Urban Ecosyst (2011) 14:771–781
DOI 10.1007/s11252-011-0168-5

Carbon budgeting in golf course soils of Central Ohio

Adam L. Selhorst · Rattan Lal

Abstract As global climate change (GCC) becomes an increasing societal concern, scientists are assessing soils' capacity to sequester atmospheric CO_2 to off-set anthropogenic emissions. Therefore, this study was conducted to determine C sequestration potential in golf turfgrass systems in Central Ohio, USA, and to determine the effect of management practices on the net soil C sink capacity. Ohio farmland soils converted to golf course turfgrasses sequestered C at mean rates of 3.55±0.08 Mg/ha/yr in fairways and 2.64±0.06 Mg/ha/yr in rough areas. Soils in both fairway and rough areas sequestered C to 15 cm depth. However, hidden C costs of golf course development and management were also significant and major C emissions were attributed to diesel fuel combustion (6,557 kg Ce (Carbon Equivalents)/yr), unleaded fuel combustion (3,618 kg Ce/yr), N fertilizer use (1,498 kg Ce/yr), fungicide application (1,377 kg Ce/yr) and irrigation (626 kg Ce/yr), for an overall C emission of 14.15 Mg Ce per course per year (0.30 Mg C/ha/yr). Analysis of sequestration and emissions data showed that a newly constructed golf course has a technical C sequestration capacity of 2,224 Mg C over a 91.4 year period or the equivalent of 0.44 Mg C/ha/yr. However, the large C emissions generated by maintenance practices render courses from sinks to sources within 30 years. To maximize the potential environmental benefits of turfgrass systems while increasing the economic efficiency of each site, management practices with low C-intensity should be utilized.

Keywords Sustainable management · Recreational land use · Urban soils · Climate change · Carbon sequestration · Turf soils

Introduction

With the rapid increase in global population and its technological advancements, humans are drastically altering the Earth's ecosystems. The release of large amounts of greenhouse

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gasses (GHGs), most notably carbon dioxide (CO_2) and methane (CH_4), are significantly contributing to abrupt climate change (ACC) (IPCC 2007). Since the industrial revolution around 1750, CO_2 emissions have increased 38% and methane emissions 157%, leading to substantial enrichment of the atmospheric C pool (WMO 2009; Lal 2004a). Increases in atmospheric concentration of GHGs may be responsible for numerous environmental issues such as global temperature increase (IPCC 2007), a shift in global vegetation zones (Ozenda and Borel 1990; Beckage et al. 2008; Metzger et al. 2008), alteration in land surface precipitation (Lal 2004a), as well as change in the quality and quantity of soil organic carbon (SOC) pools (Sachs and Luff 2002; Karhu et al. 2010). In addition, rise in mean global temperature may increase soil respiration with drastic positive feedback (Wiant 1967; Schleser 1982; Schlentner and Van Cleve 1985; Raich and Schlesinger 1992; Peterjohn et al. 1993)

One possible solution to abate ACC is to utilize soils' ability to sequester atmospheric C. If just 10% of the 120 Pg of C photosynthesized annually is retained in the terrestrial biosphere, it would be enough to completely offset the anthropogenic fuel use (Lal 2004a). Being an important recreational land use system, turfgrass soils are also a potential sink for atmospheric CO_2. The U.S. land area under urban soil use increased by 25% between 1982 and 1992 (Pendall 1999), with an estimated expenditure of $25 billion per year being spent on development and maintenance (Cockerham and Gibeault 1985). One such urban soil use is the development and maintenance of golf courses. There are an estimated 32,000 golf courses throughout the globe (Smith 2009) characterized by highly productive and fertile turfgrasses, which have production rates nearly as high as agricultural fields (Falk 1976). Such an increase in biomass productivity and fertility is coupled with an increase in the overall SOC levels (Conant et al. 2001). The SOC pool can be increased with application of fertilizers, input of biomass C (Wilson 1991; Burke et al. 1995) and use of irrigation (Conant et al. 2001), all of which are common practices utilized in golf course development and maintenance. Turfgrass systems are intensively managed and also receive high levels of controlled irrigation. Adoption of intensive management practices on grassland soils greatly increases C sink capacity (Conant et al. 2001). Furthermore, turfgrass soils are not prone to severe compaction, because most turfs are cored or aerated to minimize the compaction even in highly trafficked areas. The attendant reduction in soil bulk density improves plant growth and the overall SOC pool (Golubiewski 2006). Due to these and other important factors, turfgrass systems have shown the ability to sequester between 0.7 and 1.0 Mg C/ha/yr for periods of up to 40 years (Jo and McPherson 1995; Qian and Follett 2002; Bandaranayake et al. 2003; Huh et al. 2008; Pouyat et al. 2009b).

