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Surplus or deficit? Quantifying the total ecological compensation of Beijing-Tianjin-Hebei Region

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Abstract: The calculation of ecological compensation and boundary identification of stakeholders represent the key challenges for Beijing-Tianjin-Hebei Region in its implementation of the trans-regional ecological compensation mechanism. Breaking administrative boundaries and spatially coordinating ecological resources helps to restructure an ecological compensation mechanism of the region based on the coordinated development of Beijing, Tianjin and Hebei. According to the estimated ecological assets in the counties of the region in 2000, 2005, 2010 and 2015, a quantitative model for total ecological compensation was built based on ecological assets and county-level economic development. Then, the spatiotemporal distribution characteristics of the total ecological compensation in the region were defined, and the boundaries of ecological surplus and deficit areas were identified. Results indicate: (1) The region's annual average ecological assets amounted to ¥1379.47 billion; in terms of annual total ecological assets, Hebei ranked first (¥1123.80 billion), followed by Beijing (¥157.46 billion) and Tianjin (¥98.21 billion); and in terms of ecological assets per unit area, Beijing ranked first, Tianjin second and Hebei last. (2) Among ecosystem services, hydrological regulation and climate regulation had the highest annual average value and contributed most to the increase in ecological assets. In 2015, the contribution of water and soil conservation to the total ecological assets decreased to –15.66%, showing the degradation of the function played by different ecosystems. (3) The ecological surplus of the region in four periods of 2000, 2005, 2010 and 2015 were ¥398.98 billion, ¥870.37 billion, ¥1254.93 billion and ¥2693.94 billion respectively, basically offsetting the ecological deficit of each corresponding period, but the urgency for ecological compensation was increased. (4) The ecological surplus and deficit areas showed a great fluctuation in different time periods. Larger time span means more noticeable convergence of deficit areas towards central and eastern areas. Public resources such as education, transportation and medical care in central urban

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areas should be decentralized to encourage population dispersal, weaken the agglomeration effect of deficit areas and finally achieve the ecological synergy of the region.

Keywords: regional eco-compensation; equivalent factor; surplus and deficit evaluation; coordinated development; Beijing-Tianjin-Hebei region

1 Introduction

The coordinated development of ecological civilization in the Beijing-Tianjin-Hebei Region remains a hot issue for the current academic research and among government concerns. Since the implementation of the reform and opening up policy started in 1978, the Chinese government has proposed the idea of integrated development of the region so as to fully exploit the economic and ecological advantages of the areas that constitute parts of the region. According to the gradient transfer theory for regional economic development, Beijing, as a high-gradient area, would expand outward for better development through continuous innovation and development. Tianjin and Hebei, as medium- and low-gradient regions respectively, can achieve an anti-gradient leap-forward growth by accepting the expansion of Beijing and seeking good opportunities. Nevertheless, Hebei has failed to achieve a leap-forward growth. And Beijing, by exploiting its geographical advantage as the capital of China, has produced a siphon effect and attracted the increasing influx of human, financial and material resources. In contrast to Beijing's rapid and comprehensive development, Hebei has served as an ecological shelter for the capital. According to the data of Zhangjiakou Water Bureau, Zhangjiakou, a city of Hebei where drought prevails almost every year, had transferred 163 million cubic meters of water to Beijing free of charge for six consecutive years (2004–2009). The 18 counties and districts of Hebei that border Beijing have been designated as coal-free areas. In 2017, 22 additional counties and districts of Hebei were designated as key ecological function zones by the state. However, Hebei's per capita GDP is far lower than that of Beijing and Tianjin, with the highest share of poor counties. The distorted relationship between ecological protection and economic interests has seriously affected the harmony among different areas and stakeholders (Li and Liu, 2010; Li *et al.*, 2019; Liu *et al.*, 2019).

"Cross-region" represents the most difficult and most typical challenge for ecological compensation (Wang Y *et al.*, 2010). The existing issues such as competition for water resources, sandstorm and haze are gradually developing into regional conflicts of interest. And insufficient ecological compensation would aggravate imbalanced regional development (Zhang, 2007). There arises urgent and practical demand for coordination of regional development and relationship in regional ecological compensation research (Schroter *et al.*, 2018; Schirpke *et al.*, 2019). The quantification of regional ecological compensation and boundary identification of ecological surplus and deficit areas constitute the preconditions for regional ecological compensation and also the key links of ecological compensation between or among regions (Wu *et al.*, 2003). Since the introduction of the ecosystem service value concept, Chinese and international scholars have carried out research on the theory and measurement method of ecological compensation (Engel *et al.*, 2008; Wunder *et al.*, 2008; Mahanty *et al.*, 2013), including estimation of ecological compensation criteria (Farley *et al.*, 2010; James *et al.*, 2011; Dai, 2014; Zhang *et al.*, 2017), adjustment of ecological compensation system (Hecken and Bastiaensen, 2010), establishment of ecological compensation mechanism (Xie, 2000; Wang and Dong, 2007), ecological compensation implementation and policy analysis (Lansing, 2014; Chen *et al.*, 2015; Hu *et al.*, 2016; Salzman *et al.*, 2018). Anyhow, the following issues are becoming increasingly severe for cross-regional ecological compensation: "Who will make up and replenish who? How to make compensation? How much compensation is required?" Principally, the following two methods are adopted in the existing research to define the stakeholders involved in ecological compensation. The first is to determine the priority of regional ecological compensation by estimating the ecosystem service value in each region (Remme *et al.*, 2015) and applying the ratio of the non-market value of ecosystem services per unit area of the region to its GDP per unit area (Wang *et al.*, 2010; Sun and Huang, 2013; Zhong and Mi, 2013). In view of complicated and dynamic ecosystems, the ecological service value obtained in the existing research is usually far higher than the local GDP as the evaluation of ecosystem service value depends on the precision of the acquired data and on the quantitative method (De Groot *et al.*, 2012; Costanza *et al.*, 2014). This is more prominent in developing countries. Therefore, it is difficult to compensate directly for the value of ecosystem services without considering the local population and economic conditions (Kenter *et al.*, 2011). The second is to evaluate ecological surplus and deficit areas by applying the ecological footprint method, i.e. identifying human needs for ecosystem services (Wackernagel *et al.*, 1999) and then comparing the needs with ecological capacity (Zhang *et al.*, 2001; Xiong *et al.*, 2003). However, the ecological footprint method is weak in sustainability, lacks the prediction function, neglects land quality and part-time work in the same space. Due to these defects, the authenticity and precision of the evaluation would be significantly affected at the national, regional and even lower levels (Peng, 2006).

The improved equivalent factor method was used in this study to quantify the total value of regional ecological compensation for counties in the Beijing-Tianjin-Hebei Region in 2000, 2005, 2010 and 2015. Land use classification, NPP, precipitation, soil conservation, cost benefit and socioeconomic data of grain crops for the region were based on. The spatiotemporal variation characteristics of ecological compensation were analyzed. And the boundary between the ecological surplus area (SA) and the ecological deficit area (DA) for stakeholders involved in ecological compensation was identified. This study aims to provide theoretical and data support for promoting the building of the regional ecological compensation mechanism under the goal of achieving coordinated development of the region.

