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Soil respiration contributes substantially to urban carbon fluxes in the greater Boston area☆

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ABSTRACT

Urban areas are the dominant source of U.S. fossil fuel carbon dioxide ($FFCO_2$) emissions. In the absence of binding international treaties or decisive U.S. federal policy for greenhouse gas regulation, cities have also become leaders in greenhouse gas reduction efforts through climate action plans. These plans focus on anthropogenic carbon flows only, however, ignoring a potentially substantial contribution to atmospheric carbon dioxide (CO2) concentrations from biological respiration. Our aim was to measure the contribution of CO_2 efflux from soil respiration to atmospheric CO_2 fluxes using an automated CO_2 efflux system and to use these measurements to model urban soil CO_2 efflux across an urban area. We find that growing season soil respiration is dramatically enhanced in urban areas and represents levels of CO_2 efflux of up to 72% of $FFCO_2$ within greater Boston's residential areas, and that soils in urban forests, lawns, and landscaped cover types emit 2.62 ± 0.15, 4.49 ± 0.14, and 6.73 ± 0.26 $\mu molCO_2\ m^{-2}\ s^{-1}$, respectively, during the growing season. These rates represent up to 2.2 times greater soil respiration than rates found in nearby rural ecosystems in central Massachusetts (MA), a potential consequence of imported carbon amendments, such as mulch, within a general regime of landowner management. As the scientific community moves rapidly towards monitoring, reporting, and verification of CO_2 emissions using ground based approaches and remotely-sensed observations to measure CO_2 concentrations, our results show that measurement and modeling of biogenic urban CO_2 fluxes will be a critical component for verification of urban climate action plans.

1. Introduction

The global urban population is forecast to grow by 2.5 billion people by the year 2050, with seven of every ten people projected to reside in an urban area by mid-century (United Nations, 2014). The spatial extent of urban areas is also projected to triple, increasing by over 1 million km^2 between 2000 and 2030 (Seto et al., 2012). Though fossil fuel carbon dioxide ($FFCO_2$) emissions from cities produce the preponderance of global $FFCO_2$ emissions (Energy Information Administration, 2013), a growing urban population also has the potential to engender per-capita emissions reductions, as cities, particularly in the United States, form the vanguard of the civic response to climate change through local climate action plans (Rosenzweig et al., 2010; Wang, 2012). For climate action plans to be effective, they must be evaluated rigorously and regularly, which requires accurate reporting of greenhouse gas fluxes (e.g. the 2010 CalNex campaign; Ryerson et al., 2013), combined with monitoring and verification of atmospheric carbon dioxide (CO_2) concentrations from ground based measurements and satellite remote sensing (Duren and Miller, 2012; McKain et al., 2012; Rella et al., 2015). However, both of these approaches currently ignore the biogenic contribution to urban atmospheric CO_2 concentrations; bottom-up emissions data treat the urban carbon cycle as entirely driven by fossil fuel emissions (Kennedy et al., 2010; Hutyra et al., 2014) and measurements of column-averaged atmospheric CO_2 concentrations, such as those made by NASA's Orbiting Carbon Observatory (OCO-2) satellite (Boesch et al., 2011), are made without specific attribution between anthropogenic and biogenic sources.

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As early as 1979, researchers suggested that separating anthropogenic and biogenic CO_2 fluxes would be critical for the understanding of urban carbon cycling (McRae and Graedel, 1979). Photosynthesis has been shown to periodically reduce urban atmospheric CO_2 concentrations in diverse locations (McRae and Graedel, 1979; Day et al., 2002; Clark-Thorne and Yapp, 2003; Moriwaki and Kanda, 2004; Coutts et al., 2007; Kordowski and Kuttler, 2010; Pawlak et al., 2011), while ecosystem respiration is known to produce measureable amounts of CO_2 in urban areas (Pataki et al., 2003; Zimnoch et al., 2010; Górka and Lewicka-Szczebak, 2013). Using radioactive isotope tracers, Miller et al. (2012) detected the constant presence of biogenic CO_2 in the lower troposphere near cities and suggested that CO_2 attribution to anthropogenic sources requires measurement and exclusion of biological sources. Despite the evidence that biogenic urban CO_2 fluxes can be important, we still know little about the magnitude of the urban biogenic CO_2 flux relative to $FFCO_2$ emissions on a landscape scale. Rates of CO_2 efflux from soil respiration, a critical component of the biogenic CO_2 flux, have only been measured in a handful of urban studies in mesic systems, and the majority of these studies were either spatially or temporally limited (Kaye et al., 2005; Groffman et al., 2006; Vesala et al., 2008; Groffman et al., 2009; Chen et al., 2014; Chun et al., 2014; Smorkalov and Vorobeichik, 2015; Ng et al., 2015) precluding extrapolation and hindering comparisons with $FFCO_2$ emissions. As total CO_2 efflux from soil respiration dwarfs anthropogenic CO_2 emissions worldwide, urban soil respiration merits a closer look.

The objectives of this study were to quantify rates of growing season CO_2 efflux from soil respiration at high temporal and spatial resolution across the greater Boston, Massachusetts (MA) area and to use these rates to create a spatially explicit model of soil CO_2 efflux along an urbanization gradient. We expected to find higher rates of soil respiration in areas with more intensive landowner management, such as residential areas with pervious surfaces like lawns and flowerbeds. To address our objectives and test our hypothesis, we took direct field measurements of soil respiration using an automated soil CO_2 efflux system and used geographic information systems (GIS) and data from a landowner survey to model these fluxes along a transect originating in downtown Boston and extending 25 km west into suburban Concord, MA.

