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Exploring spatial change and gravity center movement for ecosystem services value using a spatially explicit ecosystem services value index and gravity model

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Abstract Spatially explicit ecosystem services valuation and change is a newly developing area of research in the field of ecology. Using the Beijing region as a study area, the authors have developed a spatially explicit ecosystem services value index and implemented this to quantify and spatially differentiate ecosystem services value at 1-km grid resolution. A gravity model was developed to trace spatial change in the total ecosystem services value of the Beijing study area from a holistic point of view. Study results show that the total value of ecosystem services for the study area decreased by 19.75% during the period 1996–2006 (3,226.2739 US\$ $\times$ 10^6 in 1996, 2,589.0321 US\$ $\times$ 10^6 in 2006). However, 27.63% of the total area of the Beijing study area increased in ecosystem services value. Spatial differences in ecosystem services values for both 1996 and 2006 are very clear. The center of gravity of total ecosystem services value for the study area moved 32.28 km northwestward over the 10 years due to intensive human intervention taking place in southeast Beijing. The authors suggest that policy-makers should pay greater attention to ecological protection under conditions of rapid socio-economic development and increase the area of green belt in the southeastern part of Beijing.

Keywords Ecosystem services value · Ecosystem services value index · Gravity model · Spatial heterogeneity · Spatial change · Beijing

Introduction

Humans acquire, either directly or indirectly, a range of goods and services from ecosystems (Guo et al. 2000; Kremen 2005). Ecosystem services include a series of functions such as atmospheric gas regulation, climate regulation, water supply, food production, and recreation. The quantification of ecosystem services value has therefore been identified as a key area for investigation in related academic fields in recent decades (Peters et al. 1989; Wilson and Carpenter 1999; Gustafson 1998; Velarde et al. 2005). Pearce and Moran (1994) summarized different economic valuation methods for different types of ecosystems. Costanza et al. (1997) estimated the value of the world's

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ecosystem services composed of 17 ecological services functions provided by 16 global predominant biomes. This study subsequently generated extensive debate on the valuation of ecosystem services (Rapport et al. 1998; Turner et al. 2000; Guo et al. 2001; De Groot 2002; Howarth and Farber 2002; Costanza et al. 2004).

A number of studies have developed and applied methodologies to estimate ecosystem services value at a range of spatial scales. Chen and Zhang (2000) calculated the value of China's ecosystem services. Guo et al. (2001) evaluated the ecosystem services value of Xingshan County of Hubei Province, China. Lant et al. (2005) conceptualized an agricultural watershed as a complex self-adaptive ecosystem and they valued ecosystem services at that scale. Li et al. (2007) quantified land use change and discussed the effect of this change on ecosystem services value.

At present, administrative land units or land use classes are usually used as basic evaluation or mapping units for ecosystem services valuation. However, use of these spatial units for valuation analysis generally makes it difficult to spatially differentiate ecosystem services value (Yao et al. 2006). While a number of studies effectively address the quantification of ecosystem services value (Daily 2000; Krieger 2001; Wang and Wu 2005), research on the analysis of spatial change of ecosystem services value remains a major need.

This study aimed at achieving three goals: (1) to develop a method for representing the spatial heterogeneity of ecosystem services values in the study area, (2) to compare change in the spatial distribution of ecosystem services values over time, and (3) to develop an explanatory model describing how total ecosystem services values change over time from a holistic point of view. Moreover, the authors hope the outcomes of the study will provide useful suggestions for policymakers in developing more effective measures for the protection of ecological conditions.

