73.8 square kilometers in Metropolitan Nashville, Tennessee. The RCW is comprised mostly of private residences, but also contains several municipal parks, four golf courses, and some industrial sites near the Cumberland River. The Tennessee Department of Environment and Conservation lists the RCW as impaired due to excessive nutrient pollution and *Escherichia coli*.

2.2. N_2O measurements

Nitrous oxide emissions were monitored using the closed chamber method (Crane II and Hornberger, 2012) between Jan 1 2012 and Dec 31 2012. For each measurement, the chamber was fitted to a PVC collar permanently installed into the lawn soil to form a tight seal. During non-sample collection periods, the area of the landscape within the collars remained open to the atmosphere. The static chamber tops were tightly fitted on the collars for 30 min to allow the N_2O gas to accumulate under the chamber, and sam-ples were taken 0, 15, and 30 min after chamber top placement. N_2O samples were analyzed $\leq$48 h after sample collection using a Shi-madzu GC-2010 Plus (Shimadzu Scientific Instruments, Kyoto, Japan).

2.3. The DNDC model

In this study, we applied the DNDC (DeNi-trification–DeComposition) model to simulate turfgrass growth, soil carbon and nitrogen cycles, and trace gas emissions under a wide range of turfgrass management conditions. DNDC is a process-based model that simulates carbon and nitrogen cycling processes in soil-plant-atmosphere system (Li et al., 1992). The detailed description of the DNDC model has been presented by Li, (2000) and Zhang et al., (2002).

The DNDC perennial grass crop parameter set gave the closest match to turfgrass in this study. We modified the default parame-terization for perennial grasses to reflect the characteristics of turfgrass ecosystems. Adjustments of the following default DNDC settings: Leaf and stem C:N ratio was assigned to 20 and root C:N ratio was assigned to 40 to account for the lower C:N ratio of leaf, litter, and fine roots of fertilized and irrigated turfgrass (Qian et al., 2003).

We simulated mowing activities as numerous biomass cutting events. 8% of aboveground standing biomass was cut off during each mowing (Qian et al., 2003). We then simulated clipping recycle as green manure application. Green manure is equivalent to fresh plant residue.

2.4. Model input data

Site specific soil texture was obtained from the USDA web soil survey. We collected soil samples using a tube sampler. We took a sample in conjunction with the household survey so we have up to 348 samples, and sent the soil to the University of Tennessee Agricultural Extension (UTAE) for analysis of soil bulk density, porosity, pH, and organic carbon content. The soil sampling and analysis followed the protocol of the UTAE. Meteorological data including daily maximum and minimum temperature, precipitation, and wind speed were obtained from the NOAA National Climatic Data Center at the station GHCND:USW00013897. The N deposition data was obtained from National Atmospheric Deposition Program.

There is significant variability in the how residential lawns are managed (Nielson and Smith, 2005; Polsky et al., 2014); therefore, information regarding the range of behaviors and management styles is a critical model input. These inputs were derived from survey data of 348 households in the RCW during the spring and fall of 2011 and 2012. To ensure geographic and demographic variability, a two-stage stratified sampling procedure was used to identify prospective participants. First, the RCW was stratified into 60 city-defined neighborhoods that were comprised primarily of single dwelling residences. Next, one face block (defined as 10 contiguous households plus the 10 contiguous households directly across the street) was randomly selected from within each neighborhood. All 20 households that fell within a face block were invited to participate in the survey. Surveys were conducted as face-to-face interviews with the person in the home who self-defined as making the majority of lawn care decisions. Approximately 34% of eligible households agreed to participate in the survey; the remaining households refused or were unreachable. Carrico et al. (2013) provides a more detailed description of the sampling design and data collection procedures.

Survey respondents provided information about whether the household or a lawn care provider had fertilized their lawn in the past year, the number of applications applied, the rate per application, fertilizer content (see Appendix A), the seasons in which fertilizer was applied, the form of the fertilizer (dry or liquid), whether and how often the household irrigates their lawn in each season, how often the lawn is mowed, and whether the household returns clippings to the lawn or discards of them after mowing (Table 1).

Table 1
Summary of typical lawn management behavior within the survey sample.

	Sample size (N)	Mean/%
Applies Fertilizer (%) (among fertilizer appliers)	344	54.6% (n = 190)
Number of N applications (mean, SD)	190	2.6 (1.84)
Total annual N application rate (kg N yr^{-1}) (mean, SD)	189	84.1 (87.7)
Timing of N applications		
Spring	190	91.1%
Summer	190	63.2%
Fall	190	67.4%
Winter	190	20.5%
Form of N application		
Dry	190	85.8%
Liquid	190	14.2%
Irrigates lawn (among irrigators)	343	50.4%
Timing of irrigation		
Spring	172	76.7%
Summer	172	96.5%
Fall	172	68.0%
Winter	172	3.5%
Irrigation events during growing season[a] (mean, SD)	172	38.7 (33.01)
Mowing events during growing season[a] (mean, SD)	254[b]	18.1 (9.7)
Clippings removed from lawn after mowing	340	33.5%

Note. N's across variables vary due to missing data.
[a] Growing season is defined as April through October.
[b] This question was added to the survey after the start of data collection and, therefore, was collected from only a subset of the total sample.

2.5. Sensitivity analysis

The purpose of the sensitivity test is to find those management factors that have major impacts on the SOC sequestration, N_2O flux, and net GWP. Simulation of site B from the model validation section was selected as a baseline scenario because it is close to the average lawn management condition in the RCW (Table 2). Because the impacts of lawn management on these ecosystem functions change with time, we tested the long-term impacts by running the DNDC model for 75 years with varying alternative management factors (Table 2) by (1) Half N: decreasing the fertilizer application rate from 47.52 to 23.76 kg N ha^{-1} y^{-1}, (2) Irrigation: adding 20 irriga-tion events of 2-cm water in growing season, (3) Half mowing: decreasing the mowing to 13 times, (4) CR: changing to clipping recycle, and (5) CRDF: clipping recycle with decreasing fertilizer (same as (4), except for a decreased fertilization rate to keep the total N input unchanged). Except for these management alterna-tives, other climatic, soil, and vegetation factors were kept the same as in the baseline condition.

2.6. Motivations for lawn management practices

To clarify potential opportunities for best management practices, we examined the relationship between the four lawn management behaviors included in the sensitivity analysis and two motivational considerations that may be in conflict when making decisions about lawn management: lawn appearance concern and environmental concern.

A series of random intercept generalized linear models were used to examine the relation between the four behaviors and lawn appearance concern and environmental concern. Property value (a proxy for income) was included as a control because it is a critical constraining variable due to the cost of lawn care. All variables were entered into the model simultaneously, resulting in estimates of the effect of each variable controlling for other variables in the model.