2. Methods

2.1. Site selection and measurements

The greater Boston area is the 10th largest metropolitan area in the United States (US Census Bureau, 2013) and has a temperate climate, with mean summer and winter temperatures of 21.7 °C and −0.1 °C, respectively, and approximately 110 cm of precipitation per year (National Climatic Data Center). To characterize variations in soil CO_2 efflux across this area, we sampled at 15 sites (Fig. 1) and within three potential cover types at each site: forest, lawn, and landscaped. Sites were chosen with varying amounts of surrounding development (Supplementary Fig. 1). All sites had hardwood tree canopies, no pets, and were in secured locations.

In early May 2014, 20.2 cm-diameter PVC collars were mounted into the soil at each site. After installation, collars were left to equilibrate in the soil for 2–3 weeks to avoid the pulse of CO_2 efflux associated with severed roots caused by installation. Sites that included lawn (n = 13), defined as an area whose dominant vegetation was grass at some point during the growing season, received four sample collars, with two collars in the lawn and two collars in

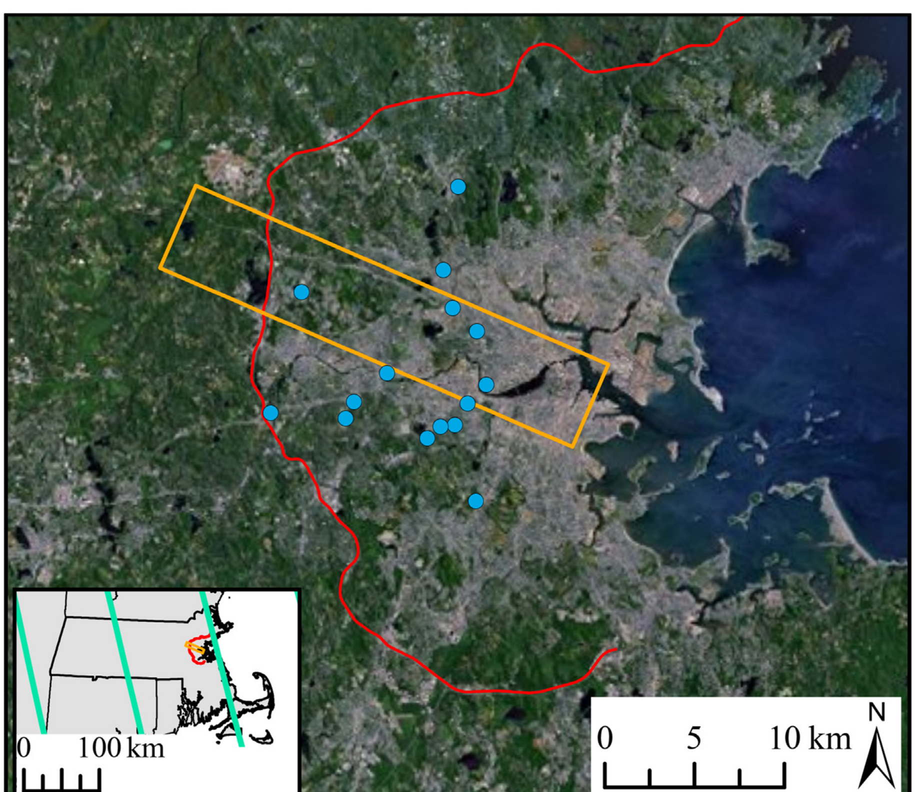

Fig. 1. Study area. Blue points represent soil respiration measurement sites. Orange box outlines 25 km transect from downtown urban Boston to suburban Concord, MA (Fig. 3). Interstate Highway 95 (I-95) is highlighted in red. In the inset, current OCO-2 summer nadir tracks are shown in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the other dominant cover type at the site, either forest or landscaped. Sites without lawn (n = 2) received two collars in the one dominant cover type at the site, either forest or landscaped. Forest cover type was defined as an unmanaged area at least 100 m in diameter whose dominant vegetation was trees. Landscaped cover type was defined as areas not covered by grass at any point during the growing season and generally contained shrubs, flowers, and trees that were confined to a small area of the property. Landscaped cover type had variable management regimes across sites, though all received some intervention from homeowners. The total number of soil respiration collars installed across all three cover types for this study was n = 56.

Soil CO_2 efflux was measured every two weeks from 27 May 2014 to 5 November 2014 using an automated CO_2 soil efflux system with a 20 cm diameter survey chamber (LiCor-8100A infrared gas analyzer, LiCor Inc., Lincoln, NE). Soil CO_2 efflux was calculated for each measurement as given in Davidson et al. (1998). At the time of measurement, volumetric water content (#88311E, Omega Engineering Inc., Stamford, CT) was recorded at a depth of 10 cm. LiCor chamber air temperature was also recorded for each observation.

Measurements of air temperature, soil moisture, soil organic matter (OM) concentration, soil carbon to nitrogen (C:N) ratio, soil pH, soil bulk density, litter depth, and litter mass were collected in each cover type at each site. Soil samples beneath the litter layer (0–10 cm depth) were collected once during the growing season using a slide hammer and 10 cm PVC liner placed inside the soil corer. Three replicate soil cores adjacent to the respiration collars were collected for each cover type at each site. Soils were sieved through a 2 mm sieve and homogenized, a subsample was removed, and the subsample oven-dried at 60 °C for one week to obtain percent soil moisture for each sample. Soil pH was determined by hydrating 5 g of soil with 10 mL of DDI H_2O, shaking for 30 min on a shaker table, and then pH measured with a pH meter. For soil organic matter, 10 g subsamples were oven-dried at 60 °C for one week, reweighed, and then placed inside a muffle furnace at 400 °C for 4 h and reweighed again. Soil C:N ratio was measured by grinding oven-dried soils into a fine powder and combusting in a C:N analyzer (NC2500 Elemental Analyzer, CE Elantech, Lakewood, NJ). Bulk density was calculated dividing mass of an oven-dried soil by its volume (excluding the mass and volume of rocks in the sample). In June and November 2014, soil litter depth was measured at four points next to each PVC collar and averaged. In August 2014, leaf litter within a 900 cm^2 square adjacent to the collar was collected, dried for two weeks, and weighed. Summary data are listed in Table 1. Model formulations using these data are listed in Table 2.