Materials and methods

Study area

Beijing (115°25′–117°30′ E, 39°26′–41°03′ N) is situated at the northeastern part of the North China Plain (see Fig. 1). The total area is approximately 1.68×10^4 km^2. Mountains that lie at the northwestern part of Beijing occupy nearly 62% of the total area, and plains only 38%. The study area is characterized by diverse land use and land cover. Since the adoption of "open-door" policy reform in 1978, Beijing has experienced rapid socioeconomic development. Especially in the last 10–15 years, the combination of accelerated economic development, the implementation of policies aimed at converting arable land back to forest and grassland, and preparations for the 2008 Beijing Olympic Games have directly resulted in major land use and land cover changes. Furthermore,

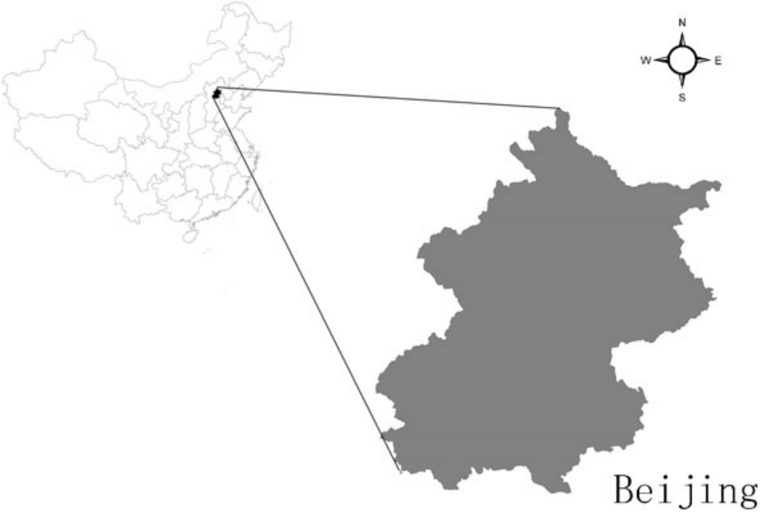

Fig. 1 The sketch map for location of Beijing

those changes have led to changes in the value of the ecosystem services of the Beijing region. The Beijing region therefore provides a good opportunity for the study of ecosystem services value and change in spatial distribution.

Data collection and processing

Data collection

In order to explore changes in the spatial distribution of ecosystem services values of Beijing, the authors utilized two digital land use maps of Beijing for the years 1996 and 2006, respectively. The reason choosing these two years was that land use and land cover changes were very significant during that period.

The two digital land use maps were acquired from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. The mapmakers applied multi-temporal and different resolution Landsat Thematic Mapping images to draw the maps based on visual interpretation methods. China's National Standard of Land Use Classification was used when categorizing land use in the interpreting process. The scale of the two digital maps was 1:100,000 and the spatial precision of data products was greater than 95%, which means the maps met accuracy requirements. In addition, the authors resolved the projection of the two maps by georeferencing them to the Albers coordinate reference system (25° and 47° parallels, 105° meridian) with a datum of Beijing 1954.

Gridding the two digital land use maps

The spatial expression of ecosystem services value is generally implemented using spatial units associated with administrative regions or land use classes. This means the spatial heterogeneity of ecosystem services value within these units cannot effectively be expressed. The authors addressed this issue by rasterizing the two digital land use maps at 1-km × 1-km grid resolution, using these grid cells as the basic units for mapping. It has been demonstrated that the gridding method can be used to effectively and efficiently spatially differentiate spatial objects in geography and landscape ecology (Yao et al. 2006).

Estimation of ecosystem services value

Before the spatial estimation of ecosystem services values in the Beijing study areas was completed, ecosystem services value per unit area for each land use category was identified. Duan et al. (2006) calculated valuation coefficients especially for Beijing by utilizing linked economic modeling and the willingness-to-pay method (see Table 1). According to the valuation coefficients in Table 2, ecosystem services value was calculated as follows:

$$ESV_t = \sum_{k=1}^{n} (ESC_k \times A_k) \tag{1}$$

where ESV_t is ecosystem services value for the year t (US$), A_k is the area (ha) and ESC_k the ecosystem services value per unit (US$ ha^{-1} year^{-1}) for land use category 'k' from Duan's study achievement, and n is the total number of land use category.