Lawn appearance concern was the respondent's answer to the question, “How important is it for you to have a lush, green lawn?” Environmental concern, was an average of the respondent's reported concern about “the environment,” “air pollution,” and “water pollution.” Responses to all of these items were made on a four-point Likert scale ranging from “not at all” to “very much”. Property values were obtained from city records.

2.7. Lawn management intensity scenario

Turfgrass management is highly variable and determined by many factors such as peer pressure, socioeconomic status, etc (Carrico et al., 2013; Larsen and Harlan, 2006). Based on the results from the single factor analysis, we examined three different lawn management behaviors with regard to their effects on SOC, N_2O emissions, and net GWP (Table 2). Using the survey data, we examined three lawn management archetypes that varied according to two dimensions: fertilizer application and irrigation. For fertilizer application, we used the median amount of N applied to lawns among households who fertilized (52 kg N ha^{-1} yr^{-1}) a s a cutoff to separate respondents into those who apply intensively (n = 87, 25.3%) and moderately (n = 102, 29.7%). Those who do not apply fertilizer were coded as such (n = 155, 45.1%). For irrigation behavior, whether the household irrigated and the median number of irrigation events (33 times per growing season) were again used to categorize households as not irrigating (n = 170, 49.7%), irrigates moderately (n = 86, 25.1%), and irrigates intensively (n = 86, 25.1%). Using this scheme (Table 3), households were categorized into one of three lawn care management archetypes: Minimal (MIN, n = 106, 30.5%), Moderate (MOD, n = 101, 33.4%), and Intensive

Table 2
The lawn management scenario used in the single factor analysis.

Management factors	Mowing	Clipping placement	Total N input from synthetic fertilizers and clippings	Irrigation
Baseline	26	Removed	47.52 kg N ha^{-1} y^{-1} (S)	None
Half N	26	Removed	23.76 kg N ha^{-1} y^{-1}(S)	None
Half mowing	13	Removed	47.52 kg N ha^{-1} y^{-1}(S)	None
Irrigation	26	Removed	47.52 kg N ha^{-1} y^{-1}(S)	20 times & 2 cm per time
CR	26	Recycle	47.52 kg N ha^{-1} y^{-1}(S) + 26 kg N ha^{-1} y^{-1}(C)	None
CRDF	26	Recycle	27 kg N ha^{-1} y^{-1}(S) + 20.52 kg N ha^{-1} y^{-1}(C)	None

S: synthetic fertilizers; C: Clippings.

(INT, $n = 95$, 31.5%). Using the survey data, we estimated the proportion of households in each archetype that removed clippings from their lawn after mowing, adding a fifth characteristic to the categorization (Table 4).

We then use INT and MIN as the upper and lower bound of SOC sequestration, N_2O fluxes, and net GWPs from the residential lawns because lawn management practices are the dominant driver of these ecosystem functions, an example of ecological homogenization caused by urbanization across regional variations in climate, parent material, and topography (Polsky et al., 2014).

2.8. Carbon costs of lawn management

The carbon costs (CC) are the amount of energy consumed by different turfgrass maintenance practices from manufacturing to the amount used in lawn management. Energy use can then be converted to units of CO_2 equivalent (CE) to represent equivalent amount of CO_2 emitted from these energy uses. CCs are summed for each turfgrass management practice to estimate the total CC (CC_t) (Zirkle et al., 2011).

$$CC_t = CC_{fertilizer} + CC_{mowing} + CC_{irrigation} \quad (1)$$

where CC_t is the total carbon costs from lawn care practices [kg CO_2 ha^{-1} y^{-1}]; $CC_{fertilizer}$ is the carbon costs of manufacturing, transporting and commercializing the fertilizer [kg CO_2 ha^{-1} y^{-1}]; CC_{mowing} is the carbon costs of mowing [kg CO_2 ha^{-1} y^{-1}]; and $CC_{irrigation}$ is the carbon costs of irrigation [kg CO_2 ha^{-1} y^{-1}].

The CE conversion of fertilizer was 4.76 kg CO_2/kg N, 0.73 kg CO_2/kg P, and 0.55 kg CO_2/kg K respectively (Lal, 2004a). $CC_{fertilizer}$ was the sum of the products of annual amount of N, P, and K in kg applied and their corresponding conversions.

To estimate CC_{mowing}, we assume that 2.47 gallon gasoline is consumed to mow one hectare lawn using a walk-behind mower (Sahu 2008). The CE conversion of gasoline is 8.87 kg CO_2 per gallon of gasoline (Lal, 2004b). To determine the total kg of CO_2 emitted each year by gasoline, we multiply 2.47 gal $ha^{-1}$by 8.87 kg CO_2 gal^{-1} and the mowing times a year.

To calculate $CC_{irrigation}$, a hand-moved sprinkler conversion of 1.9 kgCO_2 ha^{-1} per irrigation event from farm operation was adopted to represent the carbon cost of each irrigation event (Lal, 2004a).

2.9. Net GWPs estimates

To achieve a complete accounting of the climatic impact of lawn management, we adopted the following equation to calculate the combined GWPs for 100 years (Li et al., 2005):

$$Net\ GWP = 25 \times 16 \times CH_4/12 + 298 \times 44 \times N\,O/28 - 44 \times dSOC/12 + CC_t \left(kg\ CO_2\ ha^{-1}\ yr^{-1}\right) \quad (2)$$

where net GWP (kg CO_2 equivalent ha^{-1} y^{-1}) is the net global warming potential; CH_4 is CH_4 flux (kg C ha^{-1} y^{-1}); N_2O is N_2O flux (kg N ha^{-1} y^{-1}), dSOC is the change in soil organic carbon (SOC) or SOC sequestration rate (kg C ha^{-1} y^{-1}), and CC_t is the total carbon cost of lawn maintenance including mowing, fertilizer application, and irrigation (kg CO_2 ha^{-1} yr^{-1}).

3. Results

3.1. Model assessment

Soil temperature was correctly simulated through the year (Fig. 1). The overestimation of soil temperature in summer time for site A and B (up to 5 °C) likely results from a shading effect at those sites. Soil moisture dynamics was generally captured by the model except that it was underestimated by the model in June 2012.

The predicted N_2O emissions from the residential lawn at the three sites generally matched the observed N_2O fluxes (Fig. 1). At sites A, B, and C, fertilizer was applied at annual rates of 137.0, 47.5, and 26.7 kg N ha^{-1} yr^{-1}. At site B, the observed and simulated results both showed that N_2O flux increased during the spring season although the model didn't capture N_2O peaks during early spring, perhaps due to the inaccuracy of the fertilization timing data at site B. Some unreported spring fertilization events might have occurred at site B. On the other hand, the DNDC simulated more N_2O peaks than were observed in the field, probably due to the fact that low frequency field sampling was not able to capture the short N_2O pulses.

Table 3
Lawn management archetype assignments as a function of fertilizer application and irrigation behavior. Reported numbers are the subsample n and percent of sample.

