Soil Organic Carbon Input from Urban Turfgrasses

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Turfgrass is a major vegetation type in the urban and suburban environment. Management practices such as species selection, irrigation, and mowing may affect C input and storage in these systems. Research was conducted to determine the rate of soil organic C (SOC) changes, soil C sequestration, and SOC decomposition of fine fescue (*Festuca* spp.) (rainfed and irrigated), Kentucky bluegrass (*Poa pratensis* L.) (irrigated), and creeping bentgrass (*Agrostis palustris* Huds.) (irrigated) using C isotope techniques. We found that 4 yr after establishment, about 17 to 24% of SOC at 0 to 10 cm and 1 to 13% from 10 to 20 cm was derived from turfgrass. Irrigated fine fescue added the most SOC (3.35 Mg C ha^{-1} yr^{-1}) to the 0- to 20-cm soil profile but also had the highest rate of SOC decomposition (2.61 Mg C ha^{-1} yr^{-1}). The corresponding additions and decomposition rates for unirrigated fine fescue, Kentucky bluegrass, and creeping bentgrass in the top 20-cm soil profile were 1.39 and 0.87, 2.05 and 1.73, and 2.28 and 1.50 Mg C ha^{-1} yr^{-1}, respectively. Irrigation increased both SOC input and decomposition. We found that all turfgrasses exhibited significant C sequestration (0.32–0.78 Mg ha^{-1} yr^{-1}) during the first 4 yr after turf establishment. The net C sequestration rate was higher, however, for irrigated fine fescue and creeping bentgrass than for Kentucky bluegrass. To evaluate total C balance, additional work is needed to evaluate the total C budget and fluxes of the other greenhouse gases in turfgrass systems.

Abbreviations: SOC, soil organic carbon; SON, soil organic nitrogen; $\delta^{13}C$, carbon isotope ratio.

Carbon sequestration is the process of capturing and storing C in organic form in soil organic matter. Experts believe that soil C sequestration will reduce the buildup of CO_2 (a greenhouse gas) in the atmosphere while improving the nation's soil, air, and water quality and the agricultural economy (Lal and Follett, 2009). Intensive research has been conducted to quantify C sequestration in agricultural lands; however, research to quantify the C sequestration potential of turfgrass systems is very limited. Previously, we conducted an initial study to assess soil C sequestration in golf course fairways and putting greens using historic soil testing data in Colorado and Wyoming (Qian and Follett, 2002). We found that a rapid SOC accumulation occurred during the first 25 yr after turfgrass establishment, at average rates approaching 0.9 and 1.0 Mg C ha^{-1} yr^{-1}. These rates are comparable to those reported for U.S. land that has been placed in the Conservation Reserve Program (Follett et al., 2001). These results suggest that turfgrass is effective in sequestering atmospheric CO_2 and in improving soil quality. Considering that turfgrass acreage is three times larger than any irrigated crop, covering more than 16 million ha in the continental United States (Milesi et al., 2005), further research is needed to quantify C sequestration of turfgrasses under different management regimes.

Management of turfgrasses is highly variable, in part because of the different uses, species, nutrient inputs, and management levels. Milesi et al. (2005) estimated the potential C flux in turfgrass systems using the Biome-BGC ecosystem process model and assuming that the entire turf surface across 48 states was managed homogeneously. Golubiewski (2006) found, however, that management

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level dominates the response of turfgrass production and tissue N concentration, which, in turn, influences the amount of C and N both stored in and harvested from the turf site. Research to document the effects of different management scenarios on soil organic C and N changes will aid in a better understanding of the impact of turfgrass on urban ecosystem C budgets.

