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Research paper

The impact of urban residential development patterns on forest carbon density: An integration of LiDAR, aerial photography and field mensuration

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HIGHLIGHTS

- The impact of urban residential patterns on forest carbon density was explored.
- LiDAR and aerial photography were integrated for spatially explicit carbon mapping.
- Charlotte has a total amount of 3.8 million tonnes carbon ($298 million value).
- The impact of urban patterns varies across different densities of neighborhoods.

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ABSTRACT

Urban development continues to reshape forest landscapes and influence the carbon storage capacity of trees. To date, the impact of urban patterns on forest carbon density remains to be systematically evaluated. A major challenge is the lack of accurate and spatially explicit estimates of forest carbon storage over the entire urbanized area. In this study, we first developed an integrated approach that synergizes remote sensing LiDAR (light detection and ranging) and aerial photography to efficiently model landscape-level forest carbon storage in an urban environment at a fine resolution of 20 m. Using a case study in the Charlotte Metropolitan Region, USA, we were able to determine the total amount of carbon stored in the local forests to be 3.8 million tonnes ($298 million value), with an average carbon density of 53.6 t/ha. We further applied statistical analysis to investigate the relationship between urban developed patterns (i.e., landscape metrics) and forest carbon density in four types of residential neighborhoods (categorized by percent built-up ranging from low, medium-low, medium-high to high density). Results indicate a decrease of forest carbon density with an increase of carbon variance in neighborhoods where the intensity of development became higher. Residential neighborhoods with a higher built-up density were more likely to be affected by a larger number of landscape metrics. This indicates that a proper design of the neighborhood level urban spatial patterns (especially in high density neighborhoods) is essential to maximizing forest carbon storage at the landscape level.

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1. Introduction

Urban forests (i.e., trees in urban areas) are high quality carbon sinks to mitigate climate change by capturing carbon dioxide (CO_2) from the atmosphere. In the United States, trees growing on the urban land that accounts for 3% of the total landmass can sequester 14% of the amount of carbon sequestered by the entire nation's forests (Heath, Smith, Skog, Nowak, & Woodall, 2011). Nowak, Greenfield, Hoehn, and Lapoint (2013) estimated that the volume of carbon stored by urban forests in the United States is 643 million tonnes ($50.5 billion value) and their annual carbon sequestration is approximately 25.6 million tonnes ($2.0 billion value). With continued urban growth and sprawl, forests in these areas are expected to play a more critical role in climate change mitigation and associated initiatives, such as carbon offset trading (Poudyal, Siry, & Bowker, 2011; Strohbach & Haase, 2012).

Recent studies have demonstrated that the amount of carbon (per unit of tree cover) stored by urban forests is spatially non-stationary and highly related to regional context (Liu & Li, 2012;

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McPherson, 1998; McPherson, Xiao, & Aguaron, 2013; Nowak et al., 2013; Strohbach and Haase, 2012; Zhao, Kong, Escobedo, & Gao, 2010). For example, during the mapping of urban forest carbon storage across the conterminous United States, McPherson et al. (2013) and Nowak et al. (2013) found large variations in the aggregated city-level estimates of carbon density, mainly attributed to the complex local and regional determinants (e.g., land development patterns) that influence tree species composition, stand density and forest growth. Within city boundaries, the differences in tree management practices, neighborhood age or land-use types further reveal high impacts on forest carbon storage across neighborhoods (Grove et al., 2006; Zhao et al., 2010). Despite these encouraging findings, few studies have systematically quantified the impacts of urban development patterns on forest carbon density at the inner-city neighborhood level (Ren et al., 2013). Landscape patterns are often quantified using landscape metrics, which refer to a broad range of quantitative indices representing spatial heterogeneity, such as characteristics of patches, classes of patches, or entire landscape mosaics (Herold, Scepan, & Clarke, 2002; McGarigal, Cushman, Neel, & Ene, 2002; Plexida, Sfougaris, Ispikoudis, & Papanastasis, 2014; Richardson & Moskal, 2011; Riitters et al., 1995; Seto & Fragkias, 2005; Wu, Shen, Sun, & Tueller, 2003). Judiciously analyzing the relationship between landscape metrics and forest carbon density informs the practices on efficient city tree management and sustainable urban environmental design (Termorshuizen & Opdam, 2009; Xiang, 2014).