Irrigation	Fertilizer application		
	Does not apply	Applies Moderately	Applies intensively
Does not irrigate	Minimal (106, 31.4%)	Moderate (41, 12.1%)	Excluded (21, 6.2%)
Irrigates moderately	Moderate (32, 9.5%)	Moderate (28, 8.3%)	Intensive (25, 7.4%)
Irrigates intensively	Excluded (15, 4.4%)	Intensive (30, 8.9%)	Intensive (86, 25.4%)

Table 4
Means, SDs and frequencies of lawn management practices across the three management archetypes generated from the survey sample.

	Minimal	Moderate	Intensive
Total annual N application	0	21.61 (20.38)	88.96 (9.13)
# of N applications per year	0	1.08 (1.02)	3.12 (1.93)
# of mowing events (growing season)	15.8 (7.0)	15.6 (9.8)	21.6 (10.2)
# of irrigation events (growing season)	0.00	7.70 (9.63)	31.45 (3.23)
Removes clippings from lawn after mowing	15.1%	38.6%	44.0%

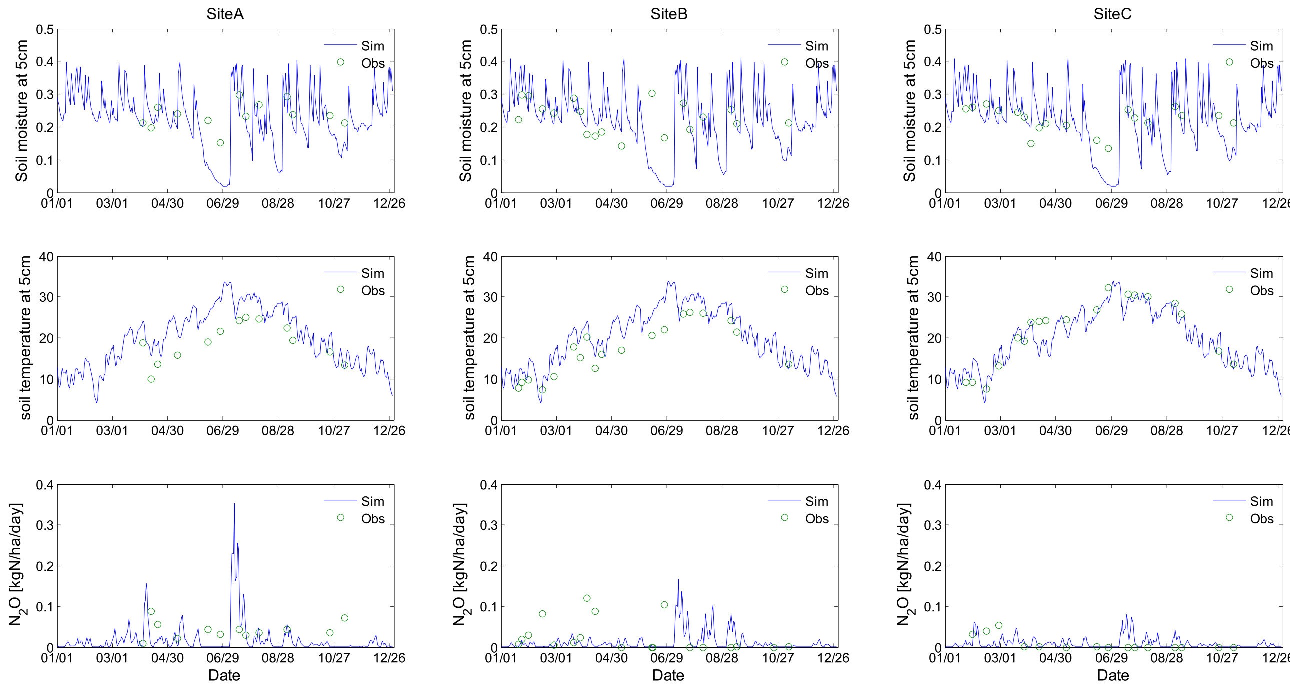

Fig. 1. The comparison of measured and simulated daily soil temperature and soil moisture at 5 cm depth, and N_2O fluxes for year 2012 at site A, B, and C.

3.2. *Sensitivity analysis*

3.2.1. *Long-term impacts on SOC*

The SOCs increased initially followed by a gradual decline over 75-year period except for a monotonic decline for the half N scenario (Fig. 2 A). The timing of the turning points ranged from year 0 (half N) to year 65 (CR). The SOC accumulation (dSOC) for the CR was greatest when turfgrasses were initially established and then slowed down over time, and finally approached zero after around year 50. The dSOC for the CR was estimated to be about 4.5 Mg C ha^{-1} over 75 years (i.e. averagely 60.2 kg C ha^{-1} yr^{-1}). On the other hand, the half N scenario had the greatest SOC loss rate (i.e. greatest negative dSOC value) of −20.7 kg C ha^{-1} yr^{-1}, indi-cating that a switch from a net SOC accumulation to a net SOC loss when the fertilization rate was halved. The half mowing and the CRDF both increased SOC accumulation compared to the baseline. Excess irrigation beyond the turfgrass's need lowered the dSOC to −16 kg C ha^{-1} yr^{-1}, compared to the baseline.

3.2.2. *Long-term impacts on N_2O fluxes*

The annual N_2O emissions increased rapidly in the first 25 years and leveled off afterward, indicating that a steady state condition had been reached. In addition, the baseline, irrigation, and half N scenario showed a slight decrease starting from year 60. The variation in the annual N_2O flux among the management scenarios increased over time. Compared to the baseline, the half mowing and CRDF increased the steady-state annual soil N_2O emission by 10% and 15%, respectively, while halving fertilization decreased the steady-state annual N_2O flux by 30%. The maximum steady-state annual N_2O flux (i.e. 2.5 kg N ha^{-1} y^{-1}) occurred at the CR sce-nario, which was 58% greater than the baseline.

3.2.3. *Long-term impacts on net GWP*

We calculated net global warming potential (net GWPs) by accounting for carbon cost (i.e. Eq. (2)) for all six management scenarios. The net GWP in the turfgrass ecosystems generally increased with time due to the decreased carbon sequestration rate and increased N_2O emissions (Fig. 2C) except for the half N. The GWP values were all positive indicating a net carbon source. The net GWP for the CR was the lowest (<500 kg CO_2-eq ha^{-1} yr^{-1}) initially, then increased rapidly over time, exceeding all other scenarios at year 40, and finally leveled off after about 70 years. The half mowing and half N scenarios decreased the steady-state net GWP value by 16% and 22%, respectively, compared to the baseline.