Restoration of degraded soils has a large potential to re-sequester much of the soil C lost through extractive land use and soil management practices. Conversion of natural to agricultural ecosystems can deplete SOC pools (Burke et al. 1989; Davidson and Ackerman 1993; Gebhart et al. 1994; Buyanovsky and Wagner 1998; Lal and Bruce 1999). In contrast, conversion of degraded agricultural soils to a restorative land use can re-sequester much of the depleted SOC pool (Burke et al. 1995; Potter et al. 1999; Lal et al. 2000; Follett et al. 2001a, b; Mensah et al. 2003). Similarly, the conversion of these depleted croplands to turfgrass systems has a potential for atmospheric C sequestration into recalcitrant SOC pool. As the majority of Central Ohio golf courses are constructed on previously cultivated land they provide a natural study site for the determination of SOC sequestration due to turf development. In addition, the optimal management levels and detailed maintenance records provide a solid rationale for the use of golf turf systems for determination of SOC sequestration and maintenance emissions.

The C sink capacity of intensively managed turfs is associated with the use of input based on fossil fuel consumption (e.g. fertilizer, pesticides, mowing, coring, irrigation). Overall energy inputs for home lawns are estimated at 578 kcal/$m^{2/}$yr (Falk 1976). However, due to the nature of their maintenance practices, it is expected that golf course systems will show higher levels of energy inputs. In addition, nitrogen (N) fertilizer application is often applied at rates similar to that applied for corn (*Zea mays L.)* production (Higby and Bell 1999). Therefore, the objectives of this study are to: assess the C budget of turfs, identify the hidden C costs of the input for turf maintenance, assess the rate of C sequestration in turfgrass soils, and to identify the potential of turfgrass soils to off-set anthropogenic emissions.

It is hypothesized that turfgrass soils will show the potential to sequester C over time and that maintenance practices will prove to be a significant source of C emissions. Furthermore, the rate of C sequestration in the golf course systems studied is expected to be around those found in prior research on turfgrass establishment with a possibility of higher rates being displayed due to the prior agricultural land use of these specific study sites. Finally, it is expected that turf soils will provide some potential benefit to offsetting anthropogenic C emissions through its sequestration processes, however, due to ongoing emissions and limited sequestration potential, these benefits are expected to be short lived.

Materials and methods

Soil samples were obtained from the fairway and rough areas of 11 private and public golf courses in central Ohio, USA. These samples were compared to soils taken from 11 paired agricultural soils within 1.6 km radius of each corresponding course. All sites were located within the till plains region of the state, and under similar climatic conditions. Oakhurst Country Club was used for assessment of the ecosystem C budget (Table 1).

Two 5.4 cm soil cores were obtained to 15 cm depth from 3 randomly selected fairway and rough soils for each of the 11 courses, as well as from each of the paired 11 agricultural sites. Courses used were specifically chosen for age chronosequences ranging from 1 year to 97 years since conversion from cropland to turfgrass. All soil samples were obtained between June 14, 2006 and July 8, 2006 and all agricultural samples were obtained from corn fields (*Zea mays L.)* prior to annual cultivation. Three of the samples at each site were used to determine the overall bulk density (ρ_b) using the Blake and Hartage method (Blake and Hartage 1986). The remaining three cores were removed with intact soil and divided into four depths; 0–2.5 cm,

