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Original Research Article

Analyzing the causal factors of carbon stores in a subtropical urban forest

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ABSTRACT

Studies of forests and urban forest ecosystems have documented the various biophysical and socioeconomic correlates of carbon storage. Tree cover in particular is often used as a determinant of carbon storage for local and national level urban forest assessments. However, the relationships among variables describing the biophysical and socioeconomic environment and carbon are not simple statistical ones. Instead, there are complex interactions that can have either a unidirectional causal effects, or produce indirect effects through interactions with other ecosystem structure and landscape characteristics. Thus, understanding the direct and indirect effects of structure, composition, and landscape characteristics is key to quantifying ecosystem services. This study used field data from plots across an urban watershed, site-specific biomass equations, and structural equation modeling of urban forest structure and landscape variables to quantify the causal influences of tree cover, land use, stand density, species composition and diversity on carbon stores. Our path analysis shows that the effect of tree cover on carbon stores is not only direct but also indirect and influential through basal area and composition. Findings suggest that species composition, species diversity and land use have much more complex relationships than previously reported in the urban forest literature. The use of path analysis in these types of studies also presents a novel method to better analyze and quantify these direct and indirect effects on urban forest carbon stores. Findings have implications for urban forest ecosystem assessments that use tree cover as the sole metric for inferring ecosystem functions and services.

1. Introduction

An increasing number of studies have documented the carbon storage and sequestration dynamics of forests and urban forest ecosystems (Escobedo et al., 2010; Hutyra et al., 2010; Schedlbauer et al., 2012; Strohbach and Haase, 2012). Recently, sequestering carbon in plant biomass has been proposed as a strategy to deal with rising atmospheric CO_2 concentrations (Millennium Ecosystem Assessment, 2003). Thus, there is increasing interest in integrating this ecosystem function as a means of mitigating climate change effects. Forest inventory and remote sensing data in particular are important for not only quantifying these functions but also for monitoring the effect of different forest management objectives on CO_2 concentrations.

Indeed, several climate change mitigation policies such as the United Nations program on Reduced Emissions from Degradation and Deforestation (REDD+) and voluntary carbon markets such as the Climate Action Reserve (http://www.climateactionreserve.org/) have been promoted as a means to offset and mitigate anthropogenic emissions and reduce land cover change and degradation in forests (Liverman, 2010). Furthermore, recent studies from temperate and subtropical urban forest ecosystems have indicated that trees are moderately effective at offsetting local-scale CO_2 emissions (Escobedo et al., 2010; Zhao et al., 2010b), and can also store more CO_2 per unit area than forested areas in the Amazon (Churkina et al., 2010). However, there is little research on the casual relations among the biophysical and socioeconomic characteristics of an urban forest ecosystem and their effect on climate regulation. More specifically, there are few quantitative analyses of casual influences or drivers of urban

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forest carbon storage in the coastal subtropics. This information is of importance since these urban and peri-urban forests are now home to 50% of the world's population and urban areas emit about 70% of all CO_2 emissions (UN-Habitat, 2011).

Rapid land use change in the form of urbanization in the subtropics has altered forest structure and diversity (Brandeis et al., 2009; Zhao et al., 2010a, 2013). Urbanization can decrease soil organic matter and carbon in the short term, but can in some instances increase it in the long-term (Hagan et al., 2012). Along with decreased forest cover, stand density and composition can also change as a result of urban morphology, choice of human management system, and policies (Tucker Lima et al., 2013; Zhao et al., 2010a). As such, land use is an important factor in driving carbon dynamics in urban and forest ecosystems (Davies et al., 2013; Raciti et al., 2012; Russo et al., 2014). In temperate areas of the eastern United States, land use change has been identified as a dominant factor contributing to the increased rate of carbon accumulation in the past several decades (Caspersen et al., 2000). Increases in forested area of $\sim$250% in Costa Rica and Vietnam have resulted in increases in sequestered carbon ha^{-1} of 130% and 180%, respectively (Hall et al., 2012). Similarly, land use has a considerable influence on urban tree growth and mortality (Lawrence et al., 2012; Tucker Lima et al., 2013), which in turn affects carbon stores and sequestration. Climate change in particular is also expected to increase hurricane frequency and severity that can in turn affect urban forest structure (Allan and Soden, 2008; Zhao et al., 2010a).

Understanding these changes in urban forest structure and species composition – as a result of land use change – is important due to their effects on ecosystem function. For example, particular urban tree species or types (e.g. invasives) have been reported to comprise the majority of carbon stores in a subtropical urban ecosystem (Escobedo et al., 2010). But, despite the increasing number of urban forest carbon studies (Churkina et al., 2010; Escobedo et al., 2010; Hutyra et al., 2010; Strohbach and Haase, 2012; Timilsina et al., 2014; Zhao et al., 2010b) little is known on the overall causal factors behind these drivers of carbon stores in urban forest ecosystems. Therefore, a better understanding of the drivers behind carbon dynamics in highly altered ecosystems in the subtropics will allow land managers to better design management strategies which aim to sequester more carbon per unit area of land.

