Carbon Sequestration in Zoysiagrass Turf under Different Irrigation and Fertilization Management Regimes

Ross C. Braun* and Dale J. Bremer

Core Ideas
- Further research is required to evaluate and develop management practices that may sequester C in turfgrass soils.
- Hidden C costs, which are energy-based inputs from turf maintenance, should be factored into soil C sequestration calculations.
- A higher-input management regime in turf will not increase net C sequestration compared with a low management input regime.
- Zoysiagrass golf course fairway turf had an average gross C sequestration rate of 1.01 Mg C ha⁻¹ yr⁻¹.

ABSTRACT
Carbon dioxide (CO₂) is an important greenhouse gas (GHG) implicated in climate change. Turfgrass covers an estimated 12.8 to 20 million ha in the United States and has the capacity to sequester or emit significant amounts of CO₂ from/to the atmosphere. Our objective was to evaluate irrigation and N fertilization management practices that may increase sequestration of atmospheric CO₂ in turf soils. The rate of change in soil organic carbon (SOC) at 0 to 30 cm was investigated under two management regimes in 'Meyer' zoysiagrass (Zoysia japonica Steud.). A high management input (HMI) (urea + medium irrigation) and low management input regime (LMI) (unfertilized [no N fertilizer] + low irrigation) were implemented. Hidden carbon costs (HCC) of maintenance practices and nitrous oxide emissions (another GHG) were estimated to account for energy expended in Mg of carbon equivalents (CE) ha⁻¹ yr⁻¹. Prior to subtracting HCC, average gross C sequestration rates were not statistically different at 1.046 and 0.976 Mg C ha⁻¹ yr⁻¹ in HMI and LMI, respectively. Once total estimated HCC was included, the average net sequestration rate was 0.412 and 0.616 Mg C ha⁻¹ yr⁻¹ in HMI and LMI, respectively, with no statistical differences. Results indicate that under the conditions of this study, a higher-input management regime will not increase net C sequestration compared with a low management input regime. Further research is required over additional turfgrass species and management regimes to develop management practices that increase C sequestration.

Abbreviations: ΔSOC, annual change in soil organic carbon; CE, carbon equivalent; C/N, carbon/nitrogen ratio; GHG, greenhouse gas; HCC, hidden carbon costs; HMI, high management input regime; LMI, low management input regime; PGC, percent green turfgrass cover; ET₀, reference evapotranspiration; SOC, soil organic carbon; SON, soil organic nitrogen.

Turfgrass covers a substantial area of land (estimated 12.8–20 million ha) in the United States, which includes both intensively and minimally managed turf areas (Milesi et al., 2005). Bartlett and James (2011) estimated there to be 2.56 million ha of intensively managed turfgrass on golf courses worldwide. In addition to economic benefits (National Turfgrass Federation, 2009), environmental benefits (Gross et al., 1990; Beard and Green, 1994; Miltner et al., 1996; Erickson et al., 2001), and human health benefits (Beard and Green, 1994; Taylor et al., 1998; Maas et al., 2009), turfgrass soils may sequester atmospheric C (Qian et al., 2010), including on golf courses (Qian and Follett, 2002). Carbon sequestration results when more carbon dioxide (CO₂), a greenhouse gas (GHG), is removed from the atmosphere via photosynthesis than is returned to the atmosphere via respiration; the "surplus" C is sequestered in the soil. Turfgrass soils reportedly sequester C within a similar range as other grassland soils (Table 1). The sequestering of C by the millions of hectares of turf could significantly impact the global GHG atmospheric inventory, and thus mitigate climate change.

Little research has been conducted to document specific effects of irrigation levels or N fertilization types on C sequestration in turfgrass, or that identify potentially optimal irrigation and N regimes for sequestering C in turf. Nitrogen fertilization, as well as irrigation applied to turfgrass during dry periods, affects photosynthesis and respiration, which likely impacts C sequestration. For example, in semiarid Nebraska, C sequestration was greater in

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irrigated than in non-irrigated fine fescue (Festuca spp.), although C costs from maintenance procedures (e.g., mowing, fertilization, irrigation, and pesticide application) were not included (Qian et al., 2010). Turfgrass management practices such as using controlled-release fertilizers combined with improved irrigation techniques (e.g., deficit irrigation) have been shown to reduce nitrous oxide (N₂O), another GHG, emissions (Braun and Bremer, 2018), and may also maximize plant CO₂ uptake, but research is lacking. The development of management practices that reduce N₂O emissions from turfgrass and enhance C sequestration in turf soils may help mitigate climate change and atmospheric ozone destruction. Therefore, further research is required to evaluate and develop management practices that may sequester C in turfgrass soils, such as through N fertilization and irrigation regimes, that also consider C maintenance costs.