Table 1 Golf course sampling sites

Sites	Location	Type	Age (yrs)
Kinsale	40°11′21.25″N 83° 5′57.98″W	Private	2
Echo Springs	40° 8′56.00″N 82°34′7.64″W	Public	11
The Lakes	40° 9′45.73″N 82°56′32.60″W	Private	17
Muirfield	40° 8′22.69″N 83° 9′10.15″W	Private	24
Little Turtle	40° 5′11.14″N 82°52′41.76″W	Private	36
Oakhurst	39°53′5.85″N 83° 9′27.18″W	Private	47
Raymond Memorial	39°59′25.00″N 83°5′59.41″W	Public	54
Ohio State	40° 1′52.66″N 83° 3′8.37″W	Public	68
Marysville	40°11′57.92″N 83°22′42.72″W	Public	74
London	39°55′13.67″N 83°24′39.45″W	Private	85
Lancaster	39°40′49.17″N 82°37′2.13″W	Private	97

2.5–5.0 cm, 5.0–10.0 cm, and 10.0–15.0 cm. Soil samples were air dried, gently ground, and passed through a 2-mm sieve. The samples were ball milled and passed through a 0.125-mm sieve to determine the overall %C using the dry combustion method with an NC 2100 soil analyzer (ThermoQuest CE Instruments, Milan, Italy). All course managers indicated that soils sampled had $\text{pH}<7.3$ so C values obtained through the dry combustion method are assumed to be SOC due to the absence of carbonates (Golubiewski 2006).

The data on SOC concentration (%) was plotted against the years since turfgrass development for all sites and for each depth. Using SAS Statistical Procedures (SAS Institute Inc., Cary, North Carolina) a nonlinear regression analysis was performed on each plot to determine the amount of C sequestered per year, per site, per depth, as well as the time needed to attain the equilibrium level of SOC concentration. Minitab 14.1 (MINITAB Inc., State College, PA) was used to conduct one-way ANOVAs to determine if there were significant differences among the following; ρ_b, and site, ρ_b and years since turfgrass development, %C and depth, %C and years since turfgrass development, %C and site and to conduct two-sample t tests to determine if there were significant differences between fairway or rough sites and their corresponding paired agricultural sites.

Five year mean gasoline and diesel fuel use was obtained from the long term maintenance data at Oakhurst Country Club. Kilograms of gasoline, and diesel fuel used was converted to kg of carbon equivalent (Ce) emitted each year (Lal 2004b). Irrigation information was obtained using long term maintenance records for total pump output for 1 year, total dynamic head (TDH), gallons per minute in which pump operates, efficiency of the system, and total irrigation emission was determined (Whiffen 1991; Pira 1997). Amount of N, P and K fertilizer as well as active ingredients from fungicide, insecticide, and pesticide applied over a 1 year period was determined from the long term maintenance data. The total amount of N, P, and K in kg was converted to kg of Ce to estimate the overall kg of Ce produced through pesticide application (Lal and Bruce 1999).

The overall area of rough and fairway for each course was determined using ArcGIS software (ESRI, Redlands, California). Greens and tees were considered part of the fairway. The overall C sequestered per site at each depth was then determined using Eqs. 1 to 3:

$$10^4\left(\mathrm{m}^2/\mathrm{ha}\right)*\mathrm{depth}(\mathrm{m})*\mathrm{Bulk\ Density}\left(\mathrm{Mg}/\mathrm{m}^3\right)*\mathrm{C}/\mathrm{yr}(\%)/100=\mathrm{Mg\ C}/\mathrm{ha}/\mathrm{yr} \tag{1}$$

$$\mathrm{Mg\ C}/\mathrm{ha}*\mathrm{ha}=\mathrm{Mg\ C\ sequestered\ per\ site} \tag{2}$$

$$\mathrm{Mg\ C\ sequestered\ per\ site}*\mathrm{years\ of\ sequestration}=\mathrm{Total\ Mg\ C\ sequestered\ per\ site} \tag{3}$$

Results & discussion

Carbon sequestration in soils

Non linear regression analysis indicated the magnitude of C accumulation in soils under fairway area following turfgrass development (Fig. 1). The rate of SOC accumulation was