Ecosystem services value index

Spatial heterogeneity of ecosystem services value across the 1-km × 1-km grids was expressed by applying ecosystem services value index. The equation for the index was as follows:

$$ESVI_h = \sum_{i=1}^{m} \left(\frac{Ai}{A} \times ESC_i \right) \tag{2}$$

Table 1 Ecosystem services value per ha for each land use category of Beijing (Duan et al. 2006)

Land use category	Ecosystem services value per hectare (US$ ha^{-1}year^{-1})
Cropland	2,803
Garden plot	883
Mountainous forest	9,315
Artificial woodland	593
Natural grassland	933
Artificial grassland	251
Construction land	−14,619
Transportation land	−14,619
Water body	3,069
Unused land	45

Table 2 Areas, ecosystem services values, and related change information for different land uses in Beijing region from 1996 to 2006

Land use category	Area (ha)		Total ecological values (US$ × 10^6)		Difference (US$ × 10^6)	Change rate
	1996	2006	1996	2006		
Cropland	343,965	232,575	964.1339	651.9077	−312.2262	−32.38%
Garden plot	99,284	122,588	87.6678	108.2452	20.5774	23.47%
Mountainous forest	602,352	629,786	5,610.9089	5,866.4566	255.5477	4.55%
Artificial woodland	29,848	61,147	17.6999	36.2602	18.5603	104.86%
Natural grassland	3,608	397	3.3663	0.3704	−2.9959	−88.99%
Artificial grassland	659	1,651	0.1654	0.4144	0.2490	150.53%
Construction land	220,393	253,253	−3,221.9253	−3,702.3056	−480.3803	−14.91%
Transportation land	35,446	44,086	−518.1851	−644.4932	−126.3082	−24.38%
Water body	88,854	85,607	272.6929	262.7279	−9.9650	−3.65%
Unused land	216,649	209,968	9.7492	9.4486	−0.3006	−3.08%
Total ecosystem value	–	–	3,226.2739	2,589.0321	−637.2418	−19.75%

Acreage data of the years 1996 and 2006 were acquired from the Beijing Municipal Statistical Bureau and Beijing Municipal Bureau of Land and Resources

where $ESVI_h$ is the ecosystem service value index for grid 'h' (US\$ ha^{-1} year^{-1}), A_i is the area (ha) and ESC_i ecosystem services value per unit (US\$ ha^{-1} year^{-1}) for land use category 'i' in the grid 'h', m is the total number of land use category, and A is the total area for the grid 'h' (ha). It is obvious that the larger $ESVI_h$ is the higher ecosystem services value is for a grid cell.

The authors categorized ecosystem services value for the two periods into five classes by applying the natural breaks method. Similarly, the difference value of ecosystem services was classified into five levels by applying the combination method of natural breaks and equal interval.

Gravity model for ecosystem services value

Gravity modeling, which has been extensively utilized in the fields of urban planning, economic geography, and land use science etc., is a modeling approach that identifies movement direction and distance to the center of gravity for targeted objects. Moreover, movement direction and distance to the center of gravity can reflect changes in quantity and change trend of the targeted object over time. In this paper, the authors applied gravity modeling to ecosystem services value to obtain an estimate of change in total ecosystem services value of Beijing for 1996–2006.

Based on the calculation formulas of center of gravity applied in land use science (Sen and Smith 1995; Liang et al. 2007), equations for the center of gravity for ecosystem services value were applied as follows:

$$X_t = \sum_{j=1}^{l} \left(ESV_{tj} \times X_{tj} \right) \Big/ \sum_{j=1}^{l} \left(ESV_{tj} \right) \quad (3)$$

$$Y_t = \sum_{j=1}^{l} \left(ESV_{tj} \times Y_{tj} \right) \Big/ \sum_{j=1}^{l} \left(ESV_{tj} \right) \quad (4)$$