Similar to farm operations, turfgrass maintenance is comprised of energy-based inputs that have been labeled hidden carbon costs (HCC) in kilograms of carbon equivalents (CE) ha⁻¹ yr⁻¹ (Selhorst and Lal, 2011; Zirkle et al., 2011; Gu et al., 2015). These HCC should also include emissions from other GHG such as N₂O (Gu et al., 2015; Zhang et al., 2013). Although emissions of N₂O do not directly affect C sequestration rates, these emissions should be also included in HCC for more complete accounting of the GHG impact of management practices in turf (Zhang et al., 2013; Gu et al., 2015). However, very few turf studies exist that have factored HCC estimates into soil C sequestration rates, and even fewer have included N₂O emissions in HCC estimates, and in this current study we included N₂O emissions in HCC estimates. False conclusions or overestimates in GHG emissions and soil C sequestration rates may arise in studies that do not take N₂O emissions into account.

Therefore, the objectives of this study were to quantify the soil organic carbon (SOC) sequestration rate in zoysiagrass (Zoysia japonica Steud.) fairway turf and determine how HCC of maintenance practices (irrigation and N fertilization) may be managed to enhance C sequestration.

### MATERIALS AND METHODS

#### Experimental Site and Management

This field experiment was conducted for 1154 d from 22 Aug. 2013 to 19 Oct. 2016 under an automated rainout shelter (12 × 12 m) at the Rocky Ford Turfgrass Research Center in Manhattan, KS, USA (39°13′53″ N lat; 96°34′51″ W long). The soil at the site was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls) with a pH of 7.0. Each year, the automated rainout shelter was activated during the summer from 1 June to at least 31 August. Upon detection of 0.254 mm of precipitation, the rainout shelter would deploy and cover the experimental area in less than 1 min and then retract 1 h after cessation of rainfall.

Eight plots (1.14 × 1.23 m) of ‘Meyer’ zoysiagrass were established via sod on 4 June 2013 with the north and south ends of the study area bordered with metal edging (10-cm depth). The turf plots were maintained at a 2.54-cm mowing height and clippings returned to the soil. This experiment was conducted in conjunction with another one on the same research plots, in which N₂O fluxes were measured (Braun and Bremer, 2018).

For the prevention and control of Rhizoctonia solani Kühn Anastomosis Group (AG)-2-2 LP), fungicide was applied (flutolanil, 4.69 kg a.i. ha⁻¹ on 14 Sept. 2014, 19 Sept. 2015, and 8 Sept. 2016; and propiconazole, 1.78 kg a.i. ha⁻¹ on 17 Apr. 2015). An insecticide (imidacloprid, 0.37 kg a.i. ha⁻¹) was applied on 13 July 2015 and 22 May 2016 for the control of white grubs (Phyllophaga spp. and Cyclocephala lurida Bland.).

#### Treatments

Two management regimes, replicated four times each, were assigned to plots in a randomized complete block design. The two management regimes included: (i) urea (46–0–0; Thrive Branded Fertilizer, Mears Fertilizer) + medium irrigation [66% reference evapotranspiration (ET) replacement]1, designated as high

<table>
<thead>
<tr>
<th>Land use</th>
<th>Soil organic C sequestration rate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golf course</td>
<td>0.9–1.0</td>
<td>Qian and Follett (2002)</td>
</tr>
<tr>
<td>Golf course</td>
<td>0.9–1.2</td>
<td>Bandaranayake et al. (2003)</td>
</tr>
<tr>
<td>Golf course</td>
<td>0.69</td>
<td>Huh et al. (2008)</td>
</tr>
<tr>
<td>Golf course</td>
<td>0.32–0.78</td>
<td>Qian et al. (2010)</td>
</tr>
<tr>
<td>Golf course</td>
<td>2.64–3.55 (0.44)†</td>
<td>Selhorst and Lal (2011)</td>
</tr>
<tr>
<td>Golf course</td>
<td>0.72</td>
<td>Wang et al. (2014)</td>
</tr>
<tr>
<td>Golf course</td>
<td>0.976–1.046 (0.412–0.616)†</td>
<td>current study</td>
</tr>
<tr>
<td>Home lawn</td>
<td>0.18</td>
<td>Pouyat et al. (2009)</td>
</tr>
<tr>
<td>Home lawn</td>
<td>0.46–2.35 (0.25–2.04)†</td>
<td>Zirkle et al. (2011)</td>
</tr>
<tr>
<td>Home lawn</td>
<td>2.80</td>
<td>Selhorst and Lal (2013)</td>
</tr>
<tr>
<td>Fertilized pasture grassland</td>
<td>0.82</td>
<td>Tyson et al. (1990)</td>
</tr>
<tr>
<td>Restored native grassland</td>
<td>0.6</td>
<td>Bruce et al. (1999)</td>
</tr>
<tr>
<td>Established grasslands</td>
<td>1.1</td>
<td>Gebhart et al. (1994)</td>
</tr>
<tr>
<td>Established grasslands (compiled)</td>
<td>0.33</td>
<td>Post and Kwon (2000)</td>
</tr>
<tr>
<td>Restored native grassland</td>
<td>0.6–0.8</td>
<td>Mensah et al. (2003)</td>
</tr>
<tr>
<td>Native tallgrass grassland (burned annually or biennially)</td>
<td>−2.31–0.27</td>
<td>Bremer and Ham (2010)</td>
</tr>
</tbody>
</table>