3.2.4. *75-year mean GWP components*

The impacts of all management scenarios on the 75-year mean GWPs from N_2O emission, dSOC, CH_4, and CC showed positive net GWP, indicating net carbon emissions from turfgrasses (Fig. 3). The dSOC was in the sequence CR > CRDF > half mowing > baseline > irrigation > half N. The half mowing, CR and CRDF scenario represented SOC sequestration (i.e. positive dSOCs), while the half N and irrigation represented a net SOC loss (i.e. negative dSOCs). The 75-year averaged N_2O emission was in the order CR > half mowing > CRDF > irrigation > baseline > half N. The CC was in the order irrigation > CR = baseline > CRDF > half N > half mowing. Among all GWP fluxes (Eqn. (2)), N_2O fluxes and CC were the two greatest contributors to net positive GWP while CH_4 flux was the major C sink term except for the CR where SOC sequestration was the major C sink. Carbon sequestration by CH_4 uptake was greatly offset by N_2O emission and CC. The 75-year mean net GWP ranged from 1120 (half mowing) to 1530 kg CO_2 ha^{-1} y^{-1} (irrigation) and was in the order irrigation > CR > baseline > CRDF > half N > half mowing.

3.3. *Motivations for lawn management practices*

Households with higher property values applied more fertilizer, irrigated more, and mowed more; however, they were no more or less likely to recycle their lawn clippings (Table 5).

Controlling for property values, lawn appearance concern was positively related to irrigation intensity and fertilizer application (though the effect was only marginally significant). Those who were more concerned about the appearance of their lawn were also

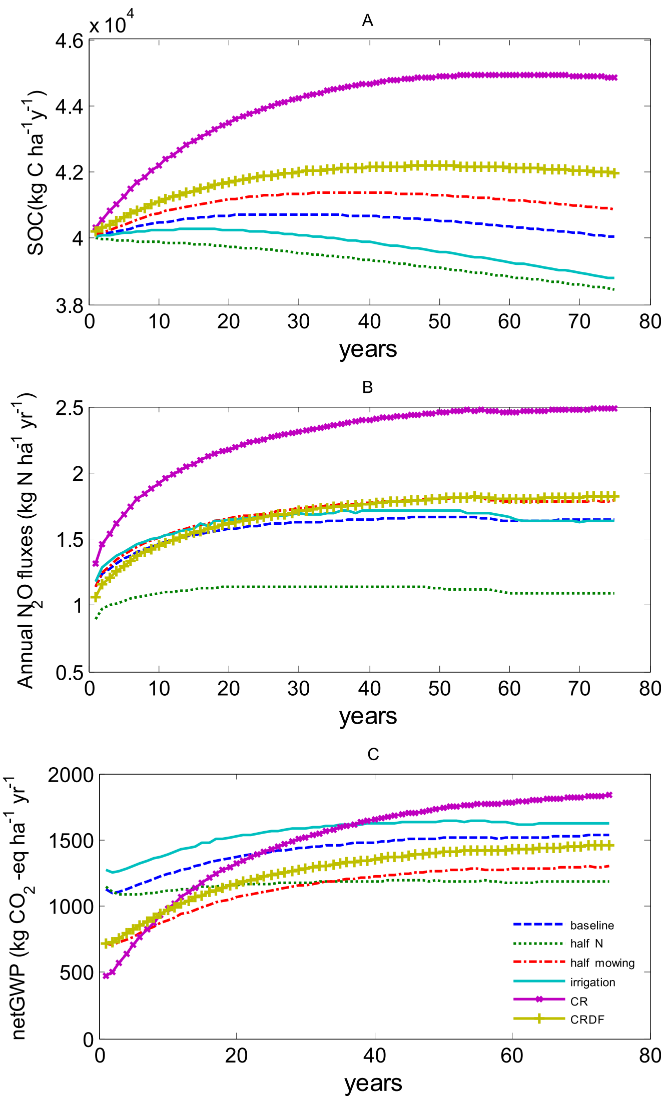

Fig. 2. DNDC modeled impacts of lawn management practices on long-term SOC sequestration rate (dSOC) (A), annual N_2O flux (B), and net Global Warming Potentials (net GWPs) (C) over 75 years.

significantly less likely to recycle their clippings. Interestingly, there was no effect of lawn appearance concern on mowing intensity.

Finally, environmental concern was unrelated to N application, mowing intensity, and clipping recycling. There was some indication that those who were more concerned about the environment irrigated their lawn less; however, the effect was only marginally significant.

3.4. *Lawn management intensity scenarios*

The lawn management scenarios had significant impacts on soil carbon sequestration, N_2O emission, and GWP (Fig. 4). The INT had the highest SOC contents and thus highest dSOC, but the INT also had the highest annual N_2O emissions, which led to the highest net GWP. Note that the SOC increased until year 35 and then decreased afterward for INT and MOD scenarios. In contrast, the SOC for MIN declined monotonically over 75 years. Both annual N_2O emission and net GWP increased with time except for the net GWP for the MIN, which decreased gradually over the simulation period. The net GWP in the MIN was higher than MOD during the initial establishment of turfgrasses. After year 23, the net GWP in the MIN dropped below the MOD and stayed low afterward.

The net GWPs for all scenarios were positive, indicating overall net carbon emission for the 75-year time range (Table 6). Among all GWP fluxes, N_2O fluxes were the single greatest contributor to positive net GWPs (50–63% of total CO_2-equivalent emission), while CH_4 flux was the dominant carbon sink (67–100% of total CO_2-equivalent sequestration). Only INT and MOD showed a net SOC accumulation (i.e. positive dSOC). Nevertheless, carbon sequestration by SOC and CH_4 uptake was greatly offset by N_2O emission and CC. Due to its greatest GWP contribution from N_2O emission and CC, the INT scenario had the greatest 75-year mean net GWP In contrast, the MIN scenario had the lowest 75-year mean net GWP primarily due to the lowest GWP contribution from N_2O emission and CC.

Three levels of lawn management intensity may provide the lowest and highest bounds of global warming contribution for our field site because lawn management is the dominant driver for the urban turfgrass ecosystem. We applied our INT scenario as a high-end estimate and MIN scenario as our lower-end estimate. Based on these estimates, the 75-year averaged annual N_2O flux from turf-grass ranged from 0.75 to 3.57 kg N ha^{-1} y^{-1}; The 75-year averaged annual SOC sequestration rate from turfgrass ranged from −28.8 to 18.47 kg C ha^{-1} yr^{-1} The 75-year averaged annual net GWPs for MIN, MOD, and INT were 697.2, 845.4, and 2442.5 kg CO_2-eq ha^{-1} y^{-1}, respectively (Table 6). The MIN reduced the 75-year mean N_2O emissions and net GWPs by 79% and 69%, respectively, when compared to the INT.