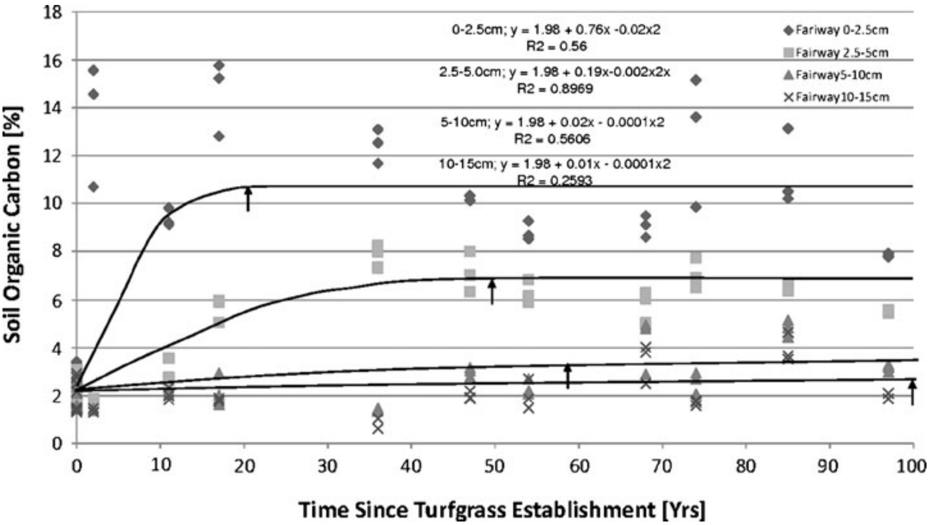


Fig. 1 The effect of fairway turfgrass development on the C pool at a depths of 0–2.5, 2.5–5, 5–10, and 10–15 cm's over a 97 year period. $N=3$ for each site each year. (Two-way ANOVA with Tukey's post test, for all interactions of %C by depth $p<0.001$, $F=19.67$, DF=32, $N=33$ for each site at each depth. *Arrows* indicate point where sequestration rate becomes negative)

the fastest in the top 2.5 cm of the soil profile (0.76% C/yr), and had the shortest time to equilibrate (14 years). In contrast, the rate of SOC accumulation was slowest in the 10–15 cm layer (0.01% C/yr), and it also took the longest time to equilibrate (81 years). The mean rate of C sequestration was estimated at 3.55±0.08 Mg/ha/yr, and the rate decreased with increase in soil depth. Furthermore, the time to attain equilibrium also increased with increase in soil depth (Table 2).

There was also an increase in SOC in soils managed under the rough area following turfgrass development (Fig. 2). The rate of SOC sequestration was the highest in the top

Table 2 C sequestration rate and time to equilibrium

Depth (cm)	Max Rate of C Sequestration (%C/yr)	Time to Equilibrium (yrs)
Fairway		
0–2.5	0.76	14
2.5–5	0.19	30
5–10	0.02	62
10–15	0.01	81
Interaction	$p<0.05$	
Rough		
0–2.5	0.46	12
2.5–5	0.22	24
5–10	0.03	68
10–15	0.01	91
Interaction	$p<0.05$	

