Soil respiration contributes substantially to urban carbon fluxes

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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, we find that growing season soil respiration efflux is dramatically enhanced in urban areas and represents levels of carbon dioxide (CO_2) loss of up to 72% of $FFCO_2$ within Greater Boston's residential areas. Based on direct measurements across the Greater Boston area, we find that soils in urban forests, lawns, and landscaped cover types emit 2.62 ± 0.15, 4.49 ± 0.14, and 6.73 ± 0.26 µmol CO_2 m^{-2} s^{-1}, respectively. These rates represent up to 2.2 times greater soil CO_2 efflux 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, measurement and modeling of biogenic urban CO_2 fluxes will be a critical component for verification of urban climate action plans.

Capsule abstract

CO_2 from soil respiration in urban areas represent a significant amount of carbon dioxide efflux during the growing season, and varies both spatially and temporally.

Keywords

Urban ecology, biogeochemistry, fossil fuels, CO_2 flux

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 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.

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 Gradel, 1979). Photosynthesis has been shown to periodically reduce urban atmospheric CO_2

concentrations in diverse locations (McRae and Graedel, 1979; Day et al., 2002; Clarke-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; Gorka 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 soil respiration in mesic urban systems, a critical component of the biogenic CO_2 flux, have only been measured in a handful of urban studies, 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, 2014; Ng et al., 2015) precluding scaling up 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.

During the growing season (May-October) of 2014, we quantified rates of soil respiration at high temporal and spatial resolution across the greater Boston, Massachusetts (MA) area, and used these rates to create a spatially explicit model of soil respiration efflux along an urbanization gradient. Soil respiration was measured at fifteen sites and within three potential cover types at each site: forest, lawn, and landscaped (Fig 1). Soil respiration measurements were made every two weeks for the entire growing season using a LiCor 8100A automated CO_2 soil efflux system. In addition, measurements of air temperature, soil moisture, soil organic matter 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.

Methods

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 respiration across this area, we sampled 15 sites with varying amounts of surrounding development (Fig 2). 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 lawns (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 the other dominant cover type at the site, either forest or landscaped area. Sites without lawn (n=2) received two collars in the one dominant cover type at the site. 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 respiration collars installed across all three cover types for this study was n=56.

Soil respiration was measured every two weeks from 27 May to 5 November 2014 using an automated CO_2 soil efflux system with 20 cm diameter survey chamber (LiCor-8100A infrared gas analyzer, LiCor Inc., Lincoln, NE). Soil 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 concentration, soil 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 collars were collected for each cover type at each site. Soils were sieved through a 2 mm sieve and homogenized, a subsample was then removed and oven-dried at 60°C for one week to obtain % soil moisture for each sample. Soil pH was measured using 5 g of soil by hydrating with 10 mL of DDI H_2O, shaking for 30 minutes, and then 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 four hours and reweighed again. Soil carbon to nitrogen (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). Separate cores were taken for soil bulk density and processed with roots, organic matter, rocks, and other foreign objects removed and weighed. 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 listed in Table 1; model formulations from multivariate model using these data in Table 2.

Survey data

The Community and Conservation Survey of Massachusetts (CCS) was used to generate estimates of the fraction of residential properties with different cover types, as well as to determine homeowner usage of soil amendments (e.g. fertilizer). The CCS is a large multipart survey instrument, 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 ~100km 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 that you don’t mow, 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 and 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) and only parcels that were completely within the exclusively residential land uses 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.

Scaling Soil Respiration

To extrapolate soil respiration rates across the 25 km transect, modeled rates were estimated based on a combination of new soil respiration observations from this study for urban areas, literature soil respiration values for non-urban land covers, and high-resolution Geographic Information Systems (GIS) land use and impervious surface areas layers from the Massachusetts Office of Geographic Information (MASSGIS, 2009). All areas covered with impervious surfaces (road, buildings, driveways, etc.), based on a 1 m-resolution GIS map, were assumed to have no soil respiration efflux. All pervious surfaces were assigned a soil respiration efflux 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 μmolCO_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).

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 U.S. Environmental Protection Agency (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 the emissions calculations are reported in the Supplementary Information.