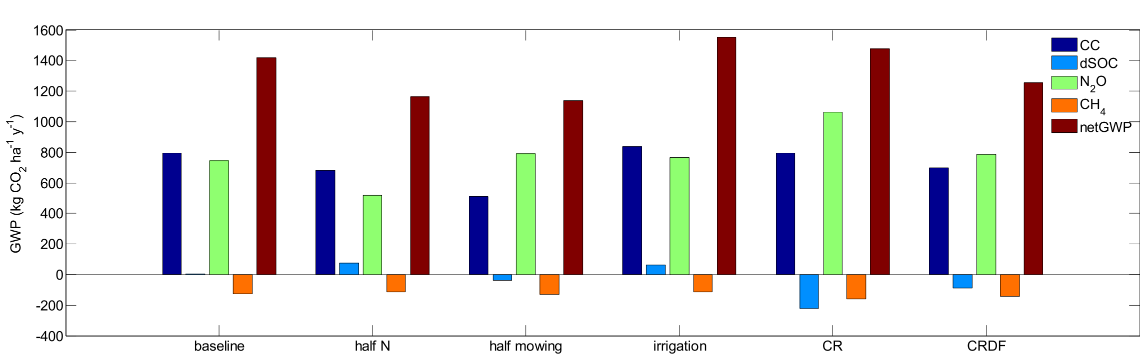

Fig. 3. Simulated 75-year mean Global Warming Potentials (GWPs) from SOC sequestration (dSOC), N_2O emissions, and CH_4 emissions, and carbon costs (CC) of lawn maintenance as well as the total net global warming potentials (nGWP) for the six lawn management scenarios by the DNDC model.

Table 5
Generalized linear modeling results.

	Annual N Application				Irrigation intensity				Mowing intensity				Clipping recycle				
	Est	*SE*	*t*	*p*	*Est*	*SE*	*t*	*p*	*Est*	*SE*	*t*	*p*	*OR*	*Est*	*SE*	*t*	*p*
Intercept	1.50	1.16	1.29	0.20	−1.43	1.06	−1.34	0.18	−10.26	6.07	−1.69	0.09	2.75	1.01	1.32	0.77	0.44
Property value (log)	0.92	0.42	2.16	0.03	1.68	0.39	4.33	<0.01	9.73	2.24	4.34	<0.01	1.00	−0.00	0.49	0.00	1.00
Lawn appearance concern	0.22	0.14	1.63	0.10	0.39	0.13	3.04	<0.01	0.85	0.63	1.34	0.18	0.69	−0.37	0.14	−2.56	0.01
Environmental concern	−0.18	0.19	−0.97	0.33	−0.28	0.17	−1.65	0.10	0.62	0.84	0.74	0.46	1.15	0.14	0.18	0.75	0.45
degrees of freedom	327				282				242				323				
AIC	1386.47				1096.18				1785.77				1454.67				
% Correct classification													75.20				

Note. Annual N Application and Irrigation events were modeled using a negative binomial distribution. Mowing events was modeled as a normal distribution, and clipping recycle was modeled as a binomial distribution. *Est* = parameter estimate, *SE* = standard error, *OR* = Odds Ratio.

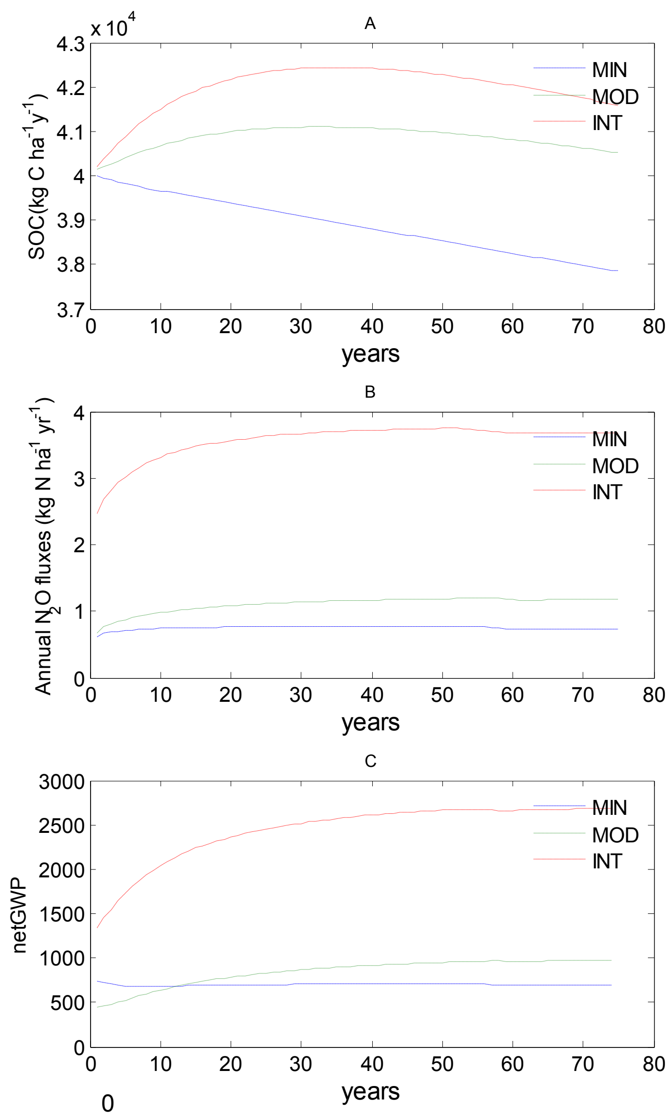

Fig. 4. DNDC modeled impacts of lawn management scenarios (i.e. MIN, MOD, and INT) on long-term SOC accumulation (A), annual N_2O flux (B), and net GWP (C) over 75 years.

4. Discussion

4.1. Impacts of turfgrass management on SOC

Our study suggests that SOC sequestration is very sensitive to lawn management behavior. Both clipping recycle and high N inputs increase SOC sequestration potential, indicating a tight coupling between C and N cycles. N fertilization increases SOC sequestration through enhancing primary productivity of plants, and thus increasing plant residues returned to the soil, while clipping recycle prevents C and N losses from clipping removal, and thus increase net C and N inputs to turfgrass ecosystems. When fertilization rates are low, the C loss through clipping removal might outcompete the C gained in the soil, leading to net SOC depletion over time. Due to the low fertilization rates (<90 kg N ha^{-1} yr^{-1}), our simulated dSOCs are much lower than previous studies (Townsend-Small and Czimczik, 2010). On the other hand, fertilizer application might decrease SOC by enhancing SOC decomposition through lowering the C:N ratio. This explains why clipping recycle is more effective than N fertilization in increasing SOC sequestration. For example, with the same amount of total N inputs, the dSOC of clipping recycle (i.e. CRRF) was higher than that of the baseline scenario. Finally, reducing turfgrass mowing enhances SOC sequestration simply due to the reduced C export through clipping removal.

The highest dSOC occurred during the initial establishment of turfgrass, indicating that land conversion to turfgrass has a high potential to sequester atmospheric CO_2 during the initial establishment stage when SOC is low. This sequestration process is either brief, ranging from 0 to 20 years when there is a net C and N deficit, or can last for a significant period of time after planting if a net C and N surplus exists (e.g. approximately 50 years and 60 years for the CRDF and CR). Finally, this SOC sequestration diminishes when the turfgrass stand ages and SOC is saturated (West and Six, 2007). In some cases, the SOC even starts to drop if the C outputs (e.g. clipping removal) exceed the C inputs. In summary, the dynamic pattern of SOC will vary depending on the antecedent SOC level, climate, soil clay content, and management (Lal, 2004b).

