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Land Use Transition and Its Eco-Environmental Effects in the Beijing–Tianjin–Hebei Urban Agglomeration: A Production–Living–Ecological Perspective

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Abstract: With the rapid development of urbanization and industrialization, China's metropolitan areas have experienced dramatic transitions of land use, which has had a profound impact on the eco-environment. Accordingly, the contradictions of regional production, living, and ecological spaces have intensified. In this context, analysis of the dynamics of regional production–living–ecological (PLE) spaces has become an important entry point for studying land use transition and its eco-environmental effects, by constructing a classification system of PLE land functions. Using remote sensing data from four periods from 1985 to 2018, this paper explores the spatiotemporal evolution characteristics of PLE spaces and their eco-environmental effects in the Beijing–Tianjin–Hebei (BTH) urban agglomeration, based on GIS and the InVEST model. The results revealed that from 1985 to 2018, the living space of the BTH region expanded rapidly, the production space gradually shrank, and the ecological land remained relatively stable. The eco-environmental quality index within the study area shows obvious regional differences, demonstrating the spatial distribution of "high in the northwest and low in the southeast", and an overall deteriorating trend in the past 33 years. Moreover, the carbon density decreased gradually from northwest to southeast, and the transformations from production land into living land and from ecological land into production land were the major types of eco-environment deterioration. Our findings will provide guidelines for land use management, and offer references for the functional division of PLE spaces and ecological civilization construction, especially in terms of the coordinated development of the BTH region.

Keywords: land use transition; eco-environmental effect; production–living–ecological spaces; Beijing–Tianjin–Hebei urban agglomeration
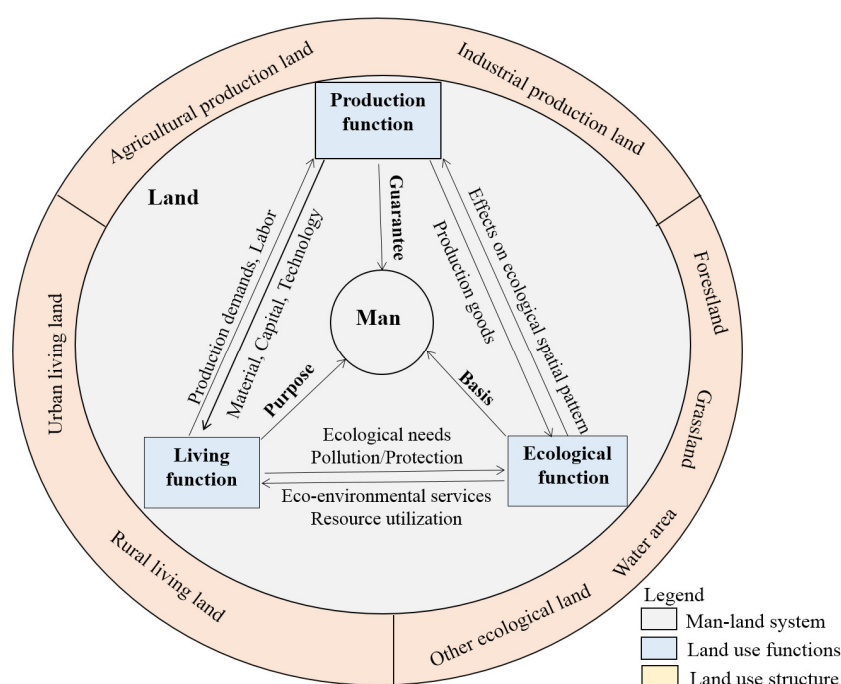
1. Introduction

The land system is an essential part of the earth's terrestrial system, and is also the main carrier of urban–rural spaces [1,2]. Hence, land use transition mirrors natural environment changes [3] and the process of social and economic development [4]. This is a double-edged sword for the sustainable development of the eco-environment. Disordered transitions and unreasonable use may lead to a series of problems related to the deterioration of ecological environments and the decline of ecosystem service function [5–7]. For example, from 1900 to 1990, the global cultivated area increased

by 56% in response to rapid population growth, which led to a tremendous decrease in forests, especially tropical rainforests [8], and other problems such as biodiversity decline and soil erosion [9,10]. Furthermore, land use transition has a significant influence on the global carbon cycle. It is estimated that since 1850, land use/cover change has caused a 145 PgC loss in global terrestrial ecosystems [11]. On the other hand, the optimal allocation and effective management of land resources are conducive to the improvement of the eco-environment and the promotion of sustainable land utilization [12,13]. For example, studies have revealed that the large-scale greening in China and India that has been occurring since the 21st century can mainly be attributed to agricultural intensification, eco-environmental protection, and afforestation policies, which reflects the importance of land use management for ecological improvement [14]. Under the global background of achieving the Sustainable Development Goals (SDGs) related to life on land [15,16], understanding the regional land use transition process and its eco-environmental effects not only provides important guidelines for resolving the contradictions between humans and land and between urban and rural areas [17,18], but contributes to the realization of regional sustainable development [19,20]. In recent years, research topics related to land use transition have gradually shifted from theory, mechanisms, and spatiotemporal patterns [21–24] to functional transformation [25,26], socioeconomic effects [27,28], ecological effects [29–32], and environmental effects [33–36] of land use, as well as its interactive mechanism with land resource management, rural transformation, and urban–rural integrated development [17,37,38].

Since the reform and opening up in 1978, rapid economic and social development in China, along with industrialization and urbanization, have fueled huge consumption of forest, agricultural products, and many other resources [39]. As a consequence, extreme land degradation ensued throughout the 1970s, 1980s, and 1990s, such as the nationwide natural forest decline, farmland overexploitation in rural areas, soil erosion and flooding problems in the Loess Plateau, and rangeland degradation and desertification in northern China, which are widely believed to be caused by unsustainable land management [40]. Since entering the new century, the ecological and environmental problems caused by rapid urbanization have become increasingly prominent in China. The expansion of construction land has led to landscape fragmentation, environmental degradation, and ecosystem services destruction [18], along with the loss of agricultural livelihoods and poverty in suburban areas, which are very common consequences during the urbanization process of developing countries [34]. In the face of these problems and challenges, since 2012, China has proposed that the national spatial development pattern should be shifted from the production-space-oriented mode to the coordinated production–living–ecological (PLE) space mode, so as to optimize the spatial distribution of land and alleviate the contradiction between urban and rural development. Production space provides products and services for human survival and livelihoods; living space, dominated by living functions, is a space for human beings to carry out various activities in order to meet their needs of living, consumption, entertainment, medical treatment, and education; ecological space provides ecological products and services needed for the formation of the ecological system and ecological processes, maintaining natural conditions [41,42] (Figure 1).