† Number in parenthesis for the study represents the calculated net soil organic C sequestration rate, which factored in hidden C costs in terms of C equivalents of turfgrass maintenance emissions. The preceding number not in parenthesis is the gross soil organic C sequestration rate (Mg C ha⁻¹ yr⁻¹) prior to calculation of hidden C costs.
management input regime (HMI); and (ii) unfertilized (receiving no N fertilizer) + low irrigation (33% ET<sub>r</sub> replacement), designated as low management input regime (LMI).

In the 2014 summer, the two deficit irrigation treatments were a medium 72% ET<sub>r</sub> replacement and low 54% ET<sub>r</sub> replacement. Researchers desired the low irrigation treatment to show signs of minor drought stress as in past research on deficit-irrigated turfgrass plots at the same site (Lewis et al., 2012). However, no drought stress was observed at either deficit irrigation level in 2014. Therefore, in 2015 the medium and low deficit irrigation levels were reduced to 68% ET<sub>r</sub> and 45% ET<sub>r</sub> replacement, respectively, from 1 June to 19 July. Yet, no visible drought stress occurred at either deficit irrigation level, and levels were reduced further to 66% ET<sub>r</sub> and 33% ET<sub>r</sub> replacement, respectively, from 20 July to 1 Sept. 2015. In 2016, irrigation levels remained at 66% and 33% ET<sub>r</sub> replacement.

The irrigation amounts were calculated and then converted to gallons of water required per plot from daily ET<sub>r</sub> rates using the American Society of Civil Engineers (ASCE) standardized reference evapotranspiration equation (Walter et al., 2001) and data from an on-site weather station (available at: http://www.ksre.ksu.edu/wdl). Irrigation was applied by hand with a watering wand attached to a hose and meter (Model 03N31, GPI) twice a week from 1 June to 11 Sept. 2014 (106 d), 1 June to 1 Sept. 2015 (92 d), and 1 June to 2 Sept. 2016 (93 d). Each year, the rainout shelter was not activated from September through May. During this time, all the turf plots received the same amount of irrigation (12.7 mm wk<sup>–1</sup> or less) from an in-ground irrigation system and any occurring precipitation (i.e., equivalent of 90% ET<sub>r</sub> replacement) to maintain well-watered conditions and avoid drought stress during the remainder or beginning of the growing season.

Urea fertilizer was applied at a rate of 49 kg N ha<sup>–1</sup> at the beginning of summer and again at mid-summer for a total of 98 kg N ha<sup>–1</sup> yr<sup>–1</sup>, and the unfertilized received no N fertilizer. Fertilization dates were 1 June and 21 July in 2014; 2 June and 16 July in 2015; and 6 June and 20 July in 2016. After fertilization, plots were individually hand-watered as described above with respect to its corresponding irrigation treatment to incorporate fertilizer into the soil and reduce ammonia volatilization (Bowman et al., 1987). Irrigation amounts for the medium and low ET<sub>r</sub> treatments immediately after fertilization were 15.7 and 11.7 mm in 2014; 12.7 and 8.6 mm in 2015, and 12.7 and 6.4 mm in 2016, respectively, in accordance to the decreased deficit irrigation levels each year, as described above.