2.2. Survey data

The Community and Conservation Survey of Massachusetts (CCS) was used to generate estimates of cover type fractions for residential properties, as well as to determine homeowner usage of soil amendments (e.g. fertilizer and mulch). The CCS is a large multipart survey instrument that was distributed to private landowners in 33 towns in eastern and central MA as part of a complementary study as well as to the 14 homeowners in this study (n = 428). The survey instrument included questions regarding property characteristics, use, management, and demographics. The survey questionnaire was developed and pre-tested through a series of six focus groups that included urban, suburban, and rural landowners. The towns included in this study fall along two transects originating in the City of Boston and extending ~100 km westward. Development patterns, land uses, vegetation, and community characteristics vary along the study transects.

Survey recipients were selected using a stratified random sampling. The sample was drawn from assessor tax records containing information on the location, size, and use of parcels as well as landowner names and mailing addresses. The survey was mailed to 1758 landowners in spring 2013, following a modified Tailored Design Method (Dillman, 2007). The survey included questions about property characteristics and demographics. Homeowners were asked to indicate the size of their property and to estimate the fraction of their property with different surface types (e.g., buildings, driveway, lawn that is mowed, other yard not mowed, woodlands), as well as to describe land management practices. Of the mailed surveys, 114 were undeliverable or disqualified because the respondent was deceased or no longer owned land in MA. A total of 414 surveys were returned and usable, giving an effective response rate of 25.2%. While the response rate varied significantly between the 33 towns included in the study, we found no significant differences in response rate of urban, suburban, and rural areas. Upon return, the landowner surveys were geocoded using the Massachusetts Land Parcel Database, v. 1.0 (Metropolitan Area Planning Council, 2013). To determine the amount of each land cover type in residential parcels, the landowner parcels were compared to the Massachusetts Office of Geographic Information (MassGIS) land use layer (MassGIS, 2009); only parcels that were completely within the exclusively residential land use classes (n = 61) were included in this study. The mean land cover type fractions (lawn, landscaped, forest) were calculated and used to estimate residential soil respiration efflux.

2.3. Scaling soil CO_2 efflux

To extrapolate rates of soil respiration across the 25 km transect,

Table 2
Multivariate model formulations.

Parameters	Coefficient	*p*-value
Intercept	−8.440	0.020
Cover type	3.813	0.041
Management	0.952	0.366
Litter depth	0.269	0.042
Soil C:N	0.521	0.001

Table 1
Litter and soil characteristics, along with soil respiration (R_s) CO_2 efflux, by cover type.

Cover type	Sites (*n*)	Obs. (*n*)	Litter[a]			Soil				
			Depth (cm)		Mass (g)	OM(%)	pH	C:N	Bulk ρ(g cm^{-3})	Seasonal mean R_s (μmolCO_2 m^{-2} s^{-1} ± SE)
			Jun	Nov						
Forest	3	83	0.92	5.09	76.72	14	5.13	18.53	0.61	2.62 ± 0.15
Lawn	13	292	0.63	3.88	1.64	8	6.28	16.06	0.88	4.49 ± 0.14
Landscaped	12	309	3.00	5.86	63.67	15	5.88	18.68	0.64	6.73 ± 0.26

[a] Leaf litter within a 900 cm^2 square adjacent to the collar.

modeled rates were estimated based on a combination of soil respiration observations from this study for urban areas, literature soil respiration values for non-urban land covers (Raich and Schlesinger, 1992; Raich and Tufekcioglu, 2000), and high-resolution GIS land use and impervious surface areas (ISA) layers from MassGIS (MassGIS, 2009). All areas covered with impervious surfaces (roads, buildings, driveways, etc.), based on a 1 m-resolution GIS map, were assumed to have no soil CO_2 efflux. All pervious (permeable) surfaces were assigned a soil respiration value based on land use (Table 3). Efflux values for nonzero, non-residential land use descriptions (Table 3) were primarily (78%) derived from measured fluxes from this study; the remainder were derived from published values (Raich and Schlesinger, 1992; Raich and Tufekcioglu, 2000). The lawn, forest, and landscape fractional area within residential land covers was estimated based the CCS. The survey showed that the pervious area of exclusively residential parcels ($n = 61$) was 53% lawn, 42% landscaped, 4% forested, and 1% open field. The pervious portions of residential areas were all assumed to have the above composition with a mean growing season soil efflux of 5.33 $\mu molCO_2\ m^{-2}\ s^{-1}$, primarily (98%) derived from measured fluxes from this study; the remainder was derived from published values (Raich and Tufekcioglu, 2000).

2.4. Fossil fuel carbon dioxide emissions

$FFCO_2$ emission estimates were based on a newly developed, high-resolution regional inventory of $FFCO_2$ emissions that assimilates multiple data sources at a 1 km gridded resolution and hourly time-steps for circa 2011. Data from the United States Environmental Protection Agency (EPA; EPA, 2014a) National Emissions Inventory and the EPA Greenhouse Gas Reporting Program (EPA, 2014b) was used to calculate $FFCO_2$ emissions for the following sectors: residential, commercial, industrial, railroads, marine vessels, non-road vehicles, airport taxiing, takeoff and landing operations, and electric power generation. On-road emissions were obtained from the Database of Road Transportation Emissions (DARTE; Gately et al., 2015). Full details of $FFCO_2$ emissions calculations are reported in the Supplementary Information.

2.5. Error

All error values in the text, as well as in Figs. 2 and 4 and Tables 1 and 3 are reported as standard error (SE), unless otherwise noted. We were not able to show error bars or bands directly on Fig. 3E due to the difficulty of representing visually accurate error on the logarithmic scale of the y-axis; consequently, error for Fig. 3E is represented in Supplementary Fig. 2 as weighted standard deviation for the spatial error in soil respiration and $FFCO_2$ emissions on a linear scale for the y-axis.