With the popularity of the "three pillars" theory of sustainable development, many scholars have carried out a lot of research related to PLE spaces, including around its concept and connotations [43,44], land classification system [42,45,46], spatial identification [47,48], and coupling coordination of the PLE functions [49,50]. Existing research provides a theoretical and empirical basis for regional sustainable development, but there are few studies on resource and environment effects from the perspective of production–living–ecological spaces. In this context, an in-depth analysis of the mutual transformation and eco-environmental effects of regional PLE spaces has become an important entry point for the study of land use transition, which is of great significance to the role of land resource management in ecological improvement and the spatial optimization of the urban–rural structure. In addition, the classification of the PLE space is the foundation of territory spatial planning [47]. The spatial functions of the PLE space are often interwoven and overlapping, forming a single or composite functional type. Therefore, the PLE space is defined by the dominant function type [41,51], aiming to form a pattern of multifunctional coordination belonging to one of the multifunctional

zoning types [52]. Yet, there is currently no unified method and standard for the quantitative identification and measurement of the PLE space. Generally, there are two main methods for identifying and classifying the PLE space. One is the evaluation system method, based on the PLE function; that is, the function evaluation and classification of the PLE space by establishing a comprehensive evaluation index system [49–51]. Due to the availability of data, this method mostly conducts research at the medium- and macroscales, such as cities, counties (districts), or towns. The other is the spatial classification method, based on land use types; that is, the merging and reclassification of land use types according to the leading function of the land, which is based on the spatial division of microscales such as grids or patches [42]. Considering that the latter method can quickly identify the spatial distribution of the PLE space and reflect the land function in terms of the land use structure, this paper studies the land use transition and its eco-environmental effects from the perspective of the PLE space by constructing the reclassification system of PLE land.

Figure 1. Relationships among production–living–ecological functions in the land system.

The Beijing–Tianjin–Hebei (BTH) metropolitan region is not only the national capital region of China but is also, by far, the biggest urbanized region in eastern Asia [53]. Over the past decades, this region has undergone rapid urbanization, population growth, and intensive land use transition, characterized by a remarkable degree of built-up land expansion [54,55]. Accordingly, it has become ecologically fragile and faces serious eco-systemic functional degradation and eco-environmental problems [56]. Based on the studies of three major urban agglomerations in China, it has been found that urban expansion in the Beijing–Tianjin–Hebei region, Yangtze River Delta, and Pearl River Delta has resulted in the loss of ecosystem service value of 9.05 billion yuan, 8.35 billion yuan, and 1.24 billion yuan, respectively, and the degradation of ecosystem services in the BTH urban agglomeration is the most significant [57]. Moreover, carbon emission reduction is considered a considerable burden for regional sustainable development [58,59]. In this context, this research looks at the BTH metropolitan region as the research area. Specifically, our objectives were to (1) quantify the spatiotemporal changes of land use categories from the perspective of production-living-ecology land use functions in the BTH region between 1985 and 2018; (2) analyze the dynamics of eco-environmental quality by constructing an evaluation index, and then study the ecological contribution of land use transition; and (3) examine carbon dynamics and their relationship to land use transition through estimating carbon stocks using the InVEST model.

2. Materials and Methods

2.1. Study Area

The Beijing–Tianjin–Hebei (BTH) region is one of the most developed word-class urban agglomerations in China [60,61]. It is located between 113°04′–119°53′ E and 36°01′–42°37′ N, with a total area of approximately 216,000 km². This region includes two municipalities (Beijing and Tianjin) and 11 prefectural cities (Shijiazhuang, Tangshan, Qinhuangdao, Baoding, Zhangjiakou, Chengde, Langfang, Cangzhou, Handan, Hengshui, and Xingtai) in Hebei province (Figure 2). The BTH region is characterized by a typical warm-temperate semihumid and semiarid continental monsoon climate, with a mean annual temperature ranging from 11.5 to 12.5 °C and annual precipitation ranging from 531 mm to 644 mm. The terrain of the whole area slopes from northwest to southeast, which connects with Yanshan Mountain in the north, Taihang Mountain in the west, and Bohai Bay in the east, so there are mountainous, hilly, and plateau areas in the northwest, with basins and valleys distributed among them, while vast plains dominate the central and southeast. The distribution of vegetation in this area shows vegetation zonality and a vertical distribution [62].

The BTH region is an urban-dense area and an economically developed area in North China, which bears 8.1% of the country's population with 2.3% of the country's land. In the past 30 years, urbanization has developed rapidly, and the average size of the city has expanded by 3.7 times [63]. By the end of 2019, the BTH region had a resident population of 113 million people, with a population urbanization rate of 66.7% and a regional GDP of 8.46 trillion yuan. However, with the continuous advancement of urbanization and industrialization, the contradiction between production, living, and ecological spaces has become increasingly prominent, mainly reflected in: (1) the rapid nonagricultural process of rural production factors, and the contradiction between urban and rural land use, have become more and more prominent. About 80% of the incremental urban land in Beijing from 1985 to 2010 came about at the expense of rural residential land (23.42%) and cultivated land (57.14%) [64]; (2) the problems of environmental pollution and ecological destruction have not been effectively solved. At present, the decline in the carrying capacity of the ecological environment, the unreasonable consumption of resources, and the destruction of living space have increased the difficulty of ecological construction in the BTH region.
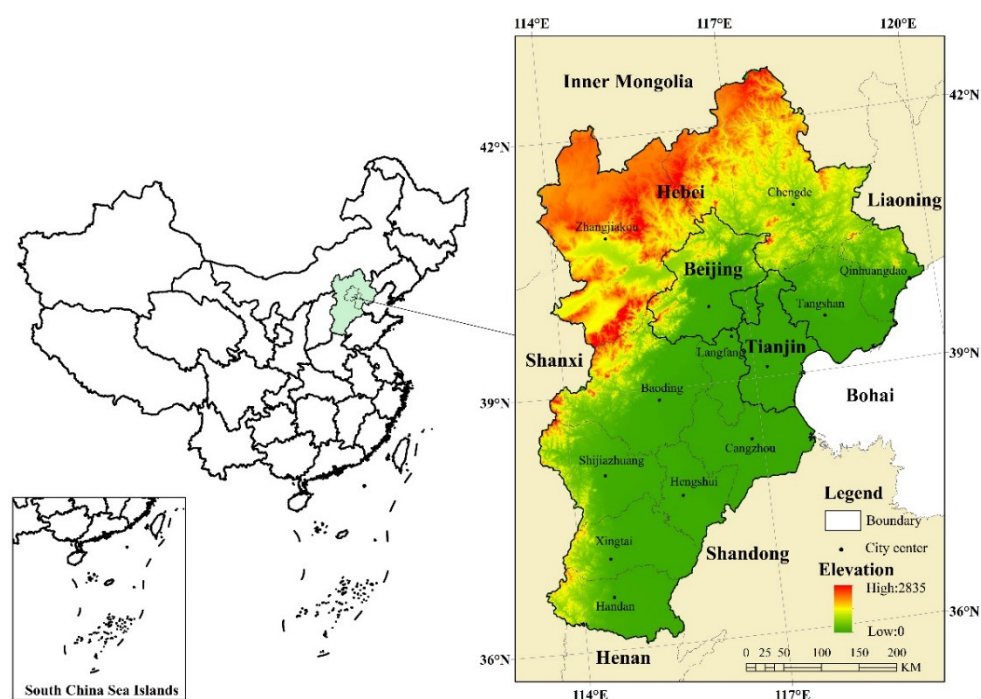

Figure 2. Location of the study area.