### Soil Carbon Measurements

Soil measurements in each plot were obtained on 22 Aug. 2013 (79 d after turf establishment) and 19 Oct. 2016 (1233 d after turf establishment). On these two dates, 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 depths: 0 to 10, 10 to 20, and 20 to 30 cm by similar methodologies as Qian et al. (2010) and Follett et al. (2009b). Soil bulk densities (ρ<sub>b</sub>) at each depth were determined from volumetric samples (volume of the soil core was 92.4 cm<sup>3</sup>). Soil bulk density (g cm<sup>–3</sup>) was determined using the dry weight of soil for the known soil core volume in accordance to USDA-NRCS (2001) methods. After ρ<sub>b</sub> samples were collected they were dried in a forced-air oven for 48 h at 105°C and then weighed separately to determine dry weight. For SOC and soil organic nitrogen (SON), one soil core (2.54 cm diam. x 10 cm) was obtained at each soil depth from within each plot for a total of three subsamples per plot. Any present plant material was removed from the soil cores and then soil cores were dried overnight in an oven at 50°C. Next, samples were ground to pass through a 2-mm sieve and then analyzed using a LECO TruSpec CN (Carbon/Nitrogen) (Leco Corp.) combustion analyzer to calculate total inorganic and organic C and N on a weight-percent basis at the Kansas State University Soil Testing Laboratory. Soil C/N ratio was determined from SOC and SON data. The annual rate of change in SOC (ΔSOC; Mg C ha<sup>–1</sup> yr<sup>–1</sup>), which was the gross C sequestration rate, was calculated from the difference between the 2013 and 2016 samples and averaged over the 3.16-yr (1154-d) period.

### Hidden Carbon Costs

Energy expenditures for turfgrass operations are similar to those of farm operations, as reviewed by Lal (2004), in terms of fuel emissions, irrigation, pesticide and fertilizer production, and transportation (Zirkle et al., 2011). Our plots were managed the same as a zoysiagrass golf course fairway in the transition zone. The HCC were estimated and converted into an average Mg CE ha<sup>–1</sup> yr<sup>–1</sup> based on emissions of N<sub>2</sub>O and inputs from maintenance practices (mowing, irrigation, and fertilizer and pesticide application) conducted within each management regime over the entire 3-yr study, using Eq. [1], a similar equation as Gu et al. (2015) and Zirkle et al. (2011):

\[
HCC = CE_{N2O \text{ emissions}} + CE_{mowing} + CE_{irrigation} + CE_{fertilizer} + CE_{pesticides}
\]  

The HCC of mowing is based on the number of cumulative annual mowing events of each treatment multiplied by mower emissions. Mowing frequency of each plot was recorded each year for the entire growing season (1 April–31 October). Mowing frequency was conducted using the following procedure. Every 4 to 7 d, grass height was measured at four random locations within each plot. If the grass height was ≥3.8 cm in at least one of four locations within a plot, that plot was mowed with a reel mower on that day and recorded. A maximum height of 3.8 cm was established for the 2.54-cm mowing height due to general guidelines of not removing more than one-third of the turfgrass canopy (Hoyle, 2017; Law et al., 2016). For each year, cumulative mowing events were summed separately for each plot and treatment means were then calculated and analyzed. To estimate emissions from cumulative annual mowing events of each plot, we assumed that 4.67 L of diesel is consumed to mow 1 ha of fairway using a large fairway reel mower-unit based on values from Rice (2010). Therefore, with the density of diesel fuel at 0.840 kg L<sup>–1</sup>, the number of kilograms of diesel was multiplied by 0.94 kg CE, utilizing data from Lal (2004), to determine kilograms of CE emitted each year by diesel.

The HCC of irrigation was based on the estimated total irrigation run time (hours) of each treatment during the summer period (June, July, and August) in each year when the rainout shelter was activated and irrigation treatments were applied, and also irrigation run times that occurred during the spring (15 March–31 May) and autumn (1 September–31 October) each year. No irrigation was applied from 1 November to 14 March due to dormancy of zoysiagrass. Therefore, irrigation emissions were calculated using total irrigation run time hours, an equivalent combustion of 9.46 L (2.5 gal conversion) of gasoline h<sup>–1</sup> of irrigation pumping (Selhorst and Lal, 2012), and 0.85 kg CE gasoline conversion factor (Lal, 2004).
Similar to Zirkle et al. (2011), the CE for fertilizer and CE for pesticides were estimated based on the conversion factors from Lal (2004) that take into account production, packaging, storage, and distribution requirements for fertilizer and pesticide active ingredient. The CE conversion of N fertilizer was 1.3 kg CE kg⁻¹ N and the CE conversion factor for pesticides was 5.1 kg CE kg⁻¹ a.i. for insecticides and 3.9 kg CE kg⁻¹ a.i. for fungicides (Lal, 2004).