Approximately 1.1% of the C in the biosphere is in the form of the stable isotope ^{13}C and 98.9% as the stable isotope ^{12}C. The photosynthetic pathways of cool- and warm-season plants discriminate ^{13}C differently, thus resulting in different C isotope ratios ($^{13}C/^{12}C$), expressed as $\delta^{13}C$ and having per mil (‰) units. The sign of the $\delta^{13}C$ value indicates whether the sample has a higher or lower $^{13}C/^{12}C$ isotope ratio than Pee Dee belemnite (PDB), a limestone standard from near Pee Dee, SC (Boutton, 1991). The mean $\delta^{13}C$ of warm-season and cool-season plant tissues are near −27 and −13‰, respectively (Clay et al., 2006; Deines, 1980; Follett et al., 2004). Therefore, the abundance of the natural ^{13}C or $\delta^{13}C$ may aid in partitioning SOC with regard to its origin. For example, when cool-season turfgrass is established on previous warm-season (such as corn [*Zea mays* L.]) fields or warm–cool-season rotation fields (such as corn–soybean [*Glycine max* (L.) Merr.] rotations), isotope techniques can be effectively used to trace how fast turfgrass can contribute to the SOC accumulation. This technique has been successfully used in agricultural and native grasslands to assess soil C sequestration. By using a C isotope methodology, Gregorich et al. (1995) was able to determine that, following 25 yr of continuously grown corn on a forest soil in eastern Ontario, about 30% of the SOC in the plow layer (0–27 cm) was derived from the corn. Gregorich et al. (1996) also used ^{13}C abundance methods to account for the higher amount of C_4 plant-derived C in long-term N-fertilized soils compared with unfertilized soils. Follett et al. (1997) had also earlier used ^{13}C abundance methods to determine the efficiency of incorporation of small-grain crop residue into soils with a native warm-season grass origin in the Great Plains. Follett et al. (2009) recently used ^{13}C abundance methods to determine that the conversion of a field that had been in 13 yr of continuous smooth bromegrass to no-till corn production did not result in any net change in SOC during a 6-yr corn production period in the western U.S. Corn Belt; however, there was a significant change in the relative amount of SOC that remained from the C_3 bromegrass and the amount added by the C_4 corn during the 6 yr, and a redistribution of SOC into different soil aggregate size classes.

The main objectives of this study were to: (i) determine the amount of SOC derived from turfgrass after 4 yr of establishment on a previous corn and soybean (as rotation crops) field using the C isotope technique; and (ii) determine soil C sequestration and organic C decomposition from different turfgrasses.

MATERIALS AND METHODS

Experimental Site and Management

The selected research site was located on Arbor Links Golf Course, Nebraska City, NE. The study site was originally a native prairie occupied by a mix of warm- and cool-season plants (Krings and Kimble, personal communication, 2008). In the 1860s, native plants were cleared to grow wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), sorghum [*Sorghum bicolor* (L.) Moench], and corn as rotation crops. The cropping sequence changed to a corn–soybean rotation in the 1970s. In 2000, the ground in this area was reshaped for golf course development. Based on the weather station record (weather station no. 255810, High Plains Regional Climate Center), the average annual precipitation rate of the study site is approximately 86 cm, with an average high temperature ranging from 0°C in January to 31°C in July and an average low temperature ranging from −21°C in January to 19°C in July. The soil of the study site is an Aksarben silty clay loam (a fine, smectitic, mesic Typic Argiudoll) with an average pH of 6.8.

In the fall of 2001, the following turfgrasses were seeded in replicated plots: unirrigated fine fescue (a mixture of hard fescue [*Festuca brevipila* R. Tracey) and sheep fescue [*Festuca ovina* L.]), irrigated fine fescue (a mixture of hard fescue and sheep fescue), Kentucky bluegrass (a blend of 'Moonlight,' 'Award,' and 'Brilliant'), and creeping bentgrass ('Seaside II'). Seeding rates were 35, 74, and 196 kg ha^{-1} for creeping bentgrass, Kentucky bluegrass, and fine fescue, respectively. After seeding, the experimental area was irrigated lightly three times daily until 3 wk after seeding. Thereafter, the plots were irrigated as needed to prevent drought and encourage establishment for the remaining season of the establishment year.