Error

All error values in the text, as well as in Figures 3 and 5 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 Figure 4E due to the difficulty of representing visually accurate error on the logarithmic scale of the y-axis; consequently, error for Figure 4E is represented in Figure 6 as weighted standard deviation for the spatial error in soil respiration and $FFCO_2$ emissions on a linear scale for the y-axis.

Results & Discussion

Soil respiration rates differed significantly (one-way ANOVA, $F = 4.69$, $p = 0.018$) between urban forest, lawn, and landscaped cover types, with growing season mean soil respiration rates of 2.62 ± 0.15, 4.49 ± 0.14, and 6.73 ± 0.26 µmolCO_2 m^{-2} s^{-1}, respectively (Fig 3, 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 µmolCO_2 m^2 s^{-1} (Giasson et al., 2013)); lawn and landscaped soil respiration rates were 1.5 and 2.2 times higher, respectively, than nearby rural forest soil respiration rates. Soil organic matter concentration ($r = 0.59$, $p = 0.0009$) and the depth of the leaf litter layer ($r = 0.57$, $p =0.001$) were significantly and positively correlated with observed soil respiration rates. We estimated a multivariate regression model of soil respiration rates including soil organic matter concentration, June litter depth, a binary indicator of management (managed vs. unmanaged), and a cover type fixed effect (forest, lawn, landscaped; $R^2 = 0.71$, $p < 0.006$; Table 2). The significant correlation between soil organic matter concentration, litter depth, and soil respiration rates, along with the discrete statistical separation of soil respiration rates by cover type (Fig 3), suggest that the magnitude of urban soil respiration efflux is tied to municipal and individual landowner management decisions. Results from 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 et al., 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 Geographic Information Systems 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 4a-d). To evaluate the magnitude of the contribution of soil respiration efflux across the spatially heterogeneous land uses of the Greater Boston area, we compared the modeled soil respiration efflux to $FFCO_2$ emissions from a new high-resolution $FFCO_2$ dataset (Gately et al., 2015) (Figs 4e & 4f). Though soil respiration is only about 1% of $FFCO_2$ emissions in the highly developed urban core of Boston (Figure 4e), within the densely populated residential area 11-18 km from the urban core of Boston, mean efflux of growing season CO_2 emitted from soil respiration averages 72 ± 7 % of $FFCO_2$ emissions (Figs 4e & 4f). 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 respiration increases up to fourfold (soil respiration/(soil respiration+$FFCO_2$); Fig 4f), approaching and surpassing efflux from $FFCO_2$ emissions in some locations. 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 soil respiration efflux.

In addition to spatial variation in soil respiration efflux, the contribution of soil respiration efflux to total urban CO_2 efflux varies temporally within the growing season. Rates of soil respiration in the Boston area 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 5). This temporal mismatch in maxima of soil respiration 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 11-18 km from the city center (Fig 5). 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.

Conclusion

We show that soil respiration contributes significantly to urban and suburban surface CO_2 fluxes, and that soil respiration fluxes display variable spatial and temporal patterns. Management decisions, such as soil amendments and irrigation, create soil efflux in some urban areas that is more than twice as high as that in rural forests. Further, it is unlikely that the large soil respiration efflux observed in this study is offset by local photosynthesis given the large soil respiration contribution from landscaped areas and low urban biomass densities (Raciti et al., 2014). The magnitude of urban soil respiration efflux on a landscape scale, along with the spatial and temporal variation, must be taken into account when assessing the urban carbon budget, particularly for cities like Boston with a high percentage of landscaped, pervious area in residential areas. 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., 2014) and further highlight the need to tie management of residential urban areas to biogeochemical fluxes.