2 Data and methodology

2.1 Overview of the region

The Beijing-Tianjin-Hebei Region covers municipalities of Beijing and Tianjin, and Hebei Province, which include 212 counties and districts (subject to the classification of administrative divisions in 2005). Covering an area of about 218,000 km^2, the region lies between 113º–119ºE, and 36º–42ºN. Located within the continental monsoon climate belt of the warm temperate zone, the region inclines from northwest to southeast (Figure 1), with diversified topographic types. The Bashang Plateau, Yanshan and Taiang mountains lie in its northern part. The North China Plain and the coastal intertidal zone are situated in its central and southeastern parts. The precipitation of the region increases from northwest to southeast. There are two river systems within the region, namely, Haihe River and Luanhe River. In 2016, the total water resources of the region were 26.23 billion cubic meters[1], only 0.8% of China's average. The water resources per capita in the region were 187.40 cubic meters then, less than 1/9 of the country's average. Groundwater is the main source of water supply here. The dominant land use in the region is cultivated land and forest. At the end of 2016, the total cultivated land area of the region reached about 6.98 million hm^2, and the total woodland area about 5.39 million hm^2. The land in the southeastern plain area is mainly used for planting and that on the western Yanshan and Taihang mountains mainly for forestry and animal husbandry. Thus, the region has become one of the typical regions that pursue comprehensive agricultural development in China. Anyhow, it is also one of the regions where economic development conflicts with resource conservation and environmental protection most. As the largest area in the whole region, Hebei Province has the greatest potential for ecological development and occupies a prominent position in ecological security. As the home to three secondary and four tertiary ecological function zones (Figure 1), the province is given the priority for coordinated development of the region.

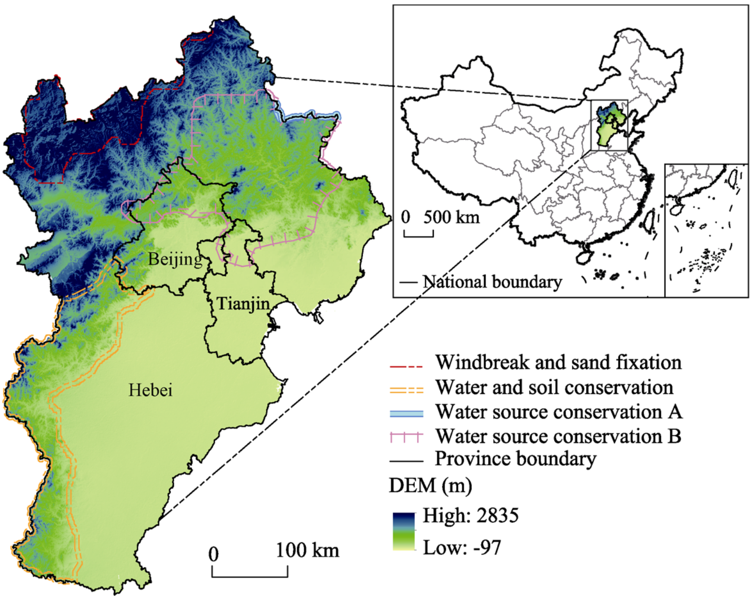

Figure 1 DEM and ecological function zoning of the region

Source: DEM 90 m data and Chinese ecological function zoning data were derived from the Data Center for Resources and Environmental Sciences of CAS.

Notes: Windbreak and sand fixation is the ecological function zone at northern foot of the Yinshan Mountain-Hunshandake Sandy Land. Soil conservation is the ecological function zone of the Taihang Mountains. Water source conservation A is the ecological function zone for West Liaohe River source conservation. Water source conservation B is the ecological function zone for Beijing-Tianjin water source conservation.

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[1] Data source: *China Environmental Statistics Yearbook 2017.*

2.2 Data sources

When quantifying the total ecological compensation at the county level of the region, we mainly adopted the following data: county-level data (subject to the classification of administrative divisions in 2005), provincial DEM 90 m data, Chinese ecological function zoning, land use classification, precipitation, NPP, soil conservation, 1 km GDP spatial distribution grid dataset, and 1km population spatial distribution grid dataset. The raw data was sourced from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (CAS) (http://www.resdc.cn). The land use data set covers four periods, namely, the four periods of 2000, 2005, 2010 and 2015. The Landsat TM/ETM remote sensing images in each period were used as main data source and were generated by means of manual visual interpretation, with a resolution of 1 km×1 km. The land use types include 6 primary ecosystem types, namely cultivated land, woodland, grassland, waters, residential land and unused land, which are sub-divided into 25 secondary types. Based on the land use data and the need for quantification of ecosystem service value, the land use was reclassified into 20 secondary types. Precipitation of the region in the four periods was extracted by masking the precipitation grid data of China based on the 1:5,000,000 vector data of the region's administrative divisions, with a resolution of 1 km×1 km. The annual average precipitation data of the country was taken from *China Water Resources Bulletin*. And we obtained the region's NPP data by masking the NPP grid data of China based on the 1:5,000,000 vector data of the region's administrative divisions. The county-level annual average NPP data was got by the regional analysis method and expressed in gC/m^2. Soil conservation was obtained by subtracting the actual soil erosion (USLE) from the potential soil erosion (RKLS). The cost-benefit data of rice, wheat, corn and soybean, four major grain crops, was sourced from *China Agricultural Products Cost-benefit Compilation of Information 2017*. The sown area data of the four grain crops was collected from the website of the National Bureau of Statistics (http://data.stats.gov.cn).

2.3 Building the model for quantifying the total regional ecological compensation

2.3.1 Building the regional ecological asset estimation model

Ecological asset valuation constitutes the basis for ecological compensation decision-making. Regional ecological assets are the sum of tangible natural resources in a specific region and the invisible services provided by different ecosystem types. The total ecological assets (*EA*) in a specific region can be expressed as follows:

$$EA=\sum_{i=1}^{n}\sum_{j=1}^{m}F_{ij}\times S_i\times V_{ij} \tag{1}$$

where i =1, 2,…; n means ecosystem types; j =1, 2, …; m means ecosystem services. In this study, 11 types of services, namely, water supply, gas regulation, climate regulation, environment purification, hydrological regulation, soil conservation, nutrient cycles maintenance, biodiversity, aesthetic landscape, food production and raw material production, were selected. Here, F_{ij} means the regulating factor of ecosystem service j under ecosystem type i; S_i means area of ecosystem type i; and V_{ij} means the unit area value of ecosystem service j for ecosystem type *i*.

By referring to the evaluation of global ecosystem service and natural capital value conducted by Costanza *et al*. (1997), Xie *et al*. (2015) proposed to revise the equivalent factors of different ecological services by using NPP, precipitation and soil conservation, and build the equivalent scale for spatiotemporal changes by month and by province within a year. In this study, we will build a spatiotemporal change equivalent factor scale by county based on the spatiotemporal change adjustment method developed by Xie *et al*. to estimate the total ecological assets of the region.

$$F_{ij} = \begin{cases} P_{kl} \times F_{n1} \text{ or} \\ R_{kl} \times F_{n2} \text{ or} \\ S_{kl} \times F_{n3} \end{cases} \tag{2}$$

where F_{ij} means the regulating factor of ecosystem service *j* under ecosystem type *i*; F_n means the equivalent factor of ecosystem service value n for a given ecosystem type; P_{kl} means the NPP spatiotemporal regulating factor of a given ecosystem type for region *k* in year *l*; R_{kl} means the precipitation spatiotemporal regulating factor of a given ecosystem type for region *k* in year *l*; and S_{kl} means the soil conservation spatiotemporal regulating factor of a given ecosystem type for region *k* in year *l*; *n*1 means water supply, gas regulation, climate regulation, environment purification, hydrological regulation, soil conservation, nutrients cycle maintenance, biodiversity, aesthetic landscape, food production, raw material production and other services; *n*2 means water supply and hydrological regulation; and *n*3 means soil conservation.