During growing seasons from 2002 to 2005, different management regimes were applied to reflect four management intensities. Briefly, creeping bentgrass plots were managed as fairway turf: mowed every other day to 1.5 cm and irrigated every other day at about 90 to 100% evapotranspiration (ET). Kentucky bluegrass plots were managed as short rough: mowed twice a week to 3.8 cm and irrigated twice a week at 90 to 100% ET. Irrigated fine fescue plots were managed as rough: mowed to 5.1 cm weekly and irrigated twice a week at 70% ET. Rainfed fine fescue plots were managed as unirrigated rough: mowed to 5.1 cm when necessary. All plots were fertilized with 150 kg ha^{-1} N annually from 2002 to 2005. During mowing events, clippings were returning to the soil.

Sample Collection, Measurement, and Analysis

In November 2001 (2 mo after seeding), November 2002 (1 yr after turf establishment), and October 2005 (4 yr after turfgrass establishment), the soil was sampled by first removing the plant material from the soil surface and then, using a flat-bladed shovel, undercutting and removing the soil from the 0- to 10- and 10- to 20-cm depths as described by Follett et al. (2009). Soil bulk densities (at 33 kPa of moisture tension) were determined on clods from each soil layer and coated with Saran F-310 (Dow Chemical, Midland, MI) for transport and measurement of soil bulk density (Burt, 2004). Three subsamples from each plot at each depth were collected. Samples were analyzed for total SOC, total soil organic N (SON), and $\delta^{13}C$. Root density was also determined in 2001 and 2005. In addition, aboveground tissues (shoots) were collected in 2005 from 100 cm^2 of each plot for determination of the plant tissue $\delta^{13}C$. To determine the root density, defined as root mass per unit mass of soil, soil samples were weighed to determine fresh and dry mass. Roots were washed free of soil using a hydro-pneumatic elutriation system, dried at 75°C for 2 d, and the root mass was determined.

For determination of SOC and SON, roots (>1 mm in length) were removed by hand before any analysis. All samples of soil, roots, and shoots were analyzed for total C, total N, and $\delta^{13}C$ using a Europa Scientific 20-20 Stable Isotope Analyzer (isotope ratio mass spectrometer) continuous flow interfaced with a Europa Scientific ANCA-NT system (automated CN analyzer) Solid/Liquid Preparation Module (Dumas combustion sample preparation system) (Sercon Ltd., Europa Scientific, Crewe, UK).

Carbon Sequestration and Turfgrass Soil Organic Carbon Contribution Calculations

The proportion of C derived from turfgrass, *X*%, at 4 yr after the establishment of the turf, was calculated by the following equation. The equation is modified from Gregorich et al. (1996) and Follett et al. (1997):

$$X\% = \frac{\delta^{13}C_{\text{turf soil 2005}} - \delta^{13}C_{\text{baseline}}}{\delta^{13}C_{\text{turf tissue}} - \delta^{13}C_{\text{baseline}}} 100 \qquad [1]$$

where $\delta^{13}C_{\text{turf soil 2005}}$ is the $\delta^{13}C$ of the soil samples collected in 2005, $\delta^{13}C_{\text{baseline}}$ is the $\delta^{13}C$ of soil samples collected in 2001, and $\delta^{13}C_{\text{turf tissue}}$ is the combined $\delta^{13}C$ of roots and shoots.

Carbon input from turfgrass during the specific period was calculated as

$$\text{Gross SOC input from turfgrass} = \text{SOC}_{2005} X\% \qquad [2]$$

Changes in SOC content at establishment and 4 yr after establishment provided the C sequestration rate for the 4 yr following establishment:

$$\text{Net C sequestration} = \text{SOC}_{2005} - \text{SOC}_{2001} \qquad [3]$$

By subtracting the net C sequestration from the gross C input, we derived the soil C decomposition data.