2.2. Data Sources

Raster land use/cover maps in 1985, 1995, 2005, and 2018 at 100 m × 100 m spatial resolution in the BTH region were downloaded from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn). The dataset was obtained through artificial visual interpretation based on remote sensing image data, which is the most accurate land use remote sensing monitoring data in China. The digital grids were classified into six first-level land types, including cultivated land, forestland, grassland, water, residential land, and unused land, and 25 s-level land types. The comprehensive accuracy of the first-level land category is above 94.3%, and the comprehensive accuracy of the second-level land category is above 91.2% [65].

2.3. Methods

2.3.1. Classification of Production–Living–Ecological Land

Production land refers to land for agricultural, industrial, and commercial activities, used for obtaining products and supplying functions, whereas living land refers to that which carries and protects human settlements, and ecology land is that which regulates, maintains, and protects the function of ecological security [51]. One land use type often has a leading function, despite its multiple functions. According to the principles of scientificity, practicability, and leading functionality, the dominant function of land use is determined based on the subjective land use intention of the behavior subject [45]. For example, cultivated land not only has the function of food production, but also has an ecological function of regulating the local climate and conserving water and soil. However, the subjective intention of human beings using cultivated land is mainly to produce grain. Therefore, it is classified as production land. According to this classification principle, the classification system of production–living–ecological (PLE) land has been established.

Meanwhile, extant studies have evaluated the eco-environmental quality index of different land use types by establishing the relationship between land use types and the corresponding ecological environment qualities. For example, Li et al. [66] explored the expert-assessment method to calculate the eco-environmental quality index of each second-level land use type in the Hexi region of China. Specifically, several experts in the fields of land use science and eco-environmental sustainability were selected; the eco-environmental quality of each land use was scored according to the experts' knowledge and experience, and the arithmetic mean of these scores of each land use was computed and the data were normalized into the range of [0,1], which was taken as the final value. In view of the wide application of this index system in China, it reflects China's actual situation of ecosystem services well [67–71], and this article hence directly adopted it without adjustment as the environmental quality index of each secondary type of basic land use classification. Then, the eco-environment quality index of the PLE land was calculated by taking the average proportions at four time points of each secondary type from the basic land use classification in corresponding subclasses from PLE land classification, using the area weighting method (Table 1).

Table 1. Production–living–ecological land classification and eco-environmental quality index.

Production–Living–Ecological Land Classification			Basic Land Use Classification	
1st Level Classes	Subclasses	Eco-Environment Quality Index	Secondary Type	Eco-Environment Quality Index
Production land	Agricultural production land	0.2522	Paddy land	0.30
			Arid land	0.25
	Industrial production land	0.1500	Other construction land	0.15
Living land	Urban living land	0.2000	Urban built-up land	0.20
	Rural living land	0.2000	Rural settlement	0.20
Ecological land	Forestland	0.7813	Woodland	0.95
			Shrub land	0.65
			Sparse woodland	0.45
			Other woodland	0.40
	Grassland	0.6306	High coverage grassland	0.75
			Medium coverage grassland	0.45
			Low coverage grassland	0.20
	Water area	0.5519	River canal	0.55
			Lake	0.75
			Reservoir pond	0.55
			Permanent glacial snow land	0.90
			Tidal flat	0.45
			Beach	0.55
	Other ecological land	0.4050	Desert	0.01
			Gobi	0.01
			Saline-alkali land	0.05
			Swamp	0.65
			Bare land	0.05
			Bare rock	0.01

2.3.2. Land Use Transfer Matrix

A land use transfer matrix is used to analyze the transformation of the PLE land structure. This method can be used to calculate the quantity and direction of land use transfer among different types of land use. It is usually used to study the transfer characteristics of land use types from the beginning to the end of a study period. The mathematical expression is as follows:

$$S_{ij} = \begin{bmatrix} S_{11} & \dots & S_{1n} \\ \dots & \dots & \dots \\ S_{n1} & \dots & S_{nn} \end{bmatrix} \tag{1}$$

where *S* is the land area; *N* is the number of land types; *i* is the land type at the beginning of the time period; and *j* is the land type at the end of the time period. When $i \neq j$, S_{ij} represents the area transferred from type *i* to type *j*; when $i = j$, S_{ij} represents the area of the land type that remains unchanged.

2.3.3. Measure of Eco-Environmental Effects of Land Use Transition

(1) Eco-environmental quality index. The eco-environmental quality index (*E*) is a quantitative description of the overall eco-environmental quality of each region (unit), found by evaluating the different ecological quality levels of PLE land. It aims to calculate the change of area of the PLE land in different periods. Grid sampling of the land use was used to spatialize the eco-environmental quality index, and the *E* value of each unit was calculated as the regional eco-environmental quality index of the sampling center. The calculation in Equation (2) is as follows:

$$E_i = \sum_{j=1}^{n} \frac{S_{ij}}{S_i} M_j \tag{2}$$

where E_i is the eco-environmental quality index of the *i* unit; M_j is the eco-environmental quality index of the *j* type of land use (Table 1); S_{ij} is the area of land type *j* in the *i* unit; S_i is the total land area of the *i* unit; and *n* is the number of land use types in the study area.

Due to the strong scale dependence of geospatial data, different conclusions might be reached by selecting different research scales. Hence, in order to obtain the optimal scale, this study selected a grid size of 2 km × 2 km to carry out equidistant sampling.

(2) Geostatistical analysis. The spatial analysis of regional eco-environmental quality was realized by the geostatistical analysis method. The semivariance analysis method was used to interpolate the regional eco-environmental quality index of the sampling center, so as to obtain the spatial distribution of the eco-environmental quality in the whole study area. The mathematical expression is in the following formula (Equation (3)):

$$r(h) = \frac{1}{2n} \sum_{i=1}^{n} \left[M(x_i) - M(x_i + h) \right]^2 \tag{3}$$

where *r(h)* is the variation function; *h* is the spatial distance of the samples; *n* is the total number of samples with spacing *h*; and $M(x_i)$ and $M(x_i + h)$ are the values of the eco-environmental quality index at x_i and $x_i + h$.

The Geostatistics Analyst tool in ArcGIS 10.2 was used to perform the statistical analysis on the *E* values at four time nodes in the BTH region. The results show that the *E* values follow a normal distribution and have a spatial correlation, so this research employed the ordinary Kriging method for spatial interpolation and the semivariation exponential function. Then, the results were divided into five levels using the natural breakpoint method: low-quality area ($E \leq 0.3$), medium-low-quality area ($0.3 < E \leq 0.4$), medium-quality area ($0.4 < E \leq 0.5$), medium-high-quality area ($0.5 < E \leq 0.65$), and high-quality area ($E > 0.65$).

