Carbon Signatures of Development Patterns along a Gradient of Urbanization

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Problem Statement

• Urbanizing regions are major determinants of global and continental scale changes in carbon budgets through land transformation, modification of related biogeochemical processes, and concentration of fossil fuel combustion activities[1].

• Recent studies of biogeochemistry in urbanizing regions provide evidence of the complex mechanisms by which urban activities affect C fluxes and stocks[1,2,3] .

• There are few empirical data on the underlying mechanisms linking urban patterns and carbon budgets to systematically evaluate how alternative patterns of urban development interact with ecosystem processes across a gradient of urbanization[4].

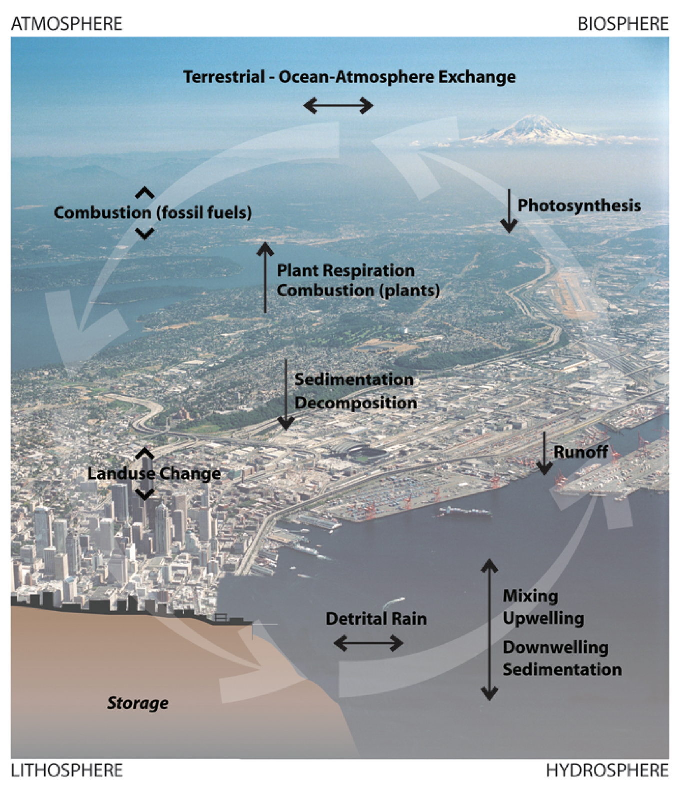

Figure 1: Changes in biogeochemistry with urbanization[4]

Urban Patterns and Carbon: A Synthesis

Table 1 provides a synthesis of what is known to date of the relationships between patterns and C stocks and fluxes, and what is highly uncertain or unknown. Our synthesis focuses on four main characteristics of urban patterns, including **urban form** (clustered vs. dispersed), **density** (high vs. low population density), **connectivity** (degree of integration of the transportation infrastructure), and **heterogeneity** (land-use mix)[5]

Land use (Intensity)	Land cover (Change)	Transportation (Mode)	Infrastructure (Energy/Water)				
↑Energy use ↑CO2 Emissions ↑Heat	↑Impervious Surface ↑Grassland ↓Forest Cover	CO2 Emissions Heat	↑CO2 Emissions ↑Heat	Climate	?Photosynthesis ?Plant Growth ↑Nutrient loss	↑CO2 Emissions ↑Temperature ↑Soil respiration	Hutyra et al. 2011; Pataki et al. 2006
↑Energy use ↑Water use	↑Impervious Surface ↑Grassland ↓Forest Cover	↑Impervious Surface ↑Grassland ↓Forest Cover	↑Dams ↑Water use ↑Heat	Hydrology	?Water availability	↑Nutrients ↓N retention	Kaye et al. 2006; Grimm et al. 2008
↑Fertilizers ↑Pesticides ↑Herbicides ↑Toxic emissions	↑Impervious Surface ↑Grassland ↓Forest Cover	↑CO2, NOx, CO, SO2, VOCs ↑Road salting	↑CO2 ↑NOx ↑CO ↑SO	Biogeochemical	?Nutrient availability	↑Temperature ↑Nutrients ? N fertilization ? CO2 fertilization	Churkina et al. 2010; Pickett et al. 2008; Coutts et al. 2007
↑Forest fragmentation ↓Riparian area ↑Invasive species	↑Forest fragmentation ↓Riparian area ↑Invasive species	↑Forest fragmentation ↓Riparian area ↑ Atmospheric pollution	↑Forest fragmentation ↓Riparian area ↓Wetlands	Biotic interactions	?Carbon/Water use efficiency ?Photosynthesis	?Carbon/Water use efficiency	Pouyat et al. 2002.
!	!	!	!	Ecosystem Processes	Carbon Stocks	Carbon Fluxes	References

