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Impacts of urban expansion on ecosystem services in the Beijing-Tianjin-Hebei urban agglomeration, China: A scenario analysis based on the Shared Socioeconomic Pathways

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ABSTRACT

Understanding the impacts of urban expansion on ecosystem services (ESs) is important for sustainable development on regional and global scales. However, due to the uncertainty of future socioeconomic development and the complexity of urban expansion, assessing the impacts of future urban expansion on ESs remains challenging. In this study, we simulated the urban expansion in the Beijing-Tianjin-Hebei (BTH) urban agglomeration in China from 2013 to 2040, and assessed its potential impacts on ESs based on the Shared Socioeconomic Pathways (SSPs) and the Land Use Scenario Dynamics-urban (LUSD-urban) model. We found that urban land in the BTH urban agglomeration is expected to increase from 7605.25 km^2 in 2013 to 9401.75–11,936.00 km^2 in 2040. With continuing urban expansion, food production (FP), carbon storage (CS), water retention (WR), and air purification (AP) will decrease by 1.34–3.16%, 0.68–1.60%, 0.80–1.89%, and 0.37–0.87%, respectively. The conversion of cropland to urban land will be the main cause of ES losses. During 2013–2040, the losses of ESs caused by this conversion will account for 83.66–97.11% of the total losses in the whole region. Furthermore, the ES losses can cause considerable negative impacts on human well-being. The loss of FP will be equivalent to the food requirement of 3.68–8.61% of the total population in 2040, and the loss of CS will be 2.55–6.01% of the total standard coal consumption in 2013. To ensure sustainable development in the region, we suggest that effective policies and regulations should be implemented to protect cropland with high ES values from urban expansion.

1. Introduction

Ecosystem services (ESs), or the benefits that people obtain from ecosystems (MEA, 2005), connect natural capital and human well-being, and constitute an important basis for realizing sustainable development and improving human well-being (Dominati et al., 2010; MEA, 2005; Wu, 2013). Urban expansion is a land-use change process that transforms non-urban land into urban land (Bai et al., 2012; He et al., 2016; López et al., 2001). On the one hand, this process directly causes substantial losses of natural habitats and ESs (e.g., food production (FP), freshwater provision, and carbon storage (CS)) due to the loss of natural vegetation and increase in impervious surfaces. On the other hand, it indirectly influences the delivery of ESs (e.g., water retention (WR), climate regulation, and nutrient retention) by altering the hydrologic cycling, atmospheric circulation, and nutrient cycling processes (Schröter et al., 2005; Wade et al., 2009; Wu et al., 2014b). During the past 30 years, urban land has, on average, expanded twice as fast as the urban population (Seto et al., 2012), which has negatively affected ESs at different scales (Forman and Wu, 2016; Grimm et al., 2008; He et al., 2014, 2016; Li et al., 2016; Marrero et al., 2017; Sanchez-Rodriguez et al., 2005; Thyberg and Tonjes, 2016; Tolessa et al., 2017; Wu, 2010). Therefore, assessing the impacts of urban expansion on ESs has become an important and urgent task for better understanding urban ecology and achieving urban sustainability.

Recently, several studies have attempted to link urban expansion models with ES models to assess the potential impacts of future urban expansion on ESs at different scales. For example, at the global scale, Nelson et al. (2010) integrated the GEOMOD model and the Integrated

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Valuation of Environmental Services and Tradeoffs (InVEST) model to simulate global urban expansion from 2000 to 2015 under two scenarios, and assessed the impacts of urban expansion on crop production, water yield, and CS. At the national scale, Eigenbrod et al. (2011) evaluated the impacts of urban expansion on flood mitigation, agricultural production, and CS in Britain from 2006 to 2031 using an urban expansion model and a hydrological model. At the local scale, Wu et al. (2014a) used the Conversion of Land Use and its Effects at Small regional extent (CLUE-S) model and the InVEST model to explore urban expansion from 2010 to 2025 in Puli Township, Taiwan, and assessed its impacts on natural habitats. However, there are still at least two challenges for current studies. First, it is difficult to compare the results among different regions and across different scales due to the lack of a consistent framework for scenario settings (Alcamo et al., 2006). Second, existing models cannot effectively simulate future urban expansion at the regional scale because the process of urban expansion is complex and involves various geophysical and socioeconomic drivers (He et al., 2016).

The Shared Socioeconomic Pathways (SSPs) provide a consistent and comparable scenario framework for simulating future urban expansion. The SSPs are a set of narrative storylines and quantified measures of socioeconomic development proposed by the Intergovernmental Panel on Climate Change (IPCC) in 2010 (O'Neill et al., 2012). Based on two socioeconomic dimensions—i.e., the challenges of climate change mitigation and adaption—five pathways are developed by setting various socioeconomic elements relevant to climate change mitigation and adaptation. The five pathways are SSP1 (sustainability), SSP2 (middle of the road), SSP3 (regional rivalry), SSP4 (inequality), and SSP5 (fossil-fueled development) (O'Neill et al., 2012, 2015). Currently, the SSPs are regarded as a set of comprehensive and comparable scenarios. First, the SSPs describe future socioeconomic development pathways by considering various elements, including demography, economy, policy, technology, environment and resources, which can comprehensively reflect the complexity of driving factors for urban expansion (Jiang and O'Neill, 2017; O'Neill et al., 2015). Second, the SSPs can be used across different study areas, and the results are comparable among these areas because the SSPs provide quantitative forecasting data under different scenarios. Therefore, the SSPs have already been used to study future global urbanization and project economic growth. For example, Jiang and O'Neill (2017) successfully projected global urbanization from 2010 to 2100 based on the five SSPs. Dellink et al. (2015) forecasted country-level economic growth for 184 countries from 2010 to 2100 under the five SSPs.