3. Results & discussion

Rates of soil respiration differed significantly (one-way ANOVA, $F = 4.69$, $p = 0.019$) between urban forest, lawn, and landscaped cover types, with growing season mean soil CO_2 efflux rates of 2.62 ± 0.15, 4.49 ± 0.14, and 6.73 ± 0.26 $\mu molCO_2\ m^{-2}\ s^{-1}$, respectively (Fig. 2, Table 1). Growing season soil respiration rates in urban forest soils were similar to soil respiration rates in a nearby rural forest (3.08 ± 0.07 $\mu molCO_2\ m^2\ s^{-1}$; Giasson et al., 2013); lawn and landscaped soil respiration rates were 1.5 and 2.2 times higher,

Table 3
Scaling soil respiration (R_s) CO_2 efflux by land cover. The MassGIS land use layer (MassGIS, 2009) is a high-resolution polygon map based on assessor records and orthographic photos that classifies the State's land use in 33 distinct descriptions. The table below summarizes the modeled soil CO_2 efflux values, seasonal patterns, overall abundance (% area), and fraction paved (ISA) within each land use description across the 25 km transect. The Reference column provides the source of the efflux value used, which came either from measurements made in this study, from values found in the literature, or from a combination of the two.

Land cover	Land use description	Reference	Seasonal R_s efflux ($\mu molCO_2\ m^{-2}\ s^{-1}$)	Seasonal Variation	Area (%)	ISA (% ± SE)
Developed	Commercial	This study (lawn)	4.49	Monthly means	10.49	86.93 ± 0.58
	Urban public/institutional	This study (lawn)	4.49	Monthly means	9.25	70.03 ± 1.00
	Transportation	This study (lawn)	4.49	Monthly means	4.99	85.14 ± 1.82
	Industrial	This study (lawn)	4.49	Monthly means	4.27	87.18 ± 1.02
	Participation recreation	This study (lawn)	4.49	Monthly means	2.78	46.30 ± 2.14
	Cemetery	This study (lawn)	4.49	Monthly means	1.12	19.66 ± 1.82
	Golf course	This study (lawn)	4.49	Monthly means	0.99	13.65 ± 3.10
	Waste disposal	This study (lawn)	4.49	Monthly means	0.16	34.81 ± 13.88
	Transitional	This study (lawn)	4.49	Monthly means	0.16	82.00 ± 5.37
	Spectator recreation	NA	0	Seasonally constant	0.10	48.49 ± 12.82
	Junkyard	NA	0	Seasonally constant	0.06	88.15 ± 9.81
	Powerline/utility	This study (lawn)	4.49	Monthly means	0.05	6.36 ± 1.58
	Water-based recreation	NA	0	Seasonally constant	0.04	50.94 ± 9.96
	Marina	NA	0	Seasonally constant	0.03	87.77 ± 7.58
Residential	Multi-family residential	This study (residential)[a]	5.33	Monthly means	14.34	64.78 ± 0.78
	High density residential	This study (residential)[a]	5.33	Monthly means	11.83	69.46 ± 0.71
	Medium density residential	This study (residential)[a]	5.33	Monthly means	4.40	35.62 ± 1.34
	Low density residential	This study (residential)[a]	5.33	Monthly means	3.88	26.04 ± 0.46
	Very low density residential	This study (residential)[a]	5.33	Monthly means	1.01	24.35 ± 0.70
Forest	Forest	This study (forest)	2.62	Monthly means	23.08	7.86 ± 0.66
	Forested wetland	This study (forest)	2.62	Monthly means	2.94	2.61 ± 0.54
Non-forest	Cropland	Raich and Tufekcioglu 2000	0.96	Seasonally constant	1.86	7.51 ± 2.30
	Non-forested wetland	Raich and Schlesinger 1992	1.09	Seasonally constant	0.89	3.35 ± 1.40
	Pasture	Raich and Tufekcioglu 2000	1.99	Seasonally constant	0.61	7.65 ± 1.30
	Open land	NA	0	Seasonally constant	0.58	25.56 ± 3.66
	Orchard	This study (forest)	2.62	Monthly means	0.05	6.43 ± 2.69
	Nursery	This study (forest)	2.62	Monthly means	0.04	77.48 ± 11.92
	Saltwater sandy beach	NA	0	Seasonally constant	0.01	25.47 ± 4.72
	Brushland/successional	Raich and Tufekcioglu 2000	1.99	Seasonally constant	0.01	25.11 ± 11.34

[a] Residential R_s = lawn fraction x this study (lawn) + forest fraction x this study (forest) + landscaped fraction x this study (landscaped) + open field fraction x 1.99 (Raich and Tufekcioglu, 2000).

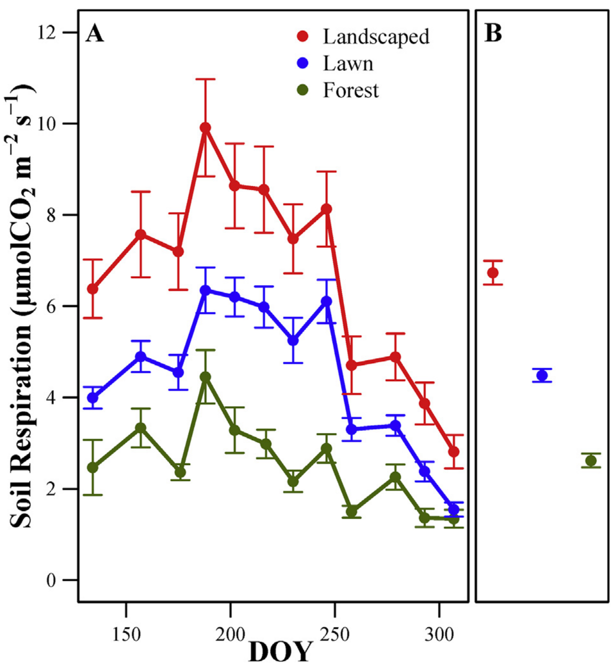

Fig. 2. Measured soil respiration (R_s) CO_2 efflux by land cover type across growing season. A, Values are means with standard error across fifteen sites at each measurement date over the growing season (27 May 2014 through 3 November 2014; DOY = day of year). **B,** Seasonal means and standard error by land cover type.

