1 **Carbon fluxes from an urban tropical grassland**

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1.0 Abstract

Turfgrass covers a large fraction of the urbanized landscape, but the carbon exchange of urban lawns is poorly understood. We used eddy covariance and flux chambers in a grassland field manipulative experiment to quantify the carbon mass balance in a Singapore tropical turfgrass. We also assessed how management and variations in environmental factors influenced CO₂ respiration. Standing aboveground turfgrass biomass was 80 gC m⁻², with a mean ecosystem respiration of 7.9±1.1 μmol m⁻² s⁻¹. The contribution of autotrophic respiration was 49-76% of total ecosystem respiration. Both chamber and eddy covariance measurements suggest the system was in approximate carbon balance. While we did not observe a significant relationship between the respiration rates and soil temperature or moisture, daytime fluxes increased during the rainy interval, indicating strong overall moisture sensitivity. Turfgrass biomass is small, but given its abundance across the urban landscape, it significantly influences diurnal CO₂ concentrations.

Capsule: We found a Singapore urban turfgrass to be approximately carbon neutral, with a mean ecosystem respiration of 7.9±1.1 μmol m⁻² s⁻¹.

2.0 Introduction

The world's population is increasingly concentrated in urban areas. With urban development, local anthropogenic carbon emissions typically increase dramatically and biogenic fluxes decrease. While any net biological carbon sink within urban areas is inherently small due to a lack of available plant growing space, urban vegetation can significantly affect diurnal and seasonal patterns in CO₂ mixing ratios (Briber et al. 2013). Future monitoring and verification of greenhouse gas emissions with urban atmospheric measurements must accurately account for biogenic greenhouse gas fluxes (McKain et al. 2012).

With urbanization, much of the previously pervious landscape (e.g. forest, agricultural areas, etc.) is replaced with impervious surfaces and lawns. For example, in the United States, turfgrasses cover a land area three times larger than any other irrigated crop (Milesi et al. 2005), making their management significant. Turfgrasses are concentrated in urban areas where they may make up 20 to 30% of the urban landscape (Nowak et al. 2002). The majority of this turf area is associated with residential landscaping, with the remainder being commercial and institutional lawns, parks, golf courses, and athletic fields (Milesi et al. 2005). Vegetation within urban areas provides a number of important ecosystem services (Dobbs et al. 2011, Nowak et al. 2006, McPherson 1992) and can have tremendous aesthetic value to the local population (McPherson et al. 2011, Beard and Green 1994). Turfgrasses have been found to sequester soil carbon (Gebhart et al. 1994, Conant et al. 2001, Qian and Follet 2002, Milesi et al. 2005, Golubiewski et al. 2006, Wu and Bauer 2012), mitigate urban heat islands (Spronken-Smith et al. 2000), enhance nutrient retention (Raciti et al. 2008), and

increase water infiltration relative to bare ground and impervious surfaces. However, the management of turfgrass also typically includes the application of herbicides and fertilizers, which can result in significant N₂O fluxes (Townsend-Small and Czimczik 2010), water contamination due to runoff (Osmond and Hardy 2004), and CO₂ emissions associated with lawn mowing and management (Jo and McPherson 1995). Note that nearly all previous studies of turfgrass biogeochemistry were carried out in temperate ecosystems.

Grass clipping from lawns have traditionally been removed from residential lawns and commercial turfgrass areas, bagged, and deposited in landfills or composting facilities. However, the transport of this organic biomass results in greenhouse gas emissions, and as landfill costs have increased, yard waste is often no longer accepted. The simplest method and often prescribed best management practice is to leave grass clipping on site to decompose and return nutrients to the soil, reducing or avoiding the need for additional fertilizer application (Kopp and Guillard 2002). Clippings management also affects the soil microclimate and substrate supply.