(3) Ecological contribution rate of land use transition. The ecological contribution rate of land use transition refers to the change of regional ecological quality caused by the change of land use type. This index quantifies the impact of land use transition on the regional ecological

environment, which is conducive to the research on the main factors that induce changes to the regional ecological environment. Its calculation formula is as follows:

$$L = (M_{t+1} - M_t)S_c / S \tag{4}$$

where L is the ecological contribution rate of land use transition; M_t and M_{t+1} are the eco-environmental quality indexes of a certain land type at the beginning and end of the study, respectively; S_c is the area of the changed land use type; and S is the total study area.

2.3.4. Carbon Sequestration Module of the InVEST Model

The carbon sequestration module of the InVEST model, which takes land use data as the main data source, provides a fast and intuitive method for carbon storage estimation, and is widely used in regional carbon storage assessment [72]. Regional carbon storage is composed of four elements: aboveground carbon storage (AGC), belowground carbon storage (BGC), soil organic carbon storage (SOC), and dead organic matter carbon storage (DOC) [73]. The InVEST carbon storage module is combined with land use/cover data to calculate ecosystem carbon storage. Its mathematical expression is shown in Equations (5) and (6).

$$C_i = C_{i\_above} + C_{i\_below} + C_{i\_soil} + C_{i\_dead} \tag{5}$$

$$C_{total} = \sum_{i=1}^{n} C_i \times S_i \tag{6}$$

where i represents the land use type; C_i is the total carbon density of land type i; C_{i_above} refers to the carbon density of the aboveground biomass of land type i; C_{i_below} refers to the carbon density of the belowground biomass of land type i; C_{i_soil} refers to the carbon density of the soil organic matter of land type i; C_{i_dead} refers to the carbon density of the dead organic matter of land type i; C_{total} is the total carbon storage; S_i represents the total area of land type i; and n represents the total number of land use types.

The accuracy of the simulation is determined by the input data and parameters. Therefore, it is necessary to reasonably define the carbon density. The larger the scale, the greater the uncertainty of the results, especially for the choice of carbon density. In this study, we adopted the average value of the carbon density of each land use type based on the published literature in recent years, whose study areas were located in the BTH region [74–78], and built a carbon density database of different land use types for this research (Table 2).

**Table 2.** Carbon density of each land use type (unit: Mg C/hm²).

| 1st Level Classes	Subclasses	C_{i_above}	C_{i_below}	C_{i_soil}	C_{i_dead}
Production land	Agricultural production land	11.19	22.9	67.24	4.11
	Industrial production land	2.00	11.94	44.24	0
Living land	Urban living land	2.00	11.94	44.24	0
	Rural living land	2.00	11.94	44.24	0
Ecological land	Forestland	28.39	35.96	133.16	10.77
	Grassland	12.44	25.73	72.92	3.74
	Water area	3.74	15.8	11.55	0
	Other ecological land	4.48	14.01	46.18	0.1

3. Results

3.1. Land Use Structure

From 1985 to 2018, the BTH region was dominated by production land and ecological land. The average proportions of production land, ecological land and living land at four time points were 51.32%, 40.97%, and 7.71%, respectively. According to the first-level classification of the PLE land, living land changed most intensely; its area increased by 9798.99 km² during the study period, with

an average annual rate of 2.31%. In contrast, production land decreased by 9164.02 km², while ecological land remained relatively stable. According to the second-level PLE land types, agricultural production land, forestland, and grassland were the most widely distributed, with average proportions of 50.04%, 20.81%, and 16.21% of the total land area, respectively, and the total proportion of the three was as high as 87.06%. Agricultural production land was concentrated in the southeastern plain area, while forestland and grassland were concentrated in the mountainous areas and the upper plateau area in the north and northwest (Figure 3). Within the research period, the land use structure of the BTH region underwent significant changes. Specifically, the agricultural production land and grassland decreased significantly, with the proportions of area dropping by 5.30% and 0.79%, respectively. Meanwhile, the proportions of urban and rural living land and industrial production land increased by 2.20%, 2.34%, and 1.05%, respectively (Figure 4). Urban living land showed the largest increase, with an average annual growth rate of 6.76%. On the whole, the BTH metropolitan area experienced the rapid expansion of living space and the shrinking of production space over the past 33 years.
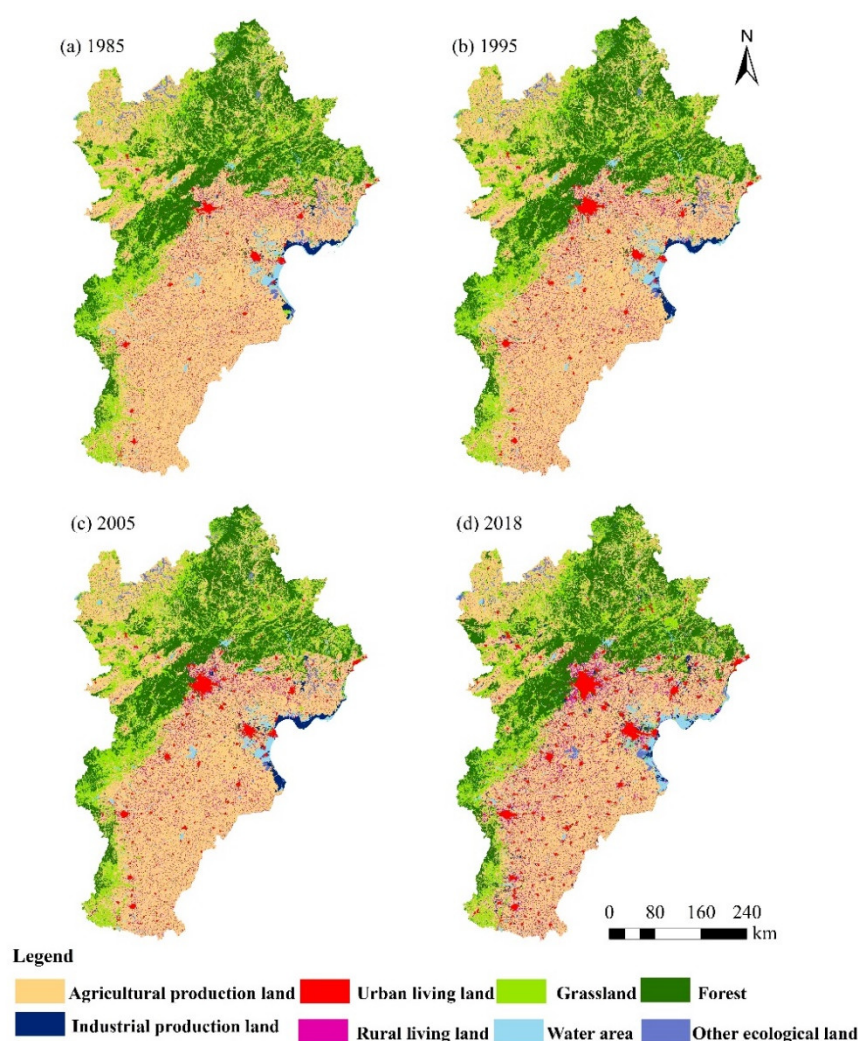
Figure 3. The production–living–ecological land use maps for the years (**a**) 1985; (**b**) 1995; (**c**) 2005; (**d**) 2018.
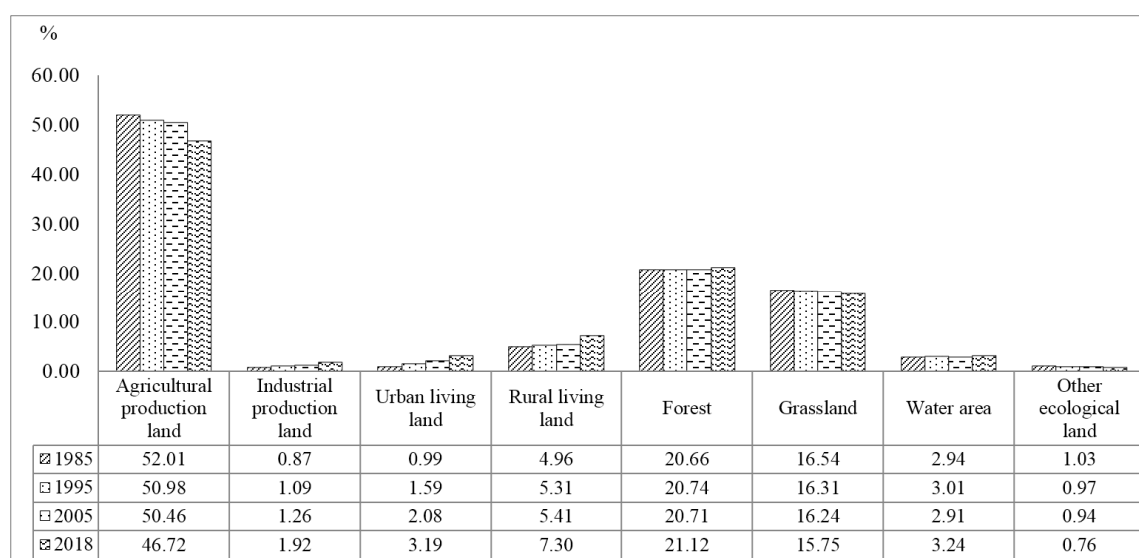
Figure 4. Change of the land use structure from 1985 to 2018.

