Ecological Indicators 94 (2018) 117–129

Contents lists available at ScienceDirect

Ecological Indicators

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

Original Articles

Analyzing spatio-temporal changes and trade-offs to support the supply of multiple ecosystem services in Beijing, China

Xiao Sun[a,b,c], Zhongming Lu[c,d], Feng Li[a,b,*], John C. Crittenden[c]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Brook Byers Institute for Sustainable Systems, School of Civil & Environmental Engineering, Georgia Institute of Technology, 828 West Peachtree St. NW, Suite 320, Atlanta, GA 30332-0595, USA
[d] School of Environment, Beijing Normal University, Beijing 100875, PR China

ARTICLE INFO

Keywords:
Land use change
Ecosystem services
Scenario
Trade-offs

ABSTRACT

Rapid urbanization has dramatically changed regional land use patterns and brought enormous pressures on ecosystem services (ESs). The assessment of the impact of urbanization on ESs is critical for sustainable urban planning and land policy in China. In this study, we used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to assess the changes in ESs based on land use patterns in Beijing from 1984 to 2015. A new comprehensive ecosystem service (CES) index was developed to spatially reflect the total supply of multiple ESs and provide references for policy makers. We further analyzed the trade-offs among various ESs through correlation analysis and designed five alternative scenarios to explore effective strategies which can improve the CES while simultaneously reducing trade-offs among different ESs in Beijing. The results showed that the average CES of Beijing decreased over the past 30 years. The ecological conservation region, which is located to the north and west of Beijing, had the best CES performance. Among the various ESs, services for water purification, soil erosion control, vegetable provision, and fruit provision increased, whereas services for carbon storage, water provision, habitat provision, and grain provision decreased from 1984 to 2015. It's worth noting that sediment export in Beijing showed no significant relationships with regulating and supporting services, which include carbon storage, water purification and habitat provision. To control soil erosion effectively, we should not only increase the area of afforestation but also plant trees on the steeper slopes. In addition, there is a major trade-off between food provision and regulating and supporting services. Vegetation restoration in both riparian zones and previously steep croplands can improve CES at the expense of reducing food provision. Moreover, forestry restoration is proved to be more effective than grass-based restoration. To reduce the trade-offs between food provision and regulating and supporting services and concurrently improve the CES, it is essential to increase the efficiency of food provision per unit area and develop urban vertical agriculture in Beijing.

1. Introduction

Urbanization is currently a global phenomenon that is often associated with immense economic and population growth (Bloom et al., 2008). People are moving to cities to find jobs and better living conditions (Larondelle and Lauf, 2016). Over the past 30 years, China has experienced rapid urbanization in response to the economic and political reforms that started in 1978 (Haas and Ban, 2014). Rapid urbanization has dramatically changed regional land use patterns and placed enormous pressures on ecosystems. Over the past half-century, 60% of ecosystem services (ESs) worldwide were degraded as a result of urbanization (MEA, 2005). In China, urbanization has led to a series of problems, such as decreased water provision (Cui and Shi, 2012), deteriorated water quality, aggravated soil erosion (Jia et al., 2014; Zhang et al., 2016), and decreased biodiversity (Li et al., 2016). These environmental problems not only threaten sustainable urban development but also harm the health of urban residents.

Over the past few decades, ES has been a central issue in studies of sustainable development and natural resources management (Dearing et al., 2012). A growing number of scientists have become involved in the evaluation of ESs, and most focus mainly on natural ecosystems (Cai et al., 2017; Gao et al., 2016; Jiang et al., 2016; Nelson et al., 2009) and

* Corresponding author at: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 18 Shuangqing Road, Haidian District, Beijing 100085, China.
E-mail addresses: Zhongming.Lu@gatech.edu (Z. Lu), lifeng@rcees.ac.cn (F. Li), john.crittenden@ce.gatech.edu (J.C. Crittenden).

https://doi.org/10.1016/j.ecolind.2018.06.049
Received 27 April 2017; Received in revised form 9 February 2018; Accepted 21 June 2018
1470-160X/

only one or few aspects of ESs (Seppelt et al., 2011), such as carbon storage (He et al., 2016) or water purification (Yang et al., 2015). In addition, assessing ESs by using a spatio-temporal approach is helpful for supporting management strategies in multi-functional landscapes (Locher-Krause et al., 2017). However, few studies have examined the spatio-temporal changes in multiple ESs in urban areas (Li et al., 2016). Urban expansion promotes the conversion of natural and semi-natural land that can provide multiple ESs, such as forest land and cropland into urban impervious surfaces (Xie et al., 2018). Land use/land cover (LU/LC) change analysis has become a fundamental tool for assessing the impacts of human activities on urban ESs. Li et al. (2010) demonstrated that the ES values of woodlands, wetlands, water bodies, and orchards accounted for more than 90% of the total value in urban areas. To predict the impact of future LU/LC change on ESs, some studies have compared a suite of alternative LU/LC scenarios associated with the future implementation of plans and policies (Polasky et al., 2011; Yang et al., 2011). Most of them focused on analyzing the changes and trade-offs of ESs under alternative scenarios. However, few studies have explored effective land use strategies and policies in urban areas that can improve ESs based on alternative scenarios and trade-offs analysis (Deng et al., 2016). For trade-off analysis, a variety of methods have been used to identify the relationships among ESs, such as descriptive methods, correlation analysis, regression analysis, and multivariate statistics (Lee and Lautenbach, 2016). Among these methods, descriptive methods have been frequently employed to investigate ES relationships without explicit quantitative calculation. Pairwise correlation analysis and multivariate statistical tests are most commonly applied to identify the general direction and strength of trade-offs and synergies. Regression analysis distinguishes the ESs into dependent and independent variables. However, errors are only considered for the dependent variables. Multivariate statistics were frequently applied to identify the ESs that tend to occur together by using principal component analysis or factor analysis (Cord et al., 2017). In this study, we used the correlation analysis to identify the relationship among ESs in Beijing because correlation approaches do not ignore no-effect relationships.

