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...
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 adaptation—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. Delink 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 6.478.9 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 km², 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 megalopolis, 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, Zhangzhou, 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
and digitalization. The maps included six LULC classes: cropland, woodland, grassland, water body, urban land, and unused land. The accuracy of LULC classification exceeded 90% (Kuang, 2011; Liu et al., 2005, 2010). Meteorological data were acquired from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). The meteorological data consisted of the annual mean temperature and annual mean precipitation from 1990 to 2013 recorded by 25 meteorological stations distributed throughout the BTH urban agglomeration. The Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), which has a spatial resolution of 90 m, was obtained from the DSNESS (http://datamirror.csdb.cn/dem/files/ys.jsp, accessed June 30, 2016). The geographical ancillary data included administrative boundaries, city centers, roads, highways, expressways, railways, and high-speed railways and were obtained from the National Administration of Surveying, Mapping, and Geoinformation of China. All the data were georegistered to the Albers coordinate system and resampled to a spatial resolution of 500 m.

3. Methods

3.1. Mapping ESs in 1990

According to the Millennium Ecosystem Assessment (MEA, 2005) and data availability, four ESs in the BTH urban agglomeration were selected (Fig. 2): FP, CS, WR, and air purification (AP). Specifically, the food provided by the cropland was very important to the local residents because the food self-sufficiency ratio in this region was above 90% (He et al., 2017; Wei et al., 2016; Wu et al., 2013; Zhan et al., 2015). Furthermore, CS, WR, and AP were also strongly relevant to the human well-being in diverse ways in this region (Ouyang et al., 2016; Peng et al., 2016; Song and Deng, 2015; Zhan et al., 2015). Based on the LULC data in 1990, we quantified the four ESs and used the mean annual precipitation during 1990–2013 to eliminate the effect of climate change.

3.1.1. Food production

According to Li et al. (2014), FP can be expressed as

$$\text{FP} = \sum_{K} \sum_{c} A_{cK} \times P_{cK}$$

where $A_{cK}$ is the area of food type $c$ provided by LULC type $K$, and $P_{cK}$ is the yield per unit area of food type $c$ provided by LULC type $K$. Following a previous study (Li et al., 2014), FP in the BTH urban agglomeration includes rice, oil, and vegetables produced by croplands; mutton and milk produced by grasslands; and aquatic products produced by water bodies. The specific parameters used in this study can be found in Table S2.

3.1.2. Carbon storage

The Carbon Storage and Sequestration module of the InVEST model was used to calculate the regional CS (Sharp et al., 2015). The CS ($CS_{k,x,y}$) for a given cell $(x, y)$ in LULC type $K$ can be expressed as

$$\text{CS}_{k,x,y} = A \times \left( \phi_{k,x,y}^{VA} + \phi_{k,x,y}^{VB} + \phi_{k,x,y}^{S} + \phi_{k,x,y}^{D} \right)$$

where $A_{k}$ denotes the actual area of each cell, $\phi_{k,x,y}^{VA}$, $\phi_{k,x,y}^{VB}$, $\phi_{k,x,y}^{S}$, and $\phi_{k,x,y}^{D}$ are the aboveground, belowground, soil organic, and dead organic matter carbon densities, respectively. The carbon densities for different LULC types were determined in the BTH urban agglomeration (Table S3) based on the studies of Fang et al. (1996) and Li et al. (2003). Additionally, according to Goldstein et al. (2012) and He et al. (2016), we assumed that the carbon stored in urban land was negligible and only calculated the CS in non-urban land because the CS in urban land
3.1.3. Water retention

According to Yang et al. (2015), WR was defined as the interception capability of natural vegetation for surface runoff. It can be calculated using the following equation:

\[ WR_{x,y} = A \times P_{x,y} \times C \times R_{K,x,y} \] (3)

where \( WR_{x,y} \) is the WR for a given cell \((x, y)\) in LULC type \(K\). \(A\) denotes the actual area of each cell, \(P_{x,y}\) is the mean annual precipitation for a given cell \((x, y)\). In this study, we used the mean annual precipitation during 1990–2013 to eliminate the effect of climate change. \(C\) is the proportion of the surface runoff to the total rainfall. \(R_{K,x,y}\) is the percentage of the surface runoff intercepted by a given cell \((x, y)\) in LULC type \(K\). According to Liu (2009) and Zhang et al. (2012), \(C\) is 0.6 in the BTH urban agglomeration. The \(R_{K,x,y}\) values for cropland, woodland, and grassland in this region are 12%, 20%, and 11%, respectively (Zhang et al., 2012). The values of \(R_{K,x,y}\) for cropland, woodland, and grassland are originated from Zhang et al. (2012). Specifically, the \(R_{K,x,y}\) for productive green space is used for cropland, the average value of \(R_{K,x,y}\) for roadside green space and defensive forestry is used for woodland, and the average value of \(R_{K,x,y}\) for public green space, residential green space, and affiliated green space is used for grassland.

