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Mapping carbon storage in urban trees with multi-source remote sensing data: Relationships between biomass, land use, and demographics in Boston neighborhoods

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HIGHLIGHTS

- Used imagery and LiDAR to develop a high resolution urban biomass map for Boston, MA
- Tree carbon storage was 355 Gg (28.8 Mg C ha^{-1}) for the City of Boston, MA
- No significant correlations between tree biomass and Boston neighborhood demographics
- Dense urban areas can contain considerable tree canopy cover and biomass stocks

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ABSTRACT

High resolution maps of urban vegetation and biomass are powerful tools for policy-makers and community groups seeking to reduce rates of urban runoff, moderate urban heat island effects, and mitigate the effects of greenhouse gas emissions. We developed a very high resolution map of urban tree biomass, assessed the scale sensitivities in biomass estimation, compared our results with lower resolution estimates, and explored the demographic relationships in biomass distribution across the City of Boston. We integrated remote sensing data (including LiDAR-based tree height estimates) and field-based observations to map canopy cover and aboveground tree carbon storage at ~1 m spatial scale. Mean tree canopy cover was estimated to be 25.5 ± 1.5% and carbon storage was 355 Gg (28.8 Mg C ha^{-1}) for the City of Boston. Tree biomass was highest in forest patches (110.7 Mg C ha^{-1}), but residential (32.8 Mg C ha^{-1}) and developed open (23.5 Mg C ha^{-1}) land uses also contained relatively high carbon stocks. In contrast with previous studies, we did not find significant correlations between tree biomass and the demographic characteristics of Boston neighborhoods, including income, education, race, or population density. The proportion of households that rent was negatively correlated with urban tree biomass ($R^2 = 0.26$, $p = 0.04$) and correlated with Priority Planting Index values ($R^2 = 0.55$, $p = 0.001$), potentially reflecting differences in land management among rented and owner-occupied residential properties. We compared our very high resolution biomass map to lower resolution biomass products from other sources and found that those products consistently underestimated biomass within urban areas. This underestimation became more severe as spatial resolution decreased. This research demonstrates that 1) urban areas contain considerable tree carbon stocks; 2) canopy cover and biomass may not be related to the demographic characteristics of Boston neighborhoods; and 3) that recent advances in high resolution remote sensing have the potential to improve the characterization and management of urban vegetation.

1. Introduction

Urbanization is a significant driver of global environmental change (Imhoff et al., 2004; Foley et al., 2005). In coming decades, increases in global population and socioeconomic advancement in developing nations will accelerate urban expansion. Up to 70% of the global population will live in cities by 2050 (UNFPA, 2007) with urban land cover expanding up to 3 times its current area (Angel et al., 2005; Seto et al., 2011). Urban growth creates widespread ecosystem modification, dramatically altering land cover in and around urbanizing regions. Current estimates of urban area range from 0.2 to 3% of global land cover (Schneider et al., 2010); however, urban ecological footprints and high demand for natural resources lead to modification of ecosystems and land covers at a much broader scale (Seto et al., 2012; Defries et al.,

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2010; Potere and Schneider, 2007; Alberti et al., 2003; Sadik, 1999). Land cover changes associated with urbanization decrease carbon storage (Seto et al., 2012; Hutyra et al., 2011a; Imhoff et al., 2004), alter biogeochemical cycles (Grimm et al., 2008; Pataki et al., 2006; Kaye et al., 2006), and influence micrometeorology and regional weather patterns (Oke, 1982; Zhang et al., 2004; Zhou et al., 2011).

The process of urban development results in immediate losses of vegetation, however, after initial land conversion, urban land cover gradually becomes composed of heterogeneous patches of impervious surfaces, buildings, street trees, urban forests, and managed green spaces (Goetz et al., 2003; Luck and Wu, 2002; Zhou and Troy, 2008). Although urban areas are the major centers for energy consumption and emissions of CO_2 (IEA, 2008), they also sequester some of the very same emissions they produce; namely in urban soils and foliar and woody biomass (Imhoff et al., 2004; McPherson et al., 2005; Golubiewski, 2006; Raciti et al., 2011; Briber et al., 2013). Urban vegetation can also aid in local carbon mitigation strategies (Nowak and Crane, 2002; McPherson et al., 2005). Though potential urban carbon sinks are likely to be modest, urban vegetation functions as a vital component of urban ecosystems and the carbon cycle while also providing aesthetic, economic, and ecological value to urban dwellers (Nowak and Crane, 2002; Raciti et al., 2012).

Tree cover makes up a significant portion of land cover within the urban mosaic, with proportions in major US cities ranging from ~10 to 54% of land area (Nowak and Greenfield, 2012). However, 'urban' is a unique and inconsistently defined land cover that can store large stocks of carbon. For example, Raciti et al. (2012) compared three commonly used urban definitions and found that vegetation carbon stock density estimates ranged from 37 ± 7 to 66 ± 8 Mg C ha^{-1} for the urban portions of the Boston metropolitan area. Hutyra et al. (2011b) found an average of 89 ± 22 Mg C ha^{-1} (57% mean canopy cover) in vegetation within the Seattle Metropolitan Statistical Area lowlands, a region that is home to over 3.2 million people. This vast range in urban C stock estimates reflects both ambiguous definitions of urban and urban land cover heterogeneity itself.

