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Research Paper

Lawn mowing frequency and its effects on biogenic and anthropogenic carbon dioxide emissions



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ABSTRACT

Decision makers in urban areas actively pursue strategies to decrease carbon dioxide (CO_2) emissions and other greenhouse gases. Lawns dominate urban lands in the U.S. and require intensive management, including frequent mowing, which may influence CO_2 emissions from both biogenic and anthropogenic sources. We tested whether different lawn mowing frequencies (every one, two or three weeks) affected soil respiration (i.e., biogenic CO_2 emissions), by changing soil moisture and temperature, and the gasoline emissions associated with lawn maintenance via lawn mowing (i.e., anthropogenic CO_2 emissions). Sixteen yards in Springfield, Massachusetts USA were assigned a mowing frequency for two seasons (2013–2014). We measured grass height, air and soil temperature, soil moisture, soil CO_2 fluxs, lawn mower emissions, tree canopy coverage and precipitation. We used a mixed effects modeling approach to test how these variables interacted with each other and responded to mowing frequency. Lawn-mowing frequency did not influence soil temperature, or biogenic soil CO_2 fluxes. Soil microclimate and soil respiration varied more with ambient climatic fluctuations and tree canopy cover. By contrast, anthropogenic emissions increased with more frequent mowing due to emissions associated with the mower. When scaled to the entire mowing season, biogenic CO_2 fluxes far exceeded the anthropogenic fluxes, thus requiring consideration for accurate accounting of urban greenhouse gas emissions. The interplay between biogenic (e.g., increasing tree canopy in lawn-dominated yards) and anthropogenic (i.e., mowing less frequently) methods of reducing CO_2 emissions in cities highlights the need for more rigorous accounting processes for cities to meet climate action goals.

1. Introduction

Urban areas currently account for \sim 70% of global fossil-fuel carbon dioxide (CO₂) emissions (Gurney et al., 2015). To reduce these emissions, many cities actively pursue strategies to reduce current and future anthropogenic CO2 emissions to historical baselines (DeBlasio, 2014; Gurney et al., 2015; Rosenzweig, Solecki, Hammer, & Mehrotra, 2010). Climate action plans, which operate on a variety of spatial scales from municipality to country, detail steps on how to achieve such emissions reductions (e.g., Geenovate Boston 2014, www.cityofboston. gov, The President's Climate Action Plan, 2013, https:// obamawhitehouse.archives.gov, and the U.S. Mayors Climate Protection Agreement, 2005-2018 https://www.usmayors.org). For example, the Greenovate Boston 2014 Climate Action Plan includes a variety of activities, such as increasing the energy efficiency of buildings, reducing miles commuted, and protecting urban vegetation and open space, to cut citywide greenhouse gas emissions 25% by 2020, with an additional 80% reduction by 2050. To be effective, activities outlined in the climate action plans should accord with current policies to help ensure the realization of stated reduction goals.

Identifying factors that control biogenic versus anthropogenic CO_2 emissions is a key step toward monitoring, reporting, and verifying information included in climate action plans that tend to focus on anthropogenic emissions targets (Decina et al., 2016; Hutyra et al., 2014). Lawns play an important role in this exercise due to their spatial extent, their capacity to both store and release C belowground, and their maintenance requirements. Although trees, shrubs and other woody plants contribute to urban ecosystem C stocks (Jo & McPherson, 1995; McPherson, Xiao, & Aguaron, 2013; Nowak, Greenfield, Hoehn, & Lapoint, 2013), lawns dominate green spaces, particularly in residential areas, blanketing more than 163,000 km² of US lands (Milesi et al., 2005). These lawns generally sequester high levels of soil organic C (SOC), equaling or exceeding their counterparts in native forests, grasslands, or adjacent agricultural areas (Golubiewski, 2006; Pouyat, Yesilonis, & Golubiewski, 2009).

Lawns can also exhibit higher rates of soil CO_2 flux as compared to other land cover types (Groffman, Williams, Pouyat, Band, & Yesilonis, 2009; Kaye, McCulley, & Burke, 2005), which may result from warmer temperatures (due to greater solar radiation inputs or urban heat island effects), greater soil moisture availability (due to irrigation), or

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enhanced nitrogen availability (due to fertilization) in the lawn system (Bowne & Johnson, 2013; Kaye et al., 2005; Lilly, Jenkins, & Carroll, 2015). Like other ecosystems, the net soil C balance of urban lawns is the difference between rates of SOC sequestration and decay (Kirschbaum, 2000). However, the high soil C storage potential of lawns may not be sufficient to offset high soil CO₂ losses (Townsend-Small & Czimczik, 2010), and in fact, total growing season soil respiration from urban soils (biogenic CO₂ emissions) can be almost as high as anthropogenic urban fossil-fuel CO₂ emissions (i.e., roughly \sim 70%; Decina et al., 2016).