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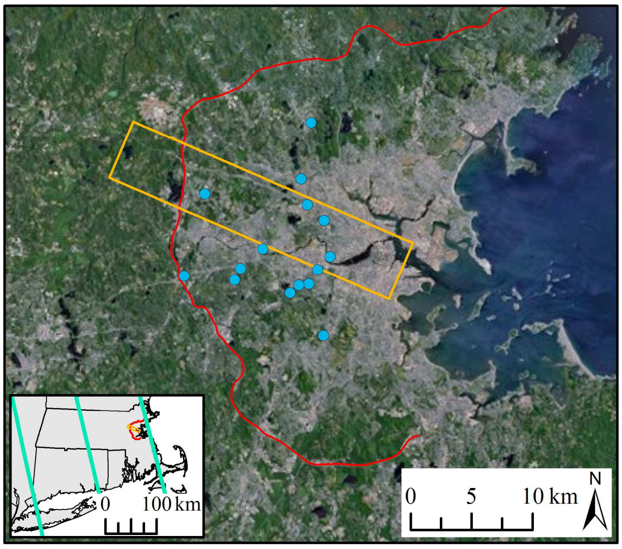


Fig 1: Study area. Blue points represent soil respiration measurement sites. Orange box outlines 25 km transect from downtown urban Boston to suburban Concord, MA. Interstate Highway I-95 is highlighted in red. In the inset, current OCO-2 summer nadir tracks are shown in green.

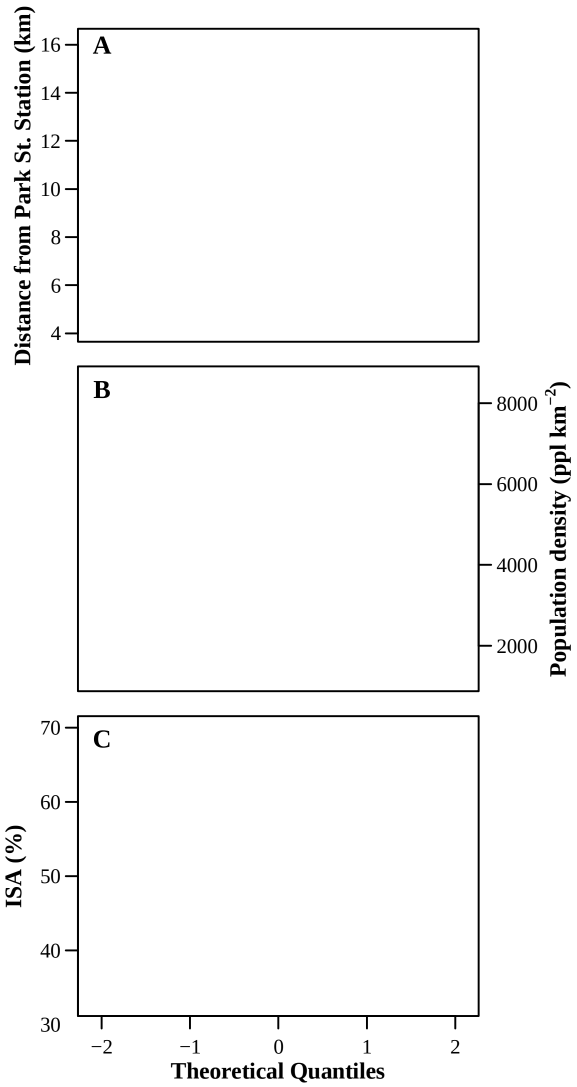


Fig 2: Quantile-quantile distribution plots. Distribution of sites is illustrated across three metrics of urban intensity: **a,** distance to downtown Park Street Station (MASSGIS, 2009) **b,** population density (Raciti et al., 2012) and **c,** impervious surface area (ISA; MASSGIS, 2009), all within 1000 m of site.

