Soil Organic Carbon Input from Urban Turfgrasses

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

Abstract

Turfgrass is a major vegetation type in the urban and suburban environment. Management practices such as species selection, irrigation, and mowing may affect carbon (C) input and storage in these systems. Research was conducted to determine the rate of soil organic carbon (SOC) changes, soil carbon sequestration, and SOC decomposition of fine fescue (*Festuca spp.*) (rain fed and irrigated), Kentucky bluegrass (*Poa pratensis* L.) (irrigated), and creeping bentgrass (*Agrostis palustris* Huds.) (irrigated) using carbon isotope techniques. Aboveground tissues were collected for biomass determination and carbon isotope ratio analysis. Soil was sampled for determination of root mass, soil bulk density, SOC, soil organic nitrogen, and C isotope ratio. Our results indicated that four years after establishment, about 17-24% of SOC at 0-10 cm and 1-13% from 10-20 cm was derived from turfgrass. Irrigated-fine fescue added the most SOC (3.35 ton C ha^{-1} yr^{-1}) to the 0-20 cm soil profile, but also had the highest rate of SOC decomposition (2.61 ton C ha^{-1} yr^{-1}). The corresponding additions and decomposition rates for non-irrigated 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 ton C ha^{-1} yr^{-1}, respectively. Thus, the irrigated fine fescue added about 140% more SOC than did the non-irrigated fine fescue, and 55% more than irrigated-Kentucky bluegrass and creeping bentgrass. Irrigation increased both net organic carbon input to the soil profile and SOC decomposition. We found that all turfgrasses exhibited significant carbon sequestration (0.32 -0.78 ton ha^{-1} yr^{-1}) during the first 4 years after turf establishment. However, the net carbon sequestration rate was higher for irrigated fine fescue and creeping bentgrass than for Kentucky bluegrass. To evaluate total carbon balance, additional work is needed to evaluate the total carbon budget and fluxes of the other greenhouse gases in turfgrass systems.

Introduction

Carbon sequestration is the process of capturing and storing carbon (C) in organic form in soil organic matter. Experts believe that soil carbon sequestration will reduce the buildup of carbon dioxide (a greenhouse gas) in the atmosphere while improving the nation's soil, air, and water quality and the agricultural economy (Lal and Follett, 2008). Intensive research has been conducted to quantify carbon sequestration in agricultural lands. However, research to quantify carbon sequestration potential in turfgrass systems is very limited. Previously, we (Qian and Follett, 2002) conducted an initial study to assess soil carbon sequestration in golf course fairways and putting greens using historic soil testing data in Colorado and Wyoming. We found that a rapid soil organic carbon accumulation occurred during the first 0-25 years after turfgrass establishment, at average rates approaching 0.9 and 1.0-ton C ha^{-1} yr^{-1}. These rates are comparable to those reported for US 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 turfgrass acreage is three times larger than that of any irrigated crop, covering more than 16 million ha in the continental United State (Milesi et al., 2005), further research is needed to quantify carbon sequestration of turfgrasses that are under different management regimes.

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

Approximately 1.1% of the carbon in the biosphere is in the form of the stable isotope ^{13}C carbon 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 ^{13}C: ^{12}C ratios, 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 PDB, a limestone standard from near Pee Dee, South Carolina (Boutton, 1991). The mean isotopic compositions ($\delta^{13}C$) 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 soil organic carbon (SOC) as to its origin. For example, when cool season turfgrass is established on previous warm-season (such as corn) fields or warm/cool season rotation fields (such as corn/soybean rotation fields), isotope technique can be effectively used to trace how fast turfgrass can contribute to the soil organic carbon accumulation. This technique has been successfully used in agricultural and native grasslands to assess soil carbon sequestration. By using 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 percent 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 to 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 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 Cornbelt, USA. However, there was a significant change in the relative amount of SOC that remained from the C3 bromegrass and the amount added by the C4 corn during the 6 yr, and a redistribution of SOC into different soil aggregate size classes.

The main objectives of this study were to: 1) determine amount of SOC derived from turfgrass after 4 years of turfgrass establishment on a previous corn and soybean (as rotation crops) field using the carbon isotope technique and 2) determine soil carbon sequestration and organic carbon decomposition of different turfgrasses.