With continued global urbanization, turfgrasses are increasing in their spatial extent, but there have been very few biogeochemical studies of turfgrass (see review by Guertal 2012). We carried out a field manipulative experiment in a Singapore grassland to characterize carbon stocks and fluxes and assess how variations in environmental factors influenced the CO₂ respiration fluxes from a tropical turfgrass. We measured CO₂ fluxes using both a closed dynamic chamber system and an eddy covariance system. In addition, we used four turf treatments to partition the sources of respiration. Soil volumetric water content, soil temperature, rainfall, atmospheric pressure, and air temperature were used to

explore sensitivity to changing environmental conditions. We also characterized soil bulk density, carbon and nitrogen content, and estimated the emissions associated with management. We hypothesized the following: (1) turf treatments will significantly influence soil CO₂ fluxes. Turfed areas will have significantly higher soil fluxes relative to bare ground and the addition of grass clippings will increase fluxes in a both turfed and bare ground areas; and (2) Soil temperature and moisture will affect soil CO₂ flux across all experimental treatments.

3.0 Methods

3.1 Study Area

Singapore has a land area of 715.8 km² with a population density of 7,669 persons km⁻², making it the third most densely populated city in the world (Statistics Singapore 2013). Managed vegetation represents 27% of Singapore's land area, a large proportion being grass (Yee et al. 2011). Singapore's climate is classified as tropical rainforest according to the Koppen climate classification with a twice-yearly monsoon, mean annual temperature of 27.4°C, and rainfall of 2358 mm year⁻¹.

Field measurements for this experiment were conducted from July through December 2012 at the Singtel-Kranji Radio Transmission Station, located in northern Singapore (103°43'49E, 1°25'53N). This area is relatively flat with a homogenous soil cover and dominated by cowgrass (*Axonopus compressus*), a C4 grass that is the most common turfgrass in Singapore (Sien et al. 1991). Like most of Singapore's turf, the site receives neither fertilizer, irrigation, nor herbicide. This site was closed to the public, offering secure location for instrumentation.

3.2 Experimental Design

Four adjacent experimental plots were established to partition the sources of respiration and assess how grass management practices influenced soil respiration fluxes. Each plot was 5m x 5m in size with four treatments (1) bare, with grass clippings (BNC); (2) bare, with grass clippings (BWC); (3) turf, no grass clippings (TNC); and (4) turf with grass clipping (TWC) (Figure 1A). The components of respiration explored in this study include ecosystem respiration (R_e), autotrophic respiration (R_A), heterotrophic respiration (R_H), and soil respiration (R_{soil}) (Table 1). All the plots were established on March 22, 2012 and were located adjacent to one another. We inserted 5 semi-permanent PVC soil respiration collars with a 23cm diameter within each plot for replicated measurements of CO_2 respiration fluxes. Collars were distributed to ensure a minimum 1.5m distance between collars and the edge of the plot. To maintain the bare ground treatment, manual weeding and herbicide (Roundup, Monsanto (Malaysia)) were used; herbicide was applied monthly to control the growth of vegetation on the bare soil plots.

The grass was mowed every 6-8 weeks to an approximate height of 4cm by a landscaping company using a riding lawnmower; clippings were not collected by the mower. Any grass clippings in the TNC and BNC treatments were carefully raked and removed from the site. In order to ensure that the quantity of clippings within the plots and collars was representative of the broader area, the total weight of the collected clippings from the TNC plot was determined and a clipping mass per area ($g\ m^{-2}$) was calculated. Based on the measured clipping mass, an appropriate amount of clippings ($\sim 100\ g\ m^{-2}$) were placed in a leaf litterbag within each collar in the BWC and TWC

treatments. Clipping litterbags were 30x20 cm and constructed from 0.5cm nylon mesh. Note that the retention of grass clipping on the TWC treatment may have reduced grass photosynthetic rates due to reduced light to penetrate – see discussion in section 5.1.

Collars were inserted approximately 5-7cm into the soil and allowed to settle for 5 months before soil respiration measurements were initiated. The long collar settling time ensured that the pulse of CO₂ efflux associated with the severing of roots during collar insertion was omitted from the experiment. The collars were not removed when the lawn was mowed; the mower was able to drive over the collars without disturbance.

3.3 Soil and Grass Characterization

The soils found at the study area have been classified as Ferric acrisols with a clay loam texture. The A1, A2 and B horizons are easily distinguished within the top 10cm of the soil profile, due to the distinct color difference between the horizons (Figure 1B). The soil is enriched in organic carbon at the surface, and shows orange accretions in the mineral layer, indicating Fe and the episodic flooded conditions, in relation to the clay content and limited water penetration.