3.2. Transition of PLE Land Use

The transition matrix was used to analyze the direction and quantity of changes among different land types (Table 3), and the characteristics of the PLE land use transitions in the BTH region from 1985 to 2018 were as follows:

(1) Production land: agricultural production land continuously decreased from 1985 to 2018. From 1985 to 1995, it mainly transferred to rural and urban living land, grassland and forestland, with transfer rates of 32.63%, 21.91%, 14.63%, and 14.49%, respectively; between 1995 and 2005, it mainly converted to urban and rural living land and industrial production land, with transfer rates of 45.30%, 22.66%, and 17.85%, respectively; from 2005 to 2018, agricultural production land decreased the most, mainly to rural living land and urban production land, with transfer rates of 39.91% and 13.22%, respectively. Industrial production land showed a continuous increasing trend in the study period, and was mainly converted from agricultural production land, with contribution rates as high as 49.32%, 62.10%, and 56.26% in the three time intervals, respectively.

(2) Living land: urban and rural living land increased significantly, mainly from agricultural production land from 1985 to 2018. At three time intervals, the contribution rates of agricultural production land to new urban living land were 75.47%, 69.47%, and 70.00%, respectively, while its contribution rates to new rural living land were 96.14%, 88.55%, and 84.65%, respectively.

(3) Ecological land: grassland decreased continuously, and was mainly converted to agricultural production land and forestland. The largest transition of grassland occurred between 2005 and 2018, related to the human activities of land reclamation and afforestation to establish the BTH ecological barrier. The area of forestland decreased slightly from 1995 to 2005, but showed increasing trends during other periods. In particular, forestland experienced the largest increase from 2005 to 2018, which was mainly derived from grassland and agricultural production land. Water and other ecological land remained relatively stable during the study period.

Table 3. Land use transfer matrix from 1985 to 2018 (km²).

		Final Year								Initial Total	Gross Loss
		Agricultural Production Land	Industrial Production land	Urban Living Land	Rural Living Land	Forest	Grassland	Water Area	Other Ecological Land		
Initial Year	**Agricultural Production Land**	*105,159.13*	*319.24*	*1030.17*	*2294.64*	*1020.43*	*1543.32*	*705.66*	*128.94*	*112,201.54*	*7042.42*
		108,315.48	296.46	752.53	376.43	54.55	14.47	158.09	8.77	109,976.79	1661.31
		93,394.36	1958.03	2042.01	6164.10	1598.85	2215.05	1299.18	167.71	108,839.28	15,444.92
	Industrial Production Land	*71.41*	*1694.47*	*57.61*	*3.21*	*10.86*	*9.47*	*21.44*	*3.86*	*1872.33*	*177.86*
		12.33	2239.42	43.77	13.02	0.96	0.58	31.03	0.62	2341.72	102.30
		225.10	655.04	195.85	275.52	45.01	95.26	1182.61	42.44	2716.84	2061.81
	Urban Living Land	*48.86*	*0.21*	*2061.01*	*0.75*	*3.10*	*2.84*	*11.68*	*4.31*	*2132.76*	*71.75*
		15.14	0.46	3406.60	0.87	0.70	0.66	1.57	0.04	3426.05	19.45
		145.92	99.35	3971.17	189.88	15.24	36.56	31.23	0.55	4489.90	518.73
	Rural Living Land	*1282.94*	*7.67*	*246.81*	*9066.26*	*26.72*	*32.20*	*28.04*	*8.69*	*10,699.33*	*1633.07*
		41.29	8.07	163.40	11,235.79	1.06	0.38	3.00	0.11	11,453.09	217.31
		2340.35	170.20	469.40	8461.05	50.73	79.95	76.42	12.79	11,660.89	3199.85
	Forest	*822.23*	*31.37*	*12.04*	*26.03*	*42,140.23*	*1466.66*	*51.56*	*8.12*	*44,558.24*	*2418.02*
		57.47	32.19	18.05	14.26	44,568.95	42.24	15.81	0.09	44,749.07	180.12
		1137.31	319.34	47.79	198.82	40,920.41	1929.27	92.79	21.13	44,666.86	3746.45
	Grassland	*1894.25*	*126.33*	*6.35*	*34.50*	*1466.55*	*31,983.87*	*123.30*	*46.79*	*35,681.94*	*3698.06*
		95.65	54.71	8.92	4.83	18.58	34,950.59	42.27	0.60	35,176.16	225.56
		1944.63	618.79	57.48	250.40	2740.04	28,994.17	248.95	180.49	35,034.94	6040.77
	Water Area	*498.77*	*95.66*	*10.89*	*21.91*	*72.38*	*91.30*	*5523.69*	*28.82*	*6343.42*	*498.77*
		267.47	82.33	75.23	13.71	18.67	20.35	5991.15	26.65	6495.57	504.41
		975.12	253.62	92.55	153.94	142.14	315.48	3919.21	427.91	6279.95	2360.74
	Other Ecological Land	*199.21*	*66.77*	*1.16*	*5.79*	*8.80*	*46.49*	*30.19*	*1865.81*	*2224.22*	*358.41*
		34.45	3.20	21.41	1.98	3.38	5.65	37.01	1988.26	2095.34	107.09
		611.61	61.09	12.26	48.87	52.27	316.03	129.78	793.21	2025.13	1231.92
	Initial Total	*109,976.79*	*2341.72*	*3426.05*	*11,453.09*	*44,749.07*	*35,176.16*	*6495.57*	*2095.34*	*215,713.79*	—
		108,839.28	2716.84	4489.90	11,660.89	44,666.86	35,034.94	6279.95	2025.13	215,713.79	—
		100,774.39	4135.46	6888.51	15,742.57	45,564.68	33,981.78	6980.17	1646.23	215,713.79	—
	Gross Gain	*4817.66*	*647.25*	*1365.04*	*2386.83*	*2608.84*	*3192.28*	*971.88*	*229.53*	—	—
		523.80	477.42	1083.30	425.11	97.91	84.35	288.79	36.87	—	—
		7380.03	3480.43	2917.34	7281.53	4644.27	4987.61	3060.96	853.02	—	—