3.1.4. Air purification

Based on a previous study (Landuyt et al., 2016), AP can be measured based on the particulate matter (PM) captured by natural vegetation. In this study, the PM_{10} (PM with aerodynamic diameters smaller than 10 μm) captured by natural vegetation was used to measure the AP:

\[ AP_{K,x,y} = A \times PM_{K,x,y} \] (4)

where \(AP_{K,x,y}\) is the volume of captured PM_{10} for a given cell \((x, y)\) in LULC type \(K\). \(A\) denotes the actual area of each cell, \(PM_{K,x,y}\) is the captured PM_{10} per unit area for a given cell \((x, y)\) in LULC type \(K\). The \(PM_{K,x,y}\) values for cropland, woodland, and grassland were obtained from Nowak et al. (2006), Tiwary et al. (2009), and Landuyt et al. (2016) and can be found in Table S3. Finally, we assumed that the ability of urban land to capture PM_{10} was negligible (Landuyt et al., 2016).
simulate the area of urban land based on historical urban population data from 1990 to 2013. Then, we projected urban land demands in this region from 2013 to 2040 under the five SSPs using the projected urban population data. In other words, the differences among the five SSPs were the urban land demands driven by urban population projection and the consequent spatial allocation of urban expansion.

### 3.2.2. Modeling urban expansion using the LUSD-urban model

In the LUSD-urban model, the probability of a non-urban cell converting to an urban cell is first calculated based on the suitability of urban expansion, the neighborhood effect, the inheritance attributes of different LULC types, and random perturbations (He et al., 2006, 2016). Then, the non-urban cell with the highest probability is converted to an urban cell. This conversion process then iterates until the total area of urban land is equal to the demand for urban land.

In this study, the LULC data in 1990 were used as the initial input data, and the LULC data in 2000 were used to calibrate the model. Specifically, an adaptive Monte Carlo approach was used to generate 500 different sets of weights for the driving factors to simulate the urban expansion in the BTH urban agglomeration during the period of 1990–2000. The 500 simulation results were compared against the actual urban land in 2000, and the best combination of weights with the highest Kappa index was identified (Table S5). The highest Kappa index for 2000 was 0.77, the overall accuracy (OA) was 99.26%, and the quantity disagreement (QD) and allocation disagreement (AD) were 0 and 0.74%, respectively (Fig. S1). Then, the distribution of urban land in 2013 was simulated, and the LULC data in 2013 were used to validate the model. The highest Kappa index for 2013 was 0.66, and the OA, QD, and AD were 97.71%, 0, and 2.29%, respectively. The calibration and validation results suggested that the LUSD-urban model was reliable for simulating urban expansion in the BTH urban agglomeration.

After the calibration and validation of the LUSD-urban model, the spatial processes of urban expansion from 2013 to 2040 were simulated based on the urban land demands under the five SSPs.

### 3.3. Assessing the potential impacts of future urban expansion on ESs

Following He et al. (2016), the total change in ES i across the whole region ∆ESi was aggregated and calculated as

\[
\Delta S_{ES_i} = \sum_{x,y} (E_{S_{ES,xy}}^{PRE-URBAN} \times (UR_{xy}^2 - UR_{xy}^1))
\]

where \(E_{S_{ES,xy}}^{PRE-URBAN}\) is the volume of ES i for a given cell (x, y) before urban expansion. In this study, it is the volume in 1990. \(UR_{xy}^2\) and \(UR_{xy}^1\) are two binary variables used to indicate whether the given cell (x, y) is an urban or non-urban cell in years \(t_2\) and \(t_1\). A value of 1 represents a non-urban status, whereas a value of 0 represents an urban status.

Using this formula, we assessed the historical impacts of urban expansion on ESs from 1990 to 2013 and the potential impacts from 2013 to 2040 at three scales: the regional, city, and county scales. At the county scale, we extracted the ten counties that experienced the greatest loss of each ES and focused on the losses of ESs caused by urban expansion in these counties.

### 4. Results

#### 4.1. ESs in the BTH urban agglomeration in 1990

In 1990, the total FP in the BTH urban agglomeration was \(113.55 \times 10^8\) t and was greater in the south than in the north (Fig. 3). Among the 13 cities, the FP in Zhangjiakou was the largest (approximately \(18.38 \times 10^8\) t), accounting for 16.19% of the total FP in the BTH urban agglomeration. In contrast, the FP in Qinhuangdao was the smallest (only \(3.18 \times 10^8\) t), accounting for 2.80% of the total FP in the BTH urban agglomeration.

Meanwhile, the CS, WR, and AP in the BTH urban agglomeration in 1990 were \(28.30 \times 10^8\) t, \(79.03 \times 10^8\) t, and \(47.41 \times 10^8\) t, respectively. The three ESs were greater in the north than in the south (Fig. 3). Among all the cities, the CS, WR, and AP in Chengde were the largest: \(7.20 \times 10^8\) t, \(18.40 \times 10^8\) t, and \(15.74 \times 10^8\) t, representing 25.45%, 23.28%, and 33.20% of the total volumes in the BTH urban agglomeration, respectively. In contrast, the three ESs in Langfang were the smallest, where the volumes of CS, WR, and AP were \(0.64 \times 10^8\) t, \(2.14 \times 10^8\) t, and \(0.56 \times 10^8\) t, accounting for only 2.28%, 2.71%, and 1.18% of the total volumes in the BTH urban agglomeration, respectively.

### 4.2. Impacts of urban expansion on ESs in the BTH urban agglomeration from 1990 to 2013

The progress of urban expansion during 1990–2013 in the BTH urban agglomeration was extensive. The total area of urban land increased by 2.61 times, from 2108.15 km² (0.98% of the total land area) in 1990 to 7605.25 km² (3.54% of the total land area) in 2013. The average annual growth rate was 239.01 km², and the average annual growth rate was 5.74%. Among all the cities, Beijing, Tianjin, and Shijiazhuang had the greatest increases in the urban land area (Table 1, Fig. 4). Between 1990 and 2013, the urban land areas in Beijing, Tianjin, and Shijiazhuang increased by 1394.75 km², 758.50 km², and 630.25 km², accounting for 25.37%, 13.80%, and 11.47% of the total expanded urban land area in the BTH urban agglomeration, respectively. In other words, although these three cities covered only 19.52% of the land in the BTH urban agglomeration, the expanded urban land area of these three cities accounted for 50.64% of the total expanded urban land area from 1990 to 2013.

