
Marina Alberti\textsuperscript{1} and Lucy Hutyra\textsuperscript{2,3}

\textsuperscript{1} Professor of Urban Design and Planning, University of Washington, Department of Urban Design and planning, Seattle, WA, USA. malberti@u.washington.edu
\textsuperscript{2} Research Scientist, Urban Ecology Research Laboratory, University of Washington, Seattle, WA, USA. lrhutyra@u.washington.edu
\textsuperscript{3} Senior Research Associate, Boston University, Department of Geography and Environment, Boston, MA, USA. hutyra@bu.edu

Summary:

Urbanizing regions are major determinants of global and continental scale changes in carbon budgets through land transformation and modification of biogeochemical processes (Pataki et al. 2006). However, direct measurements of the effects of urbanization on carbon fluxes are extremely limited. In this paper we develop a strategy to quantify urban carbon signatures (spatial and temporal changes in fluxes) through measurements that can more effectively aid urban carbon scenario and predictive modeling. We start by articulating an integrated framework that identifies the mechanisms and interactions that link urban patterns to carbon fluxes along gradients of urbanization. Building on a synthesis of the current observational studies in major US metropolitan areas we develop formal hypotheses on how alternative development patterns produce different carbon signatures and how these signatures may in turn influence patterns of urbanization.

Keywords: urbanization, land cover, development, carbon cycle, terrestrial, vegetation.

1. Introduction

Urbanizing regions are major determinants of global and continental scale changes in carbon budgets through land transformation and modification of biogeochemical processes (Pataki et al. 2006). Recent studies in urbanizing regions provide increasing evidence of the complex mechanisms by which urban activities affect both carbon emissions and pools (Pataki et al. 2007). However, empirical data of the effects of urbanization on carbon fluxes are extremely limited to establish the underlying processes and mechanisms linking urbanization patterns and carbon fluxes. The exact magnitude of and mechanisms for carbon exchange are largely uncertain for urbanizing ecosystems (Pataki et al. 2006). Also unknown is how patterns of urbanization interact with household behaviors and consumption choices. Typically, quantifications of carbon emissions are based on estimates of fossil fuel consumption from human activities (Grimmond et al. 2002). Similarly, changes in carbon uptake of vegetation are generated from remote sensing-based estimates of biomass stocks (Imhoff et al. 2004) and ecosystem models largely parameterized for ‘natural’ conditions (Churkina 2008). These estimates are inadequate to understand the relative magnitude of urban impacts of multiple urban activities and household behaviors and their variability across alternative development patterns (i.e. urban form, land use intensity, infrastructure). Predictions of future trajectories of carbon fluxes associated with urbanization require an understanding and systematic evaluation of how alternative patterns of urban development (i.e., centralized versus sprawling) affect the carbon budget over the long term. We hypothesize that in temperate, urban ecosystems key mechanisms that affect carbon stocks vary discontinuously across a gradient of urbanization.

United Nations estimates suggest that half the world's population was living in urban areas by the end of 2008 and about 70 percent of the global population is projected to become urbanites by 2050 (UNFPA 2007). The process of urban expansion results in complex patterns of intermixed high- and low-density built-up areas and a fragmentation of the natural landscape. Urbanization affects ecological processes both directly—by simplifying habit in human-dominated systems—and indirectly—by changing the biophysical attributes of the landscape that result in a variety of interrelated local and global effects (Alberti and Marzluff 2004). The complex interactions among urbanization, carbon fluxes, and ecosystem functions are influenced by both human and biophysical factors and competing positive and negative feedbacks between them. The integrated effects of urbanization (including changing land cover characteristics, land use patterns, pervious surface fractions, urban heat islands, atmospheric pollution, management activities, etc.) on land-atmosphere exchange processes of both energy and carbon remain highly uncertain despite decades of study on components of the problem.