The Land Use Scenario Dynamics-urban (LUSD-urban) model, originally developed by He et al. (2006), provides an effective way to simulate future urban expansion in China under different scenarios. By combining cellular automata with system dynamics models, the LUSD-urban model accounts for both macro- and micro-scale drivers of land-use and land-cover (LULC) change in a spatially explicit manner, and hence can effectively simulate the spatial process of urban expansion under different scenarios (He et al., 2005, 2006). For example, using the LUSD-urban model, He et al. (2015) successfully simulated urban expansion in the Beijing-Tianjin-Tangshan megalopolis area in China from 2009 to 2030 under different climate change scenarios. Moreover, He et al. (2016) found that, compared to the model used at the global scale, the LUSD-urban model can simulate the spatial process of urban expansion more accurately at the region scale. On this basis, they assessed the potential impacts of future urban expansion on regional CS in Beijing, China, by linking the LUSD-urban and the InVEST models.

The Beijing-Tianjin-Hebei (BTH) urban agglomeration is the largest urban agglomeration in northern China in terms of its economic size and vitality (Peng et al., 2016). This region has experienced rapid economic growth and urban expansion since the 1990s. From 1990 to 2014, its gross domestic product (GDP) grew from 163.97 billion to 6647.89 billion RMB yuan, and its urban population grew from 40.07 million to 67.49 million. The percentage of the total population living in urban areas (i.e., the urban population) increased from 49.40% to 61.07% (BMSB, 2015; TPGHP, 2015; TMSB, 2015). Previous studies have suggested that rapid urban expansion in this region has resulted in substantial losses of ESs during recent years (Haas and Ban, 2014; Song and Deng, 2015). From 1990 to 2010, urban expansion in this region caused an approximate 9.05 billion RMB yuan decrease in ES value, accounting for approximately 6% of this region's total ES value in 1990 (Haas and Ban, 2014). According to Song and Deng (2015), urban expansion during 1988–2008 has already significantly decreased several important ESs in this region, i.e., water conservation, nutrient cycling, gas regulation, and organic production. However, current studies mainly focused on the historical impacts of urban expansion on ESs in this region (Wu et al., 2013; Zhan et al., 2015). Few studies have assessed the potential impacts of future urban expansion on ESs under different scenarios. Furthermore, the Chinese government released the Outline of Collaborative Development of Beijing, Tianjin, and Hebei Province (OCDBTH) in 2015, paying special attention to urban expansion and its ecological consequences in this region. In this context, assessing the potential impacts of future urban expansion on ESs in the BTH urban agglomeration is of great significance for the development of urban ecology and landscape sustainability science, as well as this region's sustainable development.

The objective of this study was to assess the potential impacts of urban expansion on ESs quantitatively from 2013 to 2040 under different scenarios. To achieve this objective, we first quantified multiple ESs in the BTH urban agglomeration, China in 1990. Then, the urban expansion in this region from 2013 to 2040 was simulated by using the SSPs and the LUSD-urban model. Finally, the potential impacts of future urban expansion on ESs were evaluated at the regional, city, and county scales. The results will provide useful information for sustainable development in the BTH urban agglomeration, China.

2. Study area and data

2.1. Study area

The BTH urban agglomeration (113°27′–119°50′E, 35°03′–42°40′N) consists of Beijing, Tianjin, and Hebei province, which have a total land area of 212,962 km^2, accounting for 2.2% of the total land area of China (Zhang et al., 2015). The elevation in this region declines from the northwest to the southeast. This region is in the temperate zone, and the climate is hot and rainy in the summer, and cold and dry in the winter (Zhang et al., 2015). The average annual precipitation is approximately 538 mm and declines from the eastern coast to the western hinterland (Gao et al., 2014). There are 13 cities and 173 counties in this region. Beijing and Tianjin are megacities, with urban populations exceeding 5 million. Shijiazhuang, Tangshan, Baoding, and Handan are large cities, with urban populations between 1 million and 5 million. Zhangjiakou, Chengde, Qinhuangdao, Langfang, Cangzhou, Hengshui, and Xingtai are medium cities, with urban populations below 1 million (Bai et al., 2014) (Fig. 1).

2.2. Data

In this study, urban population data were obtained from the Climate and Global Dynamics Laboratory of the National Center for Atmospheric Research (https://www2.cgd.ucar.edu/sections/tss/iam/spatial-population-scenarios) (Jiang and O'Neill, 2017; Jones and O'Neill, 2016). Based on this urban population data, we extracted urban population under the five SSPs in the BTH urban agglomeration from 2020 to 2040 (Table S1). The spatial resolution of the data was about 10 km. The LULC maps for 1990, 2000, and 2013, which have a spatial resolution of 30 m, were collected from the Data Sharing Network of Earth System Science (DSNESS) at the Chinese Academy of Sciences. These maps were derived from remotely sensed images of Landsat Thematic Mapper/Enhanced Thematic Mapper by visual interpretation