During the urban expansion from 1990 to 2013, the FP, CS, WR, and AP experienced evident losses. Among the four ESs, FP exhibited the greatest loss, and AP suffered the smallest loss (Table 1). FP decreased by \(3.94 \times 10^8\) t, or 3.47% during 1990–2013, whereas AP only decreased by \(0.46 \times 10^8\) t, or 0.97%. Meanwhile, CS and WR decreased by 1.78% and 2.10%, respectively.

Among all the cities, Beijing, Tianjin, and Shijiazhuang experienced the greatest losses in the four ESs (Table 1). In these three cities, the loss of FP, CS, WR, and AP was \(1.92 \times 10^8\) t, \(0.25 \times 10^8\) t, \(0.81 \times 10^8\) t, and \(0.24 \times 10^8\) t, representing 48.74%, 50.00%, 48.51%, and 52.17% of the total losses in the BTH urban agglomeration, respectively.

#### 4.3. Urban expansion in the BTH urban agglomeration from 2013 to 2040

During 2013–2040, the urban land area in the BTH urban agglomeration is expected to continue to increase. Among the five SSPs, the urban land area under SSP1/SSP5 will experience the largest growth, followed by SSP4 and SSP2, whereas the urban land area under SSP3 will grow the least (Table 2). Under SSP1/SSP5, the urban land area will increase from 7605.25 km² in 2013 to 11,936.00 km² in 2040 at an annual growth rate of 1.68%. Under SSP4 and SSP2, the urban land area will increase by 4112.00 km² and 3376.50 km² at annual growth rates of 1.61% and 1.37%, respectively. Under SSP3, the urban land area will increase by just 1796.50 km² at an annual growth rate of 0.79%.

Among all the cities, Beijing, Baoding, and Tianjin will experience the greatest growth in urban land (Fig. 5, Fig. S2). Under the five SSPs, the urban land area in these three cities will increase from 3197.25 km² in 2013 to 3900.25 km², accounting for 36.65–39.13% of the total growth of urban land area across the whole region.
Fig. 3. ESs in the BTH urban agglomeration in 1990.
Note: Please refer to Fig. 1 for an explanation of the labels.

Table 1
Urban expansion and ES losses in each city from 1990 to 2013.

<table>
<thead>
<tr>
<th>City</th>
<th>Urban growth</th>
<th>FP</th>
<th>CS</th>
<th>WR</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (km²)</td>
<td>%</td>
<td>Volume (×10⁸ t)</td>
<td>Percentage</td>
<td>Volume (×10⁸ t)</td>
</tr>
<tr>
<td>Beijing</td>
<td>1394.75</td>
<td>25.37%</td>
<td>0.97</td>
<td>24.62%</td>
<td>0.13</td>
</tr>
<tr>
<td>Tianjin</td>
<td>758.50</td>
<td>13.80%</td>
<td>0.46</td>
<td>11.68%</td>
<td>0.06</td>
</tr>
<tr>
<td>Shijiazhuang</td>
<td>630.25</td>
<td>11.47%</td>
<td>0.49</td>
<td>12.44%</td>
<td>0.06</td>
</tr>
<tr>
<td>Tangshan</td>
<td>418.00</td>
<td>7.60%</td>
<td>0.27</td>
<td>6.85%</td>
<td>0.03</td>
</tr>
<tr>
<td>Baoding</td>
<td>406.75</td>
<td>7.40%</td>
<td>0.32</td>
<td>8.12%</td>
<td>0.04</td>
</tr>
<tr>
<td>Handan</td>
<td>360.00</td>
<td>6.55%</td>
<td>0.27</td>
<td>6.85%</td>
<td>0.03</td>
</tr>
<tr>
<td>Langfang</td>
<td>333.00</td>
<td>6.06%</td>
<td>0.25</td>
<td>6.35%</td>
<td>0.03</td>
</tr>
<tr>
<td>Xingtai</td>
<td>288.75</td>
<td>5.25%</td>
<td>0.25</td>
<td>6.35%</td>
<td>0.03</td>
</tr>
<tr>
<td>Zhangzhou</td>
<td>235.75</td>
<td>4.29%</td>
<td>0.19</td>
<td>4.82%</td>
<td>0.02</td>
</tr>
<tr>
<td>Hengshui</td>
<td>204.25</td>
<td>3.72%</td>
<td>0.16</td>
<td>4.06%</td>
<td>0.02</td>
</tr>
<tr>
<td>Qinhuangdao</td>
<td>198.50</td>
<td>3.61%</td>
<td>0.14</td>
<td>3.55%</td>
<td>0.02</td>
</tr>
<tr>
<td>Zhangjiakou</td>
<td>150.75</td>
<td>2.74%</td>
<td>0.12</td>
<td>3.05%</td>
<td>0.02</td>
</tr>
<tr>
<td>Chengde</td>
<td>117.85</td>
<td>2.14%</td>
<td>0.05</td>
<td>1.27%</td>
<td>0.01</td>
</tr>
<tr>
<td>Total</td>
<td>5497.10</td>
<td>100%</td>
<td>3.94</td>
<td>100%</td>
<td>0.20</td>
</tr>
</tbody>
</table>

a This percentage refers to the proportion of urban growth in each city relative to the total growth in the BTH urban agglomeration.

b This percentage refers to the proportion of ES loss in each city relative to the total loss in the BTH urban agglomeration.