To estimate HCC of \( \text{N}_2\text{O} \) emissions, soil-surface fluxes were measured in the same plots as this study from October 2014 through October 2016 by extracting gas samples at pre-determined time intervals from static vented polyvinyl chloride chambers placed on the plots using the methodology described by Braun and Bremer, 2018. Fluxes were measured at least once weekly during the growing season from May through September and once every 2 to 4 wk during winter dormancy from October through April, for a total of 69 measurement dates over 2 yr. Measurements were more frequent surrounding fertilization events in the summer. Specifically, \( \text{N}_2\text{O} \) fluxes were measured at 1.3, and 7 d after N fertilization in both years, and additionally 5 d after N fertilization in 2016. Additional details about those \( \text{N}_2\text{O} \) flux measurements and calculations can be found in Braun and Bremer (2018). To estimate HCC of \( \text{N}_2\text{O} \) in terms of CE, average \( \text{N}_2\text{O}–\text{N} \) emissions (kg \( \text{N}_2\text{O}–\text{N} \) ha⁻¹ yr⁻¹) of each treatment were first converted to CE emissions (kg CE ha⁻¹ yr⁻¹), then converted to kg CO₂ ha⁻¹ yr⁻¹ by multiplying by 298, and lastly converted to kg CO₂–C (i.e., CE) ha⁻¹ yr⁻¹ by multiplying by 0.2727 (Stocker et al., 2013; Law and Patton, 2017).

Ancillary Measurements

Weather data were collected from an on-site weather station positioned in full sun within 50 m of the study area. In 2015 and 2016, percentage green turfgrass cover (PGC) was measured weekly from mid-May through mid-September in each plot to evaluate the effects of the different management regimes on turfgrass performance. Percentage green turfgrass cover was measured with digital images (Nikon D5000, Nikon) using a lighted camera box. Images were analyzed with SigmaScan Pro (ver. 5.0, SPSS Science Marketing Dep.) (Karcher and Richardson, 2005).

Data Analysis

Differences in reported variables were evaluated by analysis of variance using PROC GLIMMIX of SAS (9.4, SAS Institute). Soil organic C, SON, \( \rho_b \), C/N, and ΔSOC were analyzed using a three-way ANOVA with management regime, measurement year (2013 and 2016), and depth as a fixed effects and block as a random effect. For all response variables, studentized residuals were investigated to check assumptions of normal distribution and homogenous variance properties. Significant outliers were also detected utilizing a conservative Bonferroni adjustment and removed from the dataset. After analysis of type III tests for fixed effects for SOC, SON, \( \rho_b \), C/N, and ΔSOC, the F test for slice effects and the t test for slice differences were conducted utilizing a conservative Bonferroni adjustment test for multiple comparisons. Tests for slice effects were conducted to analyze the following: management regimes within each depth × year, years within each management regime × depth, management regimes averaged across all depths within each measurement year, years within each management regime averaged across all depths, depths within each measurement year, and years within each depth. All other variables including HCC, cumulative annual mowing events, \( \text{N}_2\text{O} \) emissions, net sequestration rate, and PGC were analyzed using a one-way ANOVA with management regime as a fixed effect, block as a random effect, and means were separated using Fisher’s Protected LSD test (\( P \leq 0.05 \)).

RESULTS AND DISCUSSION

Soil Organic Carbon and Nitrogen Measurements

Management Regimes Within Each Soil Depth

In 2013, before N fertilizer and irrigation treatments were applied, there were no differences in measured soil variables (SOC, SON, \( \rho_b \), C/N) among plots (management regimes) at each depth (Table 2). By the end of the 1154-d study, SOC at 0 to 10 cm had increased by 24 and 21% for the HMI and LMI, respectively, and C/N at 20 to 30 cm more than doubled in the HMI (Table 2). Although the remaining SOC and C/N also increased numerically from 2013 to 2016 at each management regime × depth, none were statistically significant. No statistical changes were observed during the study period in \( \rho_b \) and SON at any management regime × depth. At the end of the study, there were no differences in the ΔSOC between the management regimes within each soil depth.