Lawns are first and foremost a social construct in residential landscapes and thus receive intensive management (e.g., fertilizer application, irrigation, frequent mowing) to promote the lawn ideal of a lush vegetative state (Cook, Hall, & Larson, 2012). These lawn management activities may result in both C benefits through enhanced biogenic C sequestration as well as indirect or hidden C costs (HCC) through increased anthropogenic CO₂ emissions (Selhorst & Lal, 2013). Retention or removal of grass clippings, mower height setting, and mowing frequency can affect soil C stocks by determining how much plant material is available for decomposition and incorporation into SOC (Allaire, Dufour-L'Arrivée, Lafond, Lalancette, & Brodeur, 2008; Huyler, Chappelka, Prior, & Somers, 2014; Lilly et al., 2015). However, these same management activities might drive SOC outputs by changing soil temperature and moisture (Allaire et al., 2008; Byrne, Bruns, & Kim, 2008; Liu & Huang, 2003; Luo, Wan, Hui, & Wallace, 2001), two of the primary drivers of SOC turnover and soil CO2 flux (Davidson, Belk, & Boone, 1998). Anthropogenic HCCs, which are expressed as grams of C equivalents (CE) m⁻² year⁻¹ (Zirkle, Lal, & Augustin, 2011), are associated with the energy consumed from fertilizer application (e.g., the additional HCCs associated with manufacturing and distributing the fertilizer), irrigation (e.g., energy costs associated with running the irrigation system) and emissions associated with maintaining the lawn with a gas-powered mower (Gu, Crane, Hornberger, & Carrico, 2015).

Although not every household irrigates or applies fertilizers (Polsky et al., 2014), most households mow on a weekly/biweekly schedule to conform to societal expectations, city ordinances, and the personal satisfaction of a neat and tidy yard (Robbins, 2007). The type of gaspowered mower and frequency of mowing has implications for HCCs. For example, although mowing time might be shorter when using a rider mower (Zirkle et al., 2011), rider mowers emit more than four times as much CO₂ compared to a push mower, largely due to engine type and associated gas consumption (a rider mower has an 18.6 kW engine and consumes 5.7 L of gasoline per hour whilst a push mower has a 3 kW engine and consumes 1.3 L of gasoline per hour; Strohbach, Arnold, & Haase, 2012). Initially, some lawn management practices (e.g., irrigation and applying fertilizer) can increase net primary production and SOC (Qian & Follet, 2002). However, once established, the HCCs related to lawn maintenance, in particular, mowing, will eventually outweigh the C storage potential of turf grasses, transforming home lawns from a C sink to a C source (Selhorst & Lal, 2013).

Despite the ubiquity of lawn mowing as a management practice, few studies have examined how mowing frequency impacts C dynamics in residential lawns. Regarding mowing-related activities, previous work has largely focused on the effects of clippings management and mower height on soil C cycling (Fissore et al., 2012; Lilly et al., 2015; Ng et al., 2015; Qian et al., 2003; Song, Burgess, Han, & Huang, 2015). The few studies that have explicitly considered mowing frequency have either implemented unrealistically long intervals for residential yards (e.g., once per season, Allaire et al., 2008), compared weekly sampling to a regime based on leaf blade height (e.g., Law & Patton, 2017), or conducted a modeling exercise based on self-reported mowing activities (e.g., number of mowing events; Gu et al., 2015), and thus have not examined how more typical mowing behaviors might affect soil C losses from urban lawns or how specific lawn features (e.g., size of lawn and time spent mowing) influences the associated HCCs for maintaining these systems. To better understand how lawn mowing frequency

affects biogenic and anthropogenic CO_2 emissions in lawn-dominated systems, we manipulated lawn mowing frequency in suburban yards to test the following three hypotheses: (1) mowing more frequently decreases soil moisture and increases soil temperature; (2) these changes in soil microclimate drive soil respiration rates, with higher rates in warmer soils under frequent mowing; and (3) frequent lawn mowing elevates HCC such as C emissions associated with the mower itself. Given their prominence in urban areas, it is paramount to understand how lawn mowing frequency contributes to C dynamics and ecosystem function in urban systems. Such understanding is especially important given the stated goals of local climate action plans to reduce CO_2 emissions.

2. Methods

2.1. Study site

We conducted the study in 16 single-family, owner-occupied suburban yards in Springfield, Massachusetts, USA. Because we were working with private households, we relied on volunteers that we recruited via a local tree planting organization. Parcels ranged in size between 0.03 and 0.18 ha, with a mean of 0.08 ha (typical of mediumdensity housing stock within Springfield), and houses were built between 1921 and 1957. Participating yards could not fertilize, apply herbicides or pesticides, or irrigate throughout the study. The research is part of a broader investigation on the impacts of lawn management behavior on biodiversity and ecosystem function (Lerman & Milam, 2016; Lerman, Contosta, Milam, & Bang, 2018).