The NPP spatiotemporal regulating factor is calculated as follows:

$$P_{kl} = B_{kl} \big/ \overline{B} \tag{3}$$

where B_{kl} means the NPP of a given ecosystem type for region *k* in year *l*, in $\mathrm{gC \cdot m^{-2}}$; and $\overline{B}$ means the annual average NPP of a given ecosystem type within the country, in $\mathrm{gC \cdot m^{-2}}$.

The precipitation spatiotemporal regulating factor is calculated as follows:

$$R_{kl} = W_{kl} \big/ \overline{W} \tag{4}$$

where W_{kl} means the average precipitation for region *k* in year *l*, in mm/yr; and $\overline{W}$ means the annual average precipitation of the country, in mm/yr.

The spatiotemporal regulating factor of soil conservation is calculated as follows:

$$S_{kl} = E_{kl} \big/ \overline{E} \tag{5}$$

where E_{kl} means the simulated soil conservation of a given ecosystem for region *k* in year *l*, in $\mathrm{t \cdot hm^{-2}}$; and $\overline{E}$ means the average simulated soil conservation per unit area of the country, in $\mathrm{t \cdot hm^{-2}}$.

2.3.2 Regional ecological asset quantification methods

Ecosystem service value represents an important form of ecological asset value (Shi *et al*., 2005), as well as important part of ecological asset valuation. In this study, we will build an equivalent scale of unit area ecosystem service value (Table 1) based on the improved equivalent change scale by taking into account data availability and computational precision, and by matching the secondary classification of ecosystems and the refined land use types.

Table 1 Unit area ecosystem service value equivalent scale

Ecosystem types		Supply service			Regulation service				Support service			Cultural service
Primary classification	Secondary classification	FP	RMP	WS	AR	CR	EP	HR	SC	NCM	BD	AL
Farmland	Dry land	0.85	0.40	0.02	0.67	0.36	0.10	0.27	1.03	0.12	0.13	0.06
	Paddy field	1.36	0.09	–2.63	1.11	0.57	0.17	2.72	0.01	0.19	0.21	0.09
Forest	Woodland	0.31	0.71	0.37	2.35	7.03	1.99	3.51	2.86	0.22	2.60	1.14
	Sparse shrubbery	0.19	0.43	0.22	1.41	4.23	1.28	3.35	1.72	0.13	1.57	0.69
Grassland	High coverage grassland	0.38	0.56	0.31	1.97	5.21	1.72	3.82	2.40	0.18	2.18	0.96
	Moderate coverage grassland	0.22	0.33	0.18	1.14	3.02	1.00	2.21	1.39	0.11	1.27	0.56
	Low coverage grassland	0.10	0.14	0.08	0.51	1.34	0.44	0.98	0.62	0.05	0.56	0.25
Waters	Canal, lake, reservoir	0.80	0.23	8.29	0.77	2.29	5.55	102.24	0.93	0.07	2.55	1.89
Wetland	Mud flat, bottom land, marsh	0.51	0.50	2.59	1.90	3.60	3.60	24.23	2.31	0.18	7.87	4.73
Desert	Sandy land, saline-alkali soil	0.01	0.03	0.02	0.11	0.10	0.31	0.21	0.13	0.01	0.12	0.05
	Bare soil, bare rock	0.00	0.00	0.00	0.02	0.00	0.10	0.03	0.02	0.00	0.02	0.01

Notes: FP: food production; RMP: raw material production; WS: water supply; AR: air regulation; CR: climate regulation; EP: environment purification; HR: hydrological regulation; SC: soil conservation; NCM: nutrients cycle maintenance; BD: biodiversity; AL: aesthetic landscape.

The key to the equivalent factor method based on unit area value is to determine the ecosystem service value of one standard equivalent factor. Ecosystem service equivalent factor refers to the potential contribution of each type of ecosystem to ecosystem service. Therefore, a standard equivalent is defined as the economic value of the annual natural grain yield for the farmland with an average yield of 1 hm^2 nationwide (Xie *et al.*, 2003). However, it seems difficult to completely avoid the impact of man-made disturbance factors on grain yield and value in practical applications. In the existing literature, there are three main ways to calculate a standard equivalent: The first is on the basis of 1/7 of the average market value of national grain yield per unit area. Although it is a common means adopted in the early application of the equivalent factor method, the basis for judgment is not explicitly described. The second is on the basis of the market value of national average grain yield per unit area (Gong *et al.*, 2014). This method is mainly used to calculate the ecological service value in the regions where agricultural output value accounts for a small proportion over economic aggregate. The third is on the basis of the net profit of grain yield per unit area (Xie *et al.*, 2015). However, according to the data of *China Agricultural Products Cost-benefit Compilation of Information*, the net profits of the three major grain crops were negative in 2016. The calculation by using the net profits of grain crops as a standard equivalent has its shortcomings in practical applications. Considering the hugged rain of agricultural labor force in China and the growing number of farmers with concurrent part-time work, the scale operation that is driven by new agricultural participants has become the major trend. Through our comparative analysis, we determined that the economic value of a standard equivalent is equal to the cash gains of major grain crops per unit area in the country. The cash gains of grains were calculated mainly based on the four major grain crops, namely rice, wheat, corn and soybean. The formula of calculation is as follows:

$$E_a = \sum_{i=1}^{n} \frac{m_i C_i}{M} \tag{6}$$

where E_a means the value of unit equivalent factor, in yuan/hm^2; i means grain crop type; m_i means the total sowing area of crop type i, in hm^2; C_i means the cash gains of grain crop type i, in yuan/hm^2; M means the total sowing area of crop type n, in hm^2.

$$C = A - (M + L + R) \tag{7}$$

where C means cash gains; A means total output value of grain crops; M means material and service costs in the grain crop production costs; L means hiring costs; and R means the rent of circulated land.

2.3.3 Building the quantification model for the total regional ecological compensation

Ecological asset estimation provides an important support for the operation of ecological compensation mechanism, while ecological compensation helps to secure the interests of ecological asset owners and to promote the stability and sustainability of ecosystems. In view of the feasibility of ecological compensation, this study starts with the flow of ecological assets, takes the socioeconomic development as comparison standard, and calculates the total compensation based on the relative input and output of ecological assets. We select the county or district-level administrative divisions of the region as study areas and define the region as a closed ecosystem in its entirety. The ecological consumption of all county- and district-level study areas within the ecological region is supplied by the entire region. The amount of ecological resources and the socio-economic development vary across different areas; thus, there exists difference in the supply and demand for ecological services in different areas. The difference between ecological assets and socioeconomic development across different study areas could directly reflect the consumption of ecological assets following economic development. With reference to Jin Yan's findings on ecological compensation and considering regional population and area (Jin *et al.*, 2009), the following quantification model is built:

$$EC_i = k \times EC_{\alpha,i} + (1-k) \times EC_{\beta,i} \tag{8}$$

where i means year; EC_i means the total ecological compensation of the study area in year i; $EC_{\alpha,i}$ means the total ecological compensation for the study area calculated according to the population spatial distribution data in year i; $EC_{\beta,i}$ means the total ecological compensation calculated on the basis of the administrative division area of the study area in year i; and k means the proportion of each factor, being 0.5 in this paper.