RESULTS AND DISCUSSION

Vegetation Biomass

Aboveground vegetation biomass was determined only in 2005 (Table 1). For the irrigated fine fescue, Kentucky bluegrass, and creeping bentgrass, a layer of thatch existed (thatch is a layer of aboveground living and decaying plant material that forms between the soil surface and the green vegetation). Therefore, the aboveground tissue was separated into thatch and shoots for biomass determination. Fine fescue, Kentucky bluegrass, and creeping bentgrass allocated approximately 60 to 64% of the aboveground biomass in the form of thatch. Thatch was not apparent, however, for the unirrigated fine fescue plots, so all the aboveground biomass was grouped as shoots. Despite the difference of thatch biomass and mowing height, all grasses produced a similar amount of total aboveground biomass (Table 1).

Table 1. Aboveground vegetation biomass of different grasses grown in the field under different management regimes.

Grass	Mowing height	2005 vegetation biomass		
		Shoots	Thatch	Total aboveground biomass
	cm	kg m^{-2}		
Fine fescue (unirrigated)	7.6	3.45 a†	N/A	3.45
Fine fescue (irrigated)	5.1	1.17 b	1.83	3.01
Kentucky bluegrass	2.5	1.25 b	2.24	3.49
Creeping bentgrass	1.2	1.31 b	1.93	3.24

† Means followed by different letters are significantly different ($P \leq 0.05$) by LSD.

Root Mass

One year after establishment (2002), the unirrigated fine fescue had a lower root density than the creeping bentgrass and irrigated fine fescue at 0 to 10 and 10 to 20 cm, respectively (Table 2). At the 0- to 10-cm depth, the creeping bentgrass exhibited 1.6 times more roots than the unirrigated fine fescue. At 10 to 20 cm, the irrigated fine fescue exhibited 140% more roots than the unirrigated fine fescue. The root density of the Kentucky bluegrass and creeping bentgrass was not different from either unirrigated or irrigated fine fescue.

Four years after establishment (in 2005), the fine fescue (both irrigated and unirrigated) had a greater root density than the Kentucky bluegrass and creeping bentgrass at both 0 to 10 and 10 to 20 cm (Table 2). Root production is probably related to mowing height and species genetic potential. Fescues are generally believed to have deeper and more extensive root systems than Kentucky bluegrass or creeping bentgrass.

Carbon Isotope Ratios

The mean $\delta^{13}C$ values for the irrigated Kentucky bluegrass, fine fescue, and creeping bentgrass shoots collected in October 2005 were −26.8, −26.2, and −27.3‰, respectively (Table 3). The mean $\delta^{13}C$ values of the roots were slightly higher than those of the shoots (Table 3). Compared with the irrigated fine fescue, the rainfed fine fescue had a less negative $\delta^{13}C$, with mean $\delta^{13}C$ values of −25.2 and −24.5‰ for its shoots and roots, respectively (Table 3). This difference reflected the greater stomatal resistance caused by lower water availability in the rainfed fine fescue.

We collected soil baseline samples in November 2001. The baseline SOC $\delta^{13}C$ was approximately −18.0‰, reflecting the historical vegetation, i.e., a mix of C_3 and C_4 vegetation for the land use history. The large distinguishable differences in isotope

Table 2. Root density of different grasses grown in the field under different management regimes.

Grass	Mowing height	2002 Root density		2005 Root density	
		0–10 cm	10–20 cm	0–10 cm	10–20 cm
	cm	g kg^{-1} dry soil			
Fine fescue (unirrigated)	5.1	3.4 b†	0.38 b	36.3 a	10.4 a
Fine fescue (irrigated)	5.1	6.67 ab	1.25 a	33.9 a	10.2 a
Kentucky bluegrass	2.5	5.69 ab	0.70 ab	16.5 b	6.1 ab
Creeping bentgrass	1.2	8.42 a	0.88 ab	13.5 b	2.9 b

† Means followed by different letters in a column are significantly different ($P \leq 0.05$) by LSD.

Table 3. Plant tissue C isotope composition 4 yr after establishment.