Fig. 4. Urban expansion in the BTH urban agglomeration from 1990 to 2013.
Note: Please refer to Fig. 1 for an explanation of the labels.
4.4. Potential impacts of urban expansion on ESs in the BTH urban agglomeration from 2013 to 2040 under the SSPs

4.4.1. Food production

With urban expansion from 2013 to 2040, FP in the BTH urban agglomeration will show a declining trend, decreasing from $109.61 \times 10^6$ t in 2013 to $106.14 \times 10^6$ – $108.14 \times 10^6$ t in 2040, with an annual loss of $0.05 \times 10^6$ – $0.13 \times 10^6$ t (Fig. 6, Table 2). Among the five SSPs, the declines in FP will be the greatest under SSP1/SSP5: $3.47 \times 10^6$ t, or 3.16% of the total volume in 2013. Under SSP2 and SSP4, FP will decrease by $2.72 \times 10^6$ t and $3.30 \times 10^6$ t, corresponding to 2.48% and 3.01% of the total volume in 2013, respectively. Under SSP3, the declines in FP will be the smallest: $1.47 \times 10^6$ t, or 1.34% of the total volume in 2013.

Among all the 13 cities, Baoding, Shijiazhuang, and Beijing will experience the greatest loss of FP (Table 3). Under the five SSPs, FP in Baoding, Shijiazhuang, and Beijing will decrease by $0.18 \times 10^6$ t to $0.45 \times 10^6$ t, or $0.21 \times 10^6$ t, respectively. In other words, the loss of FP in these three cities will account for 36.89–38.78% of the total loss across the whole region.

Among all the counties, the loss of FP will be mainly concentrated in ten counties, including Tangshan, Handan, and Baoding (Fig. 7, Table 4). The total area of these ten counties (i.e., 13,941.50 km²) covers just 6.47% of the total area of the BTH urban agglomeration, but the loss of FP in these counties (i.e., $0.45 \times 10^6$–$0.91 \times 10^6$ t) will account for 25.69–30.64% of the total loss across the whole region from 2013 to 2040.

4.4.2. Carbon storage

With future urban expansion, CS will also continue to decline, decreasing from $27.80 \times 10^8$ t to $27.36 \times 10^8$ – $27.61 \times 10^8$ t during 2013–2040 under the five SSPs. The annual loss will be $0.01 \times 10^8$ – $0.02 \times 10^8$ t (Fig. 6, Table 2). Under SSP1/SSP5, CS will experience the greatest loss and decrease by $0.44 \times 10^8$ t, or 1.60% of the total volume in 2013. Under SSP2 and SSP4, CS will decrease by $0.35 \times 10^8$ t and $0.42 \times 10^8$ t, or 1.26% and 1.52% of the total volume in 2013, respectively. CS will exhibit the smallest decline under SSP3: $0.19 \times 10^8$ t, or 0.68% of the total volume in 2013.

Among all the cities, the loss of CS will mainly occur in Baoding, Shijiazhuang, and Beijing (Table 3). Under the five SSPs, the loss of CS in Baoding, Shijiazhuang, and Beijing will be $0.02 \times 10^8$ t to $0.06 \times 10^8$ t, or $0.03 \times 10^8$ t, respectively. The total loss in these three cities will represent 36.72–41.89% of the total loss across the whole region.

At the county scale, the largest loss of CS will occur in ten counties, including Tangshan, Handan, and Fangshan (Fig. 7, Table S6). In these ten counties, the total loss of CS will be $0.03 \times 10^8$ t, accounting for 25.30–26.03% of the total loss across the BTH urban agglomeration.

4.4.3. Water retention

During the process of future urban expansion, the WR will also exhibit an obvious decreasing trend, declining from $77.36 \times 10^8$ t in 2013 to $75.89 \times 10^8$ – $76.74 \times 10^8$ t in 2040, with an annual loss of $0.02 \times 10^8$ – $0.05 \times 10^8$ t (Fig. 6, Table 2). Under SSP1/SSP5, WR will
experience the greatest loss: a loss of $1.47 \times 10^8$ t, or 1.89% of the total volume in 2013. Under SSP2, SSP3, and SSP4, the losses of WR will be $1.15 \times 10^8$ t, $0.62 \times 10^8$ t, and $1.39 \times 10^8$ t, representing 1.49%, 0.80%, and 1.80% of the total volume in 2013, respectively.

Among all the cities, Baoding, Shijiazhuang, and Beijing will experience the greatest loss of WR (Table 3). Under the five SSPs, the losses of WR in Baoding, Shijiazhuang, and Beijing will be $0.07 \times 10^8$–$0.18 \times 10^8$ t, $0.07 \times 10^8$–$0.18 \times 10^8$ t, and $0.10 \times 10^8$–$0.19 \times 10^8$ t, respectively. Altogether, the loss of WR in these three cities will represent 35.89–40.59% of the total WR loss across the whole region.

Among all counties, the loss of WR will be the greatest in ten counties, including Tangshan, Handan, and Tongzhou (Fig. 7, Table S6). The total area of these ten counties is 13,444 km², corresponding to 6.24% of the total area of the BTH urban agglomeration. The total loss of these counties will be $0.16 \times 10^8$–$0.38 \times 10^8$ t, accounting for 25.08–26.24% of the total loss in the BTH urban agglomeration.