2.2. Mowing

Lawns were mowed from May through September in 2013 and 2014, using a Toro 19" self-mulching push mower, with a 7.0 ft-lb Net Torque Toro Premium OHV 159 cc (equivalent to 7 horse power or 5.23 kW) engine with auto choke. We set the mowing height at 6.35 cm and grass clippings remained on the lawn. We assigned each yard to a mowing frequency regime: mowed every 7 days (1 week; n = 8 yards), 12–14 days (2 weeks; n = 7 yards), or 18–21 days (3 weeks; n = 8yards) to represent the range of typical mowing behaviors (1–2 weeks) to a more extreme (but realistic) frequency (3 weeks; Robbins, 2007). Seven yards participated in both years of the study and thus these repeat yards were assigned a different mowing regime for the second year of the study. To ensure households adhered to the experimental restrictions (e.g., frequency and height of mowing), we provided a free lawn mowing service for the duration of the study. We recorded the total time for each mowing event and then calculated a mean mowing time per study site. Mowing times within an individual lawn varied throughout the season due to different field assistants operating the mower. The mean mowing time per study site allowed us to account for some of this variation. We multiplied the mean mowing time per study site by number of mowing events per season to determine total seasonal mowing duration, which in turn enabled us to calculate the HCCs associated with mowing (see Section 2.5.2 below). Yard configuration (e.g., placement of sheds and driveways) and size also factored in time spent mowing, with smaller and more complex yards resulting in more frequent turns and hence, additional time (Zirkle et al., 2011).

2.3. Vegetation measurements

To calculate the percentage of different grass species growing in the lawns, we conducted two intensive sampling events per site, per year using the quadrat sampling method. Sampling areas consisted of three 1 m^2 plots per site whereby we assigned a percent coverage of each species for the plot, and then calculated a mean percentage for the parcel. Grass height was measured immediately prior to every mowing event in each yard at three separate locations, adjacent to where soil

respiration measurements were made (see Section 2.5.1 below). At each soil respiration location, we randomly selected and measured the height of three individual swards, for a total of nine height measurements per vard per sampling event. These nine replicates were averaged to produce a single grass height per yard per measurement date. We define height as the length of the sward from the soil surface to the sward tip. Biomass was determined during each mowing event in 2014 by collecting grass clippings from nine, $2 \text{ m} \times 0.48 \text{ m}$ strips. Clippings were removed from the mowing bag following each 0.96 m² sampled strip and placed in individual paper bags. They were then dried to a constant mass at 55 °C for 48 h, weighed, and converted to $g C m^{-2}$ assuming that C comprised 45% of dry biomass (e.g., Golubiewski, 2006; Law & Patton, 2017). Total seasonal vield ($g Cm^{-2} season^{-1}$) was calculated as the sum of the grass biomass sampled throughout the 2014 mowing season. We calculated tree canopy cover in ArcGIS using Google Earth imagery from 2014 and parcel data from the City of Springfield, MA online GIS mapping site (https://maps.springfield-ma.gov/gis/). We centered our calculation at the intersection of the driveway and road to capture trees located outside of the parcel that might nevertheless affect lawn microclimate by providing shade during some times of the day. To calculate total lawn area, we used a Google Earth image from 2012 with 'leaf-off' aerial view and parcel data from the City of Springfield. For both images, the scale was 1:1250, and minimum mapping unit was 3 m. The tree canopy calculation and lawn area represented yard characteristics that were not influenced by mowing frequency.

2.4. Climate data

To disentangle the effects of grass height versus ambient climate in driving soil temperature, moisture, and thus soil CO₂ flux, we compiled weather data from observations at the Hartford Bradley International Airport (Menne et al., 2012) located \sim 30 km from the study site. We opted to use this weather station due to its substantially longer period of record and significantly higher record completeness as compared to stations located within Springfield. While we acknowledge the potential for microclimatic differences between the conditions at the airport and in more residential areas, we do not expect that synoptic scale meteorology differed between the sites to impact overall trends (Spence, Walker, Robarge, Preston, & Osmond, 2015). Variables of interest were total daily precipitation (mm) and average daily air temperature (°C). These were extracted for both the day of sampling and the week prior to each measurement, which allowed us to capture the instantaneous and cumulative response of soil respiration to ambient climatic conditions (Bradford et al., 2008; Contosta, Frey, & Cooper, 2015).

2.5. Biogenic and anthropogenic CO₂ emissions

2.5.1. Biogenic emissions from soil CO_2 flux

Soil CO₂ flux was quantified during five sampling events in 2013 and five sampling events in 2014 (coinciding with the mowing season) using a static chamber technique, with a three-week interval between samples within each year. Measurements were made in three locations for each yard, prior to mowing. This involved creating a sealed chamber at each site by placing a lid over a pre-installed collar and collecting headspace samples for analysis of CO₂ (Peterjohn et al., 1994; Raich, Bowden, & Steudler, 1990). At the time of sampling, three 0.019 m³ chambers were placed on the soil surface. Each chamber was equipped with a vent tube to avoid pressure differentials between the chamber and the ambient air (Davidson, Savage, Verchot, & Navarro, 2002). Incubations occurred over a 15-min period, during which headspace samples were obtained at 5, 10 and 15-min intervals. An ambient sample was also collected from each yard to represent CO2 concentrations prior to the start of the incubation (0 min). Samples were immediately injected into evacuated, He-flushed, 30 ml, crimp-top borosilicate vials. Air and soil temperature were measured simultaneously with the soil gas exchange using a Gempler waterproof 8" digital soil

thermometer probe, and the height of the vegetation was measured to correct for chamber volume. Soil moisture was quantified as volumetric water content using a Delta-T SM150 Kit. All fluxes were measured between 0900 and 1300 h when the average of the daily flux typically occurs (Davidson et al., 1998).