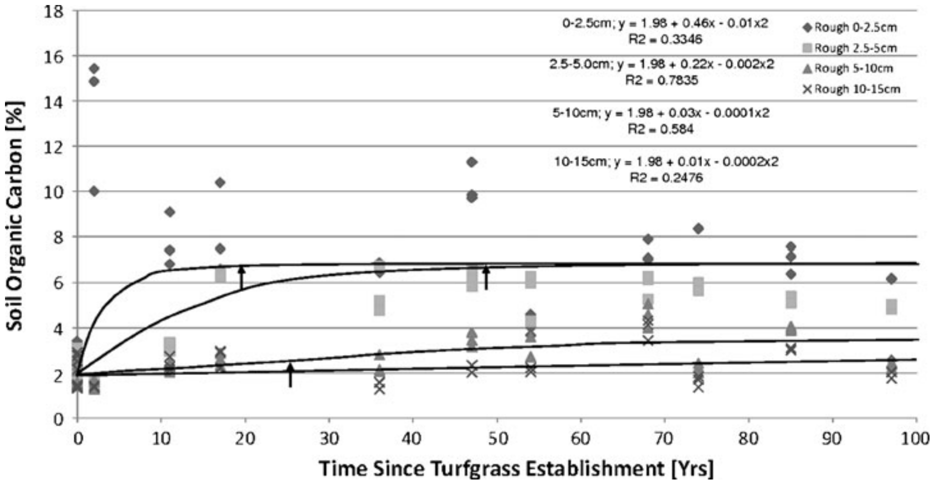


Fig. 2 The effect of rough turfgrass development on the C pool at a depths of 0–2.5, 2.5–5, 5–10, and 10–15 cm's over a 97 year period. $N=3$ for each site each year. (Two-way ANOVA with Tukey's post test, for all interactions of %C by depth $p<0.001$, $F=19.67$, DF=32, $N=33$ for each site at each depth. *Arrows* indicate point where sequestration rate becomes negative, arrow for 5–10 cm would be located at 150 years)

2.5 cm of the soil profile (0.46% C/yr), and the time to attain equilibrium was the shortest (23 years). In contrast, the rate of SOC accumulation was the lowest for the 10–15 cm layer (0.01% C/yr) and it took the longest time to equilibrate (91 years). The mean rate of C sequestration was estimated at 2.64±0.06 Mg/ha/yr and the rate decreased with increase in soil depth. Furthermore, the time to reach equilibrium also increased with increase in soil depth (Table 2). Significant differences in maximum rate of sequestration between soils managed under fairway and rough were observed only in the top 2.5 cm layer ($p<0.001$). Results in both fairway and rough plots showed higher levels of C sequestration than did previous studies in golf course systems by Qian and Follett (2002), Huh et al. (2008) and Bandaranayake et al. (2003). These studies determined sequestration rates of 1.0 Mg/ha/yr, 0.7 Mg/ha/yr, and 1.1 Mg/ha/y respectively. Courses utilized by these three studies, however, were converted from native grasslands which most likely contained higher antecedent SOC levels than did the agricultural soils that were used to create the courses in the present study, and thus had a lower initial sequestration rate.

Total SOC pool was the highest in the top 2.5 cm of the soil under fairway (11.01± 1.99%) and rough (7.80±1.61%) conditions. The SOC pool decreased with increase in soil depth for both the fairway and rough managed soils, with differences in SOC pool among management types being observed only for the top depth (Table 3). At each depth, there were significant differences in the SOC pool in fairway and rough soils and between their paired agricultural sites ($p<0.05$). There were no significant differences among depths in the SOC pool of agricultural soils, although a trend of declining SOC pool with increase in depth was observed ($p=0.069$). The mean SOC pool of both the fairway (5.38±2.26%) and rough (4.48±1.53) managed soils at a depth of 0–15 cm were found to be significantly higher than in the agriculturally (1.80±0.26) managed soil for the same depth (Table 3).

Soil ρ_b also varied among turf and agricultural sites. Soils under fairway (1.39± 0.06 Mg/m^3) and rough (1.39±0.06 Mg/m^3) areas were characterized by lower $_{\rho b}$ than those for agricultural soils (1.47±0.07; $p<0.001$).