Management Regimes across All Soil Depths (0–30 cm)

When averaged across all depths (0–30 cm), there were no differences between high and low management input regimes for any measured soil C variable (SOC, SON, \( \rho_b \), C/N, and ΔSOC) at the end of the study in 2016 (Table 3). Notably, however, SOC

<table>
<thead>
<tr>
<th>Management regime</th>
<th>n</th>
<th>( \rho_b ) (g cm⁻³)</th>
<th>SOC (Mg C ha⁻¹)</th>
<th>Son (Mg N ha⁻¹)</th>
<th>C/N</th>
<th>ΔSOC (Mg C ha⁻¹ yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>4</td>
<td>1.42</td>
<td>1.42</td>
<td>23.8 b</td>
<td>29.4 a</td>
<td>2.15</td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>1.42</td>
<td>1.44</td>
<td>24.1 b</td>
<td>29.2 a</td>
<td>2.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0–10 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>4</td>
<td>1.50</td>
<td>1.51</td>
<td>17.3</td>
<td>19.5</td>
<td>1.65</td>
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<tr>
<td>Low</td>
<td>4</td>
<td>1.55</td>
<td>1.54</td>
<td>19.6</td>
<td>21.5</td>
<td>1.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10–20 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>4</td>
<td>1.48</td>
<td>1.45</td>
<td>12.6</td>
<td>14.9</td>
<td>1.41</td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>1.52</td>
<td>1.50</td>
<td>13.7</td>
<td>16.1</td>
<td>1.56</td>
</tr>
</tbody>
</table>

† Within a row, within each category, means with different lower-case letters are significantly different according to αbon = 0.0083.
increased significantly after the 1154-d period for both HMI and LMI, and C/N increased by 66% for HMI (Table 3), which was similar to the trends noted above.

Since there were no statistical differences between management regimes within either measurement year (i.e., the beginning and end of the study) when averaged across all depths (Table 3), data were combined across both management regimes and all depths within each year. Results indicated the soil C/N ratio increased by 48% (i.e., from 10.1 in 2013 to 14.9 in 2016) \( (P = 0.0001) \) and overall SOC increased by 18% (i.e., from 18.5 Mg C ha\(^{-1}\) in 2013 to 21.8 Mg C ha\(^{-1}\) in 2016) \( (P = 0.0409) \). These overall increases in C/N and SOC in particular, which was also consistent across both management regimes (Table 3), indicates significant amounts of C were sequestered by the zoysiagrass turf system.

**SOIL DEPTHS ACROSS BOTH MANAGEMENT REGIMES**

Additional soil C data analysis was conducted since there were no differences between management regimes within each soil depth (Table 2) or across all depths (Table 3). Therefore, soil C data were averaged across both management input regimes within each depth to evaluate treatment effects at each soil depth, as well as the impact of depth on measured soil variables (Table 4).

The combined, overall effects of the management regimes was significant for SOC at all depths and for C/N at 20 to 30 cm (Table 4). Specifically, SOC increased by 10.8 to 22.6% among depths, with the greatest increase in the surface layer \( (0–10 \text{ cm}) \). Although C/N increased numerically at each depth, the increase was only significant at 20 to 30 cm. The management regimes had no effect on SON or, not surprisingly, on \( \rho_b \) during the study.

Soil depth had significant effects on all measured variables except soil C/N, both at the beginning and at the end of the study (Table 4). For example, SOC and SON were consistently greatest in the surface layer and least in the lowest depth. Perhaps most importantly, however, in terms of C sequestration, and as alluded to above, the ΔSOC was greater at 0 to 10 cm than in the two lower depths. Lemus and Lal (2005) noted most changes in SOC tend to occur in the upper profile due to being more significantly influenced by climate, microbial biomass, and larger root biomass present. Lemus and Lal (2005) reported root biomass is possibly one of the most important factors affecting potential soil C sequestration. Qian et al. (2010) concluded that 2- to 5-yr-old turfgrass systems likely favor soil C sequestration near the soil surface \( (0–10 \text{ cm}) \) compared with a lower depth of 10 to 20 cm. In our study, although there was a greater increase in C/N at the lower depths, the ΔSOC in the upper profile \( (0–10 \text{ cm}) \) was greater than in the two lower depths after 3.16 yr in zoysiagrass (Table 4). Qian et al. (2010) also reported increased SOC and C/N over 4 yr in three different turfgrass species, with a SOC rate of 0.32 to 0.78 Mg C ha\(^{-1}\) yr\(^{-1}\) and C/N values at 7.87 to 10.98 after 4 yr.

The annual ΔSOC values ranging from 0.55 to 1.77 Mg C ha\(^{-1}\) yr\(^{-1}\) in our study (Table 2) are similar to observed or modeled SOC sequestration rates in other turfgrass soils (Table 1). Also, these annual ΔSOC values in our study are similar to or higher than SOC sequestration rates in non-turf grasslands such as fertilized pastures or native prairies (Table 1; see also Haynes et al., 1991; Follett et al., 2009a). It is important to note that our study was conducted on recently established turfgrass (<4 yr), which may sequester C at higher rates than older stands (>25 yr) mown at fairway heights (Qian and Follett, 2002). During our 3-yr study, the zoysiagrass turf had an average gross C sequestration rate of 1.01 Mg C ha\(^{-1}\) yr\(^{-1}\) when averaged across both management input regimes and all three depths.