Carbon dioxide was analyzed with a LI-COR LI-6252 infrared gas analyzer (LI-COR Biosciences, Lincoln, Nebraska, USA). Rates of soil gas exchange were estimated as the linear increase in CO_2 over the 15-min incubation and converted to units of mg CO_2 -C m⁻²h⁻¹. Regressions with r² values < 0.80 were omitted from the data set. We then averaged all three fluxes, as well as soil temperature, and soil moisture measurements for each sampling date per yard (i.e., three analytical replicates per sample). Total seasonal soil respiration (g CO₂-C m⁻² season⁻¹) for both 2013 and 2014 were estimated with linear interpolation (e.g., Contosta, Frey, & Cooper, 2011). Because the start and end dates for soil respiration sampling were not equal across all treatments, total seasonal fluxes were scaled to 93 days, which was the shortest sampling window in the data set.

2.5.2. Anthropogenic emissions from the lawn mower

We used a similar approach to Horn, Escobedo, Hinkle, Hostetler, and Timilsina (2015) and Strohbach et al. (2012) to estimate HCC associated with anthropogenic CO_2 emissions from the lawn mower. Total seasonal anthropogenic emissions from each lawn (CE) were determined by multiplying the seasonal usage rate (*s*) by the fuel consumption rate of the mower (*f*) and the C emission factor of gasoline (*z*), dividing the product of these three terms by the total area of the lawn (*a*), and then scaling the result from g CO_2 to CE (g CO_2 -C) using the molecular weights of each (*m*), i.e.,

$$CE\left(\frac{gCO_2 - C}{\frac{m^2}{season}}\right) = \frac{(s \times f \times z)}{a} \times m$$

For each lawn, we determined the usage rate (*s*) in units of hours per season by calculating the total number of mowing hours during the May to September mowing period (see Section 2.2 above). The fuel consumption rate (*f*) was estimated as 1.5 L of fuel per hour for a 5.23 kW mower. The emissions factor term (*z*) was set to 2.32 kg CO₂ per L of gasoline (U.S. Environmental Protection Agency, 2005), which was scaled to g of CO₂ per L. The lawn area (*a*) was calculated in m² using the protocol described in Section 2.2. We converted the CE from units of g CO₂ m² season⁻¹ to g CO₂-C m² season⁻¹ using the molecular weight of C (12.012 g/mol) relative to the molecular weight of CO₂ (44.010 g/mol) (*m*).

2.6. Data analysis

All statistical analyses were conducted in R 3.2.3 (R Core Development Team, 2014), evaluating repeated measures data (collected every three weeks over two mowing seasons), seasonally aggregated data (cumulative grass biomass, average soil microclimate values, total C fluxes, and HCC associated with lawn mower emissions), and general plot characteristics (grass species abundance, percent tree canopy cover, and parcel size).

For repeated measures analyses, we used a mixed effects modeling approach comprised of both ANOVA- and regression-type models (Littell, Henry, & Ammerman, 1998; Pinheiro & Bates, 2000; Zuur, Iena, Walker, Saveliev, & Smith, 2009). ANOVA-type models assessed differences in grass height, soil microclimate, and soil respiration (response variables) with mowing frequency, sample round, and their interaction (predictor variables). The ANOVA approach utilized the protocol outlined in Zuur et al. (2009) to determine random effects (yard), autocorrelation (sampling round), and variance structure (mowing treatment or sampling round) using the *nlme* package (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2016). Fixed effects



(caption on next page)

Fig. 1. Box and whisker plots for the two sampling years (2013 and 2014) showing precipitation (mm) (a), air temperature (°C) (b), soil moisture (%) (c), soil temperature (°C) (d), grass height (cm) (e) and CO_2 flux (mg CO_2 -C m⁻²h⁻¹) (f) per sampling round, and, where applicable, by treatment. The top and bottom of each box indicate values at the 25th and 75th percentile, the bold line indicates the median, and whiskers extending beyond the box depict data within 1.5 times the interquartile range.

were then chosen with a backward selection procedure using both AIC and log-likelihood ratio tests (Zuur et al., 2009). After finalizing the fixed effects, we obtained model level *P*-values using the *anova* function to generate type II Wald's F-tests. We then determined pairwise differences between means using the *glht* function in the *multcomp* package (Hothorn, Bretz, & Westfall, 2008).