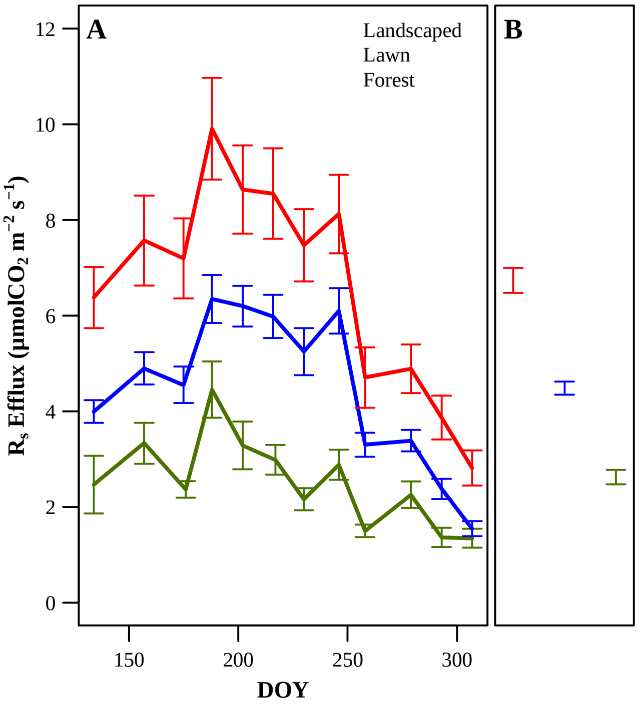


Fig 3: Measured soil respiration (R_s) efflux by land cover type across growing season. DOY = Day of year. A, Values are means with standard error across fifteen sites at each measurement date over the growing season (27 May 2014 through 3 November 2014). **B,** Seasonal means and standard error by land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