Imhoff et al. (2004) estimated that urbanization has reduced net primary production (NPP) by 0.04 Pg C yr⁻¹ (1.6%) for the USA, but the overall uncertainty remains very high due to incomplete data and understanding of the feedbacks. Change in NPP due to urbanization also differs regionally based on the ecosystem and biome. At local and regional scales, urbanization can increase NPP in resource-limited regions. Imhoff et al. (2004) show that through localized warming, “urban heat islands” can extend the growing season in colder regions (such as Seattle) and increase NPP in winter. However, benefits like these may not offset the overall negative impact of urbanization on NPP for cities in highly productive biomes (Imhoff et al. 2004). Urbanization also may increase NPP in resource-limited, low-productivity regions by increasing water availability in arid areas (such as Phoenix). For example, Buyantuyev and Wu (2008) showed that urbanization increased regional NPP in central Arizona in dry years. Introduced
plant communities (e.g., urban vegetation and crops) have higher NPP than the natural desert, and together urban and agricultural areas contributed more to the regional NPP than the desert vegetation in normal and dry years, but not in wet years. Because urbanization disrupts the coupling between vegetation and precipitation and increases spatial heterogeneity, NPP of this arid urban landscape is only weakly correlated with rainfall pattern but is strongly correlated with socio-economic variables (Buyantuyev and Wu 2008).

In this paper we develop a strategy to quantify urban carbon signatures (spatial and temporal changes in fluxes) through measurements that can more effectively aid urban carbon scenario and predictive modeling. We start by articulating an integrated framework that identifies the mechanisms and interactions that link urban patterns to carbon fluxes along gradients of urbanization. Building on a synthesis of the current observational studies in major US metropolitan areas we develop formal hypotheses on how alternative development patterns produce different carbon signatures and how these signatures may in turn influence patterns of urbanization. We focus on two key aspects of carbon cycling in urban environments that couple urban patterns to carbon fluxes: vegetation dynamics and travel behavior. We then identify a set of observations and research designs to test such hypotheses across two bioregions: Seattle (moist, temperate) and Phoenix (arid). Using these case examples we propose a monitoring strategy and modeling framework to study and assess urban carbon budgets.

2. Urban Carbon Cycle

In considering the urban CO2 (carbon) cycle, it is important to carefully differentiate the coupled changes in carbon stocks versus changes in carbon fluxes. A carbon stock is a pool of carbon (e.g. plant wood material) which can be in a solid, liquid, or gaseous state. A carbon flux is an addition or subtraction from a carbon pool (e.g. plant photosynthesis or combustion). Characterizing carbon stocks in the form of soil carbon, dead woody debris, and live vegetation is central in determining the net ecosystem productivity (NEP) of an area and overall habitat characteristics. NEP is the difference between gross primary productivity (GPP, plant photosynthesis) and ecosystem respiration (both autotrophic plant maintenance respiration (RA) and heterotrophic microbial respiration (RH)).

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NEP = GPP - (R_H + R_A)
\]  

NEP can be directly measured in the field through biometric methods. Positive NEP values indicate that an ecosystem is a net sink of atmospheric CO2, while negative NEP indicates that an ecosystem is emitting more CO2 through respiration processes to the atmosphere than it is removing through photosynthesis. NEP differs from net primary productivity (NPP) in that NEP accounts for total ecosystem respiration process while NPP only accounts for live plant respiration (NPP = GPP – RA). The carbon fluxes of a vegetated terrestrial areas vary on short time scale due weather conditions or seasonal changes and on longer time scales due to changes in forest structure (i.e. carbon stocks). Urban environments have been estimated to be significant sources of global atmospheric CO2 emissions (fluxes), with some studies suggest up to 80% (Churkina 2008). Anthropogenic carbon emissions through activities such as energy generation or transportation are a flux to the atmosphere which affects the stock of carbon in the atmosphere and subsequently interacts with vegetation.

3. Linking Urban Patterns to Carbon Fluxes

To understand mechanisms linking urban patterns and carbon fluxes we build on theories of complex coupled human-natural systems (Figure 1). In human dominated ecosystem, human and ecological factors, such as demographic and economics coupled with geomorphology and climate, affect human and ecological patterns and processes such at multiple scales. Ultimately these interactions affect ecosystem function (both biotic integrity and human wellbeing) and they can generate system shifts under alternative scenarios. Change in ecosystem functions feed back on human activities and wellbeing.