4.4.4. Air purification
Urban expansion will decrease AP from $46.95 \times 10^4$ t in 2013 to $46.54 \times 10^4$–$46.78 \times 10^4$ t in 2040, with an annual loss of

![Fig. 6. Impacts of urban expansion on the EEs in the BTH urban agglomeration from 1990 to 2040 under the SSPs.](image)

<table>
<thead>
<tr>
<th>City</th>
<th>FP (×10¹⁰ t)</th>
<th>Percentage (%)</th>
<th>CS (×10¹⁰ t)</th>
<th>Percentage (%)</th>
<th>WR (×10¹⁰ t)</th>
<th>Percentage (%)</th>
<th>AP (×10¹⁰ t)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baoding</td>
<td>0.18–0.45</td>
<td>11.99–12.99</td>
<td>0.02–0.06</td>
<td>11.46–12.54</td>
<td>0.07–0.18</td>
<td>11.03–12.02</td>
<td>0.02–0.05</td>
<td>10.07–11.26</td>
</tr>
<tr>
<td>Shijiazhuang</td>
<td>0.18–0.43</td>
<td>12.23–12.51</td>
<td>0.02–0.05</td>
<td>11.63–11.94</td>
<td>0.07–0.18</td>
<td>11.72–11.99</td>
<td>0.02–0.04</td>
<td>10.34–10.77</td>
</tr>
<tr>
<td>Beijing</td>
<td>0.21–0.40</td>
<td>11.48–14.30</td>
<td>0.03–0.06</td>
<td>13.63–17.41</td>
<td>0.10–0.19</td>
<td>13.14–16.58</td>
<td>0.04–0.07</td>
<td>17.25–22.50</td>
</tr>
<tr>
<td>Tianjin</td>
<td>0.16–0.37</td>
<td>10.60–10.86</td>
<td>0.02–0.05</td>
<td>10.12–10.37</td>
<td>0.06–0.15</td>
<td>10.19–10.36</td>
<td>0.02–0.05</td>
<td>10.42–11.07</td>
</tr>
<tr>
<td>Handan</td>
<td>0.15–0.35</td>
<td>10.18–10.52</td>
<td>0.02–0.04</td>
<td>9.73–9.97</td>
<td>0.06–0.14</td>
<td>9.42–9.68</td>
<td>0.02–0.04</td>
<td>8.82–8.96</td>
</tr>
<tr>
<td>Xingtai</td>
<td>0.12–0.30</td>
<td>8.12–8.84</td>
<td>0.01–0.04</td>
<td>7.74–8.58</td>
<td>0.05–0.12</td>
<td>7.48–8.30</td>
<td>0.01–0.03</td>
<td>6.92–8.06</td>
</tr>
<tr>
<td>Langfang</td>
<td>0.11–0.29</td>
<td>7.61–8.42</td>
<td>0.01–0.04</td>
<td>7.45–8.25</td>
<td>0.05–0.12</td>
<td>7.71–8.48</td>
<td>0.01–0.03</td>
<td>6.92–8.06</td>
</tr>
<tr>
<td>Tangshan</td>
<td>0.12–0.29</td>
<td>8.25–8.40</td>
<td>0.02–0.04</td>
<td>8.04–8.33</td>
<td>0.06–0.14</td>
<td>9.15–9.45</td>
<td>0.01–0.03</td>
<td>7.52–8.05</td>
</tr>
<tr>
<td>Cangzhou</td>
<td>0.11–0.29</td>
<td>7.72–8.28</td>
<td>0.01–0.04</td>
<td>7.38–7.97</td>
<td>0.05–0.12</td>
<td>7.83–8.45</td>
<td>0.01–0.03</td>
<td>6.45–7.07</td>
</tr>
<tr>
<td>Handan</td>
<td>0.07–0.18</td>
<td>4.78–5.23</td>
<td>0.01–0.02</td>
<td>4.49–4.93</td>
<td>0.03–0.07</td>
<td>4.13–4.44</td>
<td>0.01–0.02</td>
<td>3.92–4.35</td>
</tr>
<tr>
<td>Qinhuangdao</td>
<td>0.04–0.08</td>
<td>2.42–2.59</td>
<td>0.01</td>
<td>2.74–2.88</td>
<td>0.02–0.05</td>
<td>3.11–3.26</td>
<td>0.00</td>
<td>3.58–3.74</td>
</tr>
<tr>
<td>Hengshui</td>
<td>0.01–0.02</td>
<td>0.61–0.70</td>
<td>0</td>
<td>0.74–0.84</td>
<td>0.01</td>
<td>0.54–0.62</td>
<td>0.00</td>
<td>1.00–1.12</td>
</tr>
<tr>
<td>Chengde</td>
<td>0.01</td>
<td>0.26–0.38</td>
<td>0</td>
<td>0.55–0.66</td>
<td>0.01</td>
<td>0.54–0.61</td>
<td>0.00</td>
<td>1.17–1.33</td>
</tr>
<tr>
<td>Total</td>
<td>1.47–3.47</td>
<td>100</td>
<td>0.19–0.44</td>
<td>100</td>
<td>0.62–1.47</td>
<td>100</td>
<td>0.17–0.41</td>
<td>100</td>
</tr>
</tbody>
</table>

This number refers to the extent of ES loss under the SSPs.
This percentage refers to the proportion of ES loss in each city relative to the total loss in the BTH urban agglomeration.
0.01 \times 10^4 - 0.02 \times 10^4 t (Fig. 6, Table 2). Under SSP1/SSP5, SSP2, SSP3, and SSP4, AP will decrease by 0.41 \times 10^4 t, 0.32 \times 10^4 t, 0.17 \times 10^4 t, and 0.39 \times 10^4 t, respectively, accounting for 0.87%, 0.68%, 0.37%, and 0.82% of the total volume in 2013.