We also used a mixed-effects modeling framework to develop three multiple regression-type models (sample size of n = 120 observations) that examined relationships among grass height, soil respiration, and ambient temperature and precipitation. As with the ANOVA-type mixed models, these mixed-effects regressions explicitly considered random effects associated with yards and autocorrelation effects related to repeated measures (Littell et al., 1998; Pinheiro & Bates, 2000; Zuur et al., 2009). The first two analyzed the relative contribution of grass height and ambient climatic fluctuations in driving soil microclimate, modeling soil temperature as a function of grass height and average air temperatures during the week prior to sampling, and soil moisture as a function of grass height and cumulative precipitation for the preceding seven days. The third model explored how soil respiration varied given fluctuations in grass height, soil temperature, and soil moisture at the time of sampling. Prior to performing the regression-type mixed effects models, predictor variables were evaluated for collinearity using the variance inflation factor statistic (VIF) (Zuur et al., 2009). All three regression models used the same protocols as the ANOVA-type models in selecting random effects, autocorrelation structures, but did not specify variance structures or include pairwise comparisons because they did not contain treatment groupings. We also used the same backward selection procedure for selecting fixed effects using both AIC and log-likelihood ratio tests (Zuur et al., 2009), and then obtained Pvalues of each fixed effect using the anova function. Since model-level P and r² values typically reported for least squares regressions were not available for mixed-effect type models, these statistics were determined by fitting predicted versus observed values. In addition, we determined the relative contribution of each model term to overall model fit by omitting each independent variable in turn and comparing the full to the reduced model using Akaike's Information Criteria (Burnham, Anderson, & Huyvaert, 2011). Large increases in AIC in the reduced compared to the full model indicated that the dropped variable contributed substantially to model fit.

As with repeated measures analysis, we used an ANOVA-type mixed effects modeling framework to evaluate differences among treatments in seasonally aggregated data (total seasonal soil respiration, HCC associated with lawn mower emissions, and cumulative grass biomass C production) as well as yard characteristics (percent tree canopy cover and parcel size). Using the same approach outlined above for repeated measures ANOVA-type mixed effects models, we selected random effects and variance structures, and determined model-level *P*-values and pairwise significant differences between means. Recognizing that yard characteristics independent of mowing might impact grass height, microclimate, and respiration, we also devised additional multiple regression models on seasonally aggregated microclimatic, productivity and respiration data. Average soil moisture, soil temperature, grass height, cumulative grass biomass, and total seasonal CO₂ flux were response variables. Parcel size and percent canopy cover were additive predictors included in each multiple regression model. Model selection and reporting of significant effects and model-level *P* and r^2 values were as for the repeated measures regression-type mixed effects analyses above. We used the non-parametric Kruskal-Wallis rank sums test to evaluate differences in grass species abundance among treatments. Grass species abundance data did not follow the normal distribution necessary for a parametric test and could not be log-transformed due to the presence of some zero values in the dataset.

3. Results

Soil microclimate and soil respiration varied more with ambient climatic fluctuations and tree canopy cover than with mowing frequency and grass height. Cumulative precipitation and weekly average air temperatures varied among sample rounds (Fig. 1a and b); air temperature in particular showed a seasonal pattern of higher values at the height of summer and lower values during late spring and early fall. Soil moisture, temperature and respiration generally followed these shifts in ambient climate (Fig. 1c and d, and f), and significantly differed with sampling round (Table 1). Grass height also followed a similar pattern, though it did not vary as much between rounds (Fig. 1e). The effects of mowing frequency on soil microclimate and soil respiration were less clear. Although mowing treatment altered mean grass height (1-week: 11.2 cm, 2-weeks: 12.5 cm, 3-weeks: 15.1 cm; SI Table 1), creating a higher grass canopy in the 2- and 3-week treatments as compared to the 1-week yards (P < 0.0001), it did not consistently change soil moisture, temperature and respiration (Fig. 1, Table 1). Instead, significant differences in soil microclimate and respiration were mediated by interactions with sample round (i.e., timing of sampling events per season) that were not consistent over time. For example, soil respiration in yards mowed every three weeks was significantly lower than yards mowed every week during sampling round five (Fig. 1f), but not at any other point in the study.

While soil respiration did not change with mowing treatment, it did vary as a function of soil temperature (Fig. 2a) and grass height (Fig. 2b). Both of these predictors were significant in our multiple regression model, collectively explaining 13% of the variation in soil respiration rates (Fig. 2c, Table 2). Removing each of these effects in turn and comparing the AIC of full to reduced models indicated that soil temperature was the most significant predictor of soil respiration, followed by grass height (Table 2). However, grass height itself did not account for much of the variation in soil temperature or any of the variation in soil moisture in our study yards (Fig. 3a, d). Our final multiple regression model of soil temperature included both grass height and weekly average air temperature as significant predictors, but AIC analysis showed that weekly air temperatures contributed substantially more to overall model fit than grass height (Fig. 3d, e, Table 2). Our final soil moisture model did not even include grass height (Fig. 3f, Table 2).