Materials and Methods

1. Experimental Site and Management

The selected research site was located on Arbor Links Golf Course, Nebraska City, Nebraska. The study site was originally a native prairie occupied by a mix of warm and cool season plants (Krings and Kimble, 2008, personal communication). In the 1860s, native plants were cleared to grow wheat, oats, soghum, and corn, as rotation crops. The cropping sequence changed to a corn-soybean rotation in the 1970's. 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 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 (fine, smectitic, mesic Typic Argiudolls) with average pH of 6.8.

In the fall of 2001, the following turfgrasses were seeded in replicated plots: non-irrigated fine fescues (*Festuca spp.*) [a mixture of hard fescue (*Festuca brevipila* R. Tracey) and sheep fescue (*Festuca ovina* L.)], irrigated fine fescues (a mixture of hard fescue and sheep fescue), Kentucky bluegrass (*Poa pratensis* L.) (a blend of Moonlight, Award, and Brilliant), and creeping bentgrass (*Agrostis palustris* Huds.) (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 3 times daily until 3 wks after seeding. Thereafter, 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 4 management intensities. Briefly, creeping bentgrass plots were managed as fairway turf - mowed every other day at 1.5 cm and irrigated every other day at about 90-100% evapotranspiration (ET). Kentucky bluegrass plots were managed as short rough - mowed twice a week at 3.8 cm and irrigated twice a week at 90-100% ET. Irrigated fine fescue plots were managed as rough - mowed at 5.1 cm weekly and irrigated twice a week at 70% ET. Rainfed fine fescue plots were managed as non-irrigated rough mowed at 5.1 cm when necessary. All plots were fertilized at 150 kg ha^{-1} N annually from 2002 to 2005. During mowing events, clippings were returning to the soil.

2. Sample Collection, Measurement, and Analysis

In November 2001 (two months after seeding), November 2002 (1 year after turf establishment), and October 2005 (4 years after turfgrass establishment), 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-cm, 10- to 20-cm as described by Follett et al., 2009. Soil bulk densities (33 kPa of moisture tension) were determined on clods from each soil layer and coated with Saran F-310 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 soil organic carbon (SOC), total soil organic nitrogen (SON), and C isotope ratio ($\delta^{13}C$). Root density was also determined in 2001 and 2005. In addition, aboveground tissues (shoots) were collected in 2005 from each plot from 100 cm^2 for determination of plant tissue C isotope ratio. To determine 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 hydropneumatic elutriation system, dried at 75 C for 2 days, and 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 $^{13}C/^{12}C$ isotope ratio using a Europa Scientific 20–20 Stable Isotope Analyzer (isotope ratio mass spectrometer) continuous flow interfaced with Europa Scientific ANCA-NT system (automated nitrogen carbon analyzer) Solid/Liquid Preparation Module (Dumas combustion sample preparation system) (Sercon Ltd., Europa Scientific, Crewe Cheshire, UK)*.

3. Carbon Sequestration and Turfgrass Soil Organic Carbon Contribution Calculations

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

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

Where, $\delta^{13}C_{\text{turf soil 2005}}$ was the $\delta^{13}C$ of 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:

Gross SOC input from turfgrass = $(SOC)_{2005} \times (X\%)$ ....(2)

Changes in soil organic carbon content at establishment and 4 years after establishment provide carbon sequestration rate 4 years following establishment.

Net carbon sequestration = $SOC_{2005} - SOC_{2001}$ ....(3)

By subtracting net carbon sequestration from gross carbon input we derived soil carbon decomposition data

Results and Discussion

1. Vegetation biomass:

Aboveground vegetation biomass was only determined in 2005 (Table 1). For irrigated fine fescue, Kentucky bluegrass, and creeping bentgrass, a layer of thatch exists (thatch is a layer of aboveground living and decaying plant material that forms between the soil surface and the green vegetation). Therefore, above ground tissue was separated into thatch and shoots for biomass determination. Fine fescue, Kentucky bluegrass, and creeping bentgrass allocated approximately 60-64% of aboveground biomass in a form of thatch. However, thatch is not apparent for non-irrigated fine fescue plots; all 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).

2. Root mass:

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

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

3. Carbon isotope

The mean $\delta^{13}C$ values for 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 $\delta^{13}C$ of roots were slightly higher than that of shoots (Table 3). Compared to irrigated fine fescue, rain-fed 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 rain-fed 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 signatures of current turfgrasses vs. SOC isotope baseline suggest our experimental approach was feasible.