Urbanization can fundamentally alter carbon fluxes and NEP through changes in land cover and creation of impervious surfaces, filling of wetlands, landscape fragmentation, and the application of fertilizers. Ecosystem productivity also should vary in time at a given site as urbanization proceeds, analogous to disturbance and succession in non-urban ecosystems. Following land conversion (initial disturbance), net biomass accrual (NPP–non-plant respiration) should be maximal according to theory (Odum 1969), slowing as vegetation reaches maturity. Furthermore, waste emissions from human activities affect vegetation function and health and hence NPP (e.g., Gregg et al. 2003, Shen et al. 2008).

![Conceptual Framework of Coupled Human-Natural Systems](image)

**Research Questions and Hypotheses**

We develop a framework to empirically test hypotheses of how alternative development patterns may impose different carbon signatures (spatial and temporal changes in stocks and fluxes) and how these signatures may in turn influence patterns of urbanization (Figure 1). We aim to address four overarching questions:

1. How do urban patterns affect carbon fluxes and stocks along a gradient of urbanization?
2. How do changes in ecosystem function feed back onto urbanization patterns?
3. What are the uncertainties, lags, legacies, and feedbacks associated with urban landuse and infrastructure decisions on carbon fluxes and stocks?
4. How do the interactions between urbanization patterns and carbon processes evolve under future scenarios?

Here we limit our discussion to two initial hypotheses:

Hypothesis 1: Variability in ecosystem productivity across a gradient of urbanization is controlled by the composition and heterogeneity of the urban landscape.

Hypothesis 2: Carbon fluxes vary across an urban-to-rural gradient in relation to land uses through changes in land cover, emissions of pollutants, and modification of microclimate. The relationship is not linear due to differential effects of patterns of urbanization on carbon emissions, sequestration, and accumulation in soil and vegetation.

Mechanisms affecting carbon stocks and fluxes along an urban gradient

Our hypotheses about the variability of carbon stocks and fluxes along an urban gradient are grounded on the known mechanisms affecting carbon stocks and fluxes (modified based on Canadell 2003, Figure 2). The mechanisms influencing carbon stocks (pools of C) are distinct from those influencing C fluxes (rates of exchange per unit biomass). We identify four key mechanisms that affect change in carbon stocks and fluxes along a gradient of urbanization (Figure 3): land use, organic inputs, temperature, and N fertilization.

Carbon fluxes includes both positive (uptake: photosynthesis) and negative (loss: respiration) exchange processes. We hypothesize that the rates of per unit biomass carbon uptake will be higher in the urban core due to favorable growing conditions (human watering, fertilizer, pruning, replacements of landscaping vegetation in the Seattle region (not too hot or dry). C losses (respiration) in urban core will be higher due to increased temperatures and adequate moisture, but the removal of organic inputs (leaf litter and woody debris) will reduce the amount of substrate (stock) for decomposition. Higher urban concentrations of ozone will also dampen C uptake rates, but increased CO2 atmospheric concentrations will increase C uptake rates.

Carbon Stocks will be higher as we move away from the urban core, but we hypothesize that the changes will be non-linear. In addition, C fluxes typically respond and change on much shorter time scales (e.g. hours) than C stock (results of long-term changes in fluxes, respond on the time scale of years). Urban carbon stocks will be lowest at the urban core due to a replacement of potential growing space with buildings and pavement. Organic C stocks are kept artificially low in urban areas through leaf and debris collection and removal, but the fluxes (input rates) would be expected to increase linearly across the urban to rural gradient (directly proportional to

As the amount of C in vegetation biomass (and soils) is expected to increase with decreased development intensity, but decrease with decreasing temperatures and decreased nitrogen fertilization.

Figure 2 Mechanisms affecting carbon stocks (A) and fluxes (B) along an urban gradient (based on Canadell 2003, modified).

