Science of the Total Environment 607–608 (2017) 706–714

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Ecosystem services response to urbanization in metropolitan areas: Thresholds identification

Jian Peng [a,*], Lu Tian [b], Yanxu Liu [a], Mingyue Zhao [a], Yi'na Hu [a], Jiansheng Wu [a,b]

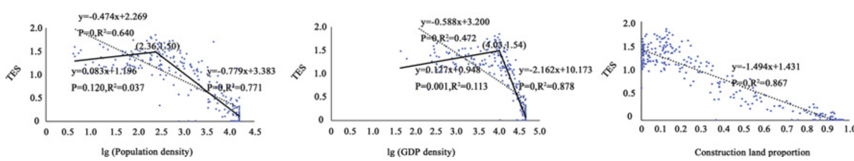
[a] Laboratory for Earth Surface Processes, Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

[b] Key Laboratory for Environmental and Urban Sciences, School of Urban Planning and Design, Shenzhen Graduate School, Peking University, Shenzhen 518055, China

HIGHLIGHTS

- Multiple advantageous area of ecosystem services (ESs) was identified.
- There were thresholds of ESs response to population and economic urbanization.
- ESs response to land urbanization was proved to be linear decreasing.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 March 2017
Received in revised form 20 June 2017
Accepted 25 June 2017
Available online 27 July 2017

Editor: Simon Pollard

Keywords:
Ecosystem services
Urbanization thresholds
Piecewise linear regression
Peri-urban area
Beijing City

ABSTRACT

Ecosystem service is the key comprehensive indicator for measuring the ecological effects of urbanization. Although various studies have found a causal relationship between urbanization and ecosystem services degradation, the linear or non-linear characteristics are still unclear, especially identifying the impact thresholds in this relationship. This study quantified four ecosystem services (i.e. soil conservation, carbon sequestration and oxygen production, water yield, and food production) and total ecosystem services (TES), and then identified multiple advantageous area of ecosystem services in the peri-urban area of Beijing City. Using piecewise linear regression, the response of TES to urbanization (i.e., population density, GDP density, and construction land proportion) and its thresholds were detected. The results showed that, the TES was high in the north and west and low in the southeast, and there were seven multiple advantageous areas (distributed in the new urban development zone and ecological conservation zone), one single advantageous area (distributed in the ecological conservation zone), and six disadvantageous areas (mainly distributed in the urban function extended zone). TES response to population and economic urbanization each had a threshold (229 person km^{-2} and 107.15 million yuan km^{-2}, respectively), above which TES decreased rapidly with intensifying urbanization. However, there was a negative linear relationship between land urbanization and TES, which indicated that the impact of land urbanization on ecosystem services was more direct and effective than that of population and economic urbanization. It was also found that the negative impact of urbanization on TES was highest in the urban function extended zone, followed in descending order by that in the new urban development zone and ecological conservation zone. According to the detected relationships between urbanization and TES, the economic and population urbanization should be strengthened accompanied by slowing or even reducing land urbanization, so as to achieve urban ecological sustainability with less ecosystem services degradation.

1. Introduction

Since the 20th century, cities have provided the most important habitat for humans (Su et al., 2011). Urbanization has become one of the most remarkable characteristics of social development (Li et al., 2012; Zhao et al., 2016; Allington et al., 2017). During the process of urbanization, on the one hand, natural ecosystems will be transformed into semi-natural and semi-artificial ecosystems and artificial ecosystems, which poses a great threat to the structure and function of ecosystems (Huang and London, 2012; Su et al., 2014a; Song and Deng, 2017). On the other hand, the progress of urban civilization means greater

* Corresponding author.
E-mail address: jianpeng@urban.pku.edu.cn (J. Peng).

http://dx.doi.org/10.1016/j.scitotenv.2017.06.218

ecological demands for sustainable provision of ecosystem services. That is to say, the impact of urbanization on the eco-environment reacts on the city itself (Huang et al., 2011). Ecosystem service refers to the environmental conditions and utilities generated and sustained by ecosystems in the ecological process (Daily, 1997), including the benefits that humans obtain from ecosystems directly or indirectly (Costanza et al., 1997). It can completely reflect the ecosystem status (Li et al., 2015; Hao et al., 2017). By changing land use and land cover, urbanization affects the flows of materials, energy and information and then alters regional ecosystem services provided for humans. In summary, ecosystem services constitute the key comprehensive indicator that characterizes ecosystem change. Thus, quantifying the relationship between ecosystem services and urbanization provides an effective way of clarifying the ecological effects of urbanization.