4.2. Impacts of turfgrass management on N_2O emission

The N_2O emissions are low when turfgrass is initially established and then increase over time until around year 40. The increasing N_2O is probably driven by high rates of soil N accumulation associated with rapid C sequestration in young turf ecosystems. Once SOC sequestration reaches a steady state, however, continuous N fertilization may lead to increasing gaseous and aqueous N losses as signs of N saturation. In our sensitivity analysis, halving fertilizer N inputs cuts down N_2O emission by 30% compared to the baseline. The slight decline in N_2O emissions at about year 57 for several lawn care practices is probably induced by the decline in SOC, which provides less substrate for N_2O production through nitrification and denitrification. The 75-year average N_2O emissions range from 0.75 to 3.57 kg N ha^{-1}, depending on turfgrass age and lawn care practices (Fig. 4 B). Our N_2O emission is

Table 6
The 75-year mean N_2O flux, SOC sequestration rate (dSOC), carbon cost (CC) and net Global Warming Potentials (GWPs) for the INT, MOD, and MIN scenarios.

	INT	MOD	MIN
Soil N_2O fluxes (kg N ha^{-1} yr^{-1})	3.57	1.11	0.75
dSOC (kg C ha^{-1} yr^{-1})	18.47	4.99	−28.8
CC_N (kg CO_2-eq ha^{-1} y^{-1})	424.23	104.87	0
CC_k (kg CO_2-eq ha^{-1} y^{-1})	55	21	0
$CC_{fertilizer}$ (kg CO_2-eq ha^{-1} y^{-1})	424.23	104.87	0
CC_{mowing} (kg CO_2-eq ha^{-1} y^{-1})	482.2	350.7	350.7
$CC_{irrigation}$ (kg CO_2-eq ha^{-1} y^{-1})	59.77	14.94	0
CC_t (kg CO_2-eq ha^{-1} y^{-1})	966.2	470.5	350.7
Net GWP(kg CO_2 ha^{-1} y^{-1})	2442.5	845.4	697.2

close to the annual N_2O flux from an urban turfgrass in Southern California (1–3 k g N h a $^{-1}$) (Townsend-Small and Czimczik, 2010). The annual N_2O fluxes in this study also fall into the range reported from other urban turfgrass systems (0.5–6 k g N $_2$O–N h a $^{-1}$)(Groffman et al., 2009; Kaye et al., 2004). Nevertheless, the N_2O fluxes reported in literatures need to be taken with caution due to the time-dependent nature of N_2O flux in turfgrass systems, which most likely increases when turfgrasses age.

Clipping recycle induces the largest N_2O emission because clippings have a low C:N ratio and can be quickly decomposed to release labile carbon and inorganic nitrogen, which later undergoes nitrification and denitrification that produce N_2O and other N losses.

4.3. *Impacts of turfgrass management on net GWP*

The net GWP of turfgrass systems is also dynamic and thus must be evaluated in light of the time of lawn establishment. The net GWPs generally show a similar trend to the N_2O emissions. The model simulated net GWP from the three management intensity levels over 75 years ranged from 697.2 to 2442.5 kg CO_2-eq ha^{-1} yr^{-1}, which is embraced by the ranges of −1080 to 2850 kg CO_2-eq ha^{-1} yr^{-1} in urban ornament lawns (Townsend-Small and Czimczik, 2010) and −1000 to 2000 kg CO_2-eq ha^{-1} yr^{-1}in a Kentucky bluegrass lawn (Zhang et al., 2013). On the other hand, the range of net GWPs of an upland crop system (2700–4684 kg CO_2-eq ha^{-1} yr^{-1}) (Huang et al., 2013) are much greater than ours. The upper bound of net GWPs in this study, is also lower than many rice cropping systems (>6000 kg CO_2-eq ha^{-1} yr^{-1}) (Ma et al., 2013; Shang et al., 2011), where CH_4 emission played a main role in GWP.

Decreasing mowing times and fertilizer application rate are the most effective management practices that can lower the net GWPs of turfgrasses, but the mechanisms that account for the lowering are quite different. The decrease in mowing event contributes to lowering the net GWPs mainly through decreasing the CC, while the decrease in N_2O emission is responsible for decreased net GWPs when fertilization is reduced. Other management scenarios have relatively small impacts on net GWPs of turfgrasses.

The net GWPs reported here are always positive, regardless of management scenario and lawn establishment history; however, model results not reported here indicate that the net GWP of turfgrasses can be negative during the establishment stage of the lawn, if the fertilization rate is set high. Previous studies indicated that turfgrass can be a net carbon sink or source depending on fertilization rates (Townsend-Small and Czimczik, 2010). Zhang et al.'s (2013) found the turfgrasses with fertilization of 150 kg N ha^{-1} yr^{-1} can act as a carbon sink for 20–30 years after establishment. In this study, we calibrate the fertilizer application rates used in the modeling analysis against actual lawn manage-ment behavior reported in a sample of households from Nashville, TN. These data suggest that the actual rate of application and total N applied throughout the year (i.e. <90 kg N ha^{-1} yr^{-1}) may be substantially lower than what has been assumed in prior analyses or recommended by fertilizer manufacturers and agricultural extension offices. Assuming this rate from the survey data is constant over the lawn establishment history, our turfgrass system has a limited SOC sequestration potential that can't offset the N_2O emission and CC, which leads to the positive net GWPs.

Our results indicate that N_2O emissions contribute significantly to positive GWPs (i.e. >50% of total CO_2-equivalent emission). Studies that do not take N_2O emissions into account would lead to a false conclusion of turfgrass as a carbon sink. Selhorst and Lal (2013) suggested a carbon sink for between 66 and 199 years in U.S. home lawns, which is a significant overestimate because they did not account for non-CO_2 greenhouse gas (e.g. N_2O) emissions.

4.4. *Implication for best management practices*

Applying a great amount of synthetic fertilizer after lawns mature would negate the carbon sequestration potential of turfgrass due to increased N_2O emission. Several studies have found that N_2O emission from fertilizer offset the potential of carbon sequestration of turfgrass systems (Zhang et al., 2013). Crutzen et al., (2008) suggested that increased N_2O emissions from fertil-izer inputs could offset any GHG reduction achieved by biofuel crops through carbon sequestration and fossil-fuel replacement. Davis et al., (2010) also found that switchgrass, corn, and prairie grasses could be net carbon sources to the atmosphere when N_2O emissions were taken into account. The CC of manufacturing, transporting, and commercializing the fertilizer, a significant portion of total CC of lawn management, further increases net GWP of turfgrasses. In addition to contributing to global warming, fertilizer application can lead to water pollution due to nutrient leaching (Groffman et al., 2009).