In view of the spatial distribution difference of population in the study area, EC_α is calculated as follows:

$$EC_{\alpha(i,j)} = \left(\frac{EA_{(i,j)}}{P_{(i,j)}} - \frac{\sum_{j=1}^{n} EA_{(i,j)}}{\sum_{j=1}^{n} P_{(i,j)}} \right) \times P_{(i,j)} - \left(\frac{GDP_{(i,j)}}{P_{(i,j)}} - \frac{\sum_{j=1}^{n} GDP_{(i,j)}}{\sum_{j=1}^{n} P_{(i,j)}} \right) \times P_{(i,j)}$$

$$= \left(EA_{(i,j)} - GDP_{(i,j)}\right) - \left(\frac{\sum_{j=1}^{n} EA_{(i,j)} - \sum_{j=1}^{n} GDP_{(i,j)}}{\sum_{j=1}^{n} P_{(i,j)}}\right) \times P_{(i,j)} \tag{9}$$

where i means year; j means No. of the study area; $EA_{(i,j)}$ means the ecological assets of area j in year i; $GDP_{(i,j)}$ means the GDP of area j in year i; $P_{(i,j)}$ means the total population of area j in year i; and $EC_{(i,j)}$ means the total ecological compensation that the area j should receive in year i.

The inconsistency in the size of study areas is another important indicator for ecological compensation. EC_{β} is calculated as follows:

$$\begin{aligned} EC_{\beta(i,j)} &= \left(\frac{EA_{(i,j)}}{S_{(i,j)}} - \frac{\sum_{j=1}^{n} EA_{(i,j)}}{\sum_{j=1}^{n} S_{(i,j)}}\right) \times S_{(i,j)} - \left(\frac{GDP_{(i,j)}}{S_{(i,j)}} - \frac{\sum_{j=1}^{n} GDP_{(i,j)}}{\sum_{j=1}^{n} S_{(i,j)}}\right) \times S_{(i,j)} \\ &= \left(EA_{(i,j)} - GDP_{(i,j)}\right) - \left(\frac{\sum_{j=1}^{n} EA_{(i,j)} - \sum_{j=1}^{n} GDP_{(i,j)}}{\sum_{j=1}^{n} S_{(i,j)}}\right) \times S_{(i,j)} \end{aligned} \tag{10}$$

where $S_{(i,j)}$ means the area of the administrative division for area j in year i; and $EC_{\beta(i,j)}$ means the total compensation that the area j should receive in year i.

2.4 Ecological surplus and deficit evaluation model

The boundary between the beneficiary and the injured party is determined based on the spatial distribution of total ecological compensation. Whether a study area is in an ecological surplus or deficit status is evaluated through comparison with the average level within the overall ecological zone. When the level of the study area is higher than the average, it indicates that the study area is an SA within the ecological zone. In such case, the study area supplies rich ecological resources to the ecological zone in addition to meeting the needs for its economic development. Thus, the study area should receive compensation. When the level of the study area is equal to the average, it indicates that the area reaches equilibrium between ecological services and economic development or is an equilibrium area. So, it requires neither expenditure nor compensation. When the level of the study area is lower than the average, it indicates that the ecological services provided by the study area cannot meet the needs for its economic development, and that the area uses ecological services from other areas within the ecological zone. Thus, it is a DA and should be entitled to ecological compensation.

The regional surplus and deficit evaluation model is thus built as follows:

$$Y=\begin{cases}1, & \textit{In case of } EC > 0, \textit{ it is a surplus area}\\ 0, & \textit{In case of } EC = 0, \textit{ it is an equilibrium area}\\ -1, & \textit{In case of } EC < 0, \textit{ it is a deficit area}\end{cases} \tag{11}$$

where Y means surplus or deficit status (surplus area =1, equilibrium area =0, deficit area = –1); and EC means the total ecological compensation to the study area.

If the time variation factor is incorporated to determine the changes in the surplus and deficit of the current period compared to the previous one, the following equation can be used for calculation:

$$Y_{i+j,i}=3Y_{i+j}-2Y_i=\begin{cases}5, & \textit{A deficit area becomes a surplus area}\\ 3, & \textit{An equilibrium area becomes a surplus area}\\ 2, & \textit{A deficit area becomes an equilibrium area}\\ 1, & \textit{A surplus area unchanged}\\ 0, & \textit{An equilibrium area unchanged}\\ -1, & \textit{A deficit area unchanged}\\ -2, & \textit{A surplus area becomes an equilibrium area}\\ -3, & \textit{An equilibrium area becomes a deficit area}\\ -5, & \textit{A surplus area becomes a deficit area}\end{cases} \tag{12}$$

where i means the year of the previous period; j means the time interval between the current period and the previous one; $Y_{i+j,i}$ means the change in surplus or deficit of the study area for the current period relative to the previous period. If $Y_{i+j,i} > 0$, the ecosystem services and the economic development in the study area are in a positive status; when $Y_{i+j,i} <0$, it is increasingly difficult for the supply of ecosystem services in the study area to meet the needs for its own economic development. At this point, this study area is in a negative status compared to the surplus or deficit status of the previous period.

3 Results and analysis

3.1 Spatiotemporal changes in ecological assets of different ecosystem types

3.1.1 Deceleration of ecological assets' growth in the region each period

Based on the remote sensing monitoring data derived from the Data Center for Resources and Environmental Sciences of CAS and correction coefficient of the land use in 2000, 2005, 2010 and 2015 of the region, the changes in the ecological assets of different ecosystem types corresponding to the six primary land types were calculated, as shown in Table 2. Based on the year 2000, the annual average ecological assets of forest ecosystem were ¥608.20 billion; those of grassland ecosystem were ¥279.67 billion and those of farmland ecosystem were ¥231.41 billion. The service value generated by these three ecosystems contributed about 80% of the total ecological assets throughout the years. The growth of forest ecosystem service value witnesses a deceleration, from 128.77% in 2005 to 1.05% in 2015. The increase in farmland ecosystem service value fluctuated dramatically and the value growth first decelerated and then rapidly accelerated. The service value growth of grassland, waters and wetland ecosystems decelerated each period. Due to the nearly zero coverage of vegetation, the desert ecosystem contributes a quite low value of ecological services, with an annual value of only ¥0.31 billion.

Table 2 Changes in ecological assets of different ecosystem types each period (billion yuan)

Ecosystem types	2000	2005	Growth rate (%)	2010	Growth rate (%)	2015	Growth rate (%)
Farmland	68.67	163.16	137.60	229.69	40.78	464.11	102.06
Forest	241.82	553.21	128.77	814.62	47.25	823.14	1.05
Grassland	101.99	235.30	130.71	357.51	51.94	423.87	18.56
Waters	77.73	171.64	120.82	253.01	47.41	259.26	2.47
Wetland	26.31	58.73	123.22	89.54	52.46	103.37	15.45
Desert	0.12	0.28	133.33	0.42	50.00	0.39	–7.14
Total (unchanged price in 2000)	516.64	1182.32	128.85	1744.79	47.57	2074.14	18.88

Notes: Constant price of all data were calculated based on the year 2000.