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

Organic carbon input from turf, C sequestration, and C decomposition

Using equation [1], the percent of soil organic carbon derived from individual turfgrasses in 2005 was calculated for both 0-10 and 10-20 cm depth (Table 5). These data show that four years after turfgrass establishment on a previous corn-soybean field in north central USA, about 17-24% of SOC was derived from turfgrass at 0-10 cm. At 10-20 cm depth, we found striking difference among turfgrass species. For shallow rooted Kentucky bluegrass and creeping bentgrass, only about 1% and 4% of SOC was derived from turfgrass at 10-20 cm, whereas for the deep rooted fine fescue about 10-13% was derived from turfgrass. Fisher et al. (1994) found that deep-rooted grasses introduced into South American savannas for agricultural purposes sequestered significant amounts of organic carbon deep in the soil profile. The authors suggested that a substantial amount of carbon, globally, could be locked up in such a manner. When we combined data from the 2 depths, about 10-18 percent of the soil organic carbon (0-20 cm) was derived from turfgrass.

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

Soil organic carbon content differences between 2005 and 2001 indicated that soil organic carbon at 0-20 cm soil profile increased 0.75, 1.10, 0.45, 1.14 g per kg soil for non-irrigated fescue, irrigated fescue, Kentucky bluegrass, and creeping bentgrass, respectively. Based on the bulk density data collected in 2001, these soil organic carbon changes translate to carbon sequestration rates of 0.52, 0.74, 0.32, and 0.78 ton C ha^{-1} yr^{-1} for non-irrigated fine fescue, irrigated-fine fescue, Kentucky bluegrass, and creeping bentgrass, respectively. All turfgrasses exhibited significant carbon sequestration. However, the net carbon sequestration rate in the 0-20 cm soil profile is higher in irrigated-fine fescue and creeping bentgrass plots. Kentucky bluegrass had the lowest carbon sequestration rate among the tested species. The carbon sequestration rate for non-irrigated fine fescue was intermediate but was not statistically different from Kentucky bluegrass or irrigated-fine fescue. Carbon sequestration potential is not only related to productivity of roots, rhizomes, and shoots, but also related to soil organic carbon decomposition or turnover rates. This range of carbon sequestration is in agreement with the following reported studies. Bruce et al. (1999) estimated a gain of 0.6 ton C ha^{-1} yr^{-1} for previously cultivated lands that have been reseeded to grass. Post and Kwon (2000) compiled literature data for soil carbon in areas where grasslands have been allowed to develop on previously disturbed lands and reported that the average rates of accumulation of C during the early grassland establishment were 0.33 ton ha^{-1} yr^{-1}. Qian and Follett (2002) reported a carbon sequestration rate of 0.9-1.0 ton 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 Kentuckly bluegrass and creeping bentgrass in this study. The lower carbon sequestration ability of Kentucky bluegrass found in this study than that reported by Qian and Follett (2002) may have been attributed to the warmer climate, less day/night temperature difference, and higher annual precipitation encountered in this study site. Bandaranayake et al. (2003) and Wang et al. (2000) suggested that higher temperature accelerates decomposition of SOC only when soil moisture is adequate, and inhibits decomposition when soil moisture becomes limited.

By subtracting net carbon sequestration from gross carbon input we derived soil carbon decomposition data (Table 6). The soil organic carbon decomposition rates were 1.73 and 1.50 ton ha^{-1} yr^{-1} for Kentucky bluegrass and creeping bentgrass, respectively, which were higher than under non-irrigated fine fescue and lower than irrigated fine fescue. By comparing irrigated and non-irrigated fine fescue plots, we found that irrigation increased net organic carbon input to the 0-20 cm soil profile by 141%. At the same time irrigation also increased soil organic carbon decomposition by 2-fold.