On the other hand, simply reducing fertilization application might compromise the quality of turfgrass growth because plant N demand must be fulfilled, and thus reduce SOC sequestration capacity especially during the initial establishment stage. N availability, however, can be increased through clipping recycle. Clipping recycle by leaving the clippings to decompose on the site after mowing can provide available N to turfgrasses so that synthetic fertilizer application can be significantly reduced. This is supported by our sensitivity analysis. The CRDF led to only 13% decrease in turfgrass yield relative to the baseline, compared to 37% decrease if N input is halved (data not shown). In addition, clipping recycle is more effective than synthetic fertilizer in enhancing SOC accumulation, which not only contributes to negating global warming but also improves soil fertility. Finally, clipping recycle can save CC from transporting to and decomposing the clippings in a landfill. Our sensitivity analysis showed that this practice reduced the 75-year averaged net GWP by 12% compared to clipping removed with a same amount of total N inputs. Thus, to keep the healthy growth of turfgrass while minimizing global warming potential and environmental pollution, clipping recycle rather than fertilizing should be adopted as a BMP for turfgrasses.

Survey data suggested that a majority of households in the RCW (65%) are already practicing this BMP. Removal of clippings was related to lawn appearance concerns, suggesting that households may be unaware of the utility of clipping recycle on turfgrass quality, or they may be concerned that the visible remains of clippings on a recently mowed lawn negatively affects its appearance. There was no relation between clipping recycle and concern for the environment, suggesting that households may not recognize the environmental benefits of this behavior or these motivations may be overwhelmed by lawn appearance concerns. The fact that clipping recycle can contribute to turfgrass quality while simultaneously reducing turfgrass GWP suggests that the motivations for lawn management intensity and the outcome of this particular BMP may be aligned with one another. In addition, recycling clippings is less time intensive and easier than removing them from the lawn, and adds no additional cost to one's lawn care regime. Finally, lawn clipping recycle can save purchase cost for synthetic fertilizers. For these reasons, the management of grass clippings may be a good target for interventions seeking to reduce the environmental impacts of lawn management.

Our results show that lawn age-dependent BMPs are warranted given the dynamic nature of the GWP fluxes. When the SOC is low during the initial lawn establishment stage, N_2O emissions are small because most of N inputs are retained in the system. On the other hand, when the land is initially converted, SOC sequestration potential is high and is the dominant C sink. Thus, the priority of BMPs in young turfgrass systems is to enhance SOC sequestration by applying fertilizer intensively. Over time, however, the SOC sequestration rate declines and high fertilization rates lead to net increases in GWP. Thus, in a time-dependent BMP, the fertilization rate should be reduced to minimize N_2O emission after turfgrass establishment as suggested by Zhang et al., (2013). Once the turfgrass reaches the mature stage, synthetic fertilization can be completely removed because nutrients can be supplied through the internal cycles (e.g. clipping recycle).

The implications of this finding are that, for the vast majority of households who are managing lawns older than 15 years, fertilizer should be applied in moderation and only if the household considers it necessary to achieve the desired lawn esthetic. Survey data suggested that annual N application was most closely related to property values, but was also associated with a household's desire for a lush, green lawn. These results suggest a need to educate consumers regarding the minimally necessary fertilizer levels as well as opportunities to substitute synthetic fertilizer with recycled lawn clipping. Maintaining minimal fertilizer inputs can also slow turfgrass growth, which can save carbon cost by decreasing the need of mowing. In the survey sample used here, only 23% of households who fertilized their lawn reported that they had had their soil tested. The somewhat weak correlation between lawn appearance concerns and fertilizer usage intensity suggests that there may be room to encourage moderation while also meeting the consumers concerns about the appearance of their lawns. The relation between fertilizer usage and income may also suggest that efforts are needed to target lawn care providers. 61% of households who applied fertilizer did so using a lawn care provider and, not surprisingly, those with higher incomes were more likely to employ a company to apply fertilizer ($r = 0.42$, $p < 0.01$).

An intensive management scheme that involves extensive irrigation, mowing and fertilizer application increases both the N_2O emissions and the carbon cost during the maintenance practices, which can greatly exceed the amount of carbon sequestered, increasing the net GWP about three times higher than the minimum maintenance scheme. Thus, to provide maximum environmental benefits, minimum lawn maintenance practices should be adopted. Water should be applied only when needed and the use of automatic timers can be used to avoid unnecessary watering. Irrigation in humid regions like the RCW is often not necessary. Our sensitivity analysis showed irrigation actually decrease turfgrass yield by 5% compared to the non-irrigated lawn (Data not shown). The number of mowings per year should be reduced as much as possible to decrease the CC, as our results suggest a 26% reduction in net GWPs by halving mowing times. An energy-efficient rotary mower should be used for small lots.

There was some indication that households respond to concerns about the environment by reducing irrigation, although the effect was small. In general, concern about the environment seemed have little influence on lawn management practices. Further education regarding the environmental impacts of lawn care may be able to strengthen this relationship. It is possible that many are not aware of the environmental implications of lawn care, and it is very unlikely that they are aware of BMP for mitigating GHG emissions.

This study also suggests that a long-term (>60 years) monitoring of SOC and greenhouse gas emissions including CO_2, N_2O, and CH_4 are critical to assess the true environmental impact of lawn management activities. Most estimates to date are derived from measurements during the first decade of land conversion to turf-grasses, when rates of soil carbon accumulation are likely to be greatest, while rates of N_2O emission are lowest. This might lead to an overestimate of carbon sequestration capacity of turfgrasses. Alternatively, a chronosequence study of turfgrasses with varying ages might be more practical than the long-term monitoring that spans multiple decades to assess the net carbon sink/source potential of turfgrass systems (Townsend-Small and Czimczik, 2010).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.01.008.

References

Bandaranayake, W., Qian, Y.L., Parton, W.J., Ojima, D.S., Follett, R.F., 2003. Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. Agron. J. 95 (3), 558–563.

Barthe, 1995. Nutrient Movement from the Lawn to the Stream. Center for Watershed Protection, Ellicott City, Maryland.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Modeling global annual N_2O and NO emissions from fertilized fields. Glob. Biogeochem. Cycles 16 (4).

Carrico, A., Vandenbergh, M., Stern, P., Gardner, G., Dietz, T., Gilligan, J.M., 2011. Energy and climate change: key lessons for implementing the behavioral wedge. J. Energy Environ. Law Winter 61–67.

Carrico, A.R., Fraser, J., Bazuin, J.T., 2013. Green with envy: psychological and social predictors of lawn fertilizer application. Environ. Behav. 45 (4), 427–454.

Crane II, J.W.A., Hornberger, G.M., 2012. Gases and grasses: sampling nitrous oxide emissions from urban and suburban lawns. In: Loucks (Ed.), World Environmental and Water Resources Congress 2012: Crossing Boundaries. American Society of Civil Engineers, Reston, VA.

