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Accounting for urban biogenic fluxes in regional carbon budgets

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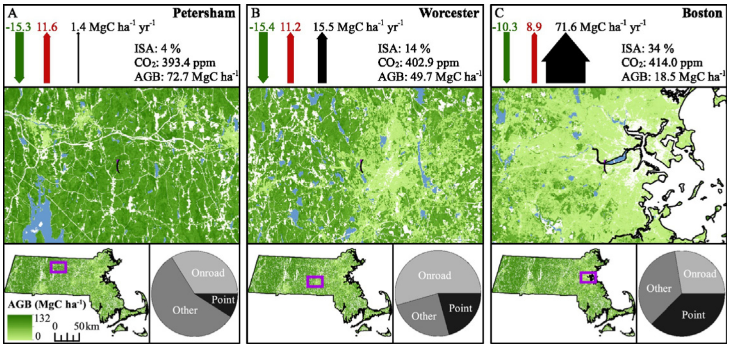
HIGHLIGHTS

- Urban areas occupy 1/3 of MA; urban biogenic fluxes are generally ignored by models.
- Boston biomass is 1/4 of nearby rural biomass, C fluxes are 2× rural rates.
- Urban biogenic C fluxes can be up to 14% of urban anthropogenic C emissions.
- Diurnal and seasonal asymmetry of biogenic fluxes results in biased flux estimates.
- Regional carbon cycle models that omit urban vegetation may be incomplete.

GRAPHICAL ABSTRACT



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ABSTRACT

Many ecosystem models incorrectly treat urban areas as devoid of vegetation and biogenic carbon (C) fluxes. We sought to improve estimates of urban biomass and biogenic C fluxes using existing, nationally available data products. We characterized biogenic influence on urban C cycling throughout Massachusetts, USA using an ecosystem model that integrates improved representation of urban vegetation, growing conditions associated with urban heat island (UHI), and altered urban phenology. Boston's biomass density is 1/4 that of rural forests, however 87% of Massachusetts' urban landscape is vegetated. Model results suggest that, kilogram-for-kilogram, urban vegetation cycles C twice as fast as rural forests. Urban vegetation releases (R_E) and absorbs (GEE) the equivalent of 11 and 14%, respectively, of anthropogenic emissions in the most urban portions of the state. While urban vegetation in Massachusetts fully sequesters anthropogenic emissions from smaller cities in the region, Boston's UHI reduces annual C storage by >20% such that vegetation offsets only 2% of anthropogenic emissions. Asynchrony between temporal patterns of biogenic and anthropogenic C fluxes further constrains the emissions mitigation potential of urban vegetation. However, neglecting to account for biogenic C fluxes in cities can impair efforts to accurately monitor, report, verify, and reduce anthropogenic emissions.

1. Introduction

Fossil fuel emissions of carbon dioxide ($FFCO_2$) originating from urban areas account for >70% of anthropogenic CO_2 emissions globally (International Energy Agency, 2008; Le Quéré et al., 2013; U.S. Energy

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Information Agency, 2013). Recent studies have improved spatial and temporal resolution of anthropogenic carbon (C) emissions estimates (Bréon et al., 2015; Gately et al., 2015; McKain et al., 2015; Turnbull et al., 2015), but the influence of urban vegetation on C flows has received less attention and remains poorly constrained (Churkina, 2008; Hutyra et al., 2014; Raciti et al., 2012). Uncertainty in the timing, magnitude, and direction of C fluxes from urban vegetation limits efforts to accurately monitor, report, verify, and mitigate urban anthropogenic C emissions.

Both bottom-up (Briber et al., 2015; Gough and Elliott, 2012) and top-down (Pataki et al., 2007; Turnbull et al., 2015) studies have demonstrated that vegetation is highly active in the urban C cycle. For example, urban biogenic sink strength has been reported to range from 1.8% to 18% of urban fossil fuel emissions (McPherson and Simpson, 1999; Yin et al., 2010; Zhao et al., 2010). Most studies of urban fluxes attribute seasonal patterns to land cover variability (e.g., urban vegetation) only in broad, qualitative terms or to spatially limited areas (i.e., immediately surrounding a flux tower), which limits city-scale understanding of the urban C cycle (Bergeron and Strachan, 2011; Crawford et al., 2011; Helfter et al., 2011; Järvi et al., 2012; Kordowski and Kuttler, 2010). The widespread presence of vegetation in and around cities complicates precise characterization of urban CO_2 budgets using atmospheric observations, particularly due to the spatially heterogeneous arrangement of urban vegetation and seasonality of urban biogenic C fluxes (Bergeron and Strachan, 2011; Crawford et al., 2011; Järvi et al., 2012). Correcting for temporal aliasing of biogenic and anthropogenic fluxes requires careful partitioning of each to attribute sources using atmospheric measurements (Briber et al., 2013; Gurney et al., 2005; Hutyra et al., 2014; Myeong et al., 2006).