Table 3 Mean soil organic carbon by depth and land use

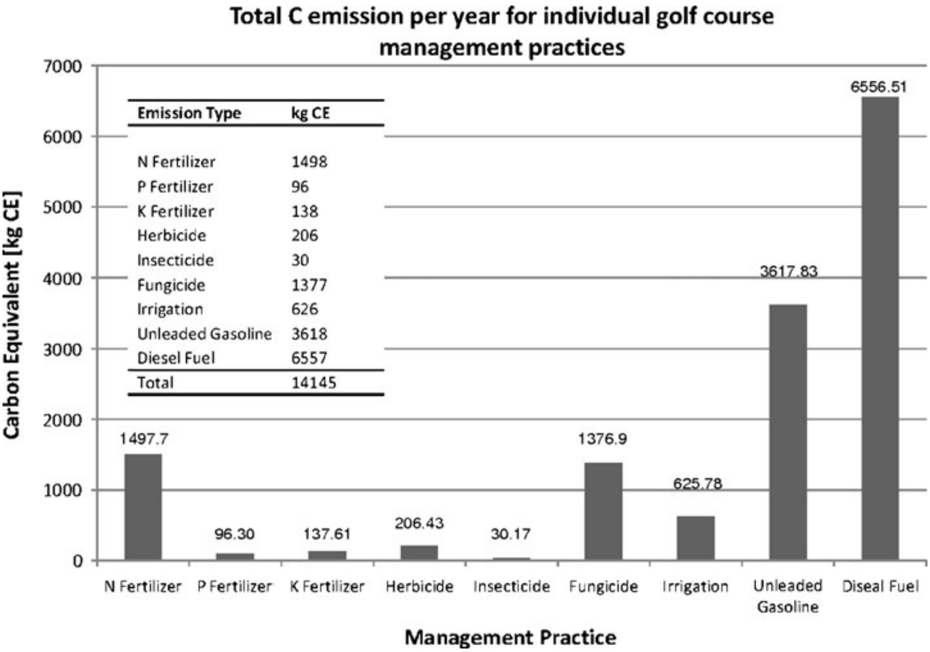
Depth (cm)	Mean Soil Organic Carbon (%)[ab]		
	Site		
	Fairway	Rough	Agriculture
0–2.5	11.01±1.99 (A)(1)	7.80±1.61 (A)(2)	1.98±0.29 (A)(3)
2.5–5.0	5.65±0.98 (B)(1)	5.00±0.90 (B)(1)	1.84±0.26 (A)(2)
5.0–10.0	2.72±0.56 (C)(1)	2.83±0.44 (C)(1)	1.71±0.21 (A)(2)
10.0–15.0	2.13±0.05 (D)(1)	2.29±0.39 (D)(1)	1.65±0.25 (A)(2)
p value	<0.001	<0.001	0.069
0–15.0	5.38±2.26 (1)	4.48±1.53 (2)	1.80±0.26 (3)

[a] values with different letters vertically represent significant difference at $p<0.05$

[b] values with different numbers horizontally represent significant difference at $p<0.05$

Effect of turfgrass maintenance and carbon emissions

Total C emissions from turfgrass maintenance practices were estimated at 6,557 kg CE from diesel and 3,618 kg CE from unleaded gasoline. Other significant sources of C emissions included fungicide use (1,377 kg CE), N fertilizer application (1,498 kg CE), and irrigation (626 kg CE) (Fig. 3). Average emissions from all management practices for the Oakhurst Country Club were 14.15 Mg C/yr, or equivalent to 0.30 Mg C/ha/yr.



Emission Type	kg CE
N Fertilizer	1498
P Fertilizer	96
K Fertilizer	138
Herbicide	206
Insecticide	30
Fungicide	1377
Irrigation	626
Unleaded Gasoline	3618
Diesel Fuel	6557
Total	14145

Fig. 3 The estimated total C emission (kg CE) per year for various golf course management practices over 46.77 ha at Oakhurst Country Club

Total carbon sequestration potential of turfgrasses

Based on the mean SOC sequestration rate, equilibrium time, and accounting for the average area of fairway (12.18±1.61 ha) and rough (42.74±5.09) soils per course, the average C sequestration per course per year was greater in soils under rough management (113.4±13.71 Mg) than those under fairway (43.6±6.8 Mg) management. Based on these estimations and subtracting the average yearly maintenance C emissions of 14.15 Mg/yr, the mean net potential of golf courses in this study to sequester C over a 91.4 year period was estimated at 2,224±88 Mg per course (Table 4). This net level of SOC sequestration, taking into account maintenance emissions, is equivalent to 0.44 Mg C/ha/yr.