Three replicate soil cores were extracted to determine bulk density for the A and B soil horizons. Soil coloration was used to differentiate the layers. A constant volume of soil was extracted through the use of standardized soil cores (5cm diameter, 5cm length) to determine soil bulk density and chemistry. Intact soil cores were weighed and then sieved using a 2mm mesh screen to remove rocks, coarse roots, and organic material. Samples were then oven dried at 105°C for 48 hours and bulk density was determined volumetrically as the mass of oven-dried sample divided by the volume of the core (98.17

cm³). Six replicate samples were analyzed to determine soil carbon content. Three samples were analyzed for total carbon and three were run with fumigation with HCl to remove inorganic carbon. Samples were oven drying to 70°C for 72 hours or until constant weight was achieved, ball-milled to fine powder, and analyzed using an elemental analyzer (varioTOC cube, Hanau, Germany). The density of C per unit area was calculated as

$$C = C_f B_D V (1 - \delta_{2mm}) \quad (1)$$

where C is carbon density, C_f is the fraction by mass of organic C, B_D is bulk density, and V is the volume of the soil core, and δ_{2mm} is the fraction of material larger than 2mm (Post et al. 1982).

Three replicate grass clipping samples were collected, dried, and element analysis was carried out to estimate the aboveground C and N fractions. Grass productivity was estimated by dividing the mass of collected clippings by the total number of days between clippings.

3.4 Soil CO₂ Respiration Measurement

A closed dynamic chamber system was used to measure soil respiration. The system recirculated air from the soil chamber to an infrared gas analyzer (IRGA; LI-6252, LI-COR Industries, Lincoln, NE) to determine the CO₂ accumulation rate over the measurement sample. A diaphragm pump was used to circulate air through the chamber with a flow rate of 0.5 L min⁻¹. The chamber system included a pig-tailed vent to maintain equilibrium pressure with the atmosphere while dampening the effects of wind blowing across the chamber. The IRGA reference air was scrubbed with soda lime and

Mg(ClO)₄ to remove water vapor and CO₂. Each measurement cycle lasted approximately 5 minutes with the first 100 seconds being omitted from analysis to allow for chamber equilibration. Soil efflux was measured approximately twice a week, throughout the daylight hours (between 0900-1830hrs).

Soil CO₂ efflux (F_{CO_2} , $\mu\text{mol m}^{-2} \text{s}^{-1}$) was calculated following Davidson et al. (1998):

$$F_{CO_2} = \frac{PV}{ART} \cdot \frac{dCO_2}{dt} \quad (2)$$

where P is the atmospheric pressure (Pa), V is the volume of the headspace gas within the chamber and sampling tubing (m³), A is the area of soil enclosed by the chamber (m²), R is the gas constant, T is the air temperature (K), and dCO₂/dt is the rate of change of CO₂ concentration ($\mu\text{mol mol}^{-1}$ dry air) in the chamber headspace between the 100 and 200 s after putting the chamber in place.

The LI-COR 6252 system was calibrated monthly to ensure the accuracy of the measurements and to avoid instrument drift. A zero gas and two CO₂ standard gases at 348ppm and 389ppm were flowed at ~0.5 L min⁻¹ for calibration. The effectiveness of the reference cell scrubber unit was tested by passing the zero air through the sample chamber.

3.5 Eddy Covariance Measurements

The net ecosystem exchange (NEE) of CO₂ was estimated using the eddy covariance method (Baldocchi et al. 1988) from a two-meter tower adjacent to the soil respiration experimental sites. A 3-axis sonic anemometer (CSAT3, Campbell Scientific, Logan, UT), was mounted adjacent to an open-path gas analyzer (LI-7500A, Licor,

Lincoln, NE) to measure winds and gas concentrations at 10Hz. Prior to covariance computation, the high frequency data was adjusted for several delays: (i) the pipeline delays of 2 and 3 scans in CSAT3 and IRGA measurements, respectively; (ii) delay caused by sensor separation; and (iii) clock drifting due to the CSAT3 recording in analog and digital modes. Data were corrected for density effects following Webb et al. (1980).