Grass	C isotope ratio ($\delta^{13}C$) Root	Shoot
	‰	
Fine fescue (unirrigated)	−24.5 a†	−25.2 a
Fine fescue (irrigated)	−25.5 b	−26.2 b
Kentucky bluegrass	−25.7 b	−26.8 b
Creeping bentgrass	−26.27 c	−27.3 c

† Means followed by different letters in a column are significantly different ($P \leq 0.05$) by LSD.

signatures of the current turfgrasses vs. the SOC isotope baseline suggest that our experimental approach was feasible.

Data on C isotope composition, SOC, SON, and the SOC/SON ratio for soil samples collected in 2002 and 2005 are presented in Table 4. During the first year after the establishment of turf (2001–2002), SOC increased and SON stayed at similar levels, which resulted in an increased C/N ratio of the soil organic matter. The increased soil organic matter C/N ratio indicated that the newly established turf systems favored N immobilization, justifying a higher N fertilization need compared with long-established and mature turfgrass systems. From 2002 to 2005, there was a continued increase in SOC for the unirrigated fine fescue, Kentucky bluegrass, and creeping bentgrass at 0 to 10 cm. At 10 to 20 cm, the change in SOC was small in magnitude. From 2002 to 2005, the unirrigated fine fescue and creeping bentgrass exhibited increases in the C/N ratio at 0 to 10 cm, whereas the soil C/N ratio of the irrigated fine fescue and Kentucky bluegrass showed no change. At 10 to 20 cm, the C/N ratio was slightly reduced from 2002 to 2005. These data suggest that 2- to 5-yr-old turf systems favor C sequestration at the surface (0–10 cm).

Organic Carbon Input from Turf, Carbon Sequestration, and Carbon Decomposition

Using Eq. [1], the percentage of SOC derived from individual turfgrasses in 2005 was calculated for both the 0- to 10- and 10- to 20-cm depths (Table 5). These data show that 4 yr after turfgrass establishment on a previous corn–soybean field in the north-central United States, about 17 to 24% of the SOC was derived from the turfgrass at 0 to 10 cm. At the 10- to 20-cm depth, we found striking differences among the turfgrass species. For shallow-rooted Kentucky bluegrass and creeping bentgrass, only about 1 and 4% of the SOC was derived from the turfgrass at 10 to 20 cm, whereas for the deep-rooted fine fescue, about 10 to 13% was derived from the turfgrass. Fisher et al. (1994) found that deep-rooted grasses introduced into South American savannas for agricultural purposes sequestered significant amounts of organic C deep in the soil profile. They suggested that a substantial amount of C, globally, could be locked up in such a manner. When we combined the data from the two depths, about 10 to 18% of the SOC (0–20 cm) was derived from turfgrass.

Using the bulk density data collected in 2001, which suggested that all plots had similar bulk densities (Table 4), gross SOC inputs by turfgrass were calculated (Tables 5 and 6). During the initial 4 yr after establishment, irrigated fine fescue had a gross input of 3.35 Mg C ha^{-1} yr^{-1} to the 0- to 20-cm soil profile, which is about 141% higher than the SOC input from unirrigated fine fescue, and 55% higher than irrigated Kentucky bluegrass or creeping bentgrass.

Soil organic C content differences between 2005 and 2001 indicated that SOC at 0 to 20 cm in the soil profile increased 0.75, 1.10, 0.45, and 1.14 g kg^{-1} soil for unirrigated fescue, irrigated fescue, Kentucky bluegrass, and creeping bentgrass, respectively. Based on the bulk density data collected in 2001, these SOC changes translate to C sequestration rates of 0.52, 0.74, 0.32, and 0.78 Mg C ha^{-1} yr^{-1} for unirrigated fine fescue, irrigated fine fescue, Kentucky bluegrass, and creeping bentgrass, respectively. All turfgrasses exhibited significant C sequestration; however, the net C sequestration rate in the 0- to 20-cm soil profile was higher in the irrigated fine fescue and creeping bentgrass plots. Kentucky bluegrass had the lowest C sequestration rate among the tested species. The C sequestration rate for unirrigated fine fescue was intermediate but was not statistically different from Kentucky bluegrass or irrigated fine fescue. The C sequestration potential is related not only to the productivity of roots,

Table 4. Plant tissue C isotope ratio ($\delta^{13}C$), soil organic C (SOC), soil organic N (SON), and soil C/N ratio at the establishment of different grasses and 1 and 4 yr after turf establishment.