Table 1 Urban Patterns and Carbon Stocks and Fluxes[5]. Synoptic table relating dimension of urban patterns to carbon stocks and fluxes through ecosystem processes. For example increasing land-use intensity increases energy use and produces changes in microclimate (increase in temperature) that affect carbon fluxes. Arrows indicate the direction of the effects and question marks symbols indicate uncertain relationships.

References

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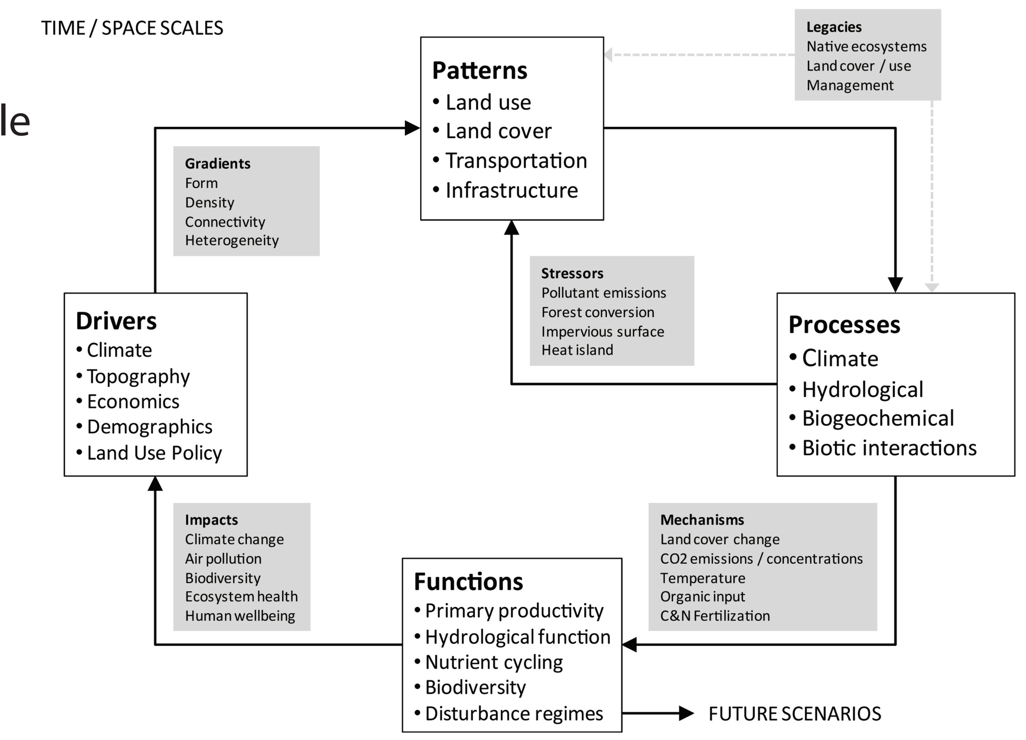
Conceptual Framework and Hypotheses[5]

Building on mechanisms established in the literature that link urban patterns and the C cycle (see Table 1), we articulate a framework (Figure 2) and set of testable hypotheses on how these mechanisms vary across a hypothetical gradient of urbanization (Figure 3).

Figure 2: Conceptual framework linking urban patterns to C stocks and fluxes. To understand the effects of urban development on the C cycle, a series of causal links and feedbacks need to be established between drivers of urbanization, patterns of land use and infrastructures, biophysical processes, and ecosystem function. We need to define the time and spatial scales of their interactions and emerging multiple equilibria under plausible future scenarios.