At the city scale, Beijing will experience the greatest AP loss: 0.04 \times 10^4 - 0.07 \times 10^4 t, accounting for 17.25–22.50% of the total loss across the whole region (Table 3). In Baoding and Shijiazhuang, the losses of AP will be 0.02 \times 10^4 - 0.05 \times 10^4 t and 0.02 \times 10^4 - 0.04 \times 10^4 t, accounting for 10.07–11.26% and 10.34–10.77% of the total losses in the BTH urban agglomeration, respectively. Overall, in these three cities, the loss of AP will account for 37.66–44.53% of the total loss in the whole BTH urban agglomeration.

At the county scale, ten counties, including Tangshan, Fangshan, and Handan, will experience the greatest loss of AP (Fig. 7, Table S6).

The total area of these counties (i.e., 13,385 km²) represents only 6.22% of the total area of the BTH urban agglomeration. However, the loss of AP in these counties will total 0.05 \times 10^4 - 0.11 \times 10^4 t, accounting for 26.22–26.67% of the total loss across the BTH urban agglomeration.

4.5. Converting cropland to urban land will be the main cause of ES loss in the BTH urban agglomeration from 2013 to 2040

The results obtained at different scales confirmed that, the conversion of cropland to urban land will be the main cause of ES loss in the context of future urban expansion in the BTH urban agglomeration (Table 5). At the regional scale, 1534.75–3629.50 km² of cropland will be converted to urban land in the BTH urban agglomeration, accounting for 83.81–85.43% of the
total new urban land arising from 2013 to 2040. This conversion will result in substantial losses of the four ESs. Indeed, the losses of FP, CS, WR, and AP caused by this conversion will reach 1.42 × 10^8–3.37 × 10^8 t, 0.18 × 10^8–0.41 × 10^8 t, 0.59 × 10^8–1.38 × 10^8 t, and 0.14 × 10^8–0.33–
\times 10^8 t, respectively, accounting for 96.90–97.11%, 92.71–93.15%, 94.27–94.47%, and 83.66–85.17% of the total loss of each ES across the whole region.

The conversion of cropland to urban land will also be the main cause of ES loss at the city scale. Among the three cities expected to experience the greatest losses of ESs (i.e., Baoding, Shijiazhuang, and Beijing), the conversion of cropland to urban land will result in substantial losses of the four ESs (Table 5). During 2013–2040, 559.00–1255.25 km² of cropland will be converted to urban land in these three cities, accounting for 79.03–79.52% of the total area of new urban land in these three cities. In this context, FP, CS, WR, and AP will decrease by 0.52 × 10^8–1.16 × 10^8 t, 0.06 × 10^8–0.14 × 10^8 t, 0.21 × 10^8–0.47 × 10^8 t, and 0.05 × 10^8–0.12 × 10^8 t, respectively, accounting for 95.00–95.48%, 86.60–88.18%, 89.73–90.87%, and 68.66–71.63% of the total loss of each ES in these three cities, respectively.

At the county scale, we also found that the conversion of cropland to urban land will also be the culprit of ES loss. Among the ten counties expected to experience the greatest losses of ESs, approximately 388.75–954.75 km² of cropland will be converted to urban land from 2013 to 2040, representing more than 80% of the total new urban land in these counties (Table 5). This conversion is expected to lead to declines in the four ESs as follows: FP, CS, WR, and AP will decrease by 0.36–
\times 10^8–0.89 × 10^8 t, 0.04 × 10^8–0.11 × 10^8 t, 0.15 × 10^8–0.37 × 10^8 t, and 0.04 × 10^8–0.09 × 10^8 t, respectively, corresponding to more than 80% of the total loss of each ES in these counties.

5. Discussion

5.1. Linking SSPs and the LUSD-urban model provides an effective way for exploring the ranges and uncertainties of the impacts of urban expansion on ESs

The SSPs can comprehensively reflect the uncertainties of future socioeconomic development in the BTH urban agglomeration of China. Among the five SSPs, SSP1 is highly consistent with the development plan, i.e., the National New-type Urbanization Plan released in 2014, the OBDBTH released in 2015, and the National 13th Five-Year Plan released in 2016, in terms of the demographical, economical, policy, environmental, and natural resource targets (Table 6). Regarding the demographic targets, both SSP1 and the OBDBTH expect relatively slow population growth in the future. According to the OBDBTH, during 2013–2020, the annual growth rate of the total population in Beijing will be 0.57%, far smaller than the value of 2.73% observed between 1990 and 2013. In terms of the economic targets, both SSP1 and the OBDBTH forecast rapid economic growth. According to China’s 13th Five-Year Plan, the annual growth rate of the GDP in the BTH urban agglomeration will remain above 6.5%, and the total GDP will double between 2016 and 2020. From the policy perspective, both SSP1 and the OBDBTH envision a policy environment that will promote sustainable development in the region. Indeed, in the BTH urban agglomeration, the Chinese central government has already established a leading group for the coordinated development of the BTH urban agglomeration and released the Plan of Economic and Social Development of Beijing, Tianjin, and Hebei Province from 2016 to 2020. This plan is the first inter-provincial regional plan in China and aims to accelerate coordinated and sustainable development in the BTH urban agglomeration. Regarding the environmental and natural resource targets, both SSP1 and the OBDBTH envision improved environment quality and resource utilization efficiency. According to the OBDBTH, the PM10 air pollution issue in the BTH urban agglomeration will be addressed in the near future, and through substantial effort, the PM10 concentration is expected to decrease by 25% from 2012 to 2017. Moreover, the energy consumption per unit GDP is predicted to decrease by 15% by 2020.