Note: Area counts of persistence on the main diagonal (in bold) and change off the main diagonal from 1985 to 1995 (in italics), 1995–2005 (underlined), 2005–2018 (waved).
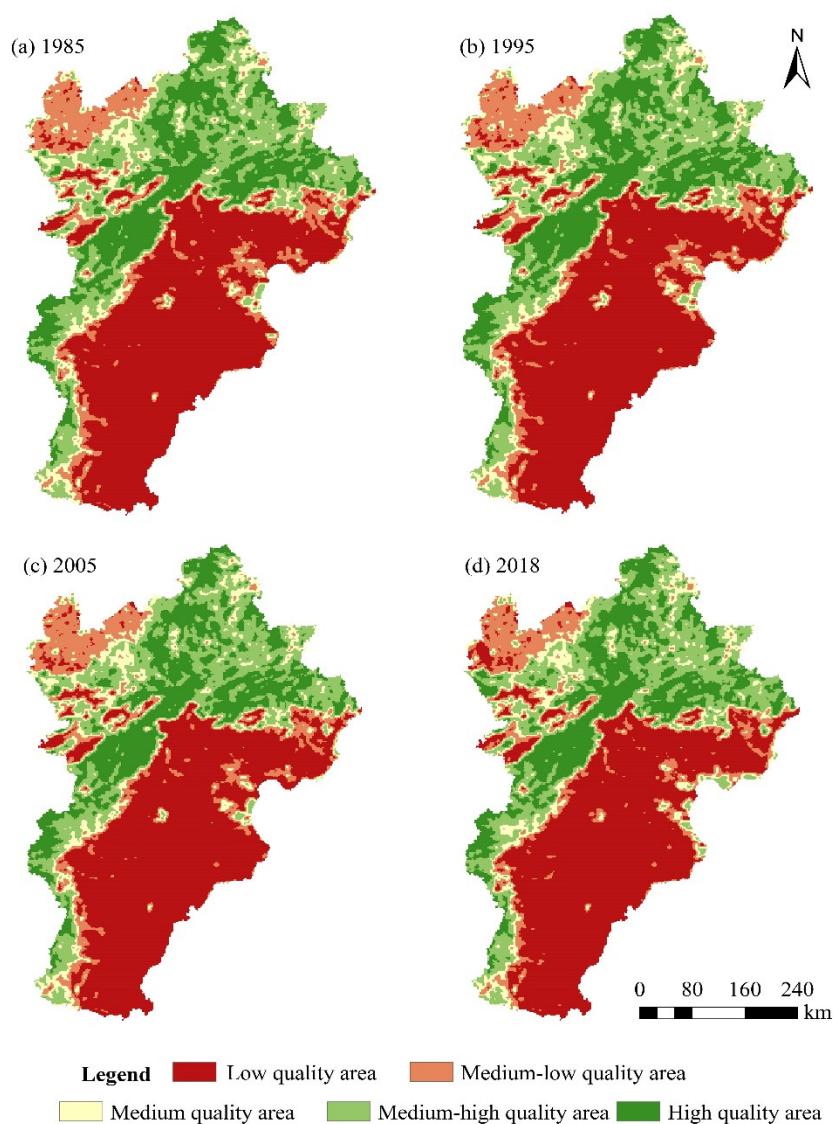
3.3. Eco-Environmental Effects of Land Use Transition

3.3.1. Characteristics of Eco-Environmental Quality

Based on Equation (2), the *E* values of the BTH region in 1985, 1995, 2005, and 2018 were 0.4306, 0.4295, 0.4282, and 0.4267, respectively, which represents a downward trend and reveals that the general quality of the regional eco-environment has deteriorated during the study period. From 1985 to 2018, the area of low-quality areas remained at around 41% (Table 4), which is the largest type. The ratio of medium-high-quality areas and high-quality areas fluctuated during the time period. Specifically, the area ratio of medium-high-quality areas showed a "decrease→increase→decrease" route at three time periods. Yet, the fluctuation characteristics of high-quality areas were the opposite of those of medium-high-quality areas. Their proportion of area increased from 1985 to 1995, and fell sharply to 17.22% by 2005, and then increased to 17.81% by 2018. The area proportion of the medium-low-quality areas continuously decreased from 1985 to 2005, and the area had slightly expanded by 2018. The area proportion of the medium-quality areas remained relatively stable. On the whole, an expanding area of low-level eco-environmental quality led to regional environmental deterioration over the past three decades in the BTH region.

From 1985 to 2018, the *E* values of the BTH region exhibited the spatial distribution of "high in the northwest and low in the southeast", with obvious regional differences and small time-series changes in the overall spatial pattern (Figure 5). High-quality areas were mainly located at the foot of the Taihang Mountain and Yanshan Mountain in the west, with the main land use types of forestland and grassland. Due to the local topography and landform, the development of industry and urban expansion were restricted, leaving the local eco-environment less damaged. The medium-low-quality areas were mainly distributed in Bashang Plateau in the north, with agricultural production land as the leading land use type. The low-quality areas were mainly concentrated in the southeast plain areas, which expanded by 2353.66 km² during the study period. The dominant land use types were agricultural production land, and urban and rural living land.