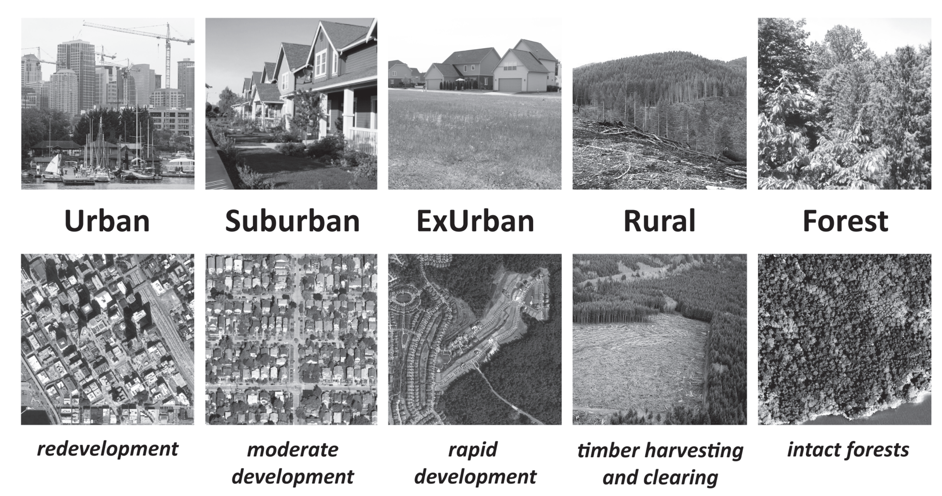


Figure 3: Hypothetical gradient. Defined by a suite of variables including the distance from the central business district (CBS), population density, intensity of land use, and dominant land cover. The gradient ranges from the urban core (characterized primarily by redevelopment) to suburban areas (where rapid development is occurring) to exurban areas (sparsely settled areas surrounded by natural habitats), rural areas (sparsely settled areas surrounded by agricultural field), and intact forest.

Research Questions and Hypotheses

1. What factors control changes in carbon stocks and fluxes along a gradient of urbanization)?
   H1: Variability in carbon stocks and fluxes across gradients of urbanization is controlled by *complex interactions between land cover, emissions, organic inputs, temperature, and N fertilization*.

2. What are the tradeoffs between stocks and fluxes associated with patterns of urbanization?
   H2: Carbon stocks and fluxes vary across an urban-to-rural gradient in relation to h*ousehold characteristics, their residential location preferences, and travel behaviors*, which affect land cover and transportation emissions.

3. What are the uncertainties, lags, legacies, and feedbacks associated with urban land use and infrastructure decisions on carbon fluxes and stocks?
   H3: The relationships between urban patterns and carbon stocks and fluxes are influenced by *natural and land-use legacies*.

4. How will the interactions between urbanization patterns and carbon processes evolve under future scenarios?
   H4: Urban development choices are sensitive to carbon mitigation policies, but their ability to shape the urban structure is highly dependent on the *existing built infrastructure*.

Box 1 Mechanisms affecting terrestrial carbon stocks and fluxes along an urban gradient[5]

We identify five key mechanisms that affect change in C stocks and fluxes along a gradient of urbanization: *land-cover change, emissions, organic inputs, temperature, and N fertilization.* Taken together, we hypothesize that these five mechanisms will produce nonlinear variations in C stocks and fluxes across the urban gradient. The amount of C in vegetative biomass (and soils) is expected to generally increase with decreased development intensity, with a small peak in the older suburbs and exurbs where larger lots have had time to accumulate biomass following initial clearing. Fluxes (per unit mass) might be expected to decrease with decreasing temperatures and decreased N and CO2 fertilization but ultimately be highest in the least dense areas because of the large amount of photosynthetically active vegetation in forests.