3.1.2 Waters and wetland characterized by high value per unit area and insufficient spatial distribution

Take the year 2015 as an example. The average spatial distribution of the value for six ecosystem services, as shown in Figure 2, demonstrates that the unit area of pixel (1 km^2) for the same ecosystem type had a small difference in ecological asset value among different areas, and the standard deviation was within 0 to 0.11, with a small degree of dispersion. In terms of average value of ecological assets per unit area, waters, wetland, forest, grassland, farmland and desert were arranged in a descending order respectively. The maximum value of ecological assets per unit area of waters was ¥125 million km^{-2}, with an average of ¥89 million km^{-2}, far above those of other ecosystems. The reason is that waters had the highest ecological service value equivalent per unit area, with a share of 48%, outclassing other ecosystems concerned. The equivalent value of hydrological regulation reached 102.24, and remained at 54.81 to 90.47, even subject to precipitation data correction. As a result, the unit area value of waters was much higher than that of other ecosystems. The average unit area value of wetland was ¥39 million km^{-2}. In terms of average unit area value for secondary classification of wetlands, bottom land, marsh and mud flat were arranged in a descending order. Nevertheless, the total ecological value of wetland was far lower than that of other ecosystems except desert due to its smaller area on the whole. Forest and grassland ecosystems were mainly distributed in the Bashang Plateau and the northwestern mountainous area of Hebei Province. Farmland ecosystem was most widely distributed. The unit area value of its ecological assets remained at ¥1 to ¥12 million km^{-2}. The average unit area value of desert was only ¥1 million km^{-2}.

3.1.3 Deceleration in value growth of hydrological regulation and soil conservation functions

Regional ecological assets are composed of the value of various services provided by different ecosystems. Among the service types provided by regional ecological assets, the most important ones are climate regulation and hydrological regulation, followed by soil conservation, gas regulation, and nutrients cycle maintenance. As shown in Table 3, the total value

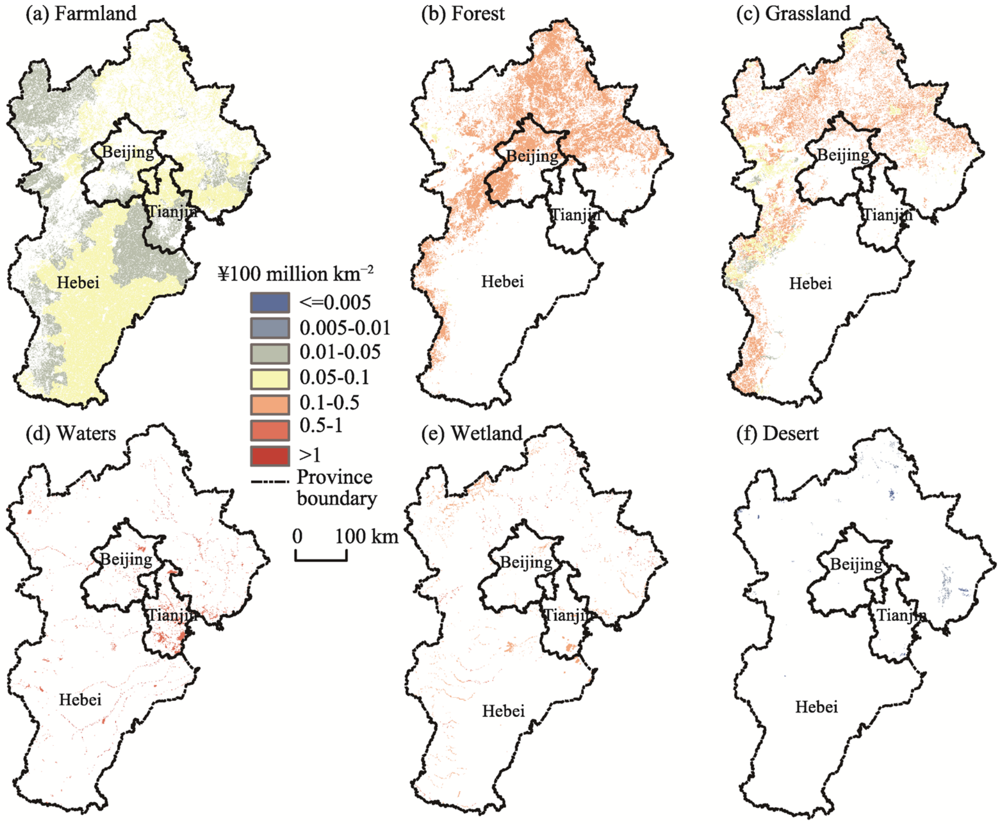

Figure 2 Distribution map of average value of ecological assets for different ecosystem types in 2015

Table 3 Changes in the value of regional ecosystem services and their contribution in different periods (¥ billion)

Service type	2000		2005		2010		2015	
	Value	Contribution (%)	Value	Contribution (%)	Value	Contribution (%)	Value	Contribution (%)
Food production	22.89	4.43	56.47	5.04	80.04	4.19	160.37	24.39
Raw material production	17.29	3.35	42.16	3.74	61.48	3.43	101.10	12.03
Water supply	10.59	2.05	17.84	1.09	27.18	1.66	27.80	0.19
Gas regulation	46.57	9.01	111.86	9.81	165.02	9.45	245.33	24.38
Climate regulation	101.28	19.60	240.08	20.85	360.67	21.44	446.60	26.09
Environment purification	33.71	6.52	80.71	7.06	120.52	7.08	149.73	8.87
Hydrological regulation	139.10	26.92	283.93	21.76	426.33	25.32	422.38	–1.20
Soil conservation	77.68	15.04	187.93	16.56	262.32	13.23	210.75	–15.66
Nutrients cycle maintenance	5.52	1.07	13.36	1.18	19.46	1.08	32.09	3.83
Biodiversity	42.39	8.20	101.04	8.81	151.53	8.98	189.65	11.57
Aesthetic landscape	19.64	3.80	46.94	4.10	70.24	4.14	88.33	5.49
Total (unchanged price in 2000)	516.64	100.00	1182.32	100.00	1744.79	100.00	2074.14	100.00

Notes: Constant price of all data were calculated based on the year 2000.

of various ecological services increased significantly in different periods. Among them, the value of climate regulation increased from ¥101.28 billion in 2000 to ¥446.60 billion in 2015, with an average annual value of ¥287.16 billion, the highest contribution to the increase in the value of total ecological assets in 2015 (26.09%). The annual average value of hydrological regulation was ¥317.94 billion, with a fluctuate contribution to the increase in the total value of ecological assets. The value even dropped to –1.20% in 2015. The function of hydrological regulation tended to decrease. Both of the value of soil conservation and its contribution to ecological assets first increased and then decreased. In 2015, the contribution to the total value of ecological assets dropped to –15.66%. It indicates the degradation of the soil and water conservation influenced by the regional ecosystems. By contrast, the impact of biodiversity and aesthetic landscape functions on ecological assets was gradually increasing.