Conclusions

As hypothesized, conversion of cropland soils to golf courses enhances the SOC pool. The magnitude of SOC sequestration was high in soils under fairway and rough areas, although, soils under fairway had higher total C accumulation in the top 2.5 cm, most likely due to more intensive management. The data presented must be viewed in consideration of several issues discussed below. The potential to sequester C for each site in this study assumed a newly constructed course, which may overestimate the SOC sink capacity as some courses may have filled all or part of their SOC sink capacity. Thus, the data presented is indicative of the overall potential of a new course to sequester C. Furthermore, greens and tees were considered as fairways although soils under these two locations are often treated differently than those under fairways. However, this should have minimal effects as greens and tees constitute only 1% of the total course area. Additionally, the mean rates of C sequestration determined proved several times higher than those in the previous literature. This may be due to the fact that previous studies utilized turfgrass establishment on grasslands and other previously non disturbed sites. However, all of the sites utilized in our study were disturbed agricultural soils immediately prior to golf course establishment. The farming of this land is likely to have depleted soil C pools and created a situation ideal for C sequestration. This fact may provide evidence for the added benefits of turfgrass development on previously disturbed soils. Construction of courses on previously cultivated soils may help reduces adverse environmental impacts, while utilizing soils severely depleted of their SOC pool, increasing their overall potential to sequester C.

Fossil fuel intensive maintenance emissions also proved to be a significant factor limiting net turfgrass sequestration potential. Substantial application of fertilizers, irrigation,

Table 4 Total C sequestration potential of golf course turfgrasses

Site	Rate of C Sequestration (Mg/ha/yr)	Total Sequestration per Course per year (Mg C/yr)	Sequestration Potential per Course over 91.4 years (Mg C)	Net Sequestration Potential per Course over 91.4 years (Mg C)
Fairway	3.55±.08	43.6±6.8	904.05±176	493.14±88.35
Rough	2.64±.06	113.4±13.71	2611.72±364.40	1730.43±374.31
Total Site		157.1±18.20	3516.88±465.05	2223.57±362.02
Interaction	$P<0.001$*			

*One-way ANOVA with Tukey's post test for all interactions of sequestration per hectare per year by site, $p<0.001$, $F=857.33$,DF=29. $N=10$ for each site and use of both diesel and unleaded gasoline for maintenance activities, reduce the net SOC sequestration potential. The data show that a newly constructed course may take 114 years to attain the equilibrium level of SOC pool. It is because of these maintenance emissions that golf turfgrass development has only a modest net C sink capacity. Additionally, estimation of the equilibrium period does not take into account the massive one time C emission due to construction of the course. This large initial emission can lower the technical SOC sequestration potential of turfs. Additionally, it must be noted that the present study is not a full lifecycle analysis of the system and gaseous C emissions through processes such as soil respiration were not measured or included in the results. If determined in future studies these gaseous emissions may provide novel information as to the total potential of these soils to sequester C.

Minimization of the maintenance emissions may prove beneficial in improving the SOC sequestration potential of golf turfgrass soils. There are several options to limit management related emissions. Enhancing use efficiency of all inputs such as irrigation, fertilizer and fungicides can greatly reduce management related emissions. Identification of an environmental management plan and construction of “green” buildings may also decrease the C footprint of golf courses. Site selection must also be carefully considered to limit important habitat destruction. Adoption of best management practices may also increase the profitability by improving efficiency and reducing the use of expensive chemicals and labor, thus creating a win-win situation for course owners and the environment.

While urbanization in the form of golf course development may hold the potential to alter C dynamics there are a number of other turfgrass systems in the U.S. which may hold a greater potential for sequestering C, including grasslands, home lawns, parks, and alternate recreational areas. While our study focused solely on golf course turf soils, evidence that sequestration takes place in home and ornamental lawns in a similar manner has been shown by Pouyat et al. (2009a) who found that C sequestration in home lawns took place for a 40 year period at a rate of 0.18 Mg/ha/yr. While this rate is lower than that found in the golf courses studied here, they may provide a more effective sink for C as inputs into systems such as home lawns are typically lower than those for golf systems. As urbanization continues to increase, there exists a strong need to assess SOC sequestration potential of alternate turf systems.

Acknowledgments We thank all of the golf course superintendents for allowing us the time and use of their land for soil sampling. Special consideration goes to John Hoyle, superintendent of Oakhurst Country Club, for providing us with long term fertilization and pesticide data, as well as fuel data and other information making this research possible.

Additional gratitude goes to Klaus Lorenz and Basant Rimal who aided in C analysis as well as Bert Bishop for his help with the statistical analysis.

This work was funded by both the Environmental Science Graduate Program and the Introductory Biology Program at The Ohio State University.

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