Total seasonal soil CO2 fluxes (i.e., biogenic emissions) did not vary

Table 1

Model-level P-values for the effects of mowing treatment, sampling round, and their interaction on grass height, soil moisture, soil temperature, and soil respiration.

	Grass height (cm)	Soil moisture (%)	Soil temperature (°C)	Soil respiration (mg CO ₂ -C m $^{-2}$)
Treatment	< 0.0001	0.134	0.0003	0.356
Sampling round	0.139	< 0.0001	< 0.0001	< 0.0001
Treatment × round	0.002	< 0.0001	< 0.0001	< 0.0001



Fig. 2. Regression plots of observed CO₂ flux and soil temperature (a), grass height (b) and the predicted CO₂ flux (c).

Table 2

Multiple linear regression model results for repeated measures of soil respiration (F_{soil}), moisture (θ), temperature (T_{soil}), seasonal average soil temperature ($T_{soil-avg}$) and total seasonal soil CO₂ flux ($F_{soil-total}$). β indicates model intercept; T_{air} represents weekly average air temperature. AIC values for individual model terms were determined by removing that term from the model. Large increases in AIC indicate that the term removed made a large contribution to the model fit.

Response	Predictor(s)	Estimate	SE	t-value	P-value	r ²	AIC
F _{soil}	β + grass	_	_	_	< 0.0001	0.13	1248
	$ht + T_{soil}$						
	β	-206.40	70.79	-2.92	0.004	—	—
	grass ht	15.36	3.15	4.88	0.000	_	1255
	T _{soil}	4.49	1.54	2.92	0.004	_	1268
θ	β + Total	_	—	—	< 0.0001	0.34	731
	precip						
	β	18.74	1.13	16.66	0.000	_	_
	Total precip	1.45	0.45	3.23	0.002	_	_
T_{soil}	β + grass	_	_	_	< 0.0001	0.62	386
	ht + T_{air}						
	β	5.48	1.91	2.87	0.005	_	—
	grass ht	0.12	0.03	3.56	0.001	—	398
	T_{air}	0.73	0.09	8.54	0.000	_	424
T _{soil-avg}	β + canopy	_	_	_	0.008	0.25	46
	cover						
	β	23.15	0.16	140.84	0.000	_	_
	canopy cover	-0.02	0.01	-2.92	0.008	—	_
F _{soil-total}	β + canopy	_	—	_	0.041	0.14	251
	cover						
	β	495.10	21.25	23.30	0.000	_	_
	canopy cover	-1.76	0.81	-2.17	0.041	_	_

among treatments (P = 0.44; Fig. 5a) and showed average values of 482, 436, and 458 g CO₂-C m⁻² season⁻¹ for the one-, two- and threeweek treatments, respectively (SI Table 1). By contrast, the C emissions resulting from the mower itself (i.e., the anthropogenic emissions) significantly differed among mowing frequencies (P < 0.0001; Fig. 5b). These values were an order of magnitude lower than biogenic emissions, averaging 17, 11, and 7 g CE m⁻² season⁻¹ for the one-, two- and three-week treatments, respectively (SI Table 1).

Similar to ambient climate fluctuations, yard characteristics affected average soil microclimate and total seasonal soil CO_2 flux more than mowing frequency. Both average soil temperature and total seasonal soil respiration exhibited significantly negative relationships with tree canopy cover such that a more extensive tree cover resulted in lower seasonal average soil temperatures (P = 0.008; Fig. 4a, Table 2) and total seasonal soil CO₂ fluxes (P = 0.04; Fig. 4b, Table 2). Tree cover was neither significantly related to average soil moisture (P = 0.32) nor to grass height (P = 0.12).

Although tree cover was a significant predictor of soil CO₂ flux, it did not differ among mowing frequencies (P = 0.78). Other yard-level

characteristics that we quantified, such as lawn size, also did not vary among mowing treatments (P = 0.27). Likewise, cumulative biomass production was similar among one-, two- and three-week yards (P = 0.08; SI Fig. 1). Percent coverage of the six grass species we documented as growing in the lawns also did not differ among mowing regimes (SI Table 2).

4. Discussion

Our study indicates that biogenic soil CO_2 emissions in lawns were not influenced by lawn management behaviors, as indicated by grass height (i.e., less frequent mowing resulted in taller grass). However, we did detect strong differences among the three mowing frequencies for HCCs, suggesting that these anthropogenic influences be included when calculating C budgets.

We found soil microclimate and soil respiration varied more with ambient climatic fluctuations and yard characteristics (e.g., canopy cover) than with mowing frequency. Although we detected a treatment effect on grass height (mowing less frequently resulted in taller grass), and grass height contributed to the overall fit of the mixed effects model (Table 1), the taller grass did not result in moister or cooler soils, nor did it have a direct effect on soil CO_2 flux (Fig. 2b). Instead, soil conditions were largely influenced by regional precipitation patterns (influencing soil moisture) and regional ambient air temperature (which affected soil temperature), and these soil microclimatic variables in turn drove soil CO_2 fluxes. Differences in canopy cover also played a significant role in driving total seasonal CO_2 fluxes; increased canopy cover was related to lower soil temperatures and respiration rates (Fig. 4).