where X_t and Y_t are x and y gravity center coordinates for ecosystem services value for the year 't', respectively, X_{tj} and Y_{tj} are x and y coordinates of gravity center and ESV_{tj} ecosystem services value (US\$) for the land use category 'j', and l is the total number of the land use categories. X_{tj} and Y_{tj} could be automatically calculated by the geographic information system software of ARCGIS. The equation of the movement distance for the center of gravity can be expressed as follows:

$$D = \sqrt{(X_{t1} - X_{t2})^2 + (Y_{t1} - Y_{t2})^2} \quad (5)$$

where D is movement distance of gravity center (km), and X_{t1}, X_{t2} and Y_{t1}, Y_{t2} are gravity center coordinates of ecosystem services value for the years t_1 and t_2.

Results

Evaluation of ecosystem services values for 1996 and 2006

The total ecosystem services values shown in Table 2 for 1996 and 2006 are 3,226.2739 US$ × 10^6 and 2,589.0321 US$ × 10^6, respectively, and the average ecosystem services values per unit for 1996 and 2006 are 1,920.4011 US$ ha^{-1} year^{-1} and 1,541.0905 US$ ha^{-1} year^{-1}, correspondingly. The total ecosystem services value decreased by 19.75% during the period 1996–2006. Among the ten land use categories identified, there had been a considerable area increase in garden plots, mountainous forest, artificial woodland, artificial grassland, construction land and transportation land, and a large decrease in the area of cropland, natural grassland, water bodies, and unused land. Accordingly, the ecosystem services values of garden plot, mountainous forest, artificial woodland, and grassland increased over the period and all other categories decreased. There were notable decreases for artificial woodland, natural grassland, and artificial grassland, where change rates of ecosystem services values reached 100%, even 150%. The ecosystem services values of cropland, mountainous forest, construction land, and transportation land changed more in quantity than that of artificial woodland, natural grassland, and artificial grassland. According to Table 2, it was clear that the decrease in ecosystem services values for cropland, construction, and transportation lands was the main contributor to the decline of the total ecosystem services value for the study area during period 1996–2006.

Spatial distribution of ecosystem services values for 1996 and 2006 and its change

The spatial differentiation of ecosystem services values for 1996 and 2006 is shown in Fig. 2a and b. The classes distinguished were ‘extremely low level’ (−14,619 US$ ha^{-1} year^{-1} to −9,968 US$

