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Identification of fine scale and landscape scale drivers of urban aboveground carbon stocks using high-resolution modeling and mapping

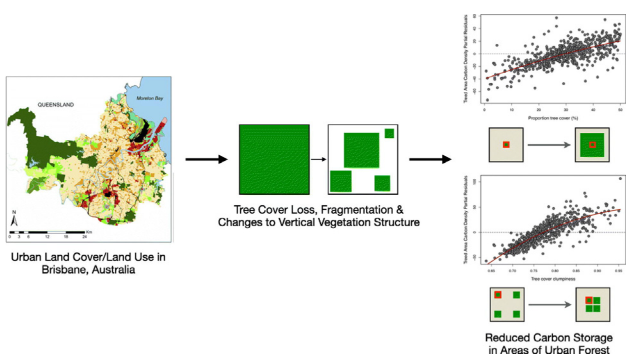
Matthew G.E. Mitchell *, Kasper Johansen, Martine Maron, Clive A. McAlpine, Dan Wu, Jonathan R. Rhodes

School of Earth and Environmental Sciences, The University of Queensland, Brisbane, QLD 4072, Australia

HIGHLIGHTS

- Drivers of urban carbon stocks at different spatial scales are largely unknown.
- We modeled urban carbon stocks at high resolution using LiDAR and field data.
- Foliage density above 5 m and canopy height strongly related to aboveground carbon.
- Carbon densities varied strongly with surrounding tree cover extent and clumpiness.
- Managing urban landscape structure important tool to influence urban carbon stocks.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban areas are sources of land use change and CO_2 emissions that contribute to global climate change. Despite this, assessments of urban vegetation carbon stocks often fail to identify important landscape-scale drivers of variation in urban carbon, especially the potential effects of landscape structure variables at different spatial scales. We combined field measurements with Light Detection And Ranging (LiDAR) data to build high-resolution models of woody plant aboveground carbon across the urban portion of Brisbane, Australia, and then identified landscape scale drivers of these carbon stocks. First, we used LiDAR data to quantify the extent and vertical structure of vegetation across the city at high resolution (5×5 m). Next, we paired this data with aboveground carbon measurements at 219 sites to create boosted regression tree models and map aboveground carbon across the city. We then used these maps to determine how spatial variation in land cover/land use and landscape structure affects these carbon stocks. Foliage densities above 5 m height, tree canopy height, and the presence of ground openings had the strongest relationships with aboveground carbon. Using these fine-scale relationships, we estimate that 2.2 ± 0.4 TgC are stored aboveground in the urban portion of Brisbane, with mean densities of 32.6 ± 5.8 MgC ha^{-1} calculated across the entire urban land area, and 110.9 ± 19.7 Mg C ha^{-1} calculated within treed areas. Predicted carbon densities within treed areas showed strong positive relationships with the proportion of surrounding tree cover and how clumped that tree cover was at both 1 km^2 and 1 ha resolutions. Our models predict that even dense urban areas with low tree cover can have high carbon densities at fine scales. We conclude that actions and policies aimed at increasing urban carbon should focus on those areas where urban tree cover is most fragmented.

* Corresponding author at: Institute for Resources, Environment and Sustainability, The University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada.
E-mail address: matthew.mitchell@ubc.ca (M.G.E. Mitchell).

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1. Introduction

Urban areas and populations around the world are increasing rapidly in size. While 54% of people today already live in cities (UN, 2014), it is predicted that urban areas will triple in size between 2000 and 2030 (Fragkias et al., 2013; Seto et al., 2012) and that urban populations will increase by 63% from 4 to 6.5 billion by 2050 (UN, 2015). Cities are focal areas of human activities that modify ecosystems and biodiversity (Mcdonald et al., 2008), land cover and landscape structure (Cadenasso et al., 2007), biogeochemical cycles (Grimm et al., 2008), and climate (McCarthy et al., 2010), often at fine spatial scales. In particular, cities are increasingly important for the global carbon cycle as they are locations where human impacts on the global carbon cycle are concentrated (e.g., CO_2 emissions, consumption of primary productivity, Imhoff et al., 2004; Dhakal, 2010) and where the impacts of climate change on human populations will be focused (Hunt and Watkiss, 2011). It is therefore critical to understand how urbanization affects carbon dynamics (Gaston et al., 2013). However, our understanding of carbon dynamics in urban ecosystems, and in particular our ability to identify landscape-scale drivers of urban carbon is underdeveloped (Davies et al., 2011; Hutyra et al., 2011). This prevents the effective planning of urban expansion in order to maintain or increase carbon storage.

Urban areas, while small, can still store significant amounts of carbon below and above the ground (Davies et al., 2011; Davies et al., 2013; Hutyra et al., 2011; Nowak et al., 2013; Raciti et al., 2012). As such, citywide estimates of carbon storage are becoming increasingly common as the need to manage cities and their ecosystems for carbon intensifies. In many cases, urban carbon storage has been found to be higher than previously estimated, sometimes by up to an order of magnitude (Davies et al., 2011). While most of these stores are belowground in soil and plant roots (Churkina et al., 2010; Edmondson et al., 2012), aboveground vegetation also stores significant amounts of carbon. Native vegetation clearing for urban growth is becoming increasingly important for aboveground carbon loss and the global carbon cycle (Churkina et al., 2010) with recent estimates that urban expansion will be the cause of ~5% (1.38 PgC) of deforestation and land use change emissions in the pan-tropics between 2000 and 2030 (Seto et al., 2012). Thus, it is critical to understand how urbanization patterns affect carbon stores.

