View of the urban landscape from the Boston University rooftop $CO_2$ observatory

# Exploring Space-Time Variation in Urban Carbon Metabolism

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Carbon dioxide is a well-mixed greenhouse gas, but how, where, and when it is exchanged with Earth's surface is a complex spatio-temporal, coupled natural-human problem. Nowhere is this challenge more pronounced than in the urban environment. Fixed objects like buildings and trees, and mobile elements like cars and people, exchange carbon (C) across a wide range of spatial and temporal scales with a dynamic set of driving variables. As cities, states, and nations undertake efforts to reduce and regulate greenhouse gas emissions, we must understand these space-time variations and the underlying drivers of biogenic and anthropogenic exchange in order to develop robust monitoring, reporting, and verification systems. Within urban areas, the concept of urban metabolism provides a framework for monitoring, reporting, and verification that allows us to account for imports, exports, and transformations of carbon within urban areas.

## Carbon dynamics of urbanizing areas

Carbon dioxide ($CO_2$) and methane ($CH_4$) are the two most important greenhouse gases (GHGs). At first glance, the monitoring of atmospheric GHGs is routine; we have an extensive international network of observations – National Aeronautics and Space Administration's (NASA) FLUXNET: http://www.fluxnet.ornl.gov/; National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL): http://www.esrl.noaa.gov/gmd/. However, the atmospheric mixing ratios of these gases are continually changing through a combination of anthropogenic emissions, biogenic exchange, and atmospheric transport. While 71% of anthropogenic $CO_2$ emissions are estimated to being attributable to urban areas (IEA, 2008), most efforts to study both atmospheric and terrestrial carbon dynamics have avoided areas heavily influenced by urbanization (Baldocchi, 2008). While more observations and studies are beginning to explore carbon cycling within urban and urbanizing areas, extraordinarily large uncertainties and knowledge gaps remain. Carbon emissions inventories are often at very coarse temporal and spatial resolutions (annual and national or 1° x 1°).

Attribution to smaller scales is very challenging (Kennedy et al., 2007) and prone to double counting and leakage given that most of the energy consumed within urban areas is generated elsewhere. This spatial mismatch between generation and consumption results in significant attribution challenges (Cannell et al., 1999). We do not yet have a sufficient understanding, the requisite measurement network, or the analytical modeling techniques necessary to adequately characterize the space-time variation in terrestrial sources or sinks within urbanizing areas that are required for future carbon regulation.

The current paucity of data about the biogeochemistry and carbon dynamics of urbanizing areas is in part a byproduct of the perception that urban ecosystems have limited ecological value because they are heavily modified by humans and are relatively small in size. However, urban areas are rapidly evolving in their spatial configurations and are growing in spatial extent (Schneider & Woodcock, 2008; UNFPA, 2007) and can contain significant pools of vegetation and soil carbon (Hutyra et al., 2011a). As urban areas grow, the ecology of cities will become ever more germane to both people's lives and the development of local to regional carbon mitigation strategies (Dhakal, 2010).

Over the last several years through a National Science Foundation (NSF) Urban Long-Term Research Area – Exploratory Award (ULTRA-Ex), we have begun exploring the spatio-temporal variation in $CO_2$ exchange across an urban-to-rural gradient in metropolitan Boston. Our results paint a picture of tremendous variation, but with some surprisingly clear signals of human activity and biotic response. Our atmospheric $CO_2$ mixing ratio measurements show the clear urban $CO_2$ hotspot observed in other studies, but also indicate seasonal vegetation metabolism signals as well as human metabolism signals in the heating and traffic patterns. Urban ecosystem structure also changes significantly across the Boston study area, with clear gradients in vegetation density, development intensity, traffic volumes, and energy use that are reflected in the $CO_2$ concentrations. Thus far, our early results raise more questions about scaling and attribution than they answer, but addressing these questions will be crucial to ultimately understanding the full complexity of urban metabolism.