**HIDDEN CARBON COSTS OF TURFGRASS MAINTENANCE**

The estimated total HCC was 0.634 and 0.360 Mg CE ha\(^{-1}\) yr\(^{-1}\) in the HMI and LMI, respectively (Table 5), with the largest contributions coming from \( \text{N}_2\text{O} \) emissions. Prior to \( \text{N}_2\text{O} \) emissions factored into HCC, the HCC estimates were 0.283 and 0.106 Mg CE ha\(^{-1}\) yr\(^{-1}\) in the HMI and LMI, respectively, which was similar to estimated maintenance emissions from past research that did not include \( \text{N}_2\text{O} \) emissions (Selhorst and Lal, 2011, 2013; Zirkle et al., 2011). These past studies reported HCC estimates of 0.302 Mg CE ha\(^{-1}\) yr\(^{-1}\) (not including \( \text{N}_2\text{O} \)) from a golf course (Selhorst and Lal, 2011), 0.129 to 0.773 Mg CE ha\(^{-1}\) yr\(^{-1}\) (not including \( \text{N}_2\text{O} \)) from minimal to intensive input best management practice lawns (Zirkle et al., 2011), and 0.254 Mg CE ha\(^{-1}\) yr\(^{-1}\) (not including \( \text{N}_2\text{O} \) and irrigation emissions) from different lawns across various ecosystems (Selhorst and Lal, 2013).

In studies that included \( \text{N}_2\text{O} \) emissions, HCC was estimated to be 0.351 to 0.966 Mg CE ha\(^{-1}\) yr\(^{-1}\) from minimal to intensive input scenarios in turf (Gu et al., 2015), and 0.200 to 0.404 Mg CE ha\(^{-1}\) yr\(^{-1}\) for maintenance and HCC estimates.

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**Table 3. Soil bulk density \( (\rho_b) \), soil organic carbon (SOC), soil organic nitrogen (SON), soil carbon/nitrogen ratio (C/N) at the beginning (2013) and end of the study (2016), and average annual change in soil organic carbon (ΔSOC) across all depths (0–30 cm) and within each management regime.**

<table>
<thead>
<tr>
<th>Management regime</th>
<th>n</th>
<th>( \rho_b ) ( \text{g cm}^{-3} )</th>
<th>SOC ( \text{Mg C ha}^{-1} )</th>
<th>SON ( \text{Mg N ha}^{-1} )</th>
<th>C/N</th>
<th>ΔSOC ( \text{Mg C ha}^{-1} \text{yr}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>12</td>
<td>1.47 ( a ) 1.44</td>
<td>17.9 ( b ) 21.3 ( a )</td>
<td>1.74 1.42</td>
<td>10.2 ( b ) 16.9 ( a )</td>
<td>1.046</td>
</tr>
<tr>
<td>Low</td>
<td>12</td>
<td>1.49 1.49</td>
<td>19.1 b 22.3 a</td>
<td>1.89 1.86</td>
<td>10.1 12.9</td>
<td>0.976</td>
</tr>
</tbody>
</table>

† Within a row, within each category, means with different upper-case letters are significantly different according to \( \alpha_{bon} = 0.0083 \).

‡ Within a column, means with different lower-case letters are significantly different according to \( \alpha_{bon} = 0.025 \).

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**Table 4. Soil bulk density \( (\rho_b) \), soil organic carbon (SOC), soil organic nitrogen (SON), soil carbon/nitrogen ratio (C/N) at the beginning (2013) and end of the study (2016), and average annual change in soil organic carbon (ΔSOC) across both management regimes and within each depth.**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>n</th>
<th>( \rho_b ) ( \text{g cm}^{-3} )</th>
<th>SOC ( \text{Mg C ha}^{-1} )</th>
<th>SON ( \text{Mg N ha}^{-1} )</th>
<th>C/N</th>
<th>ΔSOC ( \text{Mg C ha}^{-1} \text{yr}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>8</td>
<td>1.42 B ( \dagger ) 1.43 B</td>
<td>23.9 Ab ( \dagger ) 29.3 Aa</td>
<td>2.22 A 2.21 A</td>
<td>10.9 13.6</td>
<td>1.69 A</td>
</tr>
<tr>
<td>10–20</td>
<td>8</td>
<td>1.53 A 1.53 A</td>
<td>18.5 Bb 20.5 Ba</td>
<td>1.74 AB 1.57 B</td>
<td>10.7 14.3</td>
<td>0.63 B</td>
</tr>
<tr>
<td>20–30</td>
<td>8</td>
<td>1.50 AB 1.45 AB</td>
<td>13.1 Cb 15.5 Ca</td>
<td>1.48 B 1.14 B</td>
<td>8.9 b 16.8 a</td>
<td>0.71 B</td>
</tr>
</tbody>
</table>