respectively, than nearby rural forest soil respiration rates. Soil organic matter concentration ($r = 0.59$, $p = 0.0009$), soil C:N ratio ($r = 0.56$, $p = 0.001$) and the depth of the leaf litter layer ($r = 0.57$, $p = 0.001$) were significantly and positively correlated with observed soil respiration rates. Soil pH and bulk density were not significantly correlated with observed soil respiration rates. We estimated a multivariate regression model of soil respiration rates including soil C:N ratio, June litter depth, a binary indicator of management (managed vs. unmanaged), and a cover type fixed effect (forest, lawn, landscaped; $R^2 = 0.79$, $p < 0.002$; Table 2). The significant correlation between soil C:N ratio, litter depth, and soil CO_2 efflux, along with the discrete statistical separation of soil respiration rates by cover type (Fig. 2), suggest that the magnitude of urban soil CO_2 efflux is tied to municipal and individual landowner management decisions. Results from the CCS indicate that 64% of residential landowners fertilize their lawns, 37% add compost or organic fertilizer, and 90% add organic amendments such as mulch around their plants. These types of residential management choices, which import carbon and stimulate primary productivity, may explain the high rates of soil respiration in residential areas relative to rural background levels (Beesley, 2014; Chen et al., 2014).

The elevated rates of soil respiration in lawn and landscaped areas contribute significantly to urban atmospheric CO_2 concentrations on a landscape scale, the scale at which remote sensing products are measuring these concentrations. We used GIS and survey data from the CCS to model our measured growing season soil respiration rates across a 25 km transect originating in downtown Boston (Fig. 3A–D). To evaluate the magnitude of the contribution of soil respiration across the spatially heterogeneous

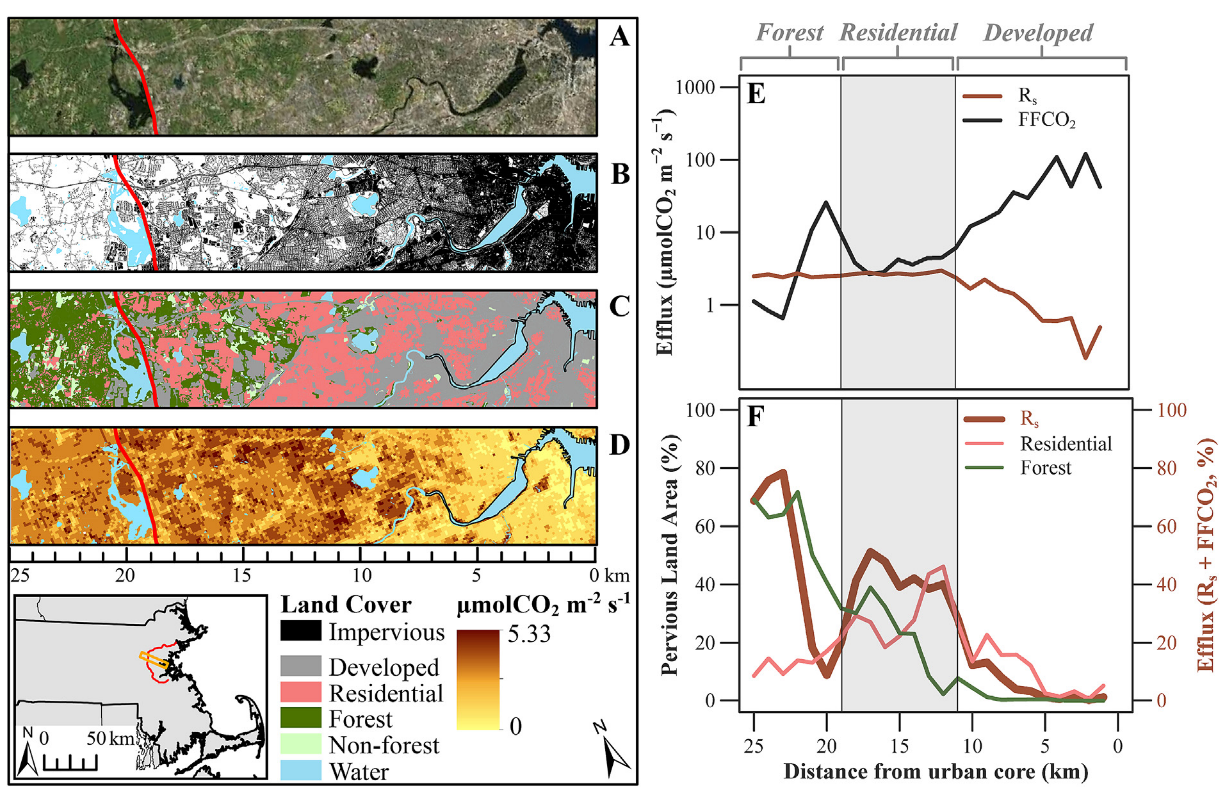

Fig. 3. Gradients in soil respiration (R_s) CO_2 efflux and $FFCO_2$ efflux along 25 km transect. A, Satellite image, **B,** Impervious surface area, **C,** Land cover, and **D,** Modeled growing season soil CO_2 efflux. **E,** Growing season modeled soil CO_2 efflux and $FFCO_2$ emissions along the transect; $FFCO_2$ enhancement at 20 km due to I-95 (red line in panels A–D denotes I-95). Gray band (11–18 km from urban core) denotes a shift from predominately developed to highly pervious residential land covers. Error reported in Supplementary Fig. 2. **F,** Percent pervious forest and residential area compared to growing season soil CO_2 efflux as a percentage of soil CO_2 efflux plus $FFCO_2$ emissions along the transect. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