## Terrestrial carbon pools

There is conflicting evidence about the importance of soils and vegetation in the urban carbon metabolism that is caused, in part, by inconsistent definitions of 'urban' land use. In Massachusetts, the US census estimates that 36% of the state is 'urban', yet remote sensing observations reveal that 50% of this urban area is forest or forested wetlands (see Figure 1). While both of these estimates can be correct, the importance of soils and vegetation on the carbon metabolism is clearly dependent on whether municipal, physical, or social definitions of urban are applied.

**Figure 1** | A fusion of remote sensing imagery from Quickbird (4-band, 2.4m image from August 4, 2007) and Light Detection and Ranging (LiDAR, 50cm horizontal resolution from the summer of 2005) observations highlights the distribution of vegetation taller than 1 m in the City of Boston, MA. The location of the $CO_2$ observation tower at Boston University is denoted with the red point (BU: 42.350N, 71.104W).

We quantified urban ecosystem contributions to terrestrial carbon pools in the Boston Metropolitan Statistical Area (MSA) using several alternative urban definitions. Aboveground biomass (DBH ≥ 5 cm) for the MSA was 7.2 ± 0.4 kg C/$m^2$, reflecting the high proportion of forest cover. Vegetation carbon was highest in forested land uses (11.6 ± 0.5 kg C/$m^2$) followed by residential

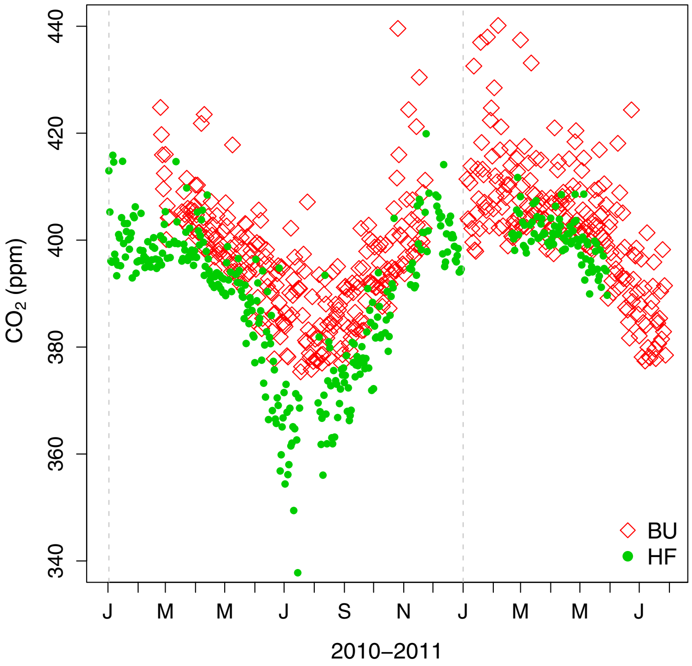
(4.6 ± 0.5 kg C/$m^2$) and then other developed (2.0 ± 0.4 kg C/$m^2$) land uses. Soil carbon (0 to 10 cm) followed the same pattern of decreasing carbon concentration from forest, to residential, to other developed land uses (4.1 ± 0.1, 4.0 ± 0.2, and 3.3 ± 0.2 kg C/$m^2$, respectively). Soil nitrogen concentrations were higher in urban areas than non-urban areas of the same land use type, except for residential areas, which had similarly high soil nitrogen concentrations. Enhanced soil carbon and nitrogen concentrations in residential areas may reflect human amendments to the system, including water and nitrogen fertilizer. When we extrapolate our estimates of soil (to a 1 m depth) and vegetation carbon pools to the Boston MSA, our estimates span a very wide range, from 1.4 to 54.5 Tg C and 4.2 to 27.3 Tg C, respectively, depending on the urban definition that was used. Conclusions about the importance of soils and vegetation in urban ecosystems are very sensitive to the definition of 'urban' used by the investigators. The development of consistent, empirical definitions of urban land use would facilitate comparative studies.