Grass	2001 baselines Shoot $\delta^{13}C$	Soil $\delta^{13}C$	SOC	SON	C/N	2002 data Bulk density	$\delta^{13}C$	SOC	SON	C/N	2005 data $\delta^{13}C$	SOC	SON	C/N
	‰		g kg^{-1}				‰	g kg^{-1}			‰	g kg^{-1}		
							0–10 cm							
Fine fescue (unirrigated)	−27.91 a†	−17.54	13.0 ab	1.25 b	10.5	1.30	−18.55	14.2 ab	1.38 ab	10.2 ab	−18.84 a	14.9	1.34	10.98
Fine fescue (irrigated)	−27.99 a	−18.05	15.5 a	1.57 a	9.9	1.25	−18.52	15.9 a	1.47 a	10.8 a	−19.9 ab	15.7	1.44	10.86
Kentucky bluegrass	−29.08 b	−18.14	14.3 ab	1.37 ab	10.3	1.35	−18.89	14.8 ab	1.38 ab	10.8 a	−19.61 ab	15.7	1.35	10.9
Creeping bentgrass	−28.66 ab	−18.35	12.3 b	1.27 b	9.2	1.32	−19.17	12.4 b	1.20 b	10.0 b	−20.07 b	14.3	1.34	10.32
							10–20 cm							
Fine fescue (unirrigated)	−27.91 a	−18.20	7.6	0.94	8.1	1.44	−18.79 NS	7.7 NS	0.87 NS	8.6 NS	−18.85 ab	7.2	0.85	7.87
Fine fescue (irrigated)	−27.99 a	−18.42	8.0	1.15	6.6	1.42	−18.93	11.5	1.10	9.9	−19.38 b	10.0	1.03	8.98
Kentucky bluegrass	−29.08 b	−17.61	11.8	1.27	9.0	1.44	−18.60	11.0	1.07	10.1	−17.68 a	11.3	1.14	9.72
Creeping bentgrass	−28.66 ab	−17.77	9.8	1.17	7.7	1.42	−18.84	10.0	1.02	8.8	−18.14 ab	10.08	1.05	8.74

† Means followed by different letters in a column are significantly different ($P \leq 0.05$) by LSD.

Table 5. Percentage of soil organic C (SOC) from turf and C inputs from turfgrass at 0 to 10 and 10 to 20 cm in the soil profile under different turfgrasses in 2005.

Grass	0–10 cm			10–20 cm			0–20 cm	
	SOC from turf	Total SOC	SOC from turf	SOC from turf	Total SOC	SOC from turf	SOC from turf	C input from turf
	%	g kg^{-1}		%	g kg^{-1}		%	g kg^{-1}
Fine fescue (unirrigated)	17.8	14.9	2.65	9.78 a†	7.2	0.70	13.8	2.03 b
Fine fescue (irrigated)	23.7	15.7	3.72	12.92 a	10.0	1.29	18.3	5.02 a
Kentucky bluegrass	18.2	15.7	2.85	0.81 b	11.3	0.09	9.5	2.94 ab
Creeping bentgrass	20.4	14.3	2.92	4.10 b	10.1	0.41	12.2	3.33 ab

† Means followed by different letters in a column are significantly different ($P \leq 0.05$) by LSD.

