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journal homepage: www.elsevier.com/locate/envpolInfluence of the geographic proximity of city features on the spatial variation of urban carbon sinks: A case study on the Pearl River Delta[☆]Qian Xu^{a,*}, Yu-xiang Dong^{b,c}, Ren Yang^b^a Guangzhou Institute of Geography, Guangdong Open Laboratory of Geospatial Information Technology and Application, Guangzhou, 510070, PR China^b Guangdong Provincial Key Laboratory of Urbanization and Geo-simulation, School of Geography and Planning, Sun Yat-sen University, Guangzhou, 510275, PR China^c Xinhua College of Sun Yat-sen University, Guangzhou, 510520, PR China

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ABSTRACT

Locations of city features, e.g., city centers, roads, railways, and rivers, may impact urban carbon sinks. Therefore, the effects of city features on spatial variations of urban carbon sinks were investigated using geographic proximity data. The main results were as follows. (1) Carbon sink function varied in a complex manner with distance from the city center and with city size. The carbon sink per unit area increased with distance from the prefecture-level city center (0–30 km), with the dominant influence occurring within a 9 km radius. The lowest carbon sink per unit area was observed at a distance of 12 km from the city center of the provincial capital city (Guangzhou) and special economic zone (Shenzhen), which may be suburban industrial zones. (2) Carbon sinks decreased with increases in road grades as a result of the different functions and traffic flow, and carbon sinks were lowest near city express ways. For highways, carbon sinks were lower near highway entrances and exits. Carbon sinks around ordinary railways were higher than those around subways and light rail, but carbon sink characteristics grew more complex with increasing distances from subways and light rail. (3) Rivers were closely related to the urban layout. Grade I (i.e., larger) rivers were associated with lower carbon sinks, and carbon sink characteristics became increasingly complex around larger rivers. Within a 0–1000 m distance of all rivers, the carbon sink per unit area increased rapidly, but carbon sink characteristics differed slightly for grade I rivers. This study implies that it is important to take urbanization spatial position effects into account while assessing regional carbon sinks during urbanization and development.

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1. Introduction

During rapid urbanization, the evolution of urban social and economic development, industrial patterns, social factors, and urban ecological security results in the continuous spatial evolution of urban structural forms (Henderson and Wang, 2005; Hu et al., 2008; Anstey, 2009; Yang et al., 2010; Soini et al., 2012). Geographical proximity, which is also called spatial proximity, is a common proximity dimension used in research (Desrochers, 2001). City environments exhibit significant variations in urban layout, concentration of industry, distribution of human activities, and surface coverage types, which all may influence urban carbon sinks.

Geographical proximity data can be used to obtain important spatial information about a city's effects on carbon sink functions (where carbon sinks represent processes and mechanisms through which plants absorb CO₂ and water from the atmosphere via photosynthesis, thereby fixing CO₂ in plants, with this eventually being translated into carbon in soil (Hannah, 2015)). Therefore, based on the perspective of geographical proximity, city centers, roads, railways, and rivers of different grades, as important spatial location nodes, are important to analyze to reveal the spatio-temporal characteristics of urban carbon sinks as well as their influencing mechanisms.

Carbon sinks in urban ecosystems are affected by both natural and human factors (Xu et al., 2016). The mechanisms controlling urban carbon sinks are much more complicated than those for a single ecosystem, but current research is limited to the mechanisms behind single ecosystems and carbon stock accounting (McGarvey et al., 2015). The urban ecosystem is a complex natural–social

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* Corresponding author.

E-mail address: xuqian19840613@163.com (Q. Xu).

economic ecosystem, which necessitates dynamic studies of the relationships between urbanization and carbon sinks (Zhang et al., 2012). Important studies on the impacts of urbanization on terrestrial ecosystems were performed in the early 2000s (Collins et al., 2000; Pickett et al., 2001). Since then, studies have mainly focused on the following aspects: the impact of an increasing urban population on carbon sink functions (Li et al., 2016); the impact of urban land expansion on carbon sinks (Larondelle and Haase, 2013; Radford and James, 2013); the urban ecosystem and carbon sink economy (Chan et al., 2017); the influence of artificial management measures on carbon sink functions (Roxburgh et al., 2006); optimization mechanisms and modeling of carbon sinks (Lee and Chen, 2012); and climate change feedback effects on urban carbon sink functions (Kurz et al., 2008). Research on the carbon dynamics of cities and the impact of urbanization is still in its infancy (Zhang et al., 2012), and research into urban ecosystem carbon cycles is lacking.