3.2 Quantitative analysis on the total ecological compensation in the region

As shown in Figure 3, according to the quantification of the total ecological compensation of the region in the four periods, from 2000 to 2015, the annual ecological surplus and deficit were increasing but the total surplus value was basically offset by the total deficit value. It indicates that ecological compensation equilibrium could be basically reached within the entire ecological zone. In the years 2000, 2005, 2010 and 2015, Fengning county of Hebei had the highest ecological compensation. The areas with the lowest compensation included the former Dagang district (now Dagang sub-district, Binhai New Area), Tianjin; Fangshan, Daxing and Haidian districts, Beijing; and the one with the highest unit area ecological compensation was Xinglong county, Hebei. In the years 2000, 2005 and 2010, the area with the lowest unit area ecological compensation was Qiaoxi district, Shijiazhuang. In 2015, the area with the lowest unit area ecological compensation was Xuanwu District (now merged into Xicheng District), Beijing.

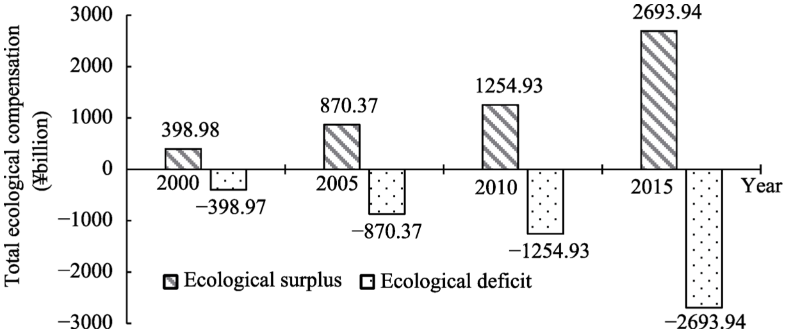

Figure 3 Total ecological compensation of the region in different periods
Notes: Constant price of all data were calculated based on the year 2000

3.2.1 Circle-shaped distribution of the average ecological compensation in counties of the region

According to the spatial distribution of the average county-level ecological compensation during the four periods in 2000, 2005, 2010 and 2015 (Figure 4a), the central and eastern areas tend to provide ecological compensation to the northeastern areas. There were always

SAs surrounding DAs, indicating relatively stable supply and demand of ecological services in the region. The calculation shows that the average ecological compensation in 98 study areas was positive, indicating these areas should receive ecological compensation. Among all study areas, Fengning county (¥108.83 billion), Weichang county (¥100.26 billion) and Longhua county (¥83.47 billion) showed the average ecological compensation exceeding ¥80 billion. All these were backward areas in Hebei. The study areas with value lower than ¥–60 billion included Tanggu district (¥–66.05 billion), Dagang district (now Dagang sub-district, Binhai New Area, ¥–72.43 billion), Haidian district (¥–89.93 billion) and Chaoyang district (¥–90.54 billion). All of them were fairly developed areas in Tianjin and Beijing. The fact shows that the average ecological compensation is normally negative in relatively developed counties. Thus, it seems hard for the ecological assets of these areas to support their own economic development and ecological services need to be provided by other areas with rich ecological assets. So, compensation should be made to the former. And those with backward economy and where their ecological assets are consumed by other areas are in urgent need of ecological compensation. The average ecological compensation in 174 counties and districts, mainly in the southwest plain, was between ¥–20 billion and ¥20 billion. The land use type of these areas was mainly farmland and their ecological assets and GDP were below the average. There was a low urgency for these areas to pay or receive ecological compensation.

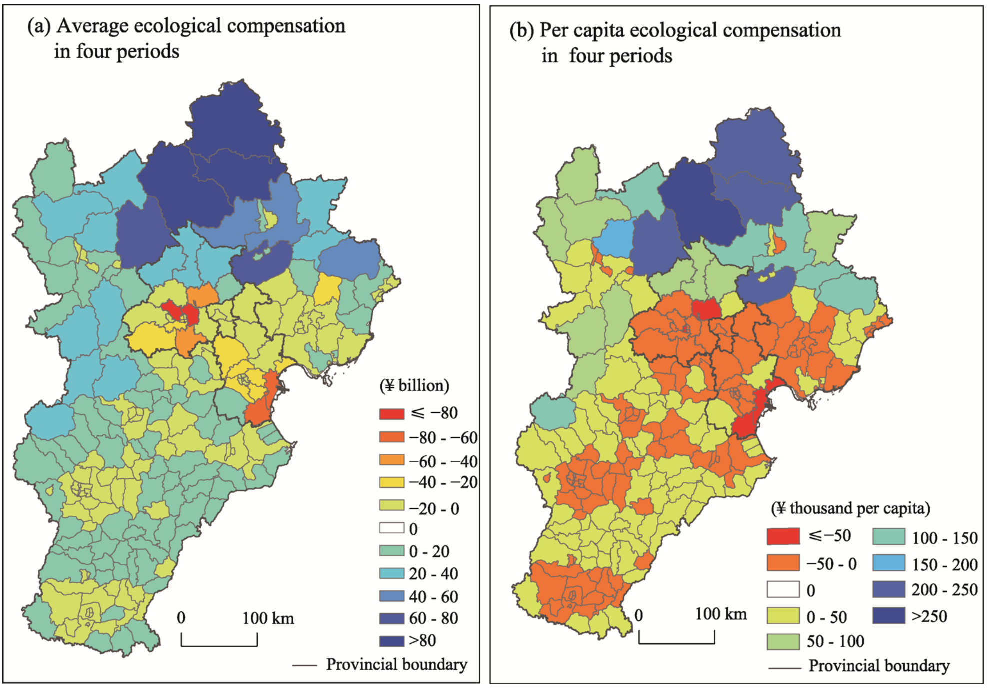

Figure 4 Spatial distribution maps of average ecological compensation among the counties in the region
Notes: Constant price of all data were calculated based on the year 2000.

3.2.2 The major area with negative ecological compensation is the densely populated central urban area

In view of the impact of population spatial distribution on ecological compensation carrying capacity and the change in the total population over time, the spatial distribution of ecological compensation per capita in the four periods was identified. As shown in Figure 4b, it was consistent with the position distribution for the average ecological compensation in the four periods, with per capita ecological compensation of the northern area higher than that of the central and southern areas. Fengning county had the highest ecological compensation per capita, ¥282,183; while Hangu had the lowest one, ¥–72,739. Among provinces and cities of the region, there were only four districts with positive ecological compensation per capita in Beijing, namely, Yanqing (¥91,186), Huairou (¥77,674), Miyun (¥65,134) and Pinggu (¥14,055). All of these are Beijing's ecological conservation areas. Other areas need to pay ecological compensation. Xuanwu, Xicheng and Shunyi districts need to pay the ecological compensation per capita of over ¥50,000. In Tianjin, only Ninghe county (¥5293 per capita) and Jinghai county (¥6187 per capita) had a positive per capita ecological compensation, while the amount of other areas were negative. By the amount of per capita ecological compensation payment, Hangu (¥–72,739), Dagang (¥–68,497), Tanggu (¥–58,975), Xiqing (¥–41,601), and Jinnan districts (¥–36,837) were in a descending order. It can be seen that the ecological compensation per capita in Tianjin is much higher than that received per capita. It indicates that Tianjin needs to make ecological compensation to other areas in the whole ecological region. In Hebei, the per capita ecological compensation of more than half of the counties and districts was positive, meaning they were the receivers of ecological compensation. The areas with negative ecological compensation per capita were mainly distributed in the southwestern and eastern parts of the province. The areas with the highest compensation per capita included Jingxing Mining District (¥–42,505) and Qian'an city (¥–38,150). Generally, the compensation paid by deficit areas in the region is slightly lower than the per capita disposable income of the corresponding areas. The payment directly made according to per capita ecological compensation would mean huge pressure. It is advisable to make an adjustment to the proportion of ecological compensation before payment of the compensation.