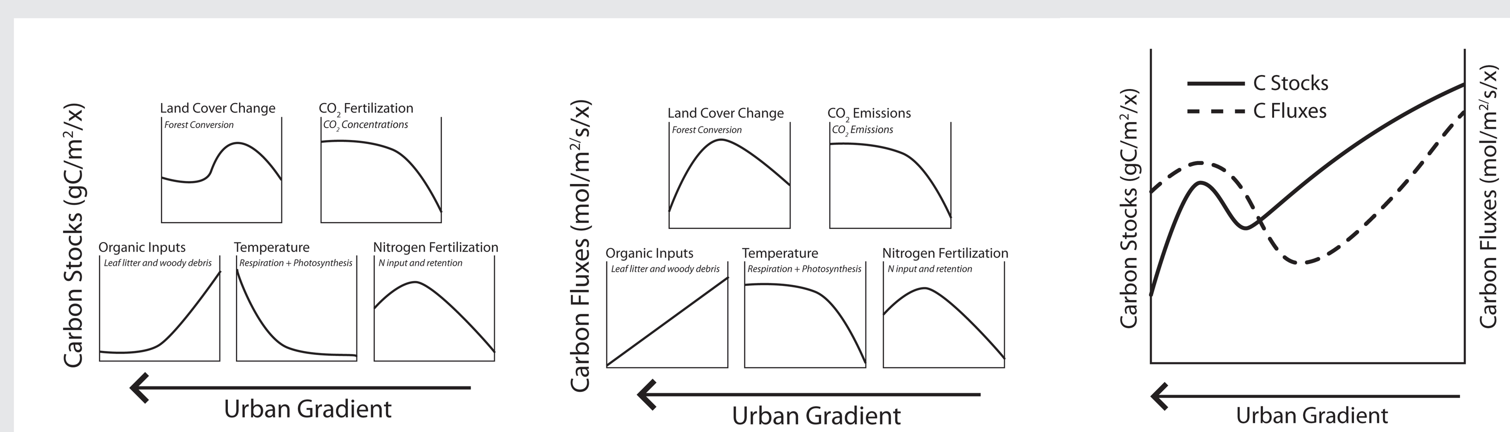


Figure 4: Hypotheses of mechanisms linking urban patterns to C stocks (a) and fluxes (b) across a gradient of urbanization. Changes in stocks and fluxes (3a and 3b) are plotted relative to changes in the driving variables (X), where X is in the unit of the particular process in question. Figure 3c provides a synthesis hypothesis of the urban C gradient.

Conclusions

• the Seattle metro area has a remarkable magnitude of C stocks

• findings point to a complex relationship between land use and land cover across the urban to rural gradient

• empirical data for diverse sources of C sinks is critical to understanding the mechanistic relationships of the urban C cycle

• patterns of rapid urban expansion have important implications for future scenarios of net emission reductions.

• installation of towers can support long term monitoring of carbon fluxes with the aim of supporting informed policy

• scenarios, leveraging observations and a mechanistic understanding, can explore alternative and divergent trajectories of land use land cover change in order to test policy strategies

Box 2: Case Study of Urban Carbon Stocks along a Gradient of Urbanization in the Seattle Metropolitan Area[6]

Initial observations in the Seattle Metropolitan Area provide insights on how C signatures vary across land-cover types on a gradient of urbanization. We used a stratified random sample of 150 plots, with a radius of 15 m, to estimate aboveground live biomass across the Seattle urbanizing region in five land-cover classes and across three transects (Figure 5). We sampled five land-cover types including high-density urban, medium urban, low urban, mixed forest, and coniferous forest; thirty sites were sampled per cover type. We used a Landsat TM (2002) land-cover classification to stratify our field samples[7,8].

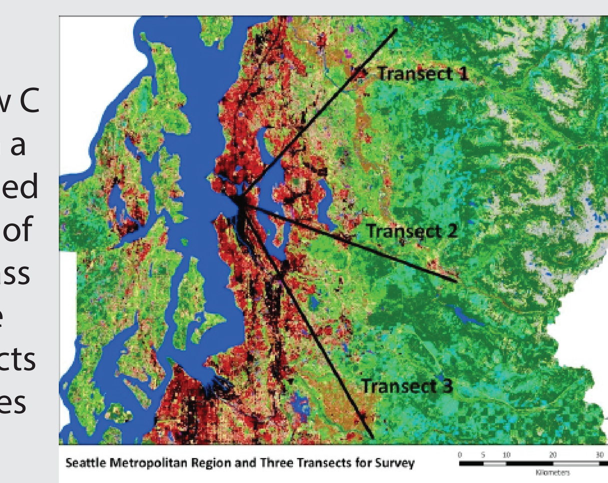


Figure 5: Sample transects for Seattle regional carbon analysis overlaid upon a 2002 land cover map.