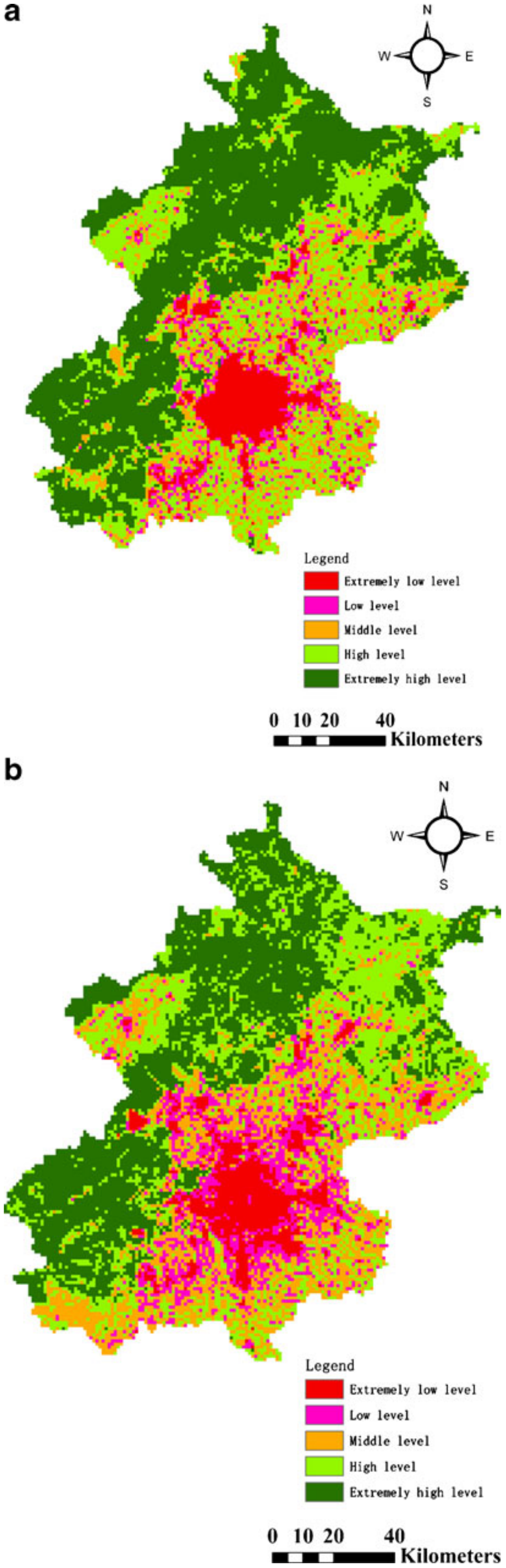

Fig. 2 Spatial distribution of ecosystem services value for ▶ Beijing. **a** Spatial distribution of ecosystem services value for 1996. **b** Spatial distribution of ecosystem services value for 2006

ha^{-1} year^{-1}), 'low level' (−9,968 US\$ ha^{-1} year^{-1} to −3,521 US\$ ha^{-1} year^{-1}), 'middle level' (−3,521 US\$ ha^{-1} year^{-1} to 741 US\$ ha^{-1} year^{-1}), 'high level' (741 US\$ ha^{-1} year^{-1} to 5,517 US\$ ha^{-1} year^{-1}), and 'extremely high level' (5,517 US\$ ha^{-1} year^{-1} to 9,315 US\$ ha^{-1} year^{-1}), respectively. In terms of the above-mentioned results, the average of total ecosystem services values for 1996 and 2006 were all classified at high level.

For the year 1996 (Fig. 2a), the regions at 'extremely high level' and 'high level' are mainly located northwest Beijing with the areas of 6,977 km^2 and 5,019 km^2, accounting for 41.53% and 29.88% of the total area of Beijing, respectively. Regions at 'extremely low level' and 'low level' are mostly situated in the plain occupying 1,157 km^2 and 1,143 km^2, which accounted for only 6.89% and 6.80% of the total area. From a spatial point of view, the spatial configuration of 'extremely high level' and 'extremely low level' classes are concentrated, while classes for 'low level', 'middle level', and 'high level' are comparatively dispersed. Simplified land uses and the other regions characterize regions with 'extremely high level' and 'extremely low level' classes by diversified land uses.

For the year 2006 (Fig. 2b), the regions with 'extremely high level' and 'high level' classes total 5,387 km^2 and 4,730 km^2, respectively, decreasing by 8.87% and 1.73% compared to 1996. On the contrary, the regions classified as 'extremely low level' and 'low level' occupy 1,264 km^2 and 1,938 km^2, respectively, with increasing rates of 0.63% and 4.74%. In comparison, regions with 'extremely high level' and 'high level', 'high level', and 'low level' classes changed very slowly. In terms of spatial configuration, regions with 'extremely high level' and 'extremely low level' classes tend to be more fragmented, while the remainders are more spatially concentrated.