Besides SSP1, SSP2 describes a socioeconomic development of this region following a historical trend. SSP3, SSP4, and SSP5 portray alternative pathways of future socioeconomic development corresponding to scenarios of regional competition, regional inequality, and fossil energy-based development, respectively (Table S4). In summary, these five SSPs reflect multiple pathways of future development in this region, including the historical socioeconomic trend, the region’s development plan developed by the central government and some other routes, e.g., rapid development based on fossil energy. To some extent, the SSPs can reflect the ranges and uncertainties of future socioeconomic development, and provide a solid basis for simulating future urban expansion.

Moreover, the LUSD-urban model can effectively simulate the urban expansion process at the regional scale. To verify the performance of the LUSD-urban model, we simulated the urban expansion in the BTH urban agglomeration from 1990 to 2013 using two commonly used urban expansion models: the GEOMOD model and the CLUE-S model (Fig. S3). This comparison revealed that the accuracy of urban expansion during 1990–2013 simulated by the LUSD-urban model was higher than the results of the GEOMOD and CLUE-S models. The average Kappa index and OA of the LUSD-urban model were 0.72 and 98.49%, respectively, higher than those values of the GEOMOD model (i.e., 0.69 and 98.45%) and the CLUE-S model (i.e., 0.60 and 97.84%) (Table S7). Therefore, the LUSD-urban model can simulate the spatial process of urban expansion in the BTH urban agglomeration more accurately than the GEOMOD and CLUE-S models.

Briefly, linking the SSPs and the LUSD-urban model can explore the ranges and uncertainties of future socioeconomic development in the BTH urban agglomeration, as well as effectively simulate the spatial
Table 5
ES losses caused by the replacement of land cover by urban expansion in the BTH urban agglomeration from 2013 to 2040 under the SSPs.

<table>
<thead>
<tr>
<th>Scale</th>
<th>LULC type</th>
<th>Urban expansion</th>
<th>ES losses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Area (km²)</td>
<td>Percentage (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The BTH urban agglomeration</td>
<td>Cropland</td>
<td>1534.75–3629.50</td>
<td>83.81–85.43</td>
</tr>
<tr>
<td></td>
<td>Woodland</td>
<td>41.00–86.00</td>
<td>1.99–2.28</td>
</tr>
<tr>
<td></td>
<td>Grassland</td>
<td>28.25–74.25</td>
<td>1.57–1.71</td>
</tr>
<tr>
<td></td>
<td>Water body</td>
<td>83.00–179.50</td>
<td>4.14–4.62</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1796.50–4330.75</td>
<td>100</td>
</tr>
<tr>
<td>Cities (The three cities that will experience the greatest ES loss)</td>
<td>Cropland</td>
<td>559.00–1255.25</td>
<td>79.03–79.52</td>
</tr>
<tr>
<td></td>
<td>Woodland</td>
<td>32.75–63.00</td>
<td>3.97–4.66</td>
</tr>
<tr>
<td></td>
<td>Grassland</td>
<td>11.75–24.75</td>
<td>1.56–1.67</td>
</tr>
<tr>
<td></td>
<td>Water body</td>
<td>51.25–103.25</td>
<td>6.50–7.29</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>703.00–1588.25</td>
<td>100</td>
</tr>
<tr>
<td>Counties (The ten counties that will experience the greatest ES loss)</td>
<td>Cropland</td>
<td>388.75–954.75</td>
<td>83.97–84.88</td>
</tr>
<tr>
<td></td>
<td>Woodland</td>
<td>12.25–23.75</td>
<td>2.09–2.67</td>
</tr>
<tr>
<td></td>
<td>Grassland</td>
<td>1.75–4.75</td>
<td>0.38–0.42</td>
</tr>
<tr>
<td></td>
<td>Water body</td>
<td>14.25–35.25</td>
<td>3.10–3.11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>458.00–1137.00</td>
<td>100</td>
</tr>
</tbody>
</table>
process of urban expansion. This linking approach can provide a solid basis for assessing the potential impacts of future urban expansion on ESs.

5.2. The ES losses can cause considerable negative impacts on human well-being in the BTH urban agglomeration

During the process of urban expansion, the losses of ESs can negatively affect the human well-being in the BTH urban agglomeration. For FP, it is closely related to the foundation of human well-being, i.e., the basic material for a good life (Wu, 2013). The loss of FP caused by urban expansion will further exacerbate the food security issue in this region. According to the Development of Chinese Food and Nutrient Program (2014–2020), the food consumption per capita will be 0.37 t. During the urban expansion from 2013 to 2040 under the five SSPs, the FP will decline by 1.47 × 10^6–3.47 × 10^6 t, corresponding to a population of 3.97–3.97 million (Fig. 8). In other words, there will be 3.97–9.37 million people, or 3.68–8.61% of the total population in 2040 influenced by FP loss in the BTH urban agglomeration.

The CS is strongly related to the mitigation of climate change. Climate change has affected human well-being in a variety of ways (Nelson et al., 2013; Pecl et al., 2017). Therefore, the loss of CS caused by urban expansion could also exert a negative impact on the well-being of people in this region. According to the calculation method for standard coal amount based on carbon storage and carbon emission proposed by Tu and Liu (2014) and Yu et al. (2009), the loss of CS caused by the future urban expansion (i.e., 0.31 × 10^6–0.72 × 10^6 t) in this region will be equivalent to a consumption of 12.05 × 10^6–28.36 × 10^6 t standard coal (Fig. 8). This amount of standard coal consumption will account for 2.55–6.01% of the total consumption in 2013 in the whole region. In other words, the loss of CS in this region will further worsen the carbon budget in the future.