rhizomes, and shoots, but also to SOC decomposition or turnover rates. This range of C sequestration is in agreement with the following reported studies. Bruce et al. (1999) estimated a gain of 0.6 Mg C ha^{-1} yr^{-1} for previously cultivated lands that had been reseeded to grass. Post and Kwon (2000) compiled literature data for soil C in areas where grasslands have been allowed to develop on previously disturbed lands and reported that the average rates of C accumulation during the early grassland establishment were 0.33 Mg ha^{-1} yr^{-1}. Qian and Follett (2002) reported a C sequestration rate of 0.9 to 1.0 Mg ha^{-1} yr^{-1} for highly managed turfgrass systems in Colorado and Wyoming. The management regime of Qian and Follett (2002) was similar as the management regimes of Kentucky bluegrass and creeping bentgrass in this study. The lower C sequestration ability of Kentucky bluegrass found in this study than that reported by Qian and Follett (2002) may have been due to the warmer climate, a smaller day–night temperature difference, and higher annual precipitation encountered at this study site. Bandaranayake et al. (2003) and Wang et al. (2000) suggested that higher temperature accelerates the decomposition of SOC only when soil moisture is adequate, and inhibits decomposition when soil moisture becomes limited.

By subtracting net C sequestration from gross C input, we derived soil C decomposition data (Table 6). The SOC decomposition rates were 1.73 and 1.50 Mg ha^{-1} yr^{-1} for Kentucky bluegrass and creeping bentgrass, respectively, which were higher than for unirrigated fine fescue and lower than for irrigated fine fescue. By comparing irrigated and unirrigated fine fescue plots, we found that irrigation increased the net organic C input to the 0- to 20-cm soil profile by 141%. At the same time, irrigation also increased SOC decomposition by twofold.

CONCLUSIONS

Urban grassland covers >16 million ha in the United States, and it is ubiquitous in the American urban landscape. Milesi et al. (2005) estimated that among the total land in the United States devoted to urban development, 39 to 54% is covered by turfgrass. Despite the large acreage of turf, the role of turf in balancing the nation's C budget has largely been unexplored. Previously, we have reported that C sequestration ability is intricately linked to the cycling of soil nutrients, including N, P, K, and micronutrients (Qian and Follett, 2002), and clipping management (Qian et al., 2003). Different C sequestration rates were observed under different treatments. Carbon sequestration rates were 0.74, and 0.78 Mg ha^{-1} yr^{-1} for irrigated fine fescue and creeping bentgrass, respectively, which are higher than those of unirrigated fine fescue and irrigated Kentucky bluegrass. In this experiment, we observed that irrigation increased both the gross SOC input to the soil profile and SOC decomposition in fine fescue. Thus, the SOC accumulation rate is associated with both turfgrass rooting depth and irrigation availability.

In summary, our experiment demonstrates that urban turfgrass systems provide a significant sink for SOC sequestration. Measurement of the C isotopic composition appears to be an appropriate approach to study SOC dynamics. Soil C sequestration and organic C decomposition rates are different for different turfgrasses and different management regimes.

To consider the net impact of urban grassland on the atmosphere's greenhouse effect, however, we need to consider fuel expenses in maintaining the turfgrass, fertilizer and pesticide use, energy for pumping water to irrigate, and the fluxes of other greenhouse gases (mainly N_2O and CH_4) in addition to soil C sequestration. Additional work is needed to evaluate the total C budget and fluxes of the other greenhouse gases in turfgrass systems.

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Table 6. Gross soil organic C (SOC) input, net soil C sequestration, and SOC decomposition in the 0- to 20-cm soil profile under different turfgrasses.

Grass	Gross SOC input from turf	Net C sequestration	SOC decomposition
	Mg ha^{-1} yr^{-1}		
Fine fescue (unirrigated)	1.39 b†	0.52 ab	0.87 c
Fine fescue (irrigated)	3.35 a	0.74 a	2.61 a
Kentucky bluegrass	2.05 ab	0.32 b	1.73 b
Creeping bentgrass	2.28 ab	0.78 a	1.50 b

† Means followed by different letters are significantly different ($P \leq 0.05$) by LSD.

REFERENCES

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

Boutton, T.W. 1991. Stable carbon isotope ratios of natural materials: I. Sample preparation and mass spectrometric analysis. p. 155–171. *In* D.C. Coleman and B. Fry (ed.) Carbon isotope techniques. Academic Press, San Diego.