Differences in ecosystem services value during the period 1996–2006 were spatially differentiated by overlaying the Fig. 2a and b maps. The grades distinguished were 'rapid decrease' (−23,934 US\$ ha^{-1} year^{-1} to −10,388 US\$ ha^{-1} year^{-1}), 'slow decrease' (−10,388 US\$ ha^{-1} year^{-1} to 0 US\$ ha^{-1} year^{-1}), 'no change' (0 US\$ ha^{-1} year^{-1}), 'slow increase' (0 US\$ ha^{-1} year^{-1} to 5,517 US\$ ha^{-1} year^{-1}), and 'rapid increase' (5,517 US\$ ha^{-1} year^{-1} to 9,315 US\$ ha^{-1} year^{-1}), respectively, as shown in Fig. 3. According to this analysis, 69.19% of the total area of Beijing deteriorated in ecological quality, while only 27.63% improved. In other words, 96.82% of the study area changed in ecosystem services value. The regions classified as 'slow decrease' occupied a total area of 11,416 km^2, a proportion of 67.78% to the total area. This corresponds to the above-mentioned result of the total ecosystem services value declining over the 10 years. Regions marked in red and dark green can be seen as actively changing regions with regard to ecosystem services

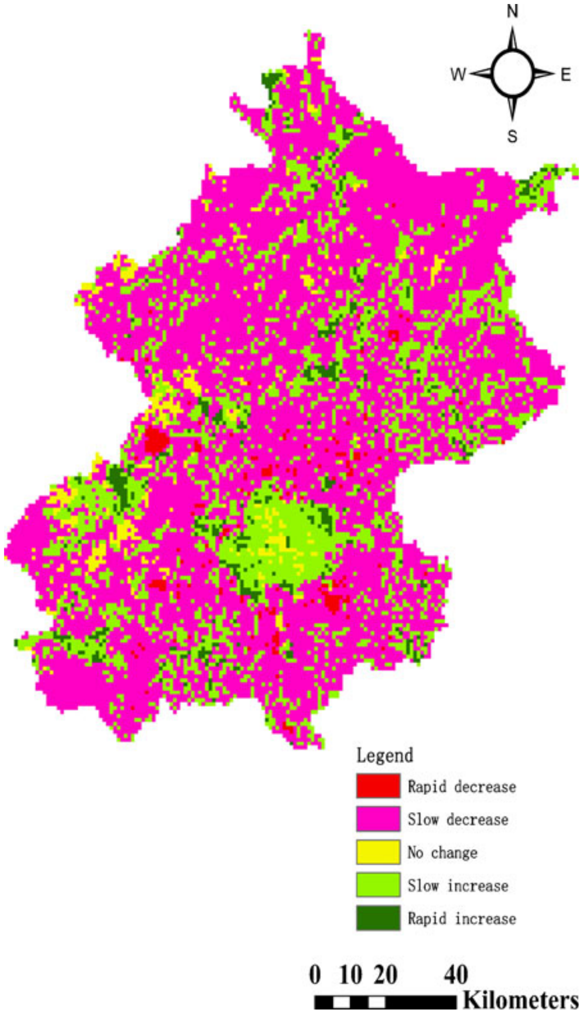

Fig. 3 Spatial distribution of difference values of ecosystem services value between 1996 and 2006

value. The spatial structure of these regions is clearly scattered. Regions with a 'rapid increase' occupy an area of 1,387 km^2 distributed at the border between mountain and plain, while those regions with a 'rapid decrease' occupy 1.41% of the total study area distributed across near and far suburban regions. Regions with 'no change' mostly are located in the mountainous forests. Construction lands only accounted for 3.18% of the total area.

Movement of gravity center of ecosystem services value during period 1996–2006

In the previous section, the authors explain aspects of spatial changes in ecosystem services value during the period 1996–2006. This section describes the application of gravity modeling to trace holistic change of the total ecosystem services value of Beijing. Figure 4 shows that the center of gravity of total ecosystem services value moved northwestward from 116.33°E, 40.50°N in 1996 to 116.25°E, 40.78°N in 2006. The movement distance was 32.28 km. The gravity centers do not match the location of geometric centers. This result indicates that the spatial distribution of ecosystem services value for the study area is not even. Ecosystem services values in northwest Beijing are higher than that in the southeastern part. We can deduce that the population of northwest Beijing enjoyed more ecological service benefits than the population located in southeast Beijing. The movement in the center of gravity of total ecosystem services value during the period 1996–2006 resulted in the further spatial separation of the gravity center and the geometric center. This indicates that the spatial distribution of ecosystem services value in Beijing has become more uneven over the 10-year study period. The intensification of human invention from plains to mountainous areas directly influences the result.