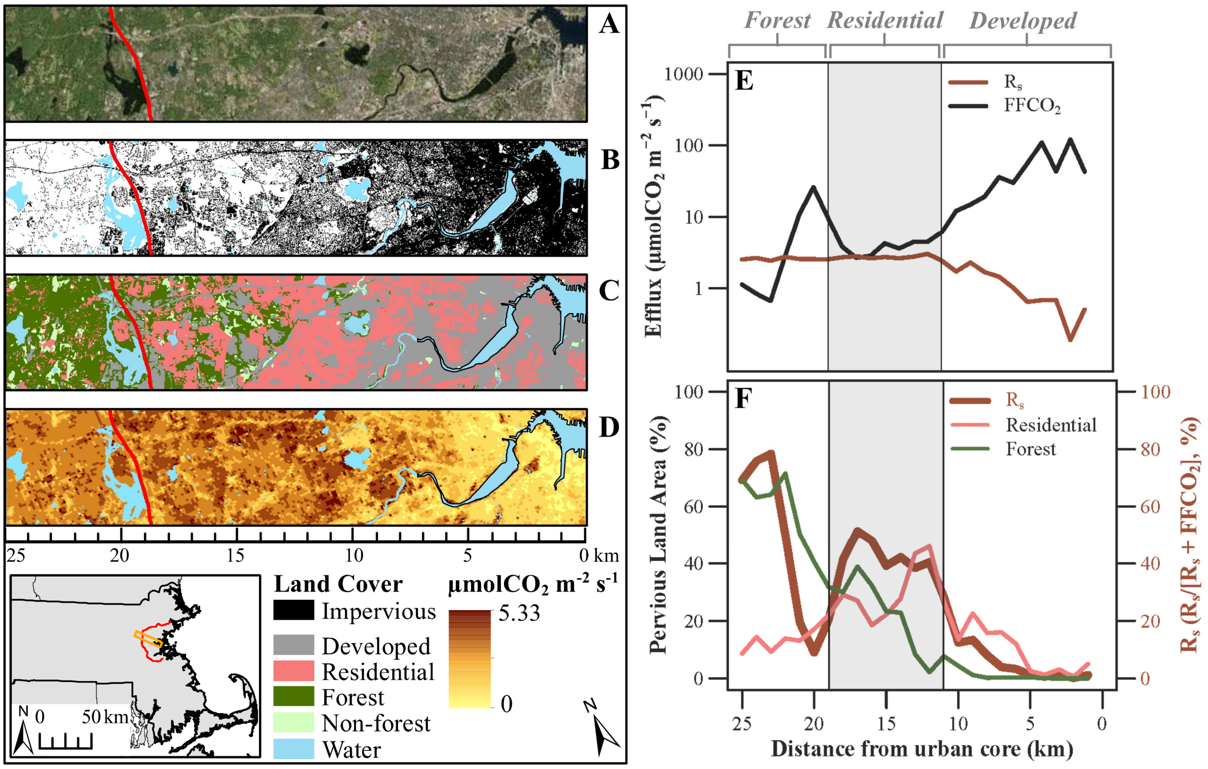


Fig 4: Gradients in soil respiration (R_s) and $FFCO_2$ efflux along 25 km transect. A, Satellite image, **B**, Impervious surface area, **C,** Land cover, and **D,** Modeled growing soil respiration efflux. **E,** Growing season modeled soil and $FFCO_2$ efflux; $FFCO_2$ enhancement at 20 km due to 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 Figure 6. **F,** Percent pervious forest and residential area compared to growing season soil respiration efflux as a percentage of total soil respiration plus $FFCO_2$ efflux.

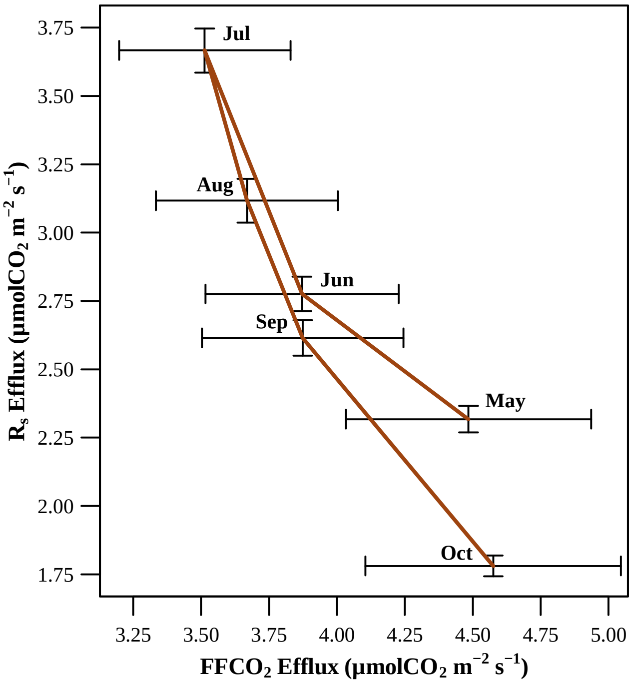


Fig 5: Monthly hysteresis curve of modeled soil respiration (R$_s$) efflux as compared to modeled FFCO$_2$ efflux. Monthly integrated mean values with standard error in the residential area from 11-18 km along 25 km transect (Figure 4) are used for both FFCO$_2$ and soil respiration efflux.

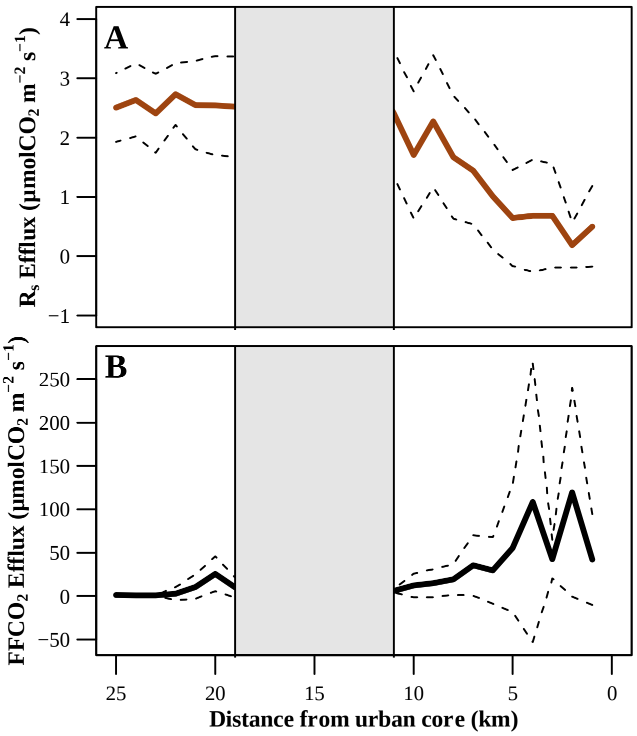


Fig 6: Soil respiration (R_s) and $FFCO_2$ mean and standard deviation (error estimates from Fig 4E). a, Soil respiration and **b,** $FFCO_2$ along 25km transect. $FFCO_2$ enhancement at 20 km is due to Interstate-95, a major regional transportation corridor. Gray band (11-18 km from urban core) corresponds to gray band in Figs 4E & 4F.