Unique growing conditions facilitate elevated biogenic C cycling rates in urban ecosystems relative to non-urban ecosystems (Hutyra et al., 2014). For example, urban areas experience elevated ambient air temperatures (the "urban heat island" effect; UHI) (Kim, 1992; Oke, 1982), which cause seasonally-dependent changes in C fluxes from urban vegetation and soils (Decina et al., 2016; Pataki et al., 2006; Zhang et al., 2004; Zhao et al., 2012), and extend the urban growing season (Melaas et al., 2016a, 2016b; Zhang et al., 2004). Urban vegetation may thus sequester atmospheric CO_2 at different rates than rural vegetation on a per unit biomass basis (Zhao et al., 2016), while urban soil respiration patterns (spatial and temporal) may differ due to elevated ambient air temperatures (i.e., UHI), impervious surface areas (ISA, i.e. pavement and buildings) that restrict diffusion of CO_2 from soils, and human addition of labile C sources (George et al., 2007; Ziska et al., 2004). Some urban growing conditions negatively impact growth rates; e.g. exposure to ozone reduces photosynthesis rates (Krupa and Manning, 1988; Ollinger et al., 2002). While urban areas are strong emitters of O_3 precursors, Gregg et al. (2003) observed higher $[O_3]$ in rural areas downwind of cities due to transport and competitive interactions that scavenge O_3 precursors. Nevertheless, Briber et al. (2015) reported growth rates of urban trees to be twice those observed in rural forests and documented accelerated tree growth following urbanization suggesting a net positive effect of urban growing conditions. Other inventory studies demonstrate potentially large C sequestration rates in cities across many biomes (Churkina et al., 2010; Jo, 2002; Nowak and Crane, 2002; Zhao et al., 2012). Despite this evidence, biogenic C fluxes from urban vegetation are often treated as known, neutral, or negligible (Gurney et al., 2005; Kennedy et al., 2012) introducing biases of unknown magnitude into the measurement and modeling of anthropogenic emissions.

To improve understanding of the influence vegetation exerts on the urban C cycle, we combined existing land cover products with field estimates of urban vegetation biomass to produce an improved map of urban biomass density. This was compared with spatially and temporally resolved model estimates of biogenic and anthropogenic C fluxes. We estimated biogenic C fluxes (gross ecosystem exchange [GEE] and ecosystem respiration [R_E]) using the Vegetation Photosynthesis and Respiration Model (VPRM) (Mahadevan et al., 2008), a remote sensing-based light use efficiency model that we modified to incorporate the altered phenology, higher air temperatures, and ISA in urban ecosystems. These fluxes are compared with new inventories of anthropogenic emissions to produce a comprehensive C budget for the state of Massachusetts. Importantly, we restricted our analysis to use nationally available data sources so that these methods can be extended to other urban areas.

2. Methods

To investigate the role of vegetation in the urban C cycle, we combined an improved map of vegetation in urban areas, an ecosystem model of biogenic C flows that incorporates urban growing conditions normally ignored by ecosystem models, and a novel, comprehensive inventory of spatially and temporally resolved anthropogenic CO_2 emissions.

2.1. Study area

Our study focused on the state of Massachusetts (MA), USA with three 20 km × 30 km (600 km^2) focal areas corresponding to communities spanning a gradient from low to high urban development intensity: Petersham (42.54°N, 72.17° W; 44 persons km^{-2}), Worcester (42.27°N, 71.84° W; 340 persons km^{-2}), and Boston (42.356°N, −71.062°W; 2049 persons km^{-2}) (population density from ORNL, 2014). All three focal areas contain atmospheric CO_2 sampling sites. MA is predominantly covered by northern mixed-deciduous forest (60%) and developed areas (25–38%), with small areas of agriculture, grasslands, and wetlands (Homer et al., 2015; US Census Bureau, 2010). Climate in MA is temperate with mean summer (JJA) and winter (DJF) temperatures of 20 °C and −4 °C, respectively, and mean annual precipitation of 1125 mm (National Climatic Data Center, 2015).

2.2. Biomass map

To develop a map depicting the quantity and distribution of aboveground biomass (AGB) across the state, we used the National Biomass and Carbon Dataset (NBCD; Kellndorfer et al., 2013) as a base estimate. While NBCD AGB estimates are tuned to be consistent with county-scale FIA data, it tends to overestimate AGB and underestimate vegetation extent in urban areas (Raciti et al., 2014). To correct this bias, we revised the NBCD urban biomass estimates using a linear statistical relationship between field measurements of AGB in urban plots ($n = 299$, see S1 for additional details on field plots), growing season mean EVI (Enhanced Vegetation Index, a satellite-derived metric of land-surface greenness), and forest canopy cover from the 2011 National Land Cover Database (NLCD) (Homer et al., 2015). While we applied this relationship using a linear model, the pattern likely asymptotes at high biomass values (Huete et al., 2002). However, high biomass areas are rare in most urban areas, and so the impact of this mis-parameterization is minimal. The relationship between biomass observed in ground plots throughout the greater Boston area and corresponding predicted values, with associated 95% confidence and predictive intervals is shown in Fig. S1-1. We produced the Better Urban Biomass Map (BU-BioM) at 30 m spatial resolution by applying this statistical relationship (SI Eq. (1), model adjusted $R^2 = 0.51$, $p < 0.01$; see S1 for additional detail) to the intersection of NLCD-defined urban areas (classes 21–24) and the areas covered by the urban areas/urban clusters (UA/UC) in the US Census (US Census Bureau, 2010). The total affected area was 20.2% of the state, or 4220 km^2. For pixels outside of the UA/UC that were classified by NLCD as urban, we retained the AGB value reported by the NBCD. Pixels inside UA/UC classified as non-urban by NLCD were also unchanged from the NBCD AGB values.