NEE was calculated every thirty minutes using the covariance of the vertical wind velocity fluctuations (w') and fluctuation in the CO_2 concentrations (c'). The vertical coordinate for wind velocities is positive upward, therefore positive values for fluxes denote emission from the system and negative values denote uptake by the system. During the daytime hours, defined here as 0900-1500 hours, NEE represents the net difference between carbon losses from R_e and uptake through photosynthesis (gross primary productivity, GPP) such that

$$NEE = R_e - GPP \quad (3)$$

During the nighttime hours, defined here as 2000-0600 hours, measured carbon fluxes represent only R_e since there is no light available for photosynthesis. The dawn and dusk hours were excluded from our daytime or R_e estimates because of unstable and transitional conditions during those hours. Only data from well-mixed periods when the friction velocity was greater than or equal to 0.05 m s^{-1} were included in analysis. The time series was not gap-filling, hourly flux estimates reported represent the median value based on all available data for a given hour. To be consistent with the soil respiration measurements, tower flux data from September 26, 2012 – December 31, 2012 were included in the analysis. Due to instrument failures and heavy rains, data were recorded

for 52% of possible hours. After also accounting for weak atmospheric turbulence, 4608 30-minute observations, or 31% of possible data were included. The energy balance closure of the system was 71%, comparable to the global average closure (Wilson et al. 2002). The eddy flux and chamber measurements provide independent estimates of carbon exchange.

3.6 Weather and Environmental Measurements

Ambient and soil conditions were monitored for each plot to evaluate their relationship with CO₂ efflux. Soil temperature was measured using thermistors (107L, Campbell Scientific Inc., Logan, UT, USA) and soil moisture was measured with time domain reflectometry (CS616, Campbell Scientific, Logan, UT, USA) using probes inserted into the soil at a low angle to obtain a composite measurement of the soil temperature and moisture for the first 0-5cm depth of the soil. All soil environmental factors were measured from the surface to a depth of 5-7cm and were recorded every minute with a datalogger (CR1000 and AM16/32, Campbell Scientific Inc., Logan, UT, USA). Soil volumetric water content measurements were calibrated after the measurement period by saturating and measuring an intact sample of soil in the laboratory, which was then oven dried at 40°C until constant weight.

Air temperature was measured at a height of 1.5 using an aspirated humidity and temperature probe (HMP155, Vaisala, Helsinki, Finland). Net radiation was measured with a radiometer (CNR1, Kipp & Zonen, The Netherlands). Rainfall was measured every minute using a tipping bucket rain gauge (Texas Electronics TR-525S, Texas, USA). Due to power failures, there were two gaps in the rainfall record from the Singtel

site, the rainfall time series was filled using a nearby weather station located approximately 13.5km away (station ID: INSWDOUB2).

3.7 Statistical Analysis

All error values reported in the text and figures represent 95% confidence intervals, unless specifically noted otherwise. We set an alpha value of 0.05 to determine the statistical significance. The R software package, version 2.15.3, was used for all statistical analyses (R Core Team 2013).

4.0 Results

The soil bulk density values were 0.80 ± 0.05 and $2.0 \pm 0.63 \text{ g cm}^{-3}$ for the A and B soil horizons, respectively, with total carbon contents of 5.54 ± 0.08 and $0.34 \pm 0.01\%$, respectively. The total organic carbon for the A and B horizons was 5.45 ± 0.06 and $0.32 \pm 0.01 \%$, respectively, indicating that nearly all of the carbon present was organic. The mean soil carbon density was 2.2 and 0.34 kg m^{-2} for the A and B horizons, respectively. Soil nitrogen for the A soil horizon was $0.5 \pm 0.2\%$; the B horizon soil nitrogen was below the detection limit for the analyzer. Roots larger than 2mm were found to have a biomass of 139 g m^{-2} with 20.8% carbon content. The grass and fresh clippings had a mean biomass of 160 g m^{-2} with a $42.6 \pm 1.4\%$ total carbon and $1.36 \pm 0.52 \%$ N content resulting in a C:N ratio of 31.3. After 41 days, the period between mowing cycles, the total carbon in the grass clippings dropped to 24.5 ± 0.55 and $33.2 \pm 0.97 \%$ for the BWC and TWC, respectively. Grass clippings were repeatedly collected from a 25m^2 plot and estimated to have a productivity of $2.39 \text{ g m}^{-2} \text{ day}^{-1}$.