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

Cover Type	Sites (*n*)	Obs. (*n*)	Litter*			Soil				
			Depth (cm)		Mass (g)	OM (%)	pH	C:N	Bulk ρ (g cm^{-3})	Seasonal Mean R_s ($\mu molCO_2\ m^{-2}\ s^{-1} \pm SE$)
			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	1.13	4.49 ± 0.14
Landscaped	12	309	3.00	5.86	63.67	15	5.88	18.68	0.64	6.73 ± 0.26

* Leaf litter within a 900 cm^2 square adjacent to the collar

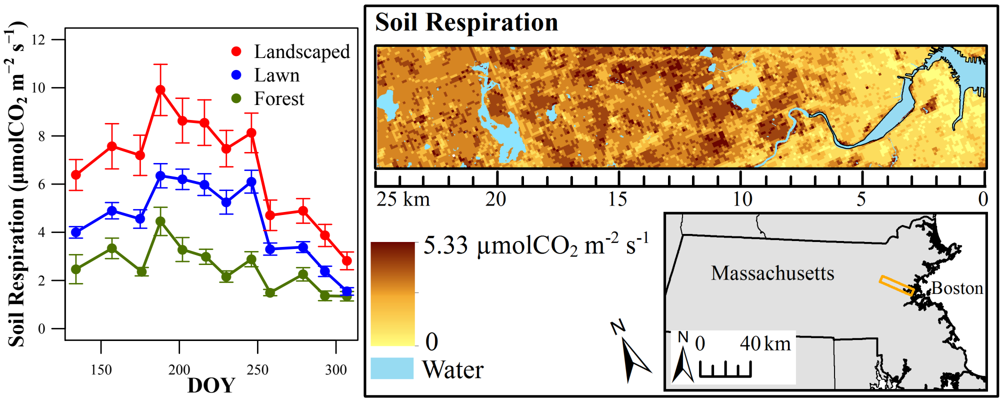
Table 2: Multivariate model formulations

Parameters	Coefficient	*p*-value
Intercept	-6.55	0.071
Cover type	7.00	0.011
Management	0.50	0.668
Litter depth	33.46	0.004
Soil organic matter	0.23	0.124

Table 3: Scaling Soil Respiration (R_s) 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 respiration values, seasonal patterns, overall abundance (% area), and fraction paved (ISA) within each land use description across the 25 km transect.

Land Cover	Land Use Description	Reference	Seasonal R_s Efflux (μmolCO$_2$ 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)*	5.33	Monthly Means	14.34	64.78 ± 0.78
	High Density Residential	this study (residential)*	5.33	Monthly Means	11.83	69.46 ± 0.71
	Medium Density Residential	this study (residential)*	5.33	Monthly Means	4.40	35.62 ± 1.34
	Low Density Residential	this study (residential)*	5.33	Monthly Means	3.88	26.04 ± 0.46
	Very Low Density Residential	this study (residential)*	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 & Tufekcioglu 2000	0.96	Seasonally Constant	1.86	7.51 ± 2.30
	Non-Forested Wetland	Raich & Schlesinger 1992	1.09	Seasonally Constant	0.89	3.35 ± 1.40
	Pasture	Raich & 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 & Tufekcioglu 2000	1.99	Seasonally Constant	0.01	25.11 ± 11.34

*Residential R_s = lawn fraction x this study (lawn) + forest fraction x this study (forest) + landscaped fraction x this study (residential) + open field fraction x 1.99 (Raich & Tufekcioglu, 2000)


Soil Respiration (μmolCO₂ m⁻² s⁻¹)
12
10
8
6
4
2
0
150
200
250
300
DOY
Landscaped
Lawn
Forest
Soil Respiration
25 km
20
15
10
5
0
5.33 μmolCO₂ m⁻² s⁻¹
0
Water
N
Massachusetts
Boston
N
0
40 km