We quantified aboveground C stocks and assessed site characteristics within the sampled five different land-cover classes (Hutyra et al. 2011a). Aboveground live biomass across the **Seattle region was 89 ± 22 Mg C^oha^{-1} per year in 2002** (including both urban and forest area), with an additional 11.8 ± 4 Mg C^oha^{-1} of coarse woody debris (CWD) biomass. The average biomass stored within forests and urban covers was 140 ± 40 and 18 ± 13.7 Mg C^oha^{-1}, respectively (Figure 6).

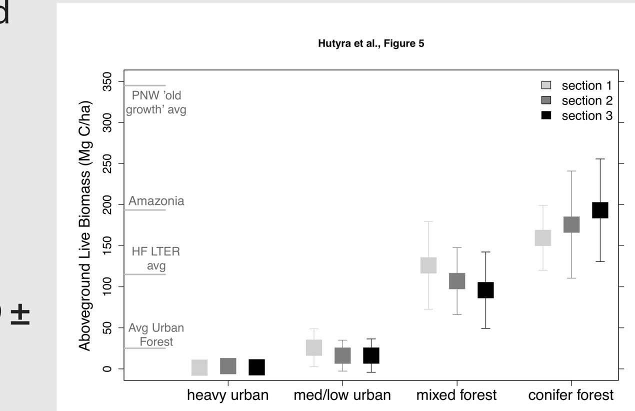


Figure 6: Carbon Stocks along the Seattle Metro Area

These results are substantially larger than the 25.1 Mg C^oha^{-1} (urban forest land only, including both above- and belowground C) reported by Nowak and Crane (2002) for ten U.S. cities and larger than the average of 53.5 Mg C^oha^{-1} for all U.S. forests (urban and rural) reported by Birdsey and Heath (1995). The carbon stocks of regional confier forests (182 ± 60 Mg C^oha^{-1}) are remarkable when compared to
The remarkable magnitude of observed C stocks in the rapidly urbanizing Seattle the biomass stored in Amazonian rainforests (197 ± 11.6 Mg C^oha^{-1})[9].

Using a time series analysis of land cover, Hutyra et al.[10] also explored the aboveground C stock patterns over two decades (1986 to 2007) in the Seattle Metropolitan Statistical Area (Figure 7). Land-cover change contributed an average annual loss of 1.2 Mg C^oha^{-1} in terrestrial C stores. **These vegetative C losses corresponded to nearly 15 percent of the regional fossil fuel emissions.**

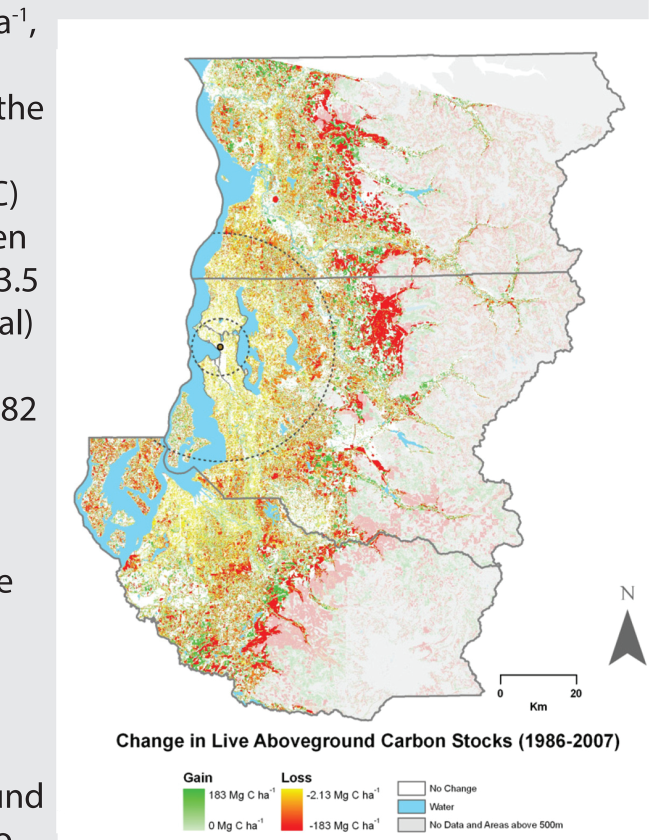


Figure 7: Map of with the change in total estimated aboveground carbon stocks between 1986 and 2007 in the lowland Seattle Metropolitan Statistical Area land cover[10]. Radial rings around the Seattle urban core indicate a 7.5 and 30 km distance.