The soil temperature differed significantly across all of the treatments (Table 1). The presence of grass clippings decreased the soil temperature in all cases, with the largest difference being observed between the BNC and BWC treatments. The soil temperature in BNC had the highest variance within a given day and was most variable across the length of the experiment (Figures 2 and 3). The treatments with turf (TWC and TNC) had consistently lower soil temperatures than the bare ground treatments (BNC and BWC) (Figures 2 and 3). The mean air temperature during the chamber respiration measurements was 30.2 ± 0.1 °C. Air temperature was warmer than the soil temperature for the turf treatments (TNC and TWC), but cooler than the bare ground treatments (BNC and BWC). Unlike soil temperature, soil volumetric water content did not statistically vary with the presence or absence of turfgrass (Table 1). However, the BNC treatment did have significantly lower soil water content (p-value ~ 0) than all the other treatments.

Soil chamber efflux rates were measured on a total of 24 days between August and December 2012. During each measurement day, each of the five collars within the four treatments was measured 2-3 times resulting in a total of 1147 unique chamber flux measurements (Table 1). Bare ground had the lowest CO₂ efflux rates with 2.4 ± 0.13 $\mu\text{mol m}^{-2} \text{s}^{-1}$, with the addition of grass clippings to the bare ground resulting in an $\sim 1/3$ increase in the efflux rate. The highest overall CO₂ efflux rates were observed in the TNC treatment, with 15% higher flux rates than TWC. The differences between the TWC-TNC and BWC-BNC treatments increased between DOY 291 and 365 (Figure 2) when the amount of precipitation and soil volumetric water content both increased.

Eddy covariance measurements were used for independent estimates of R_e , net primary productivity (NPP), and the net carbon balance (Figure 4). The median estimated

Re, based on nighttime measurements was $7.9 \pm 1.1 \mu\text{mol m}^{-2} \text{s}^{-1}$ with no statistically significant difference between the dry and wet periods (p-value=0.09). The measured median daytime fluxes were -7.9 ± 0.65 and $-15.2 \pm 0.68 \mu\text{mol m}^{-2} \text{s}^{-1}$ during the dry and wet periods, respectively. The overall median daytime net exchange was $-12.4 \pm 0.56 \mu\text{mol m}^{-2} \text{s}^{-1}$. The wet period was estimated to extend from (DOY 291-365). The 24-hour daily mean integrated flux, based on the hourly median flux rates, was +2.4 and -0.75 $\mu\text{mol m}^{-2} \text{s}^{-1}$ during the dry and wet periods, respectively (Figure 4). The mean daytime incoming net radiation was 427.8 ± 18.2 and $393.5 \pm 15.2 \text{ W m}^{-2}$ during the dry and wet periods, respectively.

In order to quantify the respiration fluxes from soil, turf, and grass clippings, we used a mass balance approach based upon the assumption that the total of mass of carbon and rates of respiration of CO₂ remains constant across the treatments of this experiment (Wan and Luo 2003, Bond-Lamberty et al. 2004, Trumbore 2006, Zhou et al. 2007). Considering the nighttime eddy covariance measurements to represent Re, we were able to approximately close the respiration budget (Table 2). RA, Rsoil, and RH were estimated by difference between treatments. RA was estimated to comprised 49-76% of total respiration.