According to Millennium Ecosystem Assessment, 15 of the 24 kinds of ecosystems show a tendency of ecosystem services degradation (Millennium Ecosystem Assessment, 2005). Generally, urbanization is believed to pose a great threat to regional ecosystem services (Holt et al., 2015; Chen et al., 2016; Mach et al., 2015). Hu et al. (2015) found that ecosystem service intensity declined with the expansion of construction land; however, population density and industrial output density had no significant impact on ecosystem service intensity. Su et al. (2014b) noticed that the increase in population and economy would lead to a reduction in ecosystem services, and the impact was stronger in districts with higher proximity to city center. Li et al. (2016) showed that the changes in ecosystem services (food supply, carbon sequestration, soil water storage, air pollution removal, habitat suitability, and recreation potential) varied in different urbanization categories (developed urban areas, developing urban areas, and rural areas) during the process of urban development. Li and Zhou (2016) proposed that most anthropogenic activities had negative impacts on ecosystem services except that population and residential land area contributed to promoting the service of agricultural production. To sum up, most studies have found either a completely negative relationship between urbanization and ecosystem services, or various relationships due to different urbanization factors or levels. However, it is still unclear whether these relationships are linear or non-linear. Especially, the thresholds identification for the ecological effects of urbanization is still lacking, which is of great significance to science-based regulation of the urbanization process. In addition, the spatial patterns of urban development are changing during the urbanization process. That is to say, urban developing area extends to the urban-rural fringe and even into rural area gradually. Thus, urbanization related studies have gradually turned to focusing on peri-urban areas, which contain the double attributes of urban and rural areas (Douglas, 2006; Su et al., 2014c; Yang et al., 2016). However, compared with detecting the social impact of urbanization, few studies have focused on the impact of urbanization on ecosystem services in peri-urban areas (Barbedo et al., 2014).

Although there may exist non-linear relationship between urbanization and ecosystem services (Zhang et al., 2016), the measurement of the relationship is still unclear. Assuming that a non-linear relationship does exist, there must also exist at least one point, at which the relationship changes, revealing where the ecological effects of urbanization change from one mode to another (Hua et al., 2017). Thus, the turning points become the thresholds for controlling the urbanization process based on ecological goals (Sun et al., 2012). Originally, ecological thresholds were mainly identified by field observation. Up to now, model simulations (e.g. system dynamics model) and statistical analysis (e.g. Meta-analysis and piecewise linear regression) have been proved to be effective in threshold identification. Meta-analysis refers to the statistical analysis which integrates the findings of abundant individual studies on the same topic to reveal a new finding, which has a wide scope of application. However, Meta-analysis requires a series of highly consistent data (Ruppert et al., 2012). Mostly applied in sustainable development assessment (Barney, 2002), system dynamics model needs mass information for characterizing the influences and reactions among system components and is seldom conducted for quantifying the ecological effects of urbanization. Compared with the two methods mentioned above, piecewise linear regression serving as broken-stick models with relatively low data requirements can effectively determine the threshold point where two trends are intersected (Toms and Lesperance, 2003), and it has been widely used in studies focusing on ecosystem change. For example, Xue et al. (2013) monitored the vegetation dynamics in the Yukon River Basin of Alaska using piecewise linear regression. Cattarino et al. (2014) combined fractal analysis and piecewise linear regression to detect the significant change of forest fragmentation patterns. Magney et al. (2016) used piecewise linear regression to identify the turning points of NDVI seasonal change. Peng et al. (2016b) found that the urban ecological land had a cooling effect and used piecewise linear regression to show that when the proportion of ecological land exceeded 70%, the cooling effect was more effective. Thus, piecewise linear regression can be used to identify the threshold of ecosystem services response to urbanization.

As one of the largest cities in China, Beijing City has experienced rapid urbanization during recent decades, accompanied by substantial landscape change and associated ecosystem services degradation. Hence, taking the peri-urban area of Beijing City as a case study, this study sought to clarify the spatial patterns of ecosystem services and their responses to urbanization, and identify the thresholds of the responses. To be specific, soil conservation (SC), carbon sequestration and oxygen production (CSOP), water yield (WY), and food production (FP) were estimated using several models, and then the total ecosystem services (TES) and multiple advantageous area of ecosystem services (MAAES) were obtained. In addition, the spatial patterns of urbanization in peri-urban area of Beijing City were detected based on population, economic, and land urbanization indicators. Finally, the impact of population urbanization, economic urbanization, and land urbanization on TES and its thresholds were quantified using simple linear regression and piecewise linear regression.

2. Material and methods

2.1. Study area and data sources

In this study, the peri-urban area of Beijing City, including 14 districts except Dongcheng and Xicheng, was selected to examine the influencing mechanism of urbanization on ecosystem services. Beijing City (39°28′N - 41°05′N, 115°25′E - 117°30′E) is situated in the northwest of the North China Plain, and is bordered by the Yanshan Mountains in the north, the Huanghuaihai Plain in the south, the Taihang Mountains in the west, and the Songliao Plain in the northeast. Beijing City has a total area of approximately 16,400 km^2, of which mountainous areas account for 62% and plains account for 38%. In the mountainous areas, the highest elevation is 2268 m, however, the terrain slopes gently in the plains, where the elevation is always $<$100 m and the lowest elevation is only 6 m. In addition, the region has a typical warm temperate semi-humid continental monsoon climate with an annual precipitation of 550.7 mm and an annual average temperature of 9.9 °C.

As China's center of politics, culture, education and international communication, Beijing City has experienced a rapid urbanization process since reform and opening policy has been adopted. During 1980–2014, the total population increased 134.17% from 9.19 million to 21.52 million, the gross domestic product (GDP) increased from 13.91 billion yuan to 2.13 trillion yuan, and the built-up area increased from 346 km^2 to 1385.6 km^2. In terms of the regional characteristics of urban development, there exist obvious differences among the districts. According to the latest administrative divisions, Beijing City is divided into four functional zones (Fig. 1): the core functional zone (including Doncheng and Xicheng), the urban function extended zone (including Chaoyang, Haidian, Fengtai, and Shijingshan), the new urban development zone (including Tongzhou, Shunyi, Daxing,