Urbanization often results in complex patterns of natural ecosystem loss and fragmentation, along with the creation and expansion of new land covers at very fine spatial scales. However, many studies only investigate spatial variation in aboveground carbon across coarse categorizations of land cover (e.g., residential, light urban, heavy urban) (Davies et al., 2011; Hutyra et al., 2011; Raciti et al., 2014), despite knowledge that forest fragmentation and ensuing edge effects are important for carbon stocks in naturally forested landscapes (Pütz et al., 2014; Remy et al., 2016). Unfortunately, these broad categories likely mask important variation in carbon within different land use types (Strohbach and Haase, 2012) and prevent the identification of important landscape-scale drivers of urban carbon, such as changes in landscape structure or urban form. For example, Hutyra et al. (2011) modeled carbon across the Seattle urban area based on five coarse land use classes that may have missed important variation in carbon at finer spatial scales (e.g., Velasco et al., 2013; Raciti et al., 2014). This knowledge gap for urban areas is in part due to the difficulty in obtaining fine-scale land cover and ecological data across entire cities.

One potential way forward is to use remotely sensed imagery and LiDAR data to quantify and model aboveground carbon stocks and landscape structure across cities. Discrete return LiDAR technology employs near-infrared laser pulses fired from an airborne transmitter to measure distances between the transmitter and surface features (Lefsky et al., 2002b). LiDAR pulses reflect off the ground and buildings but also partially reflect off plant parts, such as leaves and stems, providing high-resolution information on the three-dimensional structure of vegetation (Caynes et al., 2016; Davies and Asner, 2014). LiDAR data are increasingly being used to complete high-resolution surveys of vegetation structure over forested areas and cities (Goodwin et al., 2009; Simonson and Allen, 2014; Varhola and Coops, 2013; Alonzo et al., 2015), classify vegetation types (Tooke et al., 2009), identify urban vegetation or street trees (Höfle et al., 2012; Tanhuanpää et al., 2014), and estimate biomass and carbon storage in urban vegetation (Shrestha and Wynne, 2012; Raciti et al., 2014; Alonzo et al., 2016). However, only one study that we are aware of (Godwin et al., 2015) identifies specific landscape-scale drivers of variation in urban carbon stocks that are partially independent of land cover. This gap likely exists due to the extreme fine-scale heterogeneity of land and tree cover in cities (Cadenasso et al., 2007) and difficulty in quantifying landscape structure across urban areas. Thus, there are significant opportunities to use remotely sensed data, including LiDAR, in urban areas to quantify aboveground carbon stores and determine the important landscape-scale drivers of this carbon.

Here, we pair LiDAR-derived measures of vertical vegetation structure with field measures of aboveground woody vegetation carbon in Brisbane, Australia, to: (1) model and map aboveground urban carbon stocks using fine-scale remotely sensed measures of vegetation vertical structure; and (2) provide one of the first determinations of how landscape-scale drivers impact these aboveground urban woody plant carbon stores. These are critical steps to understand how urban carbon stocks will respond to future urban expansion and develop strategies to increase aboveground carbon in cities.

2. Materials and methods

2.1. Study area

Brisbane is a subtropical city of *c.* 1.13 million people located on the eastern coast of Australia (27°28′S, 153°07′E; Fig. 1). The Brisbane Local Government Area (LGA; hereafter referred to as "Brisbane") covers 1378 km^2 and has ~49% tree canopy coverage (Jacobs et al., 2014), with about two-thirds occurring as intact native vegetation (Garden et al., 2007). Annual average minimum and maximum temperatures are 16.3 and 26.5 °C, respectively, with ~2900 h of sunshine and 1006 mm of rain on average (ABOM, 2016). The main upland native vegetation consists of *Eucalyptus* forests dominated by *Eucalyptus signata*, *Corymbia intermedia*, *C. maculata*, *E. crebra*, *Lophostemon confertus*, and *Angophora* spp. (Beckmann et al., 1987). Lowland areas are dominated by open forests of *E. tereticornis*, *E. siderophloia*, *Melaleuca quinquenerva* (broad-leaved paper-bark) and *Casuarina* spp. (she-oak), while mangroves (*Aegiceras corniculatum* and *Avicennia marina*) occur in tidal-influenced saline flats (Beckmann et al., 1987). The urban portion of the city is concentrated along the Brisbane River, with a large conservation area and national park in the northwest. The mean density of dwellings across Brisbane is ~4 dwellings ha^{-1} with an average building height of 6.9 ± 5.2 m. While trees do at times overtop houses in Brisbane, this is not a common occurrence.

Over the last decade, Brisbane City has experienced 2% yr^{-1} population growth rates (QGSO, 2015). This has led to rapid urban expansion of the urban footprint and significant loss of remnant native vegetation and forest cover in the region (Accad and Neldner, 2015). Since 1999, the area of intense land uses (residential, industrial, services, transportation, commercial) has increased by over 3000 ha or 4.4% (DSITI, 2014). Brisbane's population is projected to increase by 15% to 1.3 million people by 2031 (Queensland Government, 2011).

2.2. Overall approach

Our approach first involved measuring aboveground carbon in field plots across an urbanizing gradient. We did this by quantifying tree cover extent and fragmentation across Brisbane and then establishing field plots along this gradient. We then paired this field data with