Table 4. Changes in the area of ecological environment quality in the Beijing–Tianjin–Hebei (BTH) region from 1985 to 2018.

Types	1985		1995		2005		2018	
	Area (km²)	%	Area (km²)	%	Area (km²)	%	Area (km²)	%
Low-quality area	87,011.58	40.34	87,294.75	40.47	90,050.27	41.75	89,365.24	41.43
Medium-low-quality area	27,390.10	12.70	27,250.79	12.63	24,511.47	11.36	25,693.21	11.91
Medium-quality area	18,778.39	8.71	18,782.55	8.71	18,746.03	8.69	18,403.21	8.53
Medium-high-quality area	44,135.46	20.46	43,894.52	20.35	45,254.22	20.98	43,825.56	20.32
High-quality area	38,398.26	17.80	38,491.18	17.84	37,151.81	17.22	38,426.57	17.81

Figure 5. Distribution of ecological environment quality in the BTH region.

3.3.2. Contribution of Land Use Transition to Eco-Environmental Quality

The contribution rate of land use transition to the eco-environmental quality index was calculated based on Equation (4). As shown in Table 5, from 1985 to 1995, the transitions from agricultural production land to forestland, grassland, and water area, and the transitions from grassland to forestland, were the main types of land transition that contributed to the improvement of the eco-environment quality in the BTH region; the total proportion of these four transition types reached 88.01%. At the same time, the transitions from agricultural production land to urban and rural living land, from forestland to agricultural production land, from grassland to agricultural and industrial production land, and from water area to agricultural production land accounted for 77.30% of the overall eco-environment deterioration. From 1995 to 2005, the transformation from agricultural production land to forestland and water area, from industrial production land to grassland, and from grassland to forestland were the predominant types of transition improving the eco-environment quality in the study area, and their contribution rate reached 74.33%. Meanwhile, the transformation from agricultural production land to industrial production land, urban and rural living land, from forestland to agricultural production land, from grassland to agricultural and industrial production land, and from water area to agricultural and industrial production land were the major types of eco-environment deterioration, with a total contribution rate of 73.78%. From 2005 to 2018, the conversion from agricultural production land into forestland, grassland, and water area, from industrial

production land into water area, and from grassland into forestland were the five major transitions leading to the improvement of eco-environment quality, which accounted for 83.53% of the contribution rate. On the contrary, the conversion from agricultural production land into industrial production land, from forestland into agricultural and industrial production land and grassland land, and from grassland and water area into agricultural and industrial production land evoked eco-environment deterioration, and the 10 types accounted for 82.90% of the total contribution rate.

To sum up, the types of land use transition that affect the eco-environment quality were similar within the three time intervals, and tended to become more complicated over time in the BTH region. The conversion from production land into ecological land was the main type of eco-environment improvement, while the conversions from production land to living land and from ecological land to production land were the major types of eco-environment deterioration. There were two coexisting trends of eco-environmental improvement and deterioration in the BTH region. However, the degree of eco-environment improvement was less than that of deterioration, causing an overall deteriorating eco-environment in this region.

Table 5. Major land use changes and contributions affecting the quality of the ecological environment in the BTH region.

| Type of Change	Land Use Function Transformation	1985–1995		1995–2005		2005–2018	
		L	%	L	%	L	%
Eco-Environment Improvement	Agricultural production land→Forestland	0.002502	30.56	0.000134	23.44	0.003921	23.86
	Agricultural production land→Grassland	0.002707	33.07	—	—	0.003885	23.64
	Agricultural production land→Water area	0.000972	11.87	0.00022	38.48	0.001805	10.98
	Industrial production land→Water area	—	—	0.000058	10.14	0.002202	13.40
	Grassland→Forestland	0.001024	12.51	0.000013	2.27	0.001914	11.65
	Total	0.007205	88.01	0.000425	74.33	0.013727	83.53
Eco-Environment Deterioration	Agricultural production land→Industrial production land	—	—	0.00014	7.54	0.000928	5.27
	Agricultural production land→Urban living land	0.000249	2.70	0.000182	9.81	0.000494	2.81
	Agricultural production land→Rural living land	0.000556	6.03	0.000091	4.90	0.001491	8.47
	Forestland→Agricultural production land	0.002019	21.90	0.000141	7.60	0.002789	15.84
	Forestland→Industrial production land	—	—	—	—	0.000934	5.30
	Forestland→Grassland	—	—	—	—	0.001348	7.66
	Grassland→Agricultural production land	0.003326	36.08	0.000168	9.05	0.003411	19.37
	Grassland→Industrial production land	0.000282	3.06	0.000122	6.57	0.001378	7.83
	Water area→Agricultural production land	0.000694	7.53	0.000372	20.04	0.001351	7.67
	Water area→Industrial production land	—	—	0.000153	8.27	0.000471	2.68
	Total	0.007126	77.30	0.001369	73.78	0.014595	82.90

3.4. Carbon Storage

The carbon density data and land use data were input into the InVEST model to obtain the spatial distribution of carbon storage at different time points in the study area (Figure 6). In the past 33 years, the spatial distribution of carbon storage in the BTH region demonstrated a slowly decreasing trend with time. The difference between the land use structure and topography had a strong impact on carbon storage between regions in the study area. Therefore, the distribution of carbon storage in the BTH region showed significant spatial variation, and had a similar pattern as

the topography. The carbon storage presented a high-value zone of "northeast-southwest", which was higher in the north and southwest, and lower in the northwest and southeast. Specifically, the high carbon sequestration areas were concentrated in the mountainous forest areas at a relatively high altitude, including Chengde, Zhangjiakou, the northern and western mountainous areas of Beijing, and the western marginal areas within Baoding, Shijiazhuang, and Xingtai. The majority of low-carbon sequestration areas were distributed in the densely populated urban areas and agricultural areas in the low-lying southern plain, where construction land and cultivated land dominate. This is consistent with the spatial distribution of forestland and grassland in the BTH region. A similar result of decreasing carbon storage in the region was reported by Cui et al. [61].

Over the past three decades, land use transition has resulted in a significant change of regional carbon storage, most of which occurred in the soil. Our results show that the total carbon storages in 1985, 1995, 2005, and 2018 were 2640.53 Tg C, 2629.52 Tg C, 2622.65 Tg C, and 2589.90 Tg C, respectively. Overall, the terrestrial ecological carbon storage in the BTH region has been declining over the last 33 years. The carbon storage decreased by 11.01 Tg C, 6.87 Tg C, and 32.75 Tg C at the three time intervals, a total loss of 53.36 Tg C during the whole study period, with an average annual loss of 1.53 Tg C and an average annual loss rate of 0.06%. Of the four carbon pools, SOC experienced the largest loss, which decreased by 24.20 Tg C, accounting for 48.20% of the total carbon storage loss across the whole region. BGC, AGC, and DOC decreased by 24.35 Tg C, 19.06 Tg C, and 8.40 Tg C, accounting for 24.35%, 19.06%, and 8.40% of the total carbon storage loss, respectively.