In addition, WR is very important to human well-being (i.e., basic need of water) in urban areas. The water retained by natural vegetation is of particular concern in urban landscapes (e.g., water supply) (MEA, 2005; Wu, 2013; Yang et al., 2015). By comparing with statistical data, the loss of WR during the process of future urban expansion under the five SSPs (i.e., 0.62 × 10^6–1.47 × 10^6 t) will account for 0.59–1.40% of the total available surface water in 2013 in the BTH urban agglomeration (Fig. 8). It indicates that the loss of WR will further threaten the water supply in this region.

Finally, AP is relevant to human well-being from the aspect of human health (Baró et al., 2015; Martin-Lopez et al., 2012). The increase in PM_{10} concentration will be harmful to human’s health and people have to spend money on improving their health (i.e., the avoided health damage cost). According to Landuyt et al. (2016), the avoided health damage cost of AP loss will be 6.87 × 10^8–16.06 × 10^8 RMB yuan, accounting for 0.03–0.07% of the total residents’ income in 2013 (Fig. 8). In summary, as a crucial bridge between the environment and society, the losses of ESs will cause considerable negative impacts on human well-being. Special measures should be formulated to protect ESs to sustain and improve human well-being and regional sustainable development.

5.3. Future perspectives

This study has some limitations. First, the urban expansion process can affect multiple ESs. However, in this study, we quantified just four ESs and did not consider several important ESs (e.g., freshwater provision, water purification, and cultural service) due to data availability and the applicability of ES mapping methods (Peng et al., 2015, 2016). Second, the green spaces and water bodies within urban areas can provide certain types of ESs, especially cultural services (Shwartz et al., 2014; Wu, 2014). However, the ESs within urban area were not quantified in this study due to the coarse spatial resolution of the data. Third, we examined the impacts of urban expansion on ESs using a linked model and did not consider the complex ecological mechanisms and processes. Finally, there is a disconnection between the SSPs and ESs in this study. In this study, we connected the five SSPs with ESs linked model and did not consider the direct impacts of SSPs on ESs. For example, under the sustainable pathway (i.e., SSP1), appropriate policies would presumably prevent the losses of ESs during the process of urban expansion.

In the future, we will select more indicators to quantify important urban ESs, such as freshwater provision, water purification, and recreation service (Andersson et al., 2015; Logsdon and Chaubey, 2013). Additionally, high-resolution LULC data could be used to quantify ESs within urban areas, especially those services originating from urban green spaces and water bodies (Santos et al., 2017; Silva et al., 2014). Third, we could explore the impacts of urban expansion on ESs by linking the urban expansion model with the ecological process models, such as the Biome-BioGeochemical Cycles (Biome-BGC) model (Robinson et al., 2013; Schneider et al., 2012). Finally, we will consider the conservation efforts of economies and policies on ESs in the future (You and Zhang, 2017).
6. Conclusions

During the urban expansion from 1990 to 2013 in the BTH urban agglomeration, FP, CS, WR, and AP exhibited decreasing trends, falling by 3.47%, 1.78%, 2.10%, and 0.97%, respectively. From 2013 to 2040, these four ESs will continue to decrease. Under the five SSPs, FP, CS, WR, and AP will decrease by 1.34–3.16%, 0.68–1.60%, 0.80–1.89%, and 0.37–0.87%, respectively. In Baoding, Shijiazhuang, and Beijing, the losses of these four ESs will account for 35.89–44.53% of the total ES losses in the whole region. Moreover, the conversion of cropland to urban land will be the main cause of ES loss. From 2013 to 2040, 1534.75–3629.50 km² of cropland will be converted to urban land, accounting for 83.81–85.43% of the total area of new urban land. The proportions of the losses of FP, CS, WR, and AP caused by this conversion relative to the total losses in the whole region will be approximately 83.66–97.11%.

During the process of urban expansion, the losses of ESs can have considerable negative impacts on human well-being in the BTH urban agglomeration. Under the influence of FP loss, there will be 3.68–8.61% of the total population in 2040 influenced by FP loss in this region. The loss of CS could be equivalent to a consumption of 12.05 × 10⁶–28.36 × 10⁶ t standard coal, accounted for 2.55–6.01% of the total consumption in 2013. In addition, the loss of WR will account for 0.59–1.40% of the total available surface water in 2013, which will threaten the water supply. The avoided health damage cost of AP loss will be 0.03–0.07% of the total residents’ income in 2013.

Therefore, we suggest that the development path in the BTH urban agglomeration should conserve cropland with high ES values, protect the provisioning ability of ESs, and fully consider the negative impacts of ES losses on human well-being. To achieve these objectives, special attention should be paid to protecting cropland in the counties surrounding Beijing and Tianjin and in those counties with large areas of cropland in the southern BTH urban agglomeration, meanwhile considering the negative impacts of ES losses, in order to sustain and
improve this region’s sustainable development.

Acknowledgements

We would like to thank the anonymous reviewers and editor for your valuable comments which led to substantial improvements of the paper. Our research was supported in part by the National Natural Science Foundation of China (Grant Nos. 41621061 & 41501092) and the National Basic Research Program of China (Grant Nos. 2014CB954302 & 2014CB954303). It was also supported by Fundamental Research Funds for the Central Universities and the project from the State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2017.06.003.

References