3.3 Evolution characteristics of surplus and deficit for the region

3.3.1 The total number of ecological surplus areas at the county or district level is less than that of ecological deficit areas

By using the surplus and deficit evaluation model and Equation 11, the distribution of SAs and DAs in different periods was identified. In different periods, the total number of SAs at the county or district level was less than that of deficit areas. In 2000, 2005 and 2010, SAs accounted for less than half of the counties and districts in the region, 31.13%, 36.79% and 34.43% respectively. In 2015, the number of SAs accounted for more than half of the total (61.79%), an increase of 65 SAs compared to the year 2000. By province, as shown in Figure 5, change in proportion of SAs over the total number of counties in Beijing shows a U-shaped curve, first decrease and then increase. In 2000 and 2015, the areas at the county or district level nearly had the same share of SAs. The number of SAs in these areas was changed, though. Changping district changed from a SA in 2000 to a DA in 2015; on the contrary, Fangshan district changed from a deficit to a surplus area in the year. In 2005, Tianjin had the most SAs at the county or district level, accounting for 33.33% of the total number of counties and districts in Tianjin. In the years 2000 and 2015, there was only one that was an SA each, namely Ninghe and Jinghai counties. Hebei had the highest share of SAs in the region, basically above 1/3 of the total SAs of the region from 2000 to 2010. In 2015, the share rapidly increased to 70.45%, 1.01 times more than that of the SAs in 2000. It indicates that with long-term consumption of ecological assets, a growing number of counties and districts are in urgent need of ecological compensation to make up for losses.

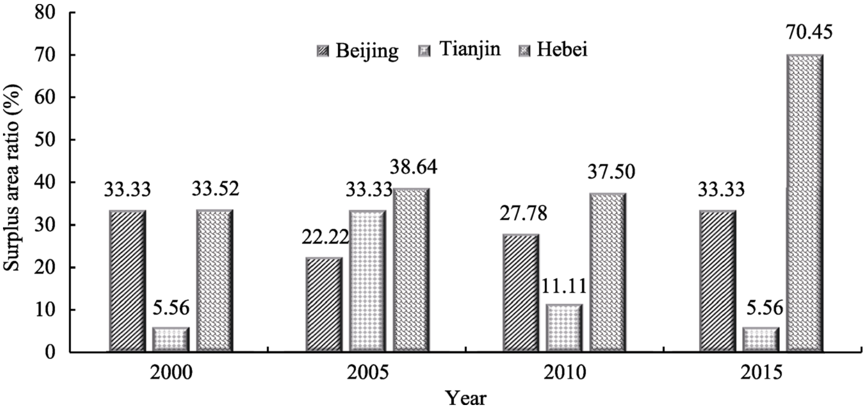

Figure 5 The share of ecological surplus areas at county level in the region in different periods

3.3.2 Obvious agglomeration of deficit areas to the central and eastern areas

Based on the evaluation of the SAs and DAs in each period, with the year 2000 as the base period, the changes in the surplus and deficit areas during different periods were identified according to Equation 12. As no area reaches an ecological equilibrium among the study areas, there were only four types of changes in surplus and deficit, namely SA (sufficient area) to DA (deficit area), DA unchanged, SA unchanged and DA to SA. As shown in Figure 6, the deficit areas in 2000 were mainly distributed in the central and southern plains of Hebei Province. With the passage of time, the deficit areas gradually converged to the central and eastern areas, which was especially obvious in 2015. Meanwhile, the surplus and deficit in some study areas were even reversed in different time periods. It indicates that whether an area would receive or pay compensation is not constant. The result may be reversed with changes in time, internal and external environmental pressure. From 2000 to 2005, 22 study areas changed from DA to SA and 10 study areas from SA to DA, such as Mentougou and Changping districts in Beijing, Bazhou city, Daming county, and Shahe city in Hebei Province. Wu'an city suffered from the most severe deficit. The analysis of the changes in the land use type of Wu'an from 2000 to 2005 shows that the construction land area of the city increased by about 20 km^2; the cultivated land decreased by about 18 km^2; and other land use types remained almost the same. The fact indicates that the expansion of construction land had resulted in the continuous decline in its ecological service value. In 2000, the ecological assets per unit area of Wu'an were 1.50 times of that of the region. In 2005, the figure decreased to 1/2, indicating the fact that ecological assets of the city itself could not satisfy the needs of its economic development.

From 2005 to 2010, 10 study areas changed from SA to DA, four of which changed from SA in 2005 to DA in 2010, i.e., Linzhang, Daming, Shexian and Raoyang counties. There were 15 study areas that changed from SA to DA, three of which were DAs through-

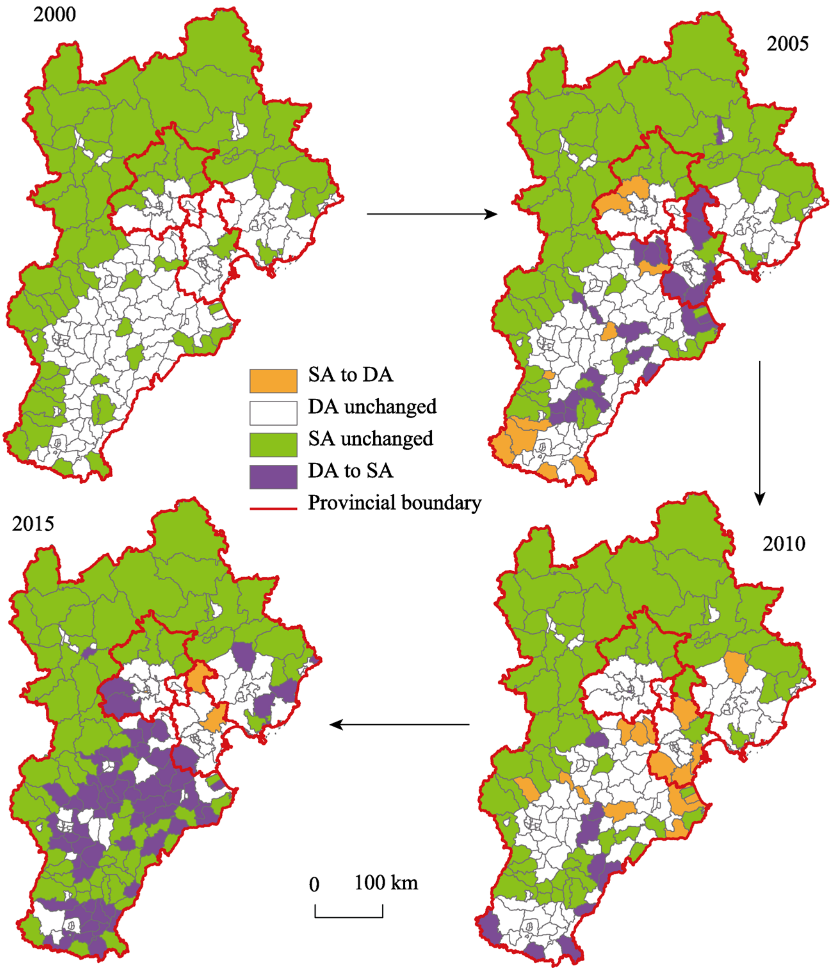

Figure 6 Spatiotemporal change distribution of ecological deficit and surplus areas in the region