Our hypotheses that mowing frequency would alter soil microclimate were based on the concept that taller turf canopies drive cooler temperatures and reduced surface evaporation (Allaire et al., 2008; Brito et al., 2015; Byrne et al., 2008; Lilly et al., 2015; Liu & Huang, 2003; Song et al., 2015). We observed instances when the disparity in grass height was as much as 20 cm between lawns mowed every week versus every three weeks, largely at the start and end of the mowing season. However, the average difference between mowing treatments was 2.5 cm, which may not have been sufficient to drive changes in soil microclimate. Prior studies that detected a difference in soil microclimate between mowing treatments have either imposed unrealistically long treatment intervals (one to three times per growing season, Allaire et al., 2008) or have occurred in warmer, drier climates (Liu & Huang, 2003) where small changes in grass canopy height may have larger effects on soil temperature than in humid, temperate regions such as where our study took place. The fact that clippings remained in all treatment plots may also explain the lack of response in both soil temperature and moisture as clippings can act as a green mulch that insulate soils from ambient climatic fluctuations (Luo et al.,



Fig. 3. Regression plots of observed soil moisture (%) and grass height (a), precipitation (b) and predicted soil moisture (c); and observed soil temperature and grass height (d), air temperature (e) and predicted soil temperature (f).



Fig. 4. Relationship between canopy cover and average soil temperature (a) and $\rm CO_2$ flux (b) for all treatments.

2001; Ng et al., 2015). Since we did not measure soil physiochemical variables such as texture and organic matter, we cannot rule out the ways in which they might have interacted with mowing regime and grass height to influence soil microclimate and biogenic CO_2 soil emissions. Future investigation into these types of interactions could generate important insights into biogenic C cycling in lawn systems (Selhorst & Lal, 2013).

We found that tree canopy cover exerts a stronger influence on soil temperature and CO₂ flux than grass height (Table 2, Fig. 4). Our findings concur with a city-wide study on the effects of urban vegetation on soil temperatures, whereby trees and shrubs better reduced soil temperatures compared with herbaceous vegetation such as lawns, particularly in urban green spaces not located in private yards (Edmonson, Stott, Davies, Gaston, & Leake, 2016). These results also fit with Huyler et al. (2014), who reported that SOC increased linearly with aboveground tree biomass but not as a function of yard maintenance activities such as clippings management, fertilization, or irrigation. Thus we suggest that planting trees and maintaining existing tree canopies may have further reaching effects on the C cycle in residential landscapes compared with reducing lawn mowing frequency. Tree preservation and planting programs are already popular means of promoting C sequestration in cities (e.g., the Million Trees New York City initiative; www.milliontreesnyc.org). Further, considering the origin of the trees has additional implications for C storage and should be selected carefully since the amount of C sequestered by native and non-invasive species can be as much as nine times higher compared with invasive and exotic species (Horn et al., 2015). The climate mitigation potential of trees may have other C benefits beyond sequestration in biomass. In addition to cooling soils, tree canopies cool buildings, leading to reduced energy consumption and GHG emissions, particularly in summer (Akbari, Pomerantz, & Taha, 2001; Pataki et al., 2011).



Fig. 5. Treatment effects of lawn mowing frequency on CO_2 flux for biogenic soil emissions (a) and anthropogenic mower emissions (b).

Similar to the HCCs associated with maintaining lawns, tree and shrub maintenance activities also have HCCs (McPherson & Kendall, 2014; Strohbach et al., 2012). In an assessment of the net C contribution of urban vegetation in Orlando, Florida, USA, Horn et al. (2015) integrated field measurements with a household survey that included information about various vard maintenance activities, including frequency and use of lawn mowers, leaf blowers, edge and hedge trimmers, chainsaws and irrigation. Although all emitted CO₂, the vegetation maintenance activities associated with the lawn (i.e., lawn mowing irrigation) emitted the majority of CO₂, averaging and $14 \, \text{g} \, \text{CE} \, \text{m}^{-2} \, \text{season}^{-1}$, while shrub and tree maintenance activities emitted 0.3 and $0.2 \text{ g CE m}^{-2} \text{ season}^{-1}$, respectively (Horn et al., 2015). We did not include the HCCs associated with tree and shrub maintenance since we were primarily concerned with lawn maintenance, though we recognize that pruning and trimming tree limbs could contribute to the shading and microclimatic conditions within our study lawns in addition to the HCCs associated with lawn mowing. However, during the course of the two-year study, we did not observe any tree or shrub maintenance activities nor did any of the study yards irrigate their lawns as part of the conditions for participation, and hence, the anthropogenic calculations represent the preponderance of HCCs for our study system.

