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Relationship between vegetation carbon storage and urbanization: A case study of Xiamen, China

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ABSTRACT

Rapid growth of the Chinese urban population and the expansion of urban areas have led to changes in urban forest structure and composition, and consequently changes in vegetation carbon storage. The purpose of this study is to quantify the effects of urbanization on vegetation carbon storage in Xiamen, a city located in southern China. Data used for this study were collected from 39,723 sample plots managed according to the forest management planning inventory program. Data from these plots were collected in 4 non-consecutive years: 1972, 1988, 1996 and 2006. The study area was divided into three zones, which were defined according to their level of urbanization: the urban core, the suburban zone, and the exurban zone. Total vegetation carbon storage and the vegetation carbon density for each study period were calculated for each zone. Our results show that urban vegetation carbon storage has increased by 865,589.71 t during the period from 1972 to 2006 (34 years) in Xiamen, with a rapid increase between 1972 and 1996, then relatively little change between 1996 and 2006. The increase in vegetation carbon storage is mainly due to the large percentages of the suburban and exurban areas which exist in Xiamen city, and the implementation of reforestation programs in these two zones. The percentage of total regional carbon storage in the city center (urban core), suburbs and exurbs was 5%, 23% and 72%, respectively. This demonstrates that the exurbs store the majority of vegetation carbon, and thus play a critical role in the vegetation carbon storage of the study area. The intensification of urbanization in the future will likely expand the urban core and reduce the area of the suburbs and exurbs, and thus potentially decrease total vegetation carbon storage. This article concludes with a discussion of the implications of these results for vegetation carbon management and urban landscape planning.

1. Introduction

Urbanization can transform the structures, functions and processes of an urban ecosystem, and thereby influence the quality of the urban ecological environment (Theobald, 2004; Ward and Johnson, 2007). The acceleration of urban population growth and urban expansion has led to a pattern of land use and cover change (LUCC) (Yolasiğmaz and Kele, 2009; Awal et al., 2010; Churkina et al., 2010). Different levels of urbanization can lead to a triple regional structure, composed of an urban core, suburb and exurb (Gill and Williams, 1996). Since the 1980s, the course of urbanization in China has increased dramatically, and a large percentage of the rural population has migrated into the cities at an unprecedented rate (Qiu, 2010; Zhao et al., 2010a,b,c). The percentage of China's population living in urban areas reached 50% in 2010, from just 17% in 1978. By 2020, this is predicted to have risen to 59%. Because of this increase, there is growing concern about the ecological impacts of intensified urbanization in major Chinese cities (Zhao et al., 2010a,b,c).

Vegetation carbon storage (t) and carbon density (t ha^{-1}) are the most important components of carbon sequestration in an urban environment (Shao et al., 2008; McPherson et al., 1994). Vegetation carbon storage measures the quantity of carbon accumulation over time, while vegetation carbon density indicates the carbon sequestration ability of the vegetation, and also reflects the degree of disturbances (Nowak et al., 2007; Desai et al., 2008; Potter et al., 2008). Maintaining suitable urban forests not only improves the urban ecological environment (e.g., reducing dust and pollution), but also sequesters a significant amount of carbon (which helps partially offset the effects of CO_2 emissions). Because of this, the protection of urban forests has been receiving increasing attention in urban planning and management (McPherson, 1997;

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Buyantuyev and Wu, 2009). However, there is a significant information gap regarding the relationship between vegetation carbon storage and urbanization (Zhang et al., 2008). Such information is urgently needed in China due to its rapid urbanization.

In spite of growing attention to urbanization research, most studies on urbanization and the environment have focused on land use changes and biogeochemical processes. Relatively few studies have been conducted to investigate the effects of urbanization on vegetation carbon dynamics. Those that have been conducted are limited to the processes and mechanisms of carbon fluxes (Lu et al., 2010). Even studies quantifying the spatial and temporal effects of different levels of urbanization on vegetation carbon storage are rare (Hancock et al., 1996; Mohamed et al., 2009). Additionally, because of the difference in culture and developmental pace, it is not possible to simply extrapolate the results from studies conducted in developed countries to Chinese cities.

Research has indicated that the rapid development of urbanization has exerted both positive and negative influences on the carbon sequestration function of urban forests (Liu et al., 2006; Robinson et al., 2009). On one hand, LUCC has given rise to permanent damage to urban forests, which in turn has led to an intensification of forest landscape fragmentation, continuous reduction of forest area and degradation of forest resource quality (Günlü et al., 2009; Joshi et al., 2009). On the other hand, the quality and area of urban forest coverage has grown considerably (Yolasiğmaz and Kele, 2009). Consequently, the influence of urbanization on the carbon storage and carbon density of urban forests requires continuous, long-term observation. Once the dynamics of vegetation carbon storage over the course of urbanization are understood, the negative effects of urbanization on carbon storage can be minimized (Martin et al., 2008; Alberti and Hutyra, 2009).