While we have found the Boston MSA holds large pools of vegetative and soil carbon, the exchange of carbon by urban vegetation is dwarfed by the local $CO_2$ emissions. Nonetheless, there is evidence that urban vegetation can provide important ecosystem services beyond carbon sequestration, including decreased storm water runoff (Xiao & McPherson, 2002), reduced airborne particulates (Nowak et al., 2006), reductions in seasonal heating/cooling demands (McPherson et al., 2005), reduction of the urban heat island through evaporative cooling (Huang et al., 2011), and provide aesthetic value and recreation space (Millward & Sabir, 2011). Unfortunately, new development may be outpacing the forest recovery that New England has enjoyed for the past 200 years (Foster et al., 2010). Depending on the trajectories and patterns of development in the region, the large carbon pools that we have found may be significantly diminished as some of the region's carbon stocks (and active C sinks) may become sources of carbon emissions (Stein et al., 2005). A recent analysis in Seattle, WA found that urban expansion resulted in a loss of 3.6 Kg C/$m^2$ between 1986 and 2007 (0.12 Kg C/$m^2$/yr) in vegetative carbon pools (Hutyra et al., 2011b). The loss of forests to urban development is compounded by other threats, including outbreaks of native and invasive pests and pathogens (Lovett & Mitchell, 2004), changes in climate, and associated shifts in the frequency of fires, storms, droughts, and other disturbances (IPCC, 2007).

## Atmospheric $CO_2$

Carbon dioxide is a well-mixed gas with a long atmospheric residence time, but we find significantly enhanced concentrations at our Boston University measurement site relative to observations at the rural Harvard Forest Long-Term Ecological Research site (~100 km distance, see Figure 2). During the summer of 2010, when $CO_2$ near the surface is depleted in the daytime by photosynthesis, the mean concentration at Boston University was 15.9 ppm higher than its rural counterpart (387.5 ± 0.4 and 371.6 ± 0.7 ppm, respectively). During the winter of 2010, when ecosystem respiration and heating of urban buildings release large amounts of carbon, the mean concentration at Boston University was only 11.2 ppm greater than the rural forested site (412.5 ± 1.0 and 401.3 ± 0.4 ppm, respectively). In Boston we also observed enhanced mid-day $CO_2$ concentration on weekdays relative to weekends due to traffic and commuting patterns (3.4 ppm during the summer and 1.7 ppm during the winter). The differences across this urban-to-rural gradient depend not only on the season and the relative magnitudes of uptake and emissions, but also on strength of horizontal and vertical mixing in the atmosphere. Atmospheric mixing and transport complicate direct interpretation of urban and rural concentration differences as an indicator of carbon metabolism. However, by coupling concentration data with high-resolution weather and atmospheric

**Figure 2** I Mid-day mean $CO_2$ concentrations for 2010-2011 at Boston University and Harvard Forest showing the seasonal cycles and urban enhancement.



transport models it is possible to assess the spatial and temporal differences in carbon flux across urban-to-rural gradients.

## Conclusions

Globally, urban areas are growing in population, land area, and ecological significance which will have dramatic impacts on regional carbon pools, fluxes, and the overall metabolism of the system. As we move forward with the development of $CO_2$ emissions reduction plans and regulations, we will need integrated estimates of $CO_2$ sources and sinks from the surface coupled with direct atmospheric $CO_2$ measurements that are able to partition the local and background $CO_2$ dynamics in a robust manner. Meaningful city, regional, or national reductions in $CO_2$ emissions will require major economic changes and self-reporting of reductions will not be enough. The framework of urban metabolism provides a platform that can integrate $CO_2$ emissions, ecosystems, atmospheric transport, and atmospheric observations to provide an independent method for reporting, monitoring, and verification of carbon.

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