out the years, namely Xingtang, Qianxi and Yanshan counties. From 2010 to 2015, 61 study areas changed from DA to SA, 10 of which changed from SA to DA in 2010 and later recovered to SA again. Only three areas, the former Xuanwu District (now merged into Xicheng District), Jixian and Ninghe counties, changed from SA in 2010 to DA in 2015. Overall, in different periods, the construction land of the region continuously expanded and the type of land occupied was mainly cultivated land, thus gradually turning its ecological service value into social and economic value. Furthermore, with the widened gap in economic development among different study areas, the siphon effect of the counties and districts, especially those in the central urban areas of the region, on the ecological, economic and other resources of the surrounding areas became prominent within the ecosystem. As a consequence, DAs were mainly distributed in the central areas of the region.

4 Discussion

Ecological compensation is an important way to coordinate ecological protection and economic development. This study which takes county as the research scale, proposes a method to quantify the total value of regional ecological compensation in the space-time dimension by combining the value of ecosystem services and the socioeconomic development. It effectively identifies the ecological profit and loss boundary and dynamic changing trend of the Beijing-Tianjin-Hebei region, providing application method support for solving the problem of “Who will make up and replenish who” in the regional compensation, which is conductive to promoting cross-regional relational coordination. In addition, based on the estimation results of different ecosystem service values, it is possible to identify the ecosystem types with higher sensitivity, and provide an overall basis and direction of compensation for the next step in formulating regional ecological compensation policies, which will help to optimize functional orientation of each region.

Different references vary in ecological asset measurement results. It is difficult to obtain the actual value of the ecological assets of the region and to directly verify the results on a quantitative basis. So, indirect test results were obtained through comparisons with other scholars’ findings in this study. The total ecological assets of the region, according to the calculation by Chen and Huang (2003), ranged from ¥590.07 billion to ¥5300.76 billion. The estimated ecological assets were relatively high. Yuan *et al.* (2017) calculated the total value of ecological services in the region in 2013, a relatively low figure of ¥553 billion. According to Wang (2017), the total value of the regional ecosystems in 2015 was ¥853.94 billion. According to the Monitoring Communique on the Value of Urban Modern Agricultural Ecological Services in Beijing in 2015, the annual value of urban modern agricultural ecological services in Beijing was ¥348.12 billion, higher than the total value of Beijing’s ecological assets for the same period obtained in this study (¥253.27 billion). In this study, the total value of annual average regional ecological assets in each period reached ¥1379.47 billion, a figure that is highly reliable compared with the results of existing research. In consideration of data acquisition costs, the resolution of land use, NPP and other data used in the study is low. Improved data precision can be achieved if remote sensing data of higher resolution is available. Moreover, the ecological compensation was calculated using the corrected equivalent factor scale and then revised by taking into account regional biomass, climate conditions and other difference. Finally, the total ecological compensation, with a high reliability, was obtained. The result reflects the changes in the total ecological compensation for different periods. However, the value of unit equivalent factor would directly affect the calculated value of ecological compensation. That may be the reason why dispute arises on whether it is proper to calculate ecological compensation by the unit equivalent factor.

5 Conclusions

By adopting the corrected equivalent factor scale and taking into account the factors of NPP spatiotemporal regulation, precipitation regulation, and soil conservation regulation, we estimated the ecological assets of Beijing-Tianjin-Hebei Region in 2000, 2005, 2010 and 2015. Then, the difference between ecological assets and spatialized GDP, as well as the population and area factors were used to identify the spatiotemporal variation characteristics of the total ecological compensation of the region and the boundaries of DAs and SAs. The following conclusions are drawn:

First, the ecosystem analysis results demonstrate the decelerated growth of all ecosystems except farmland ecosystem. The service value of farmland ecosystem first decreased and then rapidly accelerated. In the region, the service value of forest, grassland and farmland ecosystem accounted for about 80% of the total value of ecological assets throughout the years. Nevertheless, the top three were waters, wetland and forest ecosystems in terms of ecological assets per unit area. The ecological assets per unit area of waters far exceed those of the other ecosystems, with an average value of ¥89 million km^{-2}, followed by wetland, with an average value of ¥39 million km^{-2} in 2015. However, with a small area of wetland in aggregation, its overall ecological assets were far less than the other ecosystems except desert; the farmland ecosystem was most widely distributed, but its ecological assets per unit area value only remained at ¥1 to ¥12 million km^{-2}. In terms of ecological service, the annual average value of hydrological regulation and climate regulation was the highest, with the highest contribution to the increase in ecological assets. However, the contribution of hydrological regulation to total ecological assets decreased from 26.92% in 2000 to –1.20% in 2015. In addition, the annual contribution of soil and water conservation function value to the total value of ecological assets dropped to –15.66% in 2015. The weakened soil conservation of the regional ecosystems indicates priority should be given to soil erosion control in the future ecological protection.

Second, the amount of ecological compensation for the region's counties is related to their economic development. The study shows that 46.23% average ecological compensation of the counties was positive. Thus, they should receive ecological compensation. DAs and SAs were located in the backward areas of Hebei Province and the developed areas of Beijing and Tianjin, respectively. Through the calculation of per capita ecological compensation, the per capita ecological compensation of the northern areas was higher than that of its central and southern areas. Except for the four (Huairou, Pinggu, Miyun and Yanqing) districts designated as ecological conservation areas in Beijing, all ecological compensation in other areas was negative. The ecological compensation per capita in Tianjin was much higher than that received per capita. In contrast, the per capita ecological compensation in more than half of the counties and districts of Hebei was positive, and the areas with negative per capita ecological compensation were mainly in the southwestern and eastern parts of the province. With the passage of time, the central part of the region shows an increasing demand for ecosystem services from other areas. The central urban areas of Beijing and Tianjin will be the key areas to make ecological compensation.

Third, in terms of changes in DA and SA, central and eastern areas were becoming DAs with the passage of time. And the larger the time span was, the more significant this phenomenon would be. Significant differences existed among different study areas in the same period. Hebei urgently needed to cover losses by means of ecological compensation as it had a larger share of SAs than Beijing and Tianjin. In different periods, the same study area had different deficit or surplus degrees, and even changed its original status, SA to DA or DA to SA. With the increasing gap in economic development of different study areas, the siphon effect of the counties and districts represented by central urban areas of the region on ecological, economic and other resources of surrounding areas would be rapidly reinforced. As a consequence, most DAs were distributed in the central part of the region. We are required to guide population dispersal by decentralizing public resources such as education, transportation and medical care in central urban areas. By doing so, we aim to weaken the agglomeration effect of deficit areas and finally achieve the ecological synergy of the region.

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