The accurate evaluation of vegetation carbon storage is an important step in studying carbon dynamics and its relationship to other variables. Commonly used approaches include the application of forest resource inventories, remote sensing (RS), and GIS. Remote sensing images can provide us with information on the degree to which the land is being utilized, and on land cover types at a large spatial scale, but cannot supply detailed information about what is below the canopy. Thus it is difficult to estimate the age of trees (Sanchez-Azofeizi et al., 2009; Wijaya et al., 2010). RS and GIS are also useful for creating biomass models, however the construction of these models is highly subjective and there are problems relating to parameterization and model validation (mainly because of insufficient data) (Williams et al., 2005; Potter et al., 2008). Among the common approaches described above, the forest resource inventory method provides the most reliable field data; however these inventories are time-consuming and require significant financial resources to conduct (Lee and Feng, 2009; Lei et al., 2009).

For each forest in China, a forest management planning inventory (FMPI) is conducted every 10 years to support forest management and planning. Using large-scale sampling methods, this forest resource inventory collects detailed information about the characteristics and conditions of each type of forest. The FMPI also enables forest managers to make more accurate predictions of the temporal and spatial changes in carbon storage in urban ecosystems as a result of climate change and urbanization (Chen et al., 2003; Zheng et al., 2009). FMPI data together with the application of GIS provide us with an excellent opportunity to assess the relationship between vegetation carbon storage and urbanization over space and time.

Xiamen is a large city, and is typical of those undergoing rapid urbanization in China. Its population has increased from approximately 1 million in 1972 to more than 3 million in 2006. Using Xiamen as a case study, we compared the temporal and spatial distribution of vegetation carbon storage and carbon density under different levels of urban development. The primary purpose of this research was to quantify the effects of urbanization on vegetation carbon attributes (storage and density), and to compare these impacts under different levels of urbanization.

2. Materials and methods

2.1. Study area

Xiamen is a coastal city located in southeast China (17°53′–118°25′E and 24°25′–24°54′N). It has a subtropical monsoon climate with an annual average temperature of 21 °C and a relative humidity of 76%. The annual average precipitation is approximately 1100 mm, most of which falls between May and October. The most common landforms are hills and terraces, and forest soils are mainly laterite and red earth. The city has an urban forest system integrated into it, which consists of suburban forest, outer suburban forest, urban parks, botanical gardens and green belts. The whole urban forest system covers an area of 165,036 ha. There are 8690×10^4 trees in the study area with an average planting density of 527 trees ha^{-1} and forest coverage of 45%. On average, 79% of the trees are less than 15 cm in diameter at breast height (DBH) and 70% of all urban forests in Xiamen are composed of small trees (with DBH < 30 cm). Key tree species include *Acacia confuse*, *Pinus massoniana, Pinus elliottii*, *Eucalyptus* spp., *Cunninghamia lanceolata*, *Casuarina equisetifolia* and *Schima superba.* The small trees and shrub most commonly growing in Xiamen are *Vitex quinata*, *Adina rubella*, *Rhodomyrtus tomentosa*, *Ilex purpurea*, *Rhaphiolepis indica* and *Lantana camara.* During the 1980s, the total area of urban forests shrunk substantially. Under the Kyoto Protocol, the government has implemented a series of forestry carbon regulation projects including establishing a logging quota, extending the reforestation area, assigning more resources to the management of forests, and promoting the establishment of fast-growing and high-yield forests. As a result, the area of forest coverage has increased remarkably. However, with an increasing urban population, the increase of urban forests is still behind the growth of GDP. This can be attributed to the constraints on expanding forest area in regions where urban land is limited.

In China, every city consists of different local administration regions. These regions can be divided into categories such as 'old urban', 'transitional zone', and 'new urban' based on their level of urbanization. The study area consists of six administrative divisions: Siming, Huli, Jimei, Haicang, Tong'an and Xiang'an. For this study, we classified the six administrative divisions into three zones based on the degree to which they were urbanized. These zones include the urban core (old urban areas including Siming and Huli, where the population density is greater than 51 persons per ha), the suburban zone (old urban and new urban transitional zones including Haicang and Jimei, where the population density is greater than 8 persons per ha), and the exurban areas (newly urbanized areas including Tong'an and Xiang'an, where the population density is less than 8 persons per ha) (Fig. 1).

2.2. Methods

2.2.1. Data sources

The data on the urban forests of Xiamen were derived from 39,723 sample plots managed by the FMPI, sampled in the years 1972, 1988, 1996 and 2006. Data include forest resource distribution, forest volume, tree species composition, and the age of trees. A topographic map with the scale of 1:10,000 was also used. Forest volumes were estimated by regression models using data from aerial photographs and the observed volume values. The overall accuracy of sampled volumes were checked by measuring the