Given different natural processes and anthropogenic activities, each land use type has different carbon storage potential. The average carbon density of the forestland in the study area is the highest (208.28 Mg C/hm²), followed by the grassland. The average carbon density of agricultural production land is higher, while that of the urban and rural living land is lower. In addition, the water area has the lowest average carbon density (31.09 Mg C/hm²). Agricultural production land had the highest average proportion of carbon storage (43.42%) in the BTH region from 1985 to 2018, followed by forestland (35.68%; Figure 7). In addition, from 1985 to 2018, the carbon storage of agricultural production land, grassland, and other ecological land decreased by 120.48 Mg C, 19.52 Mg C, and 3.74 Mg C, respectively, which was closely related to the area loss of various land types. Nevertheless, urban and rural living land expanded by 2398.61 km² and 4081.68 km², respectively, and the areas of industrial production land and forestland increased by 1418.62 km² and 897.83 km². Accordingly, the carbon storage of urban and rural living land and industrial production land continuously increased, with a total increase of 70.18 Mg C. Meanwhile, the carbon storage of forestland increased by 20.96 Mg C. The carbon storage reduction caused by urban and rural land expansion was 16.43 Tg C, 5.67 Tg C, and 43.60 Tg C at the three time intervals, accounting for 43.07%, 57.59% and 49.12% of the total carbon storage reduction in the corresponding period. The reduction of carbon storage caused by the expansion of industrial production land was 2.48 Tg C, 1.97 Tg C, and 16.90 Tg C, respectively, accounting for 6.50%, 20.03% and 19.05% of the total carbon storage reduction in the corresponding periods. As shown in Figure 8, the decrease of carbon storage was mainly distributed in the periphery of Beijing and Tianjin from 1985 to 1995 and 1995 to 2005, in line with the direction of urban expansion of the two cities. From 2005 to 2018, the increase of carbon storage was much more significant due to the internal conversions of ecological land, such as the transformation from grassland to forestland. In conclusion, the expansion of construction land, such as urban and rural living land and industrial production land, is the primary driver of carbon storage change.
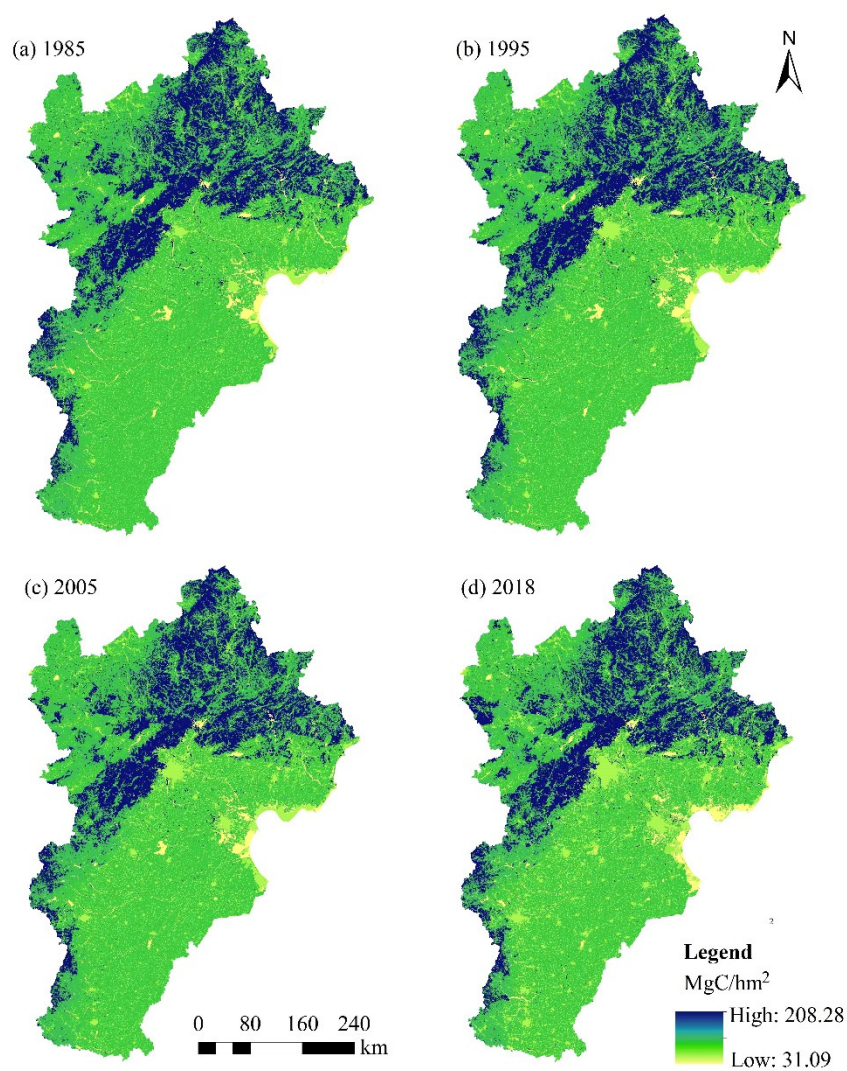
Figure 6. Carbon sequestration in the BTH region in 1985, 1995, 2005, and 2018.
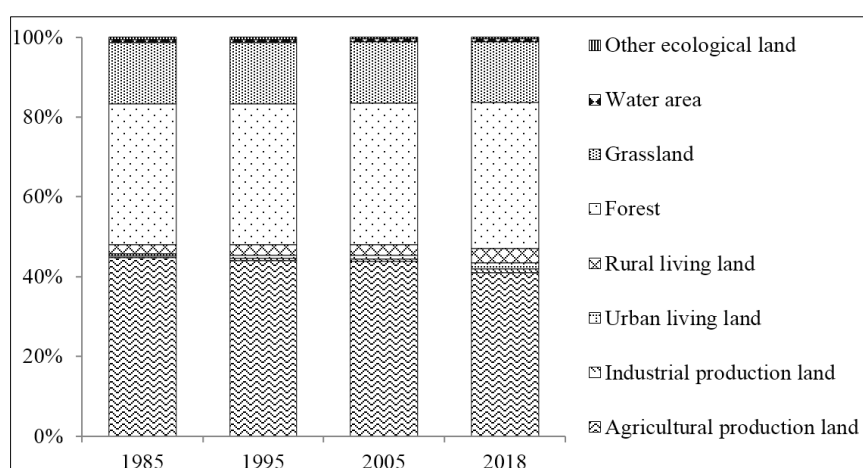
Figure 7. Carbon storage in different land use categories from 1985 to 2018.