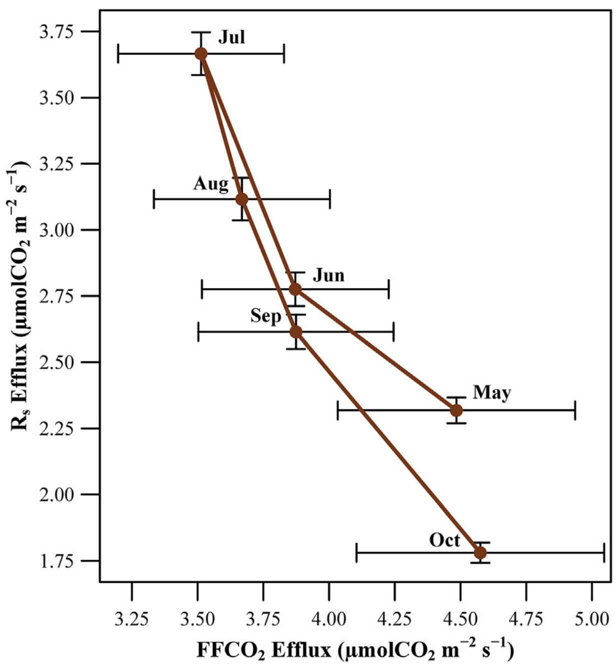

Fig. 4. Monthly hysteresis curve of modeled soil respiration (R_s) CO_2 efflux as compared to modeled $FFCO_2$ efflux along 25 km transect. Monthly integrated mean values with standard error in the residential area from 11 to 18 km along the transect (Fig. 3) are used for both $FFCO_2$ and soil CO_2 efflux.

land uses of the greater Boston area, we compared the modeled soil CO_2 efflux to $FFCO_2$ emissions from a new high-resolution $FFCO_2$ dataset (Gately et al., 2015) (Fig. 3E and F). Though soil CO_2 efflux within the 25 km transect is only about 1% of $FFCO_2$ emissions in the highly developed urban core of Boston (Fig. 3E), within the densely populated residential area of the transect 11–18 km from the urban core of Boston, mean rates of growing season CO_2 efflux from soil respiration average 72 ± 7% of $FFCO_2$ emissions (Fig. 3E and F). As pervious area (i.e. lawns, gardens, and flower beds) increases from the urban core of Boston out to suburban residential areas and passes a threshold of ~20% of total area, the magnitude of soil CO_2 efflux increases up to fourfold (i.e. soil CO_2 efflux/(soil CO_2 efflux + $FFCO_2$); Fig. 3F), approaching and surpassing efflux from $FFCO_2$ emissions in some locations within the transect (note that these $FFCO_2$ estimates represent direct, local emissions within the transect only; there are additional emissions outside of the transect associated with power generation for locations within transect that were not considered in this analysis). Considering the large spatial extent of residential soils that typically surround cities, these results underscore the strong linkages between development patterns and intensity, management decisions, and urban efflux of CO_2 from soil respiration.

In addition to spatial variation in CO_2 efflux from soil respiration, the contribution of soil CO_2 efflux to total urban CO_2 efflux varies temporally within the growing season. Rates of soil CO_2 efflux within the 25 km transect peak in the warm, wet early summer, while $FFCO_2$ emissions are lowest during this time due to the absence of heating-related emissions (Fig. 4). This temporal mismatch in maxima of soil CO_2 efflux and $FFCO_2$ emissions leads to variability in the fraction of efflux from soil respiration relative to $FFCO_2$ emissions observed from the months of May to October in the residential belt of the transect 11–18 km from the city center (Fig. 4). The distinct temporal variability in the biogenic fraction of urban CO_2 emissions has the potential to further confound efforts to both reduce and accurately measure reductions in $FFCO_2$ emissions, emphasizing the importance of accounting for urban biogenic carbon flows at not only a high spatial resolution, but at high temporal resolution as well.

4. Conclusion

We show that soil respiration contributes significantly to urban and suburban surface CO_2 fluxes and that urban soil respiration displays variable spatial and temporal patterns. Management decisions, such as soil amendments and irrigation, may create conditions which lead to soil CO_2 efflux in some urban areas that is more than twice as high as that in rural forests. With Boston's 26% canopy cover (Raciti et al., 2014), carbon uptake via photosynthesis is likely to offset some of this soil CO_2 efflux at the landscape scale; however, this large soil CO_2 efflux in residential areas of the greater Boston area may ultimately induce a net biotic source of CO_2 to the atmosphere at the local scale due to management decisions and the relatively low canopy cover in these areas. The magnitude of urban soil CO_2 efflux on a landscape scale, along with the spatial and temporal variation, should be taken into account when assessing urban carbon budgets, particularly for cities like Boston with a high percentage of landscaped, pervious area in residential areas close to the city center. As satellite measurements of column CO_2 concentrations are providing data at high temporal and spatial resolution (Boesch et al., 2011), quantification of the biogenic component of the urban CO_2 budget is crucial for proper interpretation of these remotely sensed data for monitoring and verification of urban climate action plans. These results underscore the need for a more spatially and temporally detailed accounting of urban biological carbon flows, support recent work describing the effects of management decisions on fluxes of carbon and nitrogen (Briber et al., 2013; Polsky et al., 2014; Templer et al., 2015) and further highlight the need to tie management of residential urban areas to biogeochemical fluxes.

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S.M.D., L.R.H and P.H.T. conceived and designed the research; S.M.D. performed the research, L.R.H and S.M.D. coded and analyzed the data, A.G.S and J.M.G. implemented and analyzed the CCS survey, C.K.G. and L.R.H. built the fossil fuel emissions inventories, J.M.G. performed the GIS analysis; all authors contributed to the writing of the manuscript.