Conclusions

Urban grassland covers over 16 million ha in the U.S., and it is ubiquitous in the American urban landscape. Milesi et al. (2005) estimated that among the total land in USA devoted to urban development, 39-54% 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 carbon seqestration ability is intricately linked to the cycling of soil nutrients including nitrogen, phosphorous, potassium, and other micronutrients (Qian and Follett, 2002) and clipping management (Qian et al., 2003). Different carbon sequestration rates were observed under different treatments. Carbon sequestration rates were 0.74, and 0.78 ton ha^{-1} yr^{-1} for irrigated-fine fescue and creeping bentgrass, respectively, which are higher than that of non-irrigated fine fescue and irrigated Kentucky bluegrass. In this experiment, we observed that irrigation increased both gross SOC input to the soil profile and SOC decomposition in fine fescue. Thus, soil organic C 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. Measuring of carbon isotopic composition appears to be an appropriate approach to study SOC dynamics. Soil carbon sequestration and organic carbon decomposition rates are different for different turfgrasses and different management regimes.

However, to consider the net impact of urban grassland on the atmosphere's greenhouse effect, we need to consider fuel expenses in maintaining turfgrass, fertilizer and pesticide uses, 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 carbon budget and fluxes of the other greenhouse gases in turfgrass systems.

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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
Fine fescues (non-irrigated)	7.6 cm	34.5a[†]	N/A [ns]	34.5[ns]
Fine fescue (irrigated)	5.1 cm	11.7b	18.3	30.1
Kentucky bluegrass	2.5 cm	12.5b	22.4	34.9
Creeping bentgrass	1.2 cm	13.1b	19.3	32.4

[†] Means with a common letter are not significantly different ($P \leq 0.05$) by Least Significant Difference.

[ns] Not significant

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

Grass	Mowing Height	2002 Root density (g/kg dry soil)		2005 Root density (g/kg dry soil)	
		0-10 cm	10-20 cm	0-10 cm	10-20 cm
Fine fescues (non-irrigated)	5.1 cm	3.4 b[†]	0.38b	36.3a	10.4a
Fine fescue (irrigated)	5.1 cm	6.67ab	1.25a	33.9a	10.2a
Kentucky bluegrass	2.5 cm	5.69ab	0.70ab	16.5b	6.1ab
Creeping bentgrass	1.2 cm	8.42a	0.88ab	13.5b	2.9b

[†] Means with a common letter are not significantly different ($P \leq 0.05$) by Least Significant Difference.

Table 3. Plant tissue carbon isotope composition 4 years after establishment.

Grass	C isotope ($\delta^{13}C$) Root	C isotope ($\delta^{13}C$) Shoot
	------ (‰) ------	
Fine fescue (non-irrigated)	-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 with a common letter are not significantly different ($P \leq 0.05$) by Least Significant Difference.

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

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

[†] Means with a common letter are not significantly different ($P \leq 0.05$) by Least Significant Difference.

^{ns} Not significant

Table 5: Percentage of soil organic carbon from turf, carbon input from turfgrass at 0-10 and 10-20 cm in the soil profile under different turfgrasses during 2001-2005.

Grass	% SOC from turf	Total SOC (g/kg)	SOC from turf (g/kg)	% SOC from turf	Total SOC (g/kg)	SOC from turf (g/kg)	**% SOC from turf**	**C input from turf (g/kg)**
	----------------	----------------------------	**--in 2005--**	-----------------------	-----------------------	----------------------		
	0-10 cm			10-20 cm			**0-20 cm**	
Fine fescue (non-irrigated)	17.8[ns]	14.9[ns]	2.65[ns]	9.78a	7.2[ns]	0.70[ns]	**13.8**	**2.03b**
Fine fescue	23.7	15.7	3.72	12.92a	10.0	1.29	**18.3**	**5.02a**
Kentucky bluegrass	18.2	15.7	2.85	0.81b	11.3	0.09	**9.5**	**2.94ab**
Creeping bentgrass	20.4	14.3	2.92	4.10b	10.1	0.41	**12.2**	**3.33ab**

[†] Means with a common letter are not significantly different ($P \leq 0.05$) by Least Significant Difference.

[ns] Not significant

Table 6. Gross soil organic carbon input, net soil carbon sequestration, and soil organic carbon decomposition in the 0-20 cm soil profile under different turfgrasses.

Grasses	**Gross SOC input from turf** ton/ha/year	**Net carbon sequestration** ton/ha/year	**SOC decomposition** ton/ha/year
Fine fescue (non-irrigated)	1.39b	0.52ab	0.87c
Fine fescue (irrigated)	3.35a	0.74a	2.61a
Kentucky bluegrass	2.05ab	0.32b	1.73b
Creeping bentgrass	2.28ab	0.78a	1.50b