The importance of biogenic CO₂ emissions relative to anthropogenic sources was evident in the relative magnitude of seasonal soil CO₂ flux totals versus CO₂ emissions from mowing. Although lawn mowing frequency did not influence the amount of CO₂ released from soils, the amount of CO₂ emissions from the lawn mower did increase with more frequent mowing, highlighting an important HCC. Our weekly mowing HCC results were comparable to other studies calculating the HCCs associated with lawn mowing (e.g., Horn et al., 2015; Zirkle et al., 2011) yet differed from other studies (e.g., Gu et al., 2015), perhaps due to different methods and calculations. Studies assessing the HCCs have recommended reducing mowing frequency as a possible solution to help reduce anthropogenic emissions (Selhorst & Lal, 2013; Strohbach et al., 2012). Indeed, we found that mowing every two weeks rather than every week decreased the HCCs from $17 \text{ g CE m}^{-2} \text{ season}^{-1}$ to 11 g CE m⁻² season⁻¹. Mowing every three weeks decreased the HCCs a further 7 g CE m^{-2} season⁻¹. The simple solution to mow less frequently might have broader applications and adaptation for mitigation (Hutyra et al., 2014; Kennedy et al., 2010; Pataki, Bowling, & Ehleringer, 2003). However, the effect of reducing the HCCs via mowing every two or every three-weeks might be trivial compared to the biogenic soil CO₂ flux (Fig. 5). Total seasonal CO₂ fluxes from lawns were, on average, ~40 times greater than mower emissions (mean overall total seasonal soil CO₂ flux: 458 g CO₂-C m⁻² y⁻¹, mean mower flux 11 g CE m⁻² y⁻¹; SI Table 1).

Although we failed to find significant changes in soil CO₂ fluxes with mowing frequency, we do not necessarily support the common practice of mowing once per week since a less intensive mowing regime could impact lawn C storage, and other ecosystem services, in a variety of ways. Grass and turf physiological research indicates that taller grass (i.e., less frequent mowing) leads to greater shoot lengths, increased root growth and thus greater belowground C inputs (Liu & Huang, 2003; Salaize, Horst, & Shearman, 1995). While we did not detect changes in cumulative aboveground grass biomass production (SI Fig. S1), we do not know whether belowground C allocation varied in response to mowing frequency. In addition, our two-year study was likely not long enough to detect any potential changes in soil C, particularly since changes in SOM stocks typically require ~10 years to perceive (Saby et al., 2008). In addition to shifting above- and below-ground C allocation, frequent mowing may also affect soil C storage in lawns by altering soil bulk density, even beyond the soil compaction that often occurs at lawn establishment (Campbell, Seiler, Wiseman, Strahm, & Munsell, 2014; Gregory, Dukes, Jones, & Miller, 2006). As with agricultural equipment, we propose that repeated mowing could increase bulk density, primarily from the weight of the mower and the mower operator (Gregory et al., 2006), and suggest that future research more explicitly consider changes in soil bulk density that arise from lawn management. Beyond these carbon-focused considerations, mowing frequency can influence other ecosystem attributes, such as spontaneous floral resources that support native pollinators (Lerman et al., 2018).

Climate action plans developed at local (i.e., municipal) scales can address the unique pressures and circumstances for particular regions and climates (Rosenzweig et al., 2010; Schreurs, 2008; Wang, 2012). However, these plans often assume that urban emissions are driven primarily by anthropogenic fossil fuel consumption (e.g., Greenovate Boston 2014 Climate Action Plan Update www.cityofboston.gov). Here we show that for lawn-dominated systems, biogenic CO₂ fluxes far exceed anthropogenic fluxes and require consideration for accurate reporting of urban GHG emissions (Davies, Edmondson, Heinemeyer, Leake, & Gaston, 2011; Decina et al., 2016). This interplay among biogenic (e.g., increasing tree canopy) and anthropogenic (i.e., mowing less frequently) methods of reducing CO2 emissions in cities highlights the need for a more rigorous accounting process in order for cities to meet climate action plan targets (Decina et al., 2016; Dodman, 2009; Hutyra et al., 2012; Kennedy et al., 2010; McRae & Graedel, 1979; National Research Council, 2010).

5. Conclusion

Quantifying the balance between the amount of lawn necessary for satisfying societal needs and how many trees are required to counteract the biogenic soil CO_2 emissions of lawns will be a key contribution to informing policies and landscape management recommendations. Integrating social surveys to better understand specific behaviors associated with managing yards and the types of landscapes that households desire may also be critical for shaping management decisions that affect biogenic and anthropogenic C fluxes from lawns. When challenging the traditional American lawn (e.g., weed-free, expansive, lush and neatly trimmed), we suggest that recommendations consider the aesthetics and ease of maintenance, in addition to the HCCs, since these factors, in addition to adhering to neighborhood norms largely drive landscaping decisions. Increasing tree canopy cover in lawn-dominated yards together with replacing some lawn with other vegetation that requires less intensive maintenance (e.g., planting native shrubs) might be a powerful means of reducing urban CO_2 emissions through the biogenic C sink that trees and other vegetation provide, demonstrating the potential of transforming lawns from C sources to sinks.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2018.10.016.

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