Appendix A. Supplementary information

Supplementary information related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2016.01.012.

References

Beesley, L., 2014. Respiration (CO_2 flux) from urban and peri-urban soils amended with green waste compost. Geoderma 223–225, 68–72. http://dx.doi.org/10.1016/j.geoderma.2014.01.024.

Boesch, H., Baker, D., Connor, B., Crisp, D., Miller, C., 2011. Global characterization of CO_2 column retrievals from shortwave-infrared satellite observations of the orbiting carbon observatory-2 mission. Remote Sens. 3 (12), 270–304. http://dx.doi.org/10.3390/rs3020270.

Briber, B., Hutyra, L., Dunn, A., Raciti, S., Munger, J., 2013. Variations in atmospheric CO_2 mixing ratios across a Boston, MA urban to rural gradient. Land 2 (3), 304–327. http://dx.doi.org/10.3390/land2030304.

Chen, Y., Day, S.D., Shrestha, R.K., Strahm, B.D., Wiseman, P.E., 2014. Influence of urban land development and soil rehabilitation on soil–atmosphere greenhouse gas fluxes. Geoderma 226–227, 348–353. http://dx.doi.org/10.1016/j.geoderma.2014.03.017.

Chun, J.A., et al., 2014. Estimation of CO_2 effluxes from suburban forest floor and grass using a process-based model. Atmos. Environ. 97, 346–352. http://dx.doi.org/10.1016/j.atmosenv.2014.08.044.

Clark-Thorne, S.T., Yapp, C.J., 2003. Stable carbon isotope constraints on mixing and mass balance of CO_2 in an urban atmosphere: Dallas metropolitan area, Texas, USA. Appl. Geochem. 18 (1), 75–95. http://dx.doi.org/10.1016/S0883-2927(02)00054-9.

Coutts, A.M., Beringer, J., Tapper, N.J., 2007. Characteristics influencing the variability of urban CO_2 fluxes in Melbourne, Australia. Atmos. Environ. 41 (1), 51–62. http://dx.doi.org/10.1016/j.atmosenv.2006.08.030.

Davidson, E.A., Belk, E., Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob. Change Biol. 4, 217–227. http://dx.doi.org/10.1046/j.1365-2486.1998.00128.x.

Day, T.A., Gober, P., Xiong, F.S., Wentz, E.A., 2002. Temporal patterns in near-surface CO_2 concentrations over contrasting vegetation types in the Phoenix metropolitan area. Agric. For. Meteorol. 110 (3), 229–245. http://dx.doi.org/10.1016/S0168-1923(01)00288-X.

Dillman, Don A., 2007. Mail and Internet Surveys: The Tailored Design Method. Wiley, Hoboken. ISBN: 0471323543.

Duren, R.M., Miller, C.E., 2012. Measuring the carbon emissions of megacities. Nat. Clim. Change 2 (8), 560–562. http://dx.doi.org/10.1038/nclimate1629.

Energy Information Administration (EIA), 2013. International Energy Outlook 2013, DOE/EIA-0484. U.S. Energy Inf. Admin., Off. Of Energy Analysis, U.S. Dep. of Energy, Washington, D. C.

Gately, C.K., Hutyra, L.R., Sue Wing, I., 2015. Cities, Traffic, and CO_2: a multidecadal assessment of trends, drivers, and scaling relationships. Proc. Natl. Acad. Sci. 112 (16), 4999–5004. http://dx.doi.org/10.1073/pnas.1421723112.

Giasson, M.A., et al., 2013. Soil respiration in a northeastern US temperate forest: a 22-year synthesis. Ecosphere 4 (11), 1–28. http://dx.doi.org/10.1890/ES13.00183.1.

Górka, M., Lewicka-Szczebak, D., 2013. One-year spatial and temporal monitoring of concentration and carbon isotopic composition of atmospheric CO_2 in a Wrocław (SW Poland) city area. Appl. Geochem. 35, 7–13. http://dx.doi.org/10.1016/j.apgeochem.2013.05.010.

Groffman, P.M., et al., 2006. Land use context and natural soil controls on plant community composition and soil nitrogen and carbon dynamics in urban and rural forests. For. Ecol. Manag. 236 (2–3), 177–192. http://dx.doi.org/10.1016/j.foreco.2006.09.002.

Groffman, P.M., Williams, C.O., Pouyat, R.V., Band, L.E., Yesilonis, I.D., 2009. Nitrate leaching and nitrous oxide flux in urban forests and grasslands. J. Environ. Qual. 38 (5), 1848–1860. http://dx.doi.org/10.2134/jeq2008.0521.

Hutyra, L.R., et al., 2014. Urbanization and the carbon cycle: current capabilities and research outlook from the natural sciences perspective. Earth Future 2 (10), 473–495. http://dx.doi.org/10.1002/2014EF000255.

Kaye, J.P., McCulley, R.L., Burke, I.C., 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. Glob. Change Biol. 11 (4), 575–587. http://dx.doi.org/10.1111/j.1365-2486.2005.00921.x.

Kennedy, C., et al., 2010. Methodology for inventorying greenhouse gas emissions from global cities. Energy Policy 38 (9), 4828–4837. http://dx.doi.org/10.1016/j.enpol.2009.08.050.

Kordowski, K., Kuttler, W., 2010. Carbon dioxide fluxes over an urban park area. Atmos. Environ. 44 (23), 2722–2730. http://dx.doi.org/10.1016/j.atmosenv.2010.04.039.

Massachusetts Office of Geographic Information (MassGIS), 2009. Land Use, Impervious Surface, Roads Datalayers. http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/ (Last accessed December 2014).

McKain, K., et al., 2012. Assessment of ground-based atmospheric observations for verification of greenhouse gas emissions from an urban region. Proc. Natl. Acad. Sci. 109 (22), 8423–8428. http://dx.doi.org/10.1073/pnas.1116645109.