Several spatio-temporal simulation models have been developed to integrate ESs into both public and private-sector decision-making processes (Cord et al., 2017), such as the Integrated Valuation of ESs and Tradeoffs (InVEST), the Artificial Intelligence for ESs (ARIES), Social Values for ESs (SolVES), and Ecological Asset Inventory and Management (EcoAIM). InVEST is a suite of geographic information science models that converts changes in LU/LC patterns into changes in carbon storage, water yield, crop provision, habitat for species and outputs of other ESs. This model has been applied widely to report the distribution of different ESs and trade-off maps at varying geographical scales (Polasky et al., 2011). The ARIES model is a web-accessible application that can visualize ES dynamics and assess the trade-offs between ESs and the areas where they are provided and used. The ARIES model is limited by a lack of transparency of the model code owing to its complexity and cannot be generally used until the model is developed completely (Vigerstol and Aukema, 2011). SolVES is an ArcGIS toolbar used to map social ES values based on survey data. This model is limited when the study site is too different from those in previous studies (Bagstad et al., 2013). EcoAIM uses a series of publicly available spatial datasets combined with a weighting or aggregation function to derive spatially explicit scores for ESs of interest. However, it has no capacity for independent application (Ochoa and Urbina-Cardona, 2017). In this study, we selected the InVEST model to map and value ESs in Beijing. We primarily selected this model because it can assess multiple ESs based on land use changes and can provide useful information to managers and policy-makers by analyzing trade-offs in ESs.

During the urbanization process, land use changes seriously affect the ESs cities, particularly in a few megacities. Nelson et al. (2010) projected the impacts of urban expansion on ESs at the global scale and found that land use changes could lead to declines in available habitats for species and biomass carbon storage. In China, studies have also noted that urbanization has led to decreases in climate regulation, soil formation and protection, food provisions, and habitat provision (Li et al., 2016; Xie et al., 2018). Assessing the effects of urbanization on ESs in megacities can play a guiding role in urban planning (He et al., 2016). Beijing, as the capital of China, grew to a highly developed megacity from 1984 to 2015. In this study, we first assessed the impacts of urbanization on multiple ESs in Beijing from 1984 to 2015. Then, a new index was developed to measure the comprehensive ecosystem service (CES). We also analyzed the trade-offs among various ESs through correlation analysis. Based on local land use policies and the trade-off results of different ESs, five alternative scenarios were designed to explore the effective land use strategies that can improve the CES and simultaneously reduce the trade-offs among different ESs. Finally, we put forward corresponding land use management and ecological engineering measures to improve the ESs in different regions. The evaluation process and land use planning strategies proposed in this study can provide a reliable reference for the sustainable development of megacities in China.

2. Study area

Beijing (115°25′-117°30′E, 39°26′-41°03′N) is the political, economic, and cultural center of China and one of the oldest and most densely populated megacities in the world (Yang et al., 2011). The total administrative land area of the city is 16,808 km^2, 62% of which is hilly (Zhang et al., 2010). The elevation in Beijing increases from southeast to northwest (−129 m to 2270 m). It has a mean annual temperature of 12 °C and an average precipitation of 640 mm (He et al., 2016). Since the end of the last century, Beijing entered an era of rapid urban expansion (Mu et al., 2007). The total population in Beijing increased from 9.7 million to 21.7 million from 1984 to 2015 (BMBS, 1984–2015). Driven by rapid economic and urban population growth, Beijing has suffered from serious water resource pressure (Zhang et al., 2010) and substantial pollutant emissions (Wang et al., 2016b). In recent years, urban expansion also has resulted in large regional carbon storage loss, continuous deterioration of habitat quality and extensive wetland degradation in Beijing (He et al., 2016; Xie et al., 2018; Zhang et al., 2017a).

According to the Overall Urban Planning of Beijing (2004–2020) (SCPRC and BMG, 2015), the city consists of four regions: (1) the political and cultural region (PCR), (2) the urban functional region (UFR), (3) the urban expansion region (UER), and (4) the ecological conservation region (ECR). Among them, the PCR is the political and cultural center of Beijing. This region forms the core of the urban areas and includes two districts: Xicheng (XC) and Dongcheng (DC). In 2015, this region accounted for 10.1% of the population and 0.6% of the entire area. The UFR includes four districts: Haidian (HD), Chaoyang (CY), Fengtai (FT), and Shijingshan (SJS). This region plays an important role in the economy, culture, and the daily life of residents in Beijing. The UFR is located around the PCR and accounted for 7.8% of the entire area of Beijing but 44.8% of the total population in 2015. The total gross domestic product (GDP) in this region was 1085.4 billion Chinese Yuan, representing 47.2% of the GDP of the entire area. Downtown Beijing usually refers to the PCR and UFR. The UER, which is now the focus of future urban expansion, includes five districts: Changping (CP), Shunyi (SY), Tongzhou (TZ), Daxing (DX), and Fangshan (FS). This region accounted for 32.3% of the total population in 2015 and 38.4% of the entire area. The ECR includes five districts: (1) Yanqing (YQ), (2) Huairou (HR), (3) Miyun (MY), (4) Pinggu (PG), and (5) Mentougou (MTG). These districts are mainly located in the north and west of Beijing. This region, which is very mountainous, constitutes 53.2% of the entire land area of the city but accounted for only 8.8% of the total population in 2015. In recent years, the number of residents living in the UER and ECR regions has increased because the cost of living is much lower than that in downtown Beijing (Fig. 1).