† Within a column, means with different upper-case letters are significantly different according to \( \alpha_{bon} = 0.0083 \).

‡ Within a row, within each category, means with different lower-case letters are significantly different according to \( \alpha_{bon} = 0.016 \).
from other studies listed above without N2O emissions. This was due to two reasons: (i) the low number of mowing events required in zoysiagrass due to its slow growth rate; and (ii) estimated mowing emissions were calculated for a diesel large fairway reel mowing unit, which would have better fuel efficiency than both riding home lawn mowers and home walk-behind mowers, which were used for estimates in Gu et al. (2015), Sahu (2008), and Zirkle et al. (2011). Our experimental site was managed as a simulated zoysiagrass golf course fairway, where mowing would most likely be with a diesel large fairway reel mowing unit. Zoysiagrass use on golf courses has steadily increased since the 1950s due to its low-input characteristics, such as its slow growth rate (i.e., less frequent mowing) (Patton et al., 2017). Turf species with different growth rates, on another note, turfgrass equipment manufacturers are utilizing new technology to improve fuel efficiency and alternative power sources such as electric and hybrid engines, thus there is a potential for future HCC mowing emissions to decline.

The estimates of N2O CE emissions in our study were 81 to 150% higher than those reported by Law and Patton (2017). However, our N2O emissions were intensively measured over a 2-yr period (Braun and Bremer, 2018) and therefore more comprehensive than Law and Patton (2017), who included broad estimates of N2O CE emissions from only 6 monthly N2O flux measurements, May through October in 1 yr.

### Green Turfgrass Cover

In both 2015 and 2016, HMI generally had more green turfgrass cover than LMI (Fig. 1). The separation between HMI and LMI was more evident in 2016 than in 2015. This may have been due to overall lower irrigation amounts in 2016 than 2015 as described earlier, with lower irrigation replacement levels of
Fig. 1. Effects of management input regimes on percentage green turfgrass cover of zoysiagrass in (A) 2015 and (B) 2016. Solid vertical lines at the beginning of June and end of August represent the summer when rainfall shelter was activated, and fertilizer and irrigation treatments were applied. Dashed vertical line indicates urea fertilizer application at 49 kg N ha⁻¹ on 2 June and 16 July in 2015 and 6 June and 20 July in 2016. Within each year, means with different letters are significantly different according to Fisher’s Protected LSD (P ≤ 0.05).

CONCLUSIONS

Overall, the HMI generally resulted in higher green turfgrass cover than the LMI in both summers, but this also led to significantly more mowing events and greater mowing HCC in the HMI than the LMI. After a 3-yr period, a HMI regime (urea + 66% ETo irrigation treatment) in zoysiagrass did not increase C sequestration compared with a LMI regime (no fertilizer + 33% ETo irrigation treatment). Gross C sequestration rates were higher in the 0- to 10-cm soil layer than at lower depths. Regardless of management input regime or depth, zoysiagrass exhibited enhanced SOC content and an average gross C sequestration rate of 1.01 Mg C ha⁻¹ yr⁻¹ prior to HCC estimates. However, results in our study indicate the importance of estimating HCC, and including N₂O emissions in HCC estimates. The HMI had 76% more HCC than the LMI, mainly due to N fertilization application and higher irrigation amounts. Nitrogen fertilization and higher irrigation amounts in the HMI led to not only greater N₂O emissions, but also 10.4 more mowing events per year. After subtracting the HCC from the gross SOC sequestration rates, the net SOC sequestration rates in zoysiagrass were not statistically different at 0.412 to 0.616 Mg C ha⁻¹ yr⁻¹ in HMI and LMI, respectively. Results from this study indicate that under the conditions of this study, a higher management input regime will not increase the net C sequestration compared with a low management input regime. Further research of direct SOC measurements over additional turfgrass species, management regimes, and time since establishment will increase understanding of total C budget and possibly lead to improved management practices to increase C sequestration in turfgrass systems.

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REFERENCES