5.0 Discussion

Globally, soil respiration is one of the largest terrestrial carbon fluxes, far exceeding anthropogenic fossil fuel emissions. In a global meta-analysis, Bond-Lamberty and Thomson (2010) found the mean ($\pm$ sd) soil respiration from managed tropical grasslands was $4.6 \pm 2.62 \mu\text{mol m}^{-2} \text{s}^{-1}$ (n=16 study sites) and $6.1 \pm 1.28 \mu\text{mol m}^{-2} \text{s}^{-1}$ from managed

tropical evergreen grasslands (n=6 sites in Brazil and Hawaii); their overall reported mean tropical soil respiration was $3.4 \pm 1.67 \mu\text{mol m}^{-2} \text{s}^{-1}$. Velasco et al. (2013) approximated soil respiration in a Singapore residential area to be $4.08 \mu\text{mol m}^{-2} \text{s}^{-1}$ based on a Q_{10} relationship with temperature and the mean tropical respiration rates reported in Bond-Lamberty and Thomson (2010). The mean ecosystem respiration rate we observed in this study was $7.9 \pm 1.1 \mu\text{mol m}^{-2} \text{s}^{-1}$, but our estimate included contributions from grass autotrophic respiration not typically capture in soil respiration studies. The BNC flux, representing only R_{soil} , was $2.4 \pm 0.13 \mu\text{mol m}^{-2} \text{s}^{-1}$. The relative contributions of autotrophic and heterotrophic processes are often approximately equal, but can vary dramatically (Trumbore 2006). We estimated the range of the autotrophic contribution to ecosystem respiration as 49-76% (Table 2). We are unaware of any other direct measurements of tropical lawn respiration in Southeast Asia.

5.1 Environmental Controls on Respiration

The dominant control on ecosystem respiration is believed to be temperature (Davidson and Janssens 2006). Using kinetic theory, Arrhenius (1889) first defined the basic model for soil respiration that is still used today – decomposition increases with increasing temperature when substrate availability and enzyme activity do not limit the reaction rates. This type of temperature based respiration model is dominant in global climate and ecosystem models (Friedlingstein et al. 2006). In the tropics, soil moisture and rainfall dynamics have been suggested as dominant controls on respiration because of the consistently high temperatures and greater variability in rainfall (Hutyra et al. 2007, Valentini et al. 2008).

In this study, we found only weak relationships between temperature and moisture and respiration for most of the treatments (Figures 2 and 3). The exception was the TNC treatment for which there was a significant relationship between soil temperature and flux ($R^2=0.51$). The weak temperature relations are not surprising given the narrow range of observed soil temperatures. As noted by Lellei-Kovacs et al. (2011), the strength of the temperature-respiration relationship is dependent on the ambient temperature range. Tropical ecosystems typically have high mean temperatures and a larger diel than seasonal temperature variations, obscuring the overall temperature-respiration relationship. Studies by Hashimoto et al. (2004) in Thailand and Hutyra et al. (2007) in Brazil also observed a lack of distinct relationship between soil respiration and soil temperature.

We observed a weak overall relationship between soil volumetric water and soil respiration, but there was a significant change in the respiration flux patterns with the start of the monsoon rains (Figure 2). When the rains commenced on October 17, 2012 (DOY 291), the soil volumetric water quickly increased to the point of saturation and soil temperatures decreased, but respiration rates did not follow a consistent response across treatments. During the rainy interval (DOY 291-365) the respiration rates from the TNC and TWC diverged from one another. Before the rainy interval, the respiration rates in the TNC and TWC treatments were not statistically distinguishable, 8.3 ± 0.32 and 8.1 ± 0.41 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (p-value=0.40), respectively. During the rainy interval, the TWC respiration rates decreased to 6.3 ± 0.24 , while the TNC did not show a statistically significant change with the onset of the rain. The respiration rates from the BNC also decreased during the rainy period from 2.6 ± 0.17 to 2.1 ± 0.19 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

As hypothesized, we did find that turf management practices significantly influenced the soil efflux rates, but the retention of grass clippings did not influence respiration entirely as expected. We hypothesized that clippings would enhance respiration rates since the amount of readily decomposable organic matter increased in these treatments, however, this was not consistently observed. In the bare ground treatments, there was a slight increase in the fluxes due to the mineralization of the clippings. However, the TNC had a higher mean respiration rate than TWC, particularly during the rainy period. A potential mechanism is that the retention of clipping reduced grass photosynthetic rates by covering the live grass and not allowing light to penetrate. A reduction in photosynthesis would result in a commensurate reduction in R_A . The differences in respiration fluxes emerged when soil moisture increased. The onset of the monsoon in these poorly drained clay soils may have induced anoxia in the TWC due to the thick clippings layer, resulting in a decrease in TWC respiration rates. The soil moisture in the TWC and TNC treatments was similar integrating across the 0-7cm depth (Figure 2), but the surface moisture conditions (not measured) may have been sufficiently higher in the TWC to dampen respiration rates.