Fig. 4 Coordinates, movement direction, and distance of gravity center of ecosystem services value from 1996 to 2006

Discussion

Our study showed that spatial heterogeneity and changes in ecosystem service value could be clearly depicted by applying a spatially explicit ecosystem services value index and gravity model. An ecosystem services value index, coupled with gridded data processing, cannot only differentiate spatial heterogeneity in ecosystem service values but also enable more precise spatial expression of service value. Gravity modeling is able to generalize regional change in ecosystem service value. These methods, implemented using digital land use maps derived from remote-sensing images, facilitate large-scale and multi-temporal land use analysis with relatively little cost—an attribute favorable to rapid and large-scale spatial monitoring of ecosystem services value.

Major land use change has taken place in China in the past 30 years since the adoption of "open-door" policy reform. Change has intensified particularly in the last 10–15 years following rapid economic development. This general trend is especially evident in the Beijing region that has witnessed dramatic changes in land use. Inevitably, those changes have led to differences in distribution and quantity of ecosystem service values. Change in the distribution and quantity of ecosystem service values result from both natural and human interventions; however, human interventions dominate in Beijing in the period from 1996 to 2006, as shown in Table 2. Rapid economic growth and increasing population have seized ever-larger areas of land for construction and transportation. One sign that symbolizes the period of rapid economic development between 2000 and 2006 is the extraordinary increase in land prices for residential housing, factories, and high-tech industry. This has resulted in the conversion of land uses that have low comparative economic benefit, such as arable land and water bodies, to high economic value land uses, such as construction and transportation. In addition, local farmers have been encouraged to convert cropland into artificial forest through projects aimed at reclaiming forest and grassland. Farmers have also adopted agricultural intensification, converting much remaining arable land to garden plots cultivating higher value crops. The total area of arable land has therefore been very significantly reduced. The result of these trends in land use change has meant that the total value of ecosystem services has declined significantly over time. Although the local government has paid much attention to ecological protection for all kinds of purposes (for instance, preparations for the 2008 Beijing Olympic Games), an expanding population continues to impose unsustainable ecological pressures.

Intensive ecologically damaging human activities, such as the construction of residential and commercial properties and the development of factories, have mostly occurred in the southeast plain of Beijing, taking up farmland, unused land, and even areas set aside as green belt. In spite of more recent policies promoting ecological conservation, the conversion of farmland to forest and grassland, negative affect by economic and population growth continues and is yet to be offset. In addition, human activities have brought about more fragmented and isolated spatial distribution of ecosystem services value. If such a trend cannot be effectively curbed, the center of gravity of ecosystem services value will keep moving towards northwest, and the total value of ecosystem service will decline. Fortunately, the values of ecosystem services value per unit area in Beijing is still relatively high; moreover, ecological conditions have been improving in core areas of capital construction land and in the border areas between the mountains and plains. These points to a promising future for ecosystem services in Beijing provided effective measures being put in place.

Conclusions

The authors suggest that stakeholders, in dealing with ecological issues in Beijing, need to adopt a more science-based approach to resolving tradeoffs between economic development and improved environmental outcomes. While the capacity to implement ecological conservation in the Beijing region is dependent on continued economic growth, the challenge is to achieve an effective balance between beneficial economic and environmental outcomes. The authors emphasize in this article the need to find a balancing point between economic growth and eco-conservation to achieve a more even spatial distribution of ecosystem service values in Beijing. Prompt actions need to be taken to achieve this outcome—effectively curbing population growth, expanding green belt areas in southeastern Beijing, and further improving public awareness on eco-conservation. More importantly, short-, middle-, and long-term planning for land use in Beijing needs to be developed to conserve eco-environmental values in a more robust and sustainable way.

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