Figure 3 The urban carbon gradient hypothesis.

4. Research Methods

To test our methodological framework and better articulate our hypotheses we have developed an initial pilot study using remote sensing and ground-based observations to
Figure 4. A.) Three sample transects were established radiating outward from the Seattle, WA, USA urban core (UTM zone 10N: 549518E, 5273765N). Transects overlaid on 2002 land cover map. Black, red, and pink colors denote high, medium, and low urban, respectively. Green denotes vegetation. B.) Distribution of land cover across the three transects as a function of distance from the central urban core.

determine the variability in ecosystem productivity across a gradient of urbanization and relating it to landscape structure and processes driven by urbanization. We hypothesize that the explicit characterization of land cover and land use variables across a gradient of urbanization is critical to understand the underling mechanisms influencing the relationship between urbanization between landscape heterogeneity, vegetation structure, and carbon fluxes. Land cover provides information on the actual physical patterns and land use provides information about the functional use of the land. We use remote sensing-based land-cover classifications to characterize changes in urbanization in the Seattle region. We have produced a systematic classification of 30-m resolution remote-sensing images for the Central Puget Sound for five time steps (Landsat TM 1986, 1991, 1993, 1995, 1999, 2002, and 2007) (Alberti et al. 2004) Parcel-level GIS data and road networks data was obtained from the counties, and attribute data including land use, building units, and year built of the existing development are derived from the assessor records.

We expect that household characteristics will help explain the variability of carbon fluxes across development patterns along a gradient of urbanization (Baker et al. 2007). Using available household surveys we will estimate baseline household carbon emissions that can be related to development patterns across the suite of development typologies. We will use census data in conjunction with lifestyle characteristics databases (such as the Claritas Prizm surveys) to determine how socio-economic characteristics are associated with household carbon flux rates. We will complement these data with the Tax Assessor’s parcel-level data to estimate the building footprint, occupant density, lawn and impervious surface area, vegetation, and demographics. Building upon the work by Baker et al. (2007) we will use spatially explicit household surveys to couple socioeconomic and housing patterns.

A. Vegetation Carbon Stocks

An initial pilot study delineates three transects (Figure 4) and use a stratified random sampling approach to select 150 plots, with a radius of 15 meters distributed across five land cover classes and across the transects. The land cover classification include: high urban, medium urban, low urban, mixed forest, and coniferous forest (Figure 5). We will sample 30 plots per cover type. The transects were further divided into 3 sections (0-7.5km, 7.5-30km, >30km from the Seattle urban core) based on the observed distribution of land cover and impervious surface area (Figure 5). Within each of the sections, 10 plots per cover type were sampled (random sampling across all three transects).

B. Field Measurements

Our initial focus is aboveground (plants with a diameter greater than 5-cm at a height of 1.3 m, residential yards, and dead woody debris (diameter greater than 10 cm and length greater than 1 m)). Vegetation carbon stocks and NPP are quantified through biometric methods (Fahey and Knapp 2007). Using plant-diameter measurements and allometric equations (species specific where possible), we estimate carbon stocks in the live and dead carbon pools. In the future we plan to add plant photosynthesis and soil respiration measurements which will supplement the plot surveys to provide information about instantaneous flux responses. Soil carbon stocks will be estimated through core samples and measurements of depth of the litter layer.

C. Social Surveys

Coupled with field measurements we develop strategy to collect observations of households. While household-level emission data are useful to assess the variability of carbon emissions associated with household socioeconomic characteristics, using spatially explicit household surveys will allow us to couple socioeconomic and housing patterns and assess their effects on carbon emissions. We design a strategy to link spatially explicit surveys on residential location, demographics, and travel-mode choices are available for Seattle Puget Sound (Transportation Panel, Murakami and Watterson 1992).