Finally, it is also possible that this result is an artifact of the experimental design. In order to retain grass within the collars, grass clippings were put in a litterbag and placed on top of grass in the TWC treatment. This design resulted in a thick mat of grass being constantly present, covering the grass below. While conditions like this do certainly occur with lawn management along the mowing row edges and in cases of tall grass with infrequent mowing, a mat of this thickness is not representative for turfgrasses generally.

5.2 Net carbon balance

Previous studies from temperate turfgrass systems estimate a wide range in biomass from 200-700 gC m² with NPP rates of 0.24–0.96 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (0.25–1 gC m⁻² day⁻¹; Falk 1976, Falk 1980, Jo and McPherson 1995, Qian et al. 2003, Kaye et al. 2005, Golubiewski, 2006, Guertal 2012). But, carbon uptake into grass biomass is ephemeral compared to woody biomass. Since turfgrasses do not accumulate woody biomass, the carbon fixed through photosynthesis will quickly either be released as CO₂ respiration or move into the soil C pool.

In this study, we estimated aboveground biomass of 67.5 gC m⁻² and belowground biomass of 29 gC m⁻². These biomass values are low compared to previous studies, but most of the previous studies are from temperate lawns. Kong et al. (2014) estimated aboveground biomass within irrigated and fertilized lawns in Hong Kong to be 120-530 gC m⁻². Based on lawn clipping mass, mowing frequency and the measured carbon concentrations, we estimated aboveground NPP to be 1.02 gC m² day⁻¹. Belowground production was not measured, but others have found belowground and aboveground production to be comparable in magnitude (Falk 1980). Schlesinger and Bernhardt (2013) report a typical NPP for tropical savannahs of 1.48 gC m⁻² d⁻¹. Heterotrophic respiration was estimated to be 24-49% of R_E, 1.8–3.8 gC m⁻² day⁻¹ (Table 2), suggesting that this lawn was in approximate carbon balance.

The ecosystem NPP can also be estimated using primarily eddy covariance data. During the daytime, the eddy covariance measurements represent the difference between GPP and R_e; during the nighttime, NEE is R_e. Using all of the daylight measurements of NEE (0800-1700, Figure 4) and assuming a constant R_e of 7.6 gC m⁻² day⁻¹ (7.9 $\mu\text{mol m}^{-2}$

s⁻¹; Figure 4), daily GPP is approximately 7.7 gC m⁻² day⁻¹. Given the range of estimated R_A from the chamber measurements (Table 2), this suggests a mean daily NPP of 1.7–3.8 gC m⁻² day⁻¹. Similar to the production and chamber-based estimates, the eddy covariance measurements also suggest that this site is approximately carbon neutral. While the range in all these estimates is large, it is broadly consistent.

In addition to biogenic CO₂ release through respiration, we estimate emissions from lawn mowing to be 0.12 gC m⁻² day⁻¹, based on mowing every 7 weeks with an emission per mow of 5.66 gC m⁻² (Jo and McPherson 1995). The mowing emissions from this site were low due to infrequent mowing schedule.

The chamber and eddy covariance measurements are consistent in suggesting that this site is in approximate carbon balance. While more frequent mowing could clearly shift the carbon balance of this site through fuel emissions, additional studies are required to determine how productivity and respiration rates change with mowing frequency. The eddy covariance measurements suggest that this site was a net carbon source during the dry period and a net sink during the rainy period, but the short duration of this study does not allow us to reliably estimate the annual carbon balance. The chamber measurements of respiration captured a range of weather conditions, but did not show a simple temperature or moisture dependence that would allow for reliable modeling of the annual carbon fluxes.