Societal benefits of urban forest, like urban forest extent itself, are not equally distributed within and across metropolitan areas (Iverson and Cook, 2000; Flocks et al, 2011; Szantoi et al, 2012). Szantoi et al. (2012) found that urban tree cover was related to ethnicity, age, education level, mean annual household income, and housing tenure in Miami-Dade County, Florida. Heynen et al. (2006) found that lower household incomes, a higher proportion of renters, and a higher proportion of minority residents were all correlated with lower residential tree canopy cover in Milwaukee, WI. The ability to accurately map urban tree cover, combined with the use of quantitative tools such as the tree Priority Planting Index (Nowak and Greenfield, 2008), can assist communities in locating areas where urban greening initiatives will have the largest positive influence on communities (Raciti et al., 2006).

Researchers have used satellite data to monitor deforestation, map biomes, and extract vegetation characteristics such as Leaf Area Index (LAI) and plant productivity. Recent studies have begun to extract important functional characteristics such as biomass, phenology, and plant productivity for urban vegetation (Zhang et al., 2004; Myeong et al., 2006; Diem et al., 2006; O'Neil-Dunne et al., 2012). Myeong et al. (2006) used Landsat TM imagery from Syracuse, NY to quantify the aboveground carbon storage of urban trees by using ground samples and a US Forest Service (USFS) urban tree model to estimate per pixel biomass. The agreement between a Normalized Difference Vegetation Index (NDVI) and biomass in Syracuse was significant, but 30 m resolution Landsat data lacks the detail needed for accurate urban vegetation mapping, including the ability to differentiate between lawns, shrubs, and trees, which vary considerably in their contribution to above ground biomass.

Very high resolution imagery from the commercial satellites IKONOS and QuickBird have been used to map urban vegetation in many cities worldwide including Hong Kong (Nichol and Wong, 2007), Vancouver, BC (Tooke et al., 2009), Kuala Lumpur (Chen et al., 2009), and Los Angeles (McPherson et al., 2013). Some of the more recent works have integrated LiDAR data to further refine classification accuracies (Chen et al., 2009; Huang et al., 2013). Segmentation and object-oriented approaches have also been used to identify species in the urban canopy. Walker and Briggs (2007) used 0.6 m true color digital aerial photography and an object oriented analysis to classify urban vegetation and various genera in Phoenix, AZ. Despite the availability of only 3 spectral bands, they were still able to map urban vegetation with an accuracy of 81% and differentiate between species with moderate success. With the exception of the work done by Myeong et al. (2006), Nowak and Crane (2002), Hutyra et al. (2011a), and Davies et al. (2011, 2013), few studies have used remote sensing to estimate biomass in urban environments. None of the aforementioned studies provided biomass maps that are spatially explicit beyond the location of broad land use or vegetation classes, for which a single mean biomass value was applied. LiDAR-based tree height data have been used to estimate biomass in forested systems (e.g. Kellndorfer et al., 2013), but these data have not been widely used to model tree biomass in urban areas beyond the identification of broad vegetation types (e.g. Davies et al., 2011).

Spatially detailed maps of urban vegetation represent an important tool for urban forest management and for the modeling of biogenic carbon dynamics and ecosystem services within urban systems. In this paper, we demonstrate 1) how combining multisource, very high resolution remotely sensed data can help improve the mapping of tree canopy cover, 2) how LiDAR-based tree height metrics can be used to estimate tree biomass in urban areas, 3) how the spatial scale of remote sensing data influences our ability to resolve urban biomass, and 4) how patterns of biomass in the City of Boston differ across neighborhoods with widely varying demographic characteristics.

2. Methods and data

Detailed below is our approach to estimating urban tree biomass using multiple remotely sensed data sources. We developed a multi-level segmentation process to delineate crown and canopy area using a combination of QuickBird imagery and LiDAR point cloud data. Direct field measurements of tree diameters and allometric scaling were used in conjunction with the segmented canopies to build a height-based model of urban tree biomass. Model estimates were validated using both open-grown and closed-canopy trees.

2.1. Site description

Our analysis focused on Boston, Massachusetts (42.356°N, −71.062°W; land area of 125 km^2). Boston is the northernmost city of the largest megalopolis in the United States, which extends from Boston to Washington DC (the 'BosWash corridor'). The 'BosWash' region typifies dispersed urban sprawl style development and is home to 20% of the U.S. population (Schneider and Woodcock, 2008). Like many North American cities, the greater Boston region has experienced significant population growth and subsequent widespread urbanization over the past several decades, most of which has occurred well outside of the urban core. As one of North America's oldest cities, Boston proper has been extensively developed and built-out; however, the City has some of the nation's oldest and most well known parklands and open spaces (e.g. Boston Common and The Emerald Necklace). Boston is commonly classified in the temperate deciduous forest biome and a humid continental climate under the Koppen climate classification system. Native vegetation of the area is dominated by deciduous trees including red oak (*Quercus rubra*), red maple (*Acer rubrum*), sugar maple (*Acer saccharam*), Eastern hemlock (*Tsuga canadensis*), and black cherry (*Prunus serotina*). Similar to many other urban areas, Boston has great diversity in its flora, due to the introduction of exotic,