Bruce, J.P., M. Frome, H. Haites, H. Janzen, R. Lal, and K. Paustian. 1999. Carbon sequestration in soils. J. Soil Water Conserv. 54:382–389.

Burt, R. (ed.). 2004. Soil survey laboratory methods manual. Soil Surv. Invest. Rep. 42, Version 4.0. NRCS, Washington, DC.

Clay, D.E., C.G. Carlson, S.A. Clay, C. Reese, Z. Liu, J. Chang, and M.M. Ellsbury. 2006. Theoretical derivation of stable and nonisotopic approaches for assessing soil organic carbon turnover. Agron. J. 98:443–450.

Deines, P. 1980. The isotopic composition of reduced organic carbon. p. 329–406. *In* P. Fritz and J.C. Fontes (ed.) Handbook of environmental isotope geochemistry. Vol. 1. The terrestrial environment. Part A. Elsevier, Amsterdam.

Fisher, M.J., I.M. Rao, M.A. Ayarza, C.E. Lascano, J.I. Sanz, R.J. Thomas, and R.R. Vera. 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature 371:236–238.

Follett, R.F., J. Kimble, S.W. Leavitt, and E. Pruessner. 2004. Potential use of C isotope analyses to evaluate paleoclimate. Soil Sci. 169:471–488.

Follett, R.F., E.A. Paul, S.W. Leavitt, A.D. Halvorson, D. Lyon, and G.A. Peterson. 1997. Carbon isotope ratios of Great Plains soils in wheat–fallow systems. Soil Sci. Soc. Am. J. 61:1068–1077.

Follett, R.F., S.E. Samson-Liebig, J.M. Kimble, E.G. Pruessner, and S.W. Waltman. 2001. Carbon sequestration under the Conservation Reserve Program in the historic grassland soils of the United States of America. p. 27–40. *In* R. Lal (ed.) Soil carbon sequestration and the greenhouse effect. SSSA Spec. Publ. 57. SSSA, Madison, WI.

Follett, R.F., G.A. Varvel, J.M. Kimble, and K.P. Vogel. 2009. No-till corn after bromegrass: Effect on soil carbon and soil aggregates. Agron. J. 101:261–268.

Golubiewski, N.E. 2006. Urbanization increases grassland carbon pools: Effects of landscaping in Colorado's Front Range. Ecol. Appl. 16:555–571.

Gregorich, E.G., B.H. Ellert, C.F. Drury, and B.C. Liang. 1996. Fertilization effects on soil organic matter turnover and corn residue C storage. Soil Sci. Soc. Am. J. 60:472–476.

Gregorich, E.G., B.H. Ellert, and C.M. Monreal. 1995. Turnover of soil organic matter and storage of corn residue carbon estimated from natural ^{13}C abundance. Can. J. Soil Sci. 75:161–167.

Lal, R., and R.F. Follett (ed.). 2009. Soil carbon sequestration and the greenhouse effect. SSSA Spec. Publ. 57. 2nd ed. SSSA, Madison, WI.

Milesi, C., S.W. Running, C.D. Elvidge, J.B. Dietz, B.T. Tuttle, and R.R. Nemani. 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environ. Manage. 36:426–438.

Post, W.M., and K.C. Kwon. 2000. Soil carbon sequestration and land-use change: Processes and potential. Global Change Biol. 6:317–327.

Qian, Y.L., and R.F. Follett. 2002. Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data. Agron. J. 94:930–935.

Qian, Y.L., W. Bandaranayake, W.J. Parton, B. Mecham, A.M. Harivandi, and A.R. Mosier. 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil carbon and nitrogen dynamics: The CENTURY model simulation. J. Environ. Qual. 32:1694–1700.

Wang, Y., R. Amundson, and X. Niu. 2000. Seasonal and altitudinal variation in decomposition of soil organic matter inferred from radiocarbon measurements of soil CO_2 flux. Global Biogeochem. Cycles 14:199–211.