1.1. Drivers of carbon storage in urban forest ecosystems

The factors influencing carbon storage (i.e. drivers) are most often reported as the various biophysical and socioeconomic correlates of carbon stores. These drivers are defined as ecological or human factors that affect ecosystem structure and function, thus increasing or decreasing the provision of ecosystem services (Hanson et al., 2010; Millennium Ecosystem Assessment, 2003). Forest structural characteristics (e.g. overstory cover, basal area, species diversity), disturbances (e.g. urbanization, hurricanes), and socioeconomic variables (land use, management, demographics) both at the site and landscape scale will affect carbon storage. For example, structural characteristics that measure site competition, such as tree density have been shown to be correlated to aboveground tree carbon storage (Hoover and Heath, 2011; Woodall et al., 2011). Additionally, Hall et al. (2012) found that in Chile and Ecuador, increased area of forest plantations decreased both carbon storage and native floristic biodiversity.

In many national urban forest assessments, tree cover is assumed to be directly related to carbon storage (Nowak and Crane, 2002; Nowak et al., 2013). Also, urban soil quality and patterns of aboveground vegetation and forest structure have been found to be correlated with management regimes and the degree of urbanization (Dobbs et al., 2011). Similarly, land cover, tenure, and socioeconomics – among other factors – are also related to the spatial distribution of subtropical urban forests (Brandeis et al., 2009; Zhao et al., 2010a). But these relationships are complex as shown by Timilsina et al. (2014) who found that grass cover was related to tree biomass and Lawrence et al. (2012) who reported that the amount of grass and herbaceous cover was positively correlated with tree growth and that higher amounts of grass and herb cover were usually related to higher amounts of maintenance activities. However, forest soil properties interact with forest structure and organic matter to influence understory plant abundance and richness (Laughlin et al., 2007). Further, studies of forested ecosystems have also reported a relationship between plant species richness and biomass, and higher species richness is usually found at low to intermediate levels of biomass (Garcia et al., 1993; Huston, 1994). Similarly, increased urban forest maintenance activities can lead to higher soil moisture and increased nutrients, which can therefore influence species composition, growth (Lawrence et al., 2012) and subsequent carbon stores.

Despite these complex relationships, there are discernible patterns and quantifiable interactions that can be parsed out using ecological theory. According to the redundancy hypothesis, ecosystem function increases as more species are present up to a point, after which more species will not result in enhanced ecosystem function (Walker, 1992). The rivet hypothesis suggests that "just as a plane can fly even if it loses a few rivets", an ecosystem can lose a few species without fatal consequences; however, like a plane that loses many rivets, the loss of many species will lead to ecosystem collapse (Ehrlich and Ehrlich, 1981). In support of the rivet hypothesis, a controlled experiment demonstrated that carbon sequestration and plant productivity declined along with species richness (Lawton, 1994). On the other hand, the idiosyncratic response hypothesis indicates that ecosystem function changes according to diversity, but its magnitude and direction are unpredictable because individual species characteristics and their respective roles are complex and varied (Lawton, 1994). Several studies have additionally reported the positive influence of species diversity on overall ecosystem functions (Naeem et al., 1994; Schwartz et al., 2000; Zhao et al., 2010b). On the other hand, Woodall et al. (2011) found that aboveground carbon in forest stands of the eastern US with varying species mixtures, did not vary with tree species diversity, but maximum aboveground carbon did. Moreover, aboveground live tree carbon was the greatest in mixed species stands, with the exception of yellow poplar (*Liriodendron tulipifera*) dominated stands. While many studies have been conducted in natural forest stands, to our knowledge, these types of causal relationships have not been extensively explored in the urban forest literature.

1.2. Methods for determining the effects on carbon stores

Urban forest carbon dynamics are complex and influenced by several factors, which separately or collectively will impact aboveground carbon stores (Davies et al., 2013; Dobbs et al., 2011; Raciti et al., 2012). But, using more advanced statisticaplex relationships. Jonsson and Wardle (2009) for example, using structural equation modeling (SEM) found that aboveground carbon was *directly* affected by time since fire and *indirectly* affected through alteration of litter decomposition, species diversity and composition, and net primary productivity. The effects of biophysical and socioeconomic drivers are often multifaceted interaction between biotic and abiotic factors (Hall et al., 2012; Lawton, 1994). These relationships, therefore, are not simple but can have either a unidirectional causal effect on ecosystem function, or produce indirect effects through interactions with other drivers.