To date, a major challenge confronting such analysis is the lack of accurate, up-to-date, and spatially explicit carbon estimates over the entire urban landscapes. For logistical and privacy reasons (up to 90% of urban trees are on private land in the U.S.), field observation using limited number of plots may cause large errors in sampling and leads to high uncertainties in carbon estimation (Clark, Matheny, Cross, & Wake, 1997; McPherson et al., 2013). Conventional optical remote sensing provides a viable alternative to study Earth surface of large geographical coverage in a timely and cost-effective manner. However, researchers have noticed that optical sensors are limited in their capabilities for capturing the understory vegetation in multi-strata forests, and the inaccurate retrieval of tree vertical structure makes carbon estimation a challenging task (Lu, 2005). Over the past decade, airborne LiDAR technology has attracted increased attention for measuring forest carbon density across biomes (Chen, Wulder, White, Hilker, & Coops, 2012). Lefsky et al. (2002) applied LiDAR to estimate aboveground biomass (ABG) of three species groups (temperate deciduous, temperate coniferous, and boreal coniferous biomes) using a single regression, which still explained 84% of variance in biomass. Asner et al. (2012) developed a universal LiDAR model for four tropical regions to estimate forest carbon density at a relatively high accuracy ($R^2 = 0.80$). In an effort to study urban forests of Oklahoma, Shrestha and Wynne (2012) evaluated the performance of LiDAR biomass modeling at the individual tree level. Despite a high diversity of tree growth rates and plant species types in local forests, their research unveiled a good agreement between LiDAR estimates and field measurements ($R^2 = 0.63$) making LiDAR a promising tool to offer high-accuracy and wall-to-wall forest carbon estimates over large urbanized areas (Seto, Güneralp, & Hutyra, 2012).

The primary goal of this research was to explore the impact of urban development patterns on forest carbon density at the neighborhood level. Here, we emphasize on the residential neighborhoods, because the majority of urban forests are located in these areas where trees also have high impacts on property values (Escobedo, Adams, & Timilsina, in press). To achieve the goal, we integrated LiDAR, aerial photography and field mensuration to extract spatially explicit forest carbon distribution and landscape metrics over the entire urbanizing landscapes of the study area.

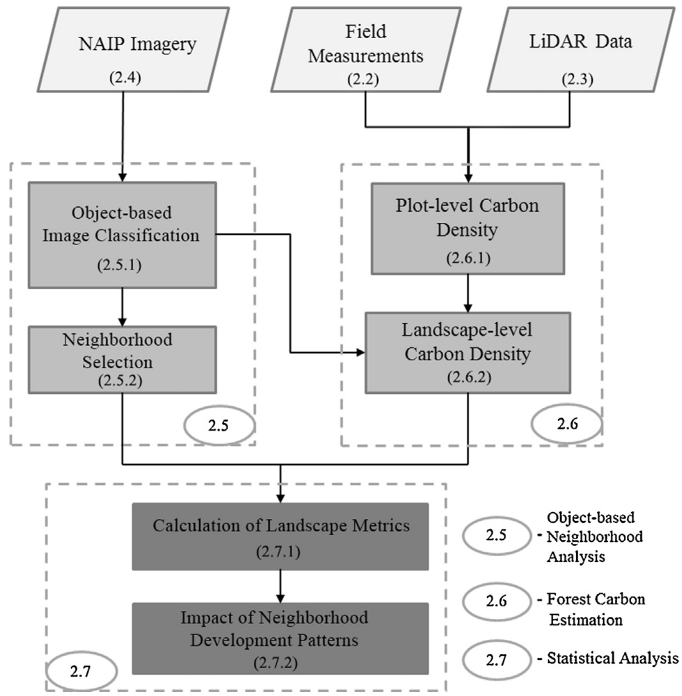

Fig. 1. Analytical schematics for the study with reference to Section 2.

Statistical analysis was then used to quantify the relationship between landscape metrics and carbon density. The flowchart in Fig. 1 summarizes these steps; while the following sections provide greater details and explanations.

2. Methods

2.1. Study area

The study area (1415 km^2 and centered at 35°15′N, 80°50′W) is located in Mecklenburg County of North Carolina, United States (Fig. 2). The region is often referred to as Charlotte–Mecklenburg County or the Charlotte Metropolitan Area. The rolling landscape of the region is characterized by the southern Piedmont physiography with secondary growth forests that have developed on former timber plantation sites and abandoned agricultural lands. Elevation of the County ranges from 252 m above sea level in the north to 159 m in the southern part. Forested landscapes, initially covered by widespread mixed oak forests interspersed with prairies, represent a mix of oak, hickory and pine. Mecklenburg County is one of the fastest developing regions of the southeastern United States. According to a report of U.S. Census Bureau (2013), it has grown in population from 0.4 million in 1980 to approximately 1 million people in 2013, a trend that is expected to continue. During the similar period between 1985 and 2008, the region lost 33% of its tree canopy and gained 60% developed land (Singh, Vogler, Shoemaker, & Meentemeyer, 2012). The rapid population growth, characterized by urban sprawl with low to high housing density, has replaced forest and farmland dominated landscapes with an array of developed land use types including managed treescapes and highly fragmented urban forests.

2.2. Field measurements

A total of 75 circular field plots (0.04 ha each) were measured during the years of 2010–2012 in vegetated areas covering all major forest types. The plots were designed following the typically used i-Tree ECO (Urban Forest Effects; also known as UFORE)