Although research on urban carbon sinks is gradually increasing, few studies have comprehensively evaluated the influence of different layouts of complex urban systems on urban carbon sinks. The influences of different spatial positions in urban systems will add complexity to analyses of carbon sink effects. In different urban locations, types of land use are different, so carbon sink functions have different characteristics (Haregeweyn et al., 2012; Schneider, 2012). Urbanization results in different transformations between different land use types in different urban locations, which can cause dynamic changes in carbon stocks (Defries et al., 1999). Liu et al. (2016) studied the differences in carbon sinks caused by different locations between urban and rural areas, and they argued that vegetation carbon stocks and soil organic carbon content in urban areas is lower than that in rural areas. The influences of urban and rural land use changes during rapid urbanization on urban carbon sinks remain unclear. Under the influence of urbanization, improved land use management practices can change the vegetation carbon sink function of urban green spaces (Pataki et al., 2006). Studies have shown that areas of artificial management have higher carbon sink levels than those in other areas, and this can offset carbon losses caused by changes in land use activity (Zhang et al., 2014a). In general, carbon sink differences can be caused by different locations between pervious and impervious surfaces in urban systems; for example, Yan et al. (2015) have shown that soil organic carbon (SOC) decreased by 16% because of the expansion of impervious surface areas in Urumqi, Xinjiang, China. Moreover, landscape heterogeneity in urban ecosystems is much more complex than that in natural ecosystems, and thus, the internal carbon effects may differ for the same land use type, which adds uncertainty to our knowledge of carbon sink effects in urban ecosystems (Lorebz and Lal, 2012).

In fact, the influences of different spatial positions of city features on urban ecosystem carbon sinks can be expected to differ. For example, in China, geographical proximity effects on the carbon sinks imparted by the locations of city centers likely differ according to the different grades of cities, such as Guangzhou (provincial capital city) and Dongguan (prefecture-level city). Furthermore, the intensive river network in the Pearl River Delta region has played an important role in the spatial layout of urban development, and it is likely that changes in soil moisture with distance from the river have effects on vegetation carbon sink functions. Thus, rivers may influence urban carbon sink characteristics in both direct and indirect (urban space development) ways. Additionally, traffic grades and the distribution of transportation networks influence the spatial expansion patterns of urban built-up land. Highway entrances and exits are areas with the greatest vehicle density, and thus, these areas may display prominent differences in urban carbon sink characteristics. Therefore, in

this study, we use the Pearl River Delta region, which is a typical urban agglomeration containing urban centers, roads, railways, and rivers of different grades, to explore the influences of spatial positions of city features in terms of geographical proximity on urban carbon sinks.

2. Study area and methods

2.1. Study area

The Pearl River Delta area (21°17.6'N–23°55.9'N, 111°59.7'E–115°25.3'E) was predominantly formed by alluvial deposits. This area falls within the southern subtropics, and subtropical evergreen broad-leaved forest vegetation is present. Average rainfall is approximately 1600 mm, and it is mainly concentrated in the summer; conversely, winters are drier. The relief is flat, and the area is bounded to the west and north by the Luoping Mountains. There are 79–92 sunshine days per year, and the annual average daytime temperature is greater than 20 °C. In terms of administrative areas, Guangzhou city lies at the center of the Pearl River Delta, and sub-centers include Shenzhen, Foshan, and Zhuhai as well as Dongguan, Zhongshan, Jiangmen, part of Huizhou, and part of Zhaoqing, which constitutes a total of nine cities (one provincial capital, one special administrative region, and seven prefecture-level cities) (Fig. 1). The Pearl River Delta encompasses an area of $41.09 \times 10^3 \text{ km}^2$, and it has a permanent resident population of 56.82 million (2012) (Table 1) and a high urbanization rate, with urban residents representing 83.84% of the population (2012). It is a very important urban agglomeration area in China. Land use is characterized by circle-type developments (Fig. 2). In the delta, the area of construction land has been expanding rapidly, whereas areas of cultivated and forest land are showing rapid declines. The land use structure is thus changing from a complex one to a simpler form (Xu et al., 2016).

2.2. Methods

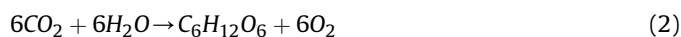
2.2.1. Carbon sinks

This study uses the improved CASA (Carnegie–Ames–Stanford Approach) light energy utilization model to calculate net primary productivity (NPP), and this model was improved by Zhu Wenqun (Zhu et al., 2006; Zhu et al., 2007) based on the CASA model Potter presented (Potter et al., 1993). The model overcomes the disadvantages of using the maximal light use efficiency (ϵ_{\max}) of world vegetation as a definite value. We referred to earlier work for the vegetation types and characteristics of the regional natural environment in Guangzhou to determine ϵ_{\max} and to evaluate the NPP in Guangzhou:

$$NPP_{\text{year}} = \sum_{i=1}^{12} APAR_i \times \epsilon_i \quad (1)$$

where NPP_{year} is the NPP for a particular year, i is the month, $APAR$ is the absorbed photosynthetic active radiation, and ϵ is the actual light energy utilization.

In ecosystems, various vegetation types absorb carbon dioxide from the atmosphere and release oxygen during photosynthesis. The related chemical reaction is as follows:



Based on this photosynthetic reaction equation, the production of 1 kg of dry matter can fix 1.63 kg CO_2 (Hao, 2009). By using a pre-measured amount of NPP material (the production of dry matter in an ecosystem) and the photosynthetic reaction equation, we

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