Crutzen, P.J., Mosier, A.R., Smith, K.A., Winiwarter, W., 2008. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos. Chem. Phys. 8 (2), 389–395.

Davis, S.C., Parton, W.J., Dohleman, F.G., Smith, C.M., Del Grosso, S., Kent, A.D., DeLucia, E.H., 2010. Comparative biogeochemical cycles of bioenergy crops reveal nitrogen-fixation and low greenhouse gas emissions in a Miscanthus × giganteus agro-ecosystem. Ecosystems 13 (1), 144–156.

Dietz, T., Gardner, G.T., Gilligan, J., Stern, P.C., Vandenbergh, M.P., 2009. Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. Proc. Natl. Acad. Sci. U. S. A. 106 (44), 18452–18456.

Fissore, C., Baker, L.A., Hobbie, S.E., King, J.Y., McFadden, J.P., Nelson, K.C., Jakobsdottir, I., 2011. Carbon, nitrogen, and phosphorus fluxes in household ecosystems in the Minneapolis-Saint Paul, Minnesota, urban region. Ecol. Appl. 21 (3), 619–639.

Groffman, P.M., Williams, C.O., Pouyat, R.V., Band, L.E., Yesilonis, I.D., 2009. Nitrate leaching and nitrous oxide flux in urban forests and grasslands. J. Environ. Qual. 38 (5), 1848–1860.

Horgan, B.P., Branham, B.E., Mulvaney, R.L., 2002. Mass balance of N-15 applied to Kentucky bluegrass including direct measurement of denitrification. Crop Sci. 42 (5), 1595–1601.

Huang, T., Gao, B., Christie, P., Ju, X., 2013. Net global warming potential and greenhouse gas intensity in a double-cropping cereal rotation as affected by nitrogen and straw management. Biogeosciences 10 (12), 7897–7911.

IPCC, 2007. Changes in atmospheric constituents and in radiative forcing. climate change 2007: the physical science basis. In: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Rep., pp. 130–234 (Cambridge, UK and New York, NY).

Kaye, J.P., Burke, I.C., Mosier, A.R., Guerschman, J.P., 2004. Methane and nitrous oxide fluxes from urban soils to the atmosphere. Ecol. Appl. 14 (4), 975–981.

Lal, R., 2004a. Carbon emission from farm operations. Environ. Int. 30 (7), 981–990.
Lal, R., 2004b. Soil carbon sequestration to mitigate climate change. Geoderma 123 (1–2), 1–22.
Larsen, L., Harlan, S.L., 2006. Desert dreamscapes: residential landscape preference and behavior. Landsc. Urban Plan. 78 (1–2), 85–100.
Law, N.L., Band, L.E., Grove, J.M., 2004. Nitrogen input from residential lawn carepractices in Suburban Watersheds in Baltimore County, MD. J. Environ. Plan. Manag. 47 (5), 737–755. http://dx.doi.org/10.1080/0964056042000274452.
Li, C.S., 2000. Modeling trace gas emissions from agricultural ecosystems. Nutr. Cycl. Agroecosystems 58 (1–3), 259–276.
Li, C.S., Frolking, S., Frolking, T.A., 1992. A model of nitrous-oxide evolution from soil driven by rainfall events .1. Model structure and sensitivity. J. Geophys. Res. Atmos. 97 (D9), 9759–9776.
Li, C.S., Frolking, S., Butterbach-Bahl, K., 2005. Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. Clim. Change 72 (3), 321–338.
Ma, Y.C., Kong, X.W., Yang, B., Zhang, X.L., Yan, X.Y., Yang, J.C., Xiong, Z.Q., 2013. Net global warming potential and greenhouse gas intensity of annual rice-wheat rotations with integrated soil-crop system management. Agr. Ecosyst. Environ. 164, 209–219.
Milesi, C., Running, S.W., Elvidge, C.D., Dietz, J.B., Tuttle, B.T., Nemani, R.R., 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environ. Manag. 36 (3), 426–438.
Nielson, L., Smith, C.L., 2005. Influences on residential yard care and water quality: Tualatin watershed, Oregon. J. Am. Water Resour. Assoc 41 (1), 93–106.
Polsky, C., et al., 2014. Assessing the homogenization of urban land management with an application to US residential lawn care. Proc. Natl. Acad. Sci. U. S. A. 111 (12), 4432–4437.
Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. Glob. Change Biol. 6 (3), 317–327.
Pouyat, R.V., Yesilonis, I.D., Nowak, D.J., 2006. Carbon storage by urban soils in the United States. J. Environ. Qual. 35 (4), 1566–1575.
Qian, Y.L., Follett, R.F., 2002. Assessing soil carbon sequestration in turfgrass systemsusing long-term soil testing data. Agron. J. 94 (4), 930–935.
Qian, Y.L., Bandaranayake, W., Parton, W.J., Mecham, B., Harivandi, M.A., Mosier, A.R., 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics: the CENTURY model simulation. J. Environ. Qual. 32 (5), 1694–1700.
Robbins, P., Polderman, A., Birkenholtz, T., 2001. Lawns and toxins – an ecology of the city. Cities 18 (6), 369–380.
Robertson, G.P., Paul, E.A., Harwood, R.R., 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289 (5486), 1922–1925.
Sahu, R., 2008. Technical Assessment of the Carbon Sequestration Potential of Managed Turfgrass in the United States. Research report (accessed 06.01.15.). http://multivu.prnewswire.com/broadcast/33322/33322cr.pdf.
Selhorst, A., Lal, R., 2013. Net carbon sequestration potential and emissions in Home lawn turfgrasses of the United States. Environ. Manag. 51 (1), 198–208.
Shang, Q.Y., Yang, X.X., Gao, C.M., Wu, P.P., Liu, J.J., Xu, Y.C., Shen, Q.R., Zou, J.W.,Guo, S.W., 2011. Net Annual Global Warming Potential and Greenhouse Gas Intensity in Chinese Double Rice-Cropping Systems: a 3-Year Field Measure-ment in Long-term Fertilizer Experiments.
Selhorst, A.L., Lal, R., 2011. Carbon budgeting in golf course soils of Central Ohio. Urban Ecosyst. 14 (4), 771–781.
Townsend-Small, A., Czimczik, C.I., 2010. Carbon sequestration and greenhouse gas emissions in urban turf. Geophys Res. Lett. 37.
West, T.O., Six, J., 2007. Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. Clim. Change 80 (1–2), 25–41.
Zhang, Y., Li, C.S., Zhou, X.J., Moore, B., 2002. A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture. Ecol. Model. 151 (1), 75–108.
Zhang, Y., Qian, Y.L., Bremer, D.J., Kaye, J.P., 2013. Simulation of nitrous oxide emissions and estimation of global warming potential in turfgrass systems using the DAYCENT model. J. Environ. Qual. 42 (4), 1100–1108.
Zirkle, G., Lal, R., Augustin, B., 2011. Modeling carbon sequestration in home lawns. Hortscience 46 (5), 808–814.