McRae, J.E., Graedel, T.E., 1979. Carbon dioxide in the urban atmosphere: dependencies and trends. J. Geophys. Res. 84 (C8), 5011–5017. http://dx.doi.org/10.1029/JC084iC08p05011.

Metropolitan Area Planning Council (MAPC), 2013. Massachusetts Land Parcel Database, V. 1.0. Available athttp://www.mapc.org/parceldatabase.

Miller, J.B., et al., 2012. Linking emissions of fossil fuel CO_2 and other anthropogenic trace gases using atmospheric 14CO2. J. Geophys. Res. 117 (D8), D08302. http://dx.doi.org/10.1029/2011JD017048.

Moriwaki, R., Kanda, M., 2004. Seasonal and diurnal fluxes of radiation, heat, water vapor, and carbon dioxide over a suburban area. J. Appl. Meteorol. 43, 1700–1710. http://dx.doi.org/10.1175/JAM2153.1.

National Climatic Data Center, Climate Data Online: Data Tools, www.ncdc.noaa.gov/cdo-web/datatools/normals (Last accessed October 12, 2015).

Ng, B.J.L., et al., 2015. Carbon fluxes from an urban tropical grassland. Environ. Pollut. 203, 227–234. http://dx.doi.org/10.1016/j.envpol.2014.06.009.

Pataki, D.E., Bowling, D.R., Ehleringer, J.R., 2003. Seasonal cycle of carbon dioxide and its isotopic composition in an urban atmosphere: anthropogenic and biogenic effects. J. Geophys. Res. 108 (D23) http://dx.doi.org/10.1029/2003JD003865, 8.1–8.8.

Pawlak, W., Fortuniak, K., Siedlecki, M., 2011. Carbon dioxide flux in the centre of Łódź, Poland-analysis of a 2-year eddy covariance measurement data set. Int. J. Climatol. 31 (2), 232–243. http://dx.doi.org/10.1002/joc.2247.

Polsky, C., et al., 2014. Assessing the homogenization of urban land management with an application to US residential lawn care. Proc. Natl. Acad. Sci. 111 (12), 4432–4437. http://dx.doi.org/10.1073/pnas.1323995111.

Raciti, S.M., Hutyra, L.R., Newell, J.D., 2014. Mapping carbon storage in urban trees with multi-source remote sensing data: relationships between biomass, land use, and demographics in Boston neighborhoods. Sci. Total Environ. 500–501C, 72–83. http://dx.doi.org/10.1016/j.scitotenv.2014.08.070.

Raich, J.W., Tufekcioglu, A., 2000. Vegetation and soil respiration: correlations and controls [review]. Biogeochemistry 48 (1), 71–90. http://dx.doi.org/10.1023/A:1006112000616.

Raich, J.W., Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44B, 81–99. http://dx.doi.org/10.1034/j.1600-0889.1992.t01-1-00001.x.

Rella, C.W., Tsai, T.R., Botkin, C.G., Crosson, E.R., Steele, D., 2015. Measuring emissions from oil and natural gas well pads using the mobile flux plane technique. Environ. Sci. Technol. 49 (7), 4742–4748. http://dx.doi.org/10.1021/acs.est.5b00099.

Rosenzweig, C., Solecki, W., Hammer, S.A., Mehrotra, S., 2010. Cities lead the way in climate-change action. Nature 467, 909–911. http://dx.doi.org/10.1038/467909a.

Ryerson, T.B., et al., 2013. The 2010 California research at the nexus of air quality and climate change (CalNex) field study. J. Geophys. Res. Atmos. 118 (11), 5830–5866. http://dx.doi.org/10.1002/jgrd.50331.

Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. 109 (40), 16083–16088. http://dx.doi.org/10.1073/pnas.1211658109.

Smorkalov, I.A., Vorobeichik, E.L., 2015. The impact of a large industrial city on the soil respiration in forest ecosystems. Eurasian Soil Sci. 48 (1), 106–114. http://dx.doi.org/10.1134/S1064229315010147.

Templer, P.H., Toll, J.W., Hutyra, L.R., Raciti, S.M., 2015. Nitrogen and carbon export from urban areas through removal and export of litterfall. Environ. Pollut. 197, 256–261. http://dx.doi.org/10.1016/j.envpol.2014.11.016.

United Nations, 2014. World Urbanization Prospects.

United States Census Bureau, 2013. Population Change for Metropolitan and Micropolitan Statistical Areas in the United States and Puerto Rico (February 2013 Delineations): 2000 to 2010. http://www.census.gov/population/www/cen2010/cph-t/cph-t-5.html (Last accessed October 12, 2015).

United States Environmental Protection Agency (EPA), 2014a. 2011 National Emissions Inventory. Available at. http://www.epa.gov/ttnchie1/net/2011inventory.html (Last accessed November 1, 2014).

United States Environmental Protection Agency (EPA), 2014b. Greenhouse Gas Reporting Program, 2013 Data. Available at. http://www2.epa.gov/ghgreporting/ghg-reporting-program-data-sets (Last accessed September 14, 2014).

Vesala, T., et al., 2008. Surface–atmosphere interactions over complex urban terrain in Helsinki, Finland. Tellus B 60 (2), 188–199. http://dx.doi.org/10.1111/j.1600-0889.2007.00312.x.

Wang, R., 2012. Leaders, followers, and laggards: adoption of the US conference of mayors climate protection agreement in California. Environ. Plan. C Gov. Policy 30 (6), 1116–1128. http://dx.doi.org/10.1068/c1122.

Zimnoch, M., Godlowska, J., Necki, J.M., Rozanski, K., 2010. Assessing surface fluxes of CO_2 and CH_4 in urban environment: a reconnaissance study in Krakow, Southern Poland. Tellus B 62 (5), 573–580. http://dx.doi.org/10.1111/j.1600-0889.2010.00489.x.