5. Pilot Study Initial Findings

Our initial observations (currently underway) will provide an empirical basis for refining our framework and hypotheses. The carbon stored in the living and dead vegetation in the selected plots ranges between 0 and 154.5 Mg C ha\(^{-1}\) in live biomass (Figure 6) and between 0 and 21.5 Mg C ha\(^{-1}\) in dead biomass. The distribution of carbon in live biomass across the land cover classes is shown in Figure 6. As expected, the forested plots have the highest carbon storage, but we found significant amount of carbon across the different developed sites and it varies considerably. While the results are only for a partial sample (results to date) the terrestrial carbon stocks within many of the Seattle urbanized plots within 7.5 km of downtown Seattle are significantly higher than the national average carbon density for trees in forests 53.5 (Birdsey and Heath 1995) and of the initial Seattle observations are comparable to terrestrial carbon stocks.
with rain forest (e.g. Pyle et al. 2009 reported live vegetation carbon stocks of ~150 Mg C ha\(^{-1}\) in several undisturbed Amazonian rain forests).

![Figure 6 Preliminary data showing the relationship between land cover and terrestrial aboveground carbon stocks in live in vegetation.](image)

6. Future Scenarios

Advancing the study of coupled human-natural systems in urbanizing regions requires moving beyond idiosyncratic studies towards integrated, cross-regional comparisons (Grimm et al. 2008). The success of such studies depends on developing a robust comparative framework and common metrics and methods for identifying and testing hypotheses of similarities and differences in both urbanization patterns and mechanisms governing urban ecosystems dynamics. In our study we use a gradient approach, field observations, and social surveys to gain insights on the mechanisms that link urbanization patterns to carbon fluxes in metropolitan regions by focusing on vegetation dynamics and household behaviors.

Given biophysical and social influences on urbanization, carbon fluxes and ecosystem responses are likely to exhibit regional differences (Grimm et al. 2008). Both socio-demographic and socio-economic factors are key drivers of urbanization patterns, but these patterns are significantly influenced by a biophysical template of regional climate and geomorphology. We expect that differences in socioeconomic and biophysical characteristics between the metropolitan regions will drive alternative carbon footprints and influence both the nature of the coupling and strength of feedbacks across a gradient of urbanization. We expect that patterns of development drive emissions from transportation in both metropolitan regions, thus differences in land use policy and transportation infrastructure may be key mechanisms. Enhanced water

availability through extensive modification of hydrologic structure and change in thermal conditions may be the predominant mechanisms by which urban carbon fluxes are changed in arid metropolitan areas such as Phoenix. Forest loss and fragmentation may control the relationship between urbanization and carbon fluxes in temperate regions such as Seattle. These regions may thus be sensitive to different land-use policy and infrastructure scenarios.

7. Conclusions

Urbanizing regions are major determinants of global and continental scale changes in carbon budgets through land transformation and modification of biogeochemical processes (Pataki et al. 2006). However, empirical data of the effects of urbanization on carbon fluxes are extremely limited to establish the underlying processes and mechanisms linking urbanization patterns and carbon fluxes. Also unknown is how patterns of urbanization interact with household behaviors and consumption choices. Typically, quantifications of carbon emissions are based on estimates of bottom-up emissions estimates based on fossil fuel and energy consumption (Grimmond et al. 2002). Similarly, changes in carbon uptake of vegetation have been largely generated from remote sensing-based estimates of biomass stocks (Imhoff et al 2004) and ecosystem models largely parameterized for ‘natural’ conditions (Churkina 2008). Predictions of future trajectories of carbon fluxes associated with urbanization and increasing urban populations require an
understanding and systematic evaluation of how alternative patterns of urban development (i.e., centralized versus sprawling) affect the carbon budget over the long term.

In this paper we have articulated a set of hypotheses about the key mechanisms that affect terrestrial carbon stocks and fluxes across a gradient of urbanization in temperate regions. Further, we have developed a strategy to quantify urban carbon signatures (spatial and temporal changes in fluxes) through measurements that can more effectively aid urban carbon scenario and predictive modeling.

References:


Acknowledgements: This work has been supported by the Bullitt Foundation and NSF BE/CHN 0508002. Thanks for Michael Strohback and Bryan Yoon for assistance in the field.