6.0 Conclusions

Urbanization, and all of the landscape changes associated therein, is a fundamental driver of current and future global change. Across the globe, urban land

cover is expanding rapidly and the land area occupied by turfgrass continues to steadily increase. Turfgrass can require significant management and energy inputs to maintain, but its biogeochemical fluxes have not been well characterized. The observations from this study provide new data on turfgrass carbon and nitrogen densities, the overall rates of respiration, carbon exchange, and insensitivity to weather. The observed rates of CO₂ respiration were high relative to grasslands, but comparable in magnitude to the few other previous urban turf studies. This site was mowed infrequently, resulting in both low management emissions and large and episodic inputs of clippings to the system. The results of reduced turf respiration with clippings during the wet period may reflect this infrequent mowing regime and large episodic inputs of clippings, additional studies in more intensively managed turfgrass systems are required to determine if this result is generalizable. The duration of this study does not allow us to speculate as to the annual net carbon balance, but both the chamber and the eddy covariance measurements highlight that the CO₂ fluxes are large on a diel basis. Given the abundance of turfgrass within urban landscapes, its productivity and respiration dynamics will influence urban atmospheric mixing ratios of CO₂. Further studies are required to better constrain the vegetative contribution to the urban carbon balance and overall atmospheric CO₂ signal.

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9.0 Tables & Captions

Table 1. Mean CO₂ respiration rates, soil moisture and temperature conditions across the four turf treatment regimes. The components of ecosystem respiration captured across the treatments include soil (R_{soil}), grass clippings (R_H), and grass autotrophic (R_A) respiration.

Treatments	Components of ecosystem respiration included	Mean CO ₂ respiration (μmol m ⁻² s ⁻¹)	N	Soil volumetric water (%)	Soil temperature (°C)
BNC	R _{soil}	2.4 ± 0.13	243	64.6 ± 3.0	32.8 ± 0.3
BWC	R _{soil} + R _H	3.2 ± 0.14	294	80.5 ± 1.7	31.1 ± 0.2
TNC	R _{soil} + R _A	8.4 ± 0.24	302	64.1 ± 2.0	29.7 ± 0.1
TWC	R _{soil} + R _A + R _H	7.1 ± 0.25	308	63.3 ± 2.4	29.5 ± 0.1

Table 2. Mass balance based estimates of autotrophic, heterotrophic, and total ecosystem respiration. The nighttime eddy flux is assumed to capture total ecosystem respiration in this budget. * TWC is second, independent potential estimate of total ecosystem respiration, but the thickness of the clipping mat may have dampened autotrophic respiration.

Source	Component of respiration	Calculation	Respiratory Flux (μmol/m ² /s)	Percent of Total Ecosystem Respiration (TWC)
Turfgrass	Autotrophic	TWC – BWC	7.1 – 3.2 = 3.9	49%
		TNC – BNC	8.4 – 2.4 = 6.0	76%
Soil	Soil	BNC	2.4	30%
Grass Clippings	Heterotrophic	BWC-BNC	3.2 – 2.4 = 0.8	10%
Total	Ecosystem (Autotrophic & Heterotrophic)	TWC*	7.1 ± 0.25	90%
		Nighttime Eddy Flux	7.9 ± 1.1	100%

Figure 1. A. Experimental treatment design showing the location of the four treatment plots and the proximity of the eddy flux tower. B. Photo of soil respiration PVC collars with litterbags. C. Sample collar and soil measurement locations within each treatment. D. Grass and soil profile.

Figure 2. Time series of chamber-based respiration flux measurements (a), soil temperature (b), soil volumetric water content (c), and daily precipitation (d). The vertical lines at DOY 291 and 365 denote the wet period of measurements.

Figure 3. Relationship between soil temperature (A) and soil volumetric moisture (B) and the chamber measured CO₂ respiration rates across the four treatments.

Figure 4. Diel cycle in the hourly median ($\pm$ SE) flux rates as measured by the eddy covariance. The shading denotes the nighttime hours used for calculating eddy covariance-based R_{eco}. The wet period extends from DOY 291-365.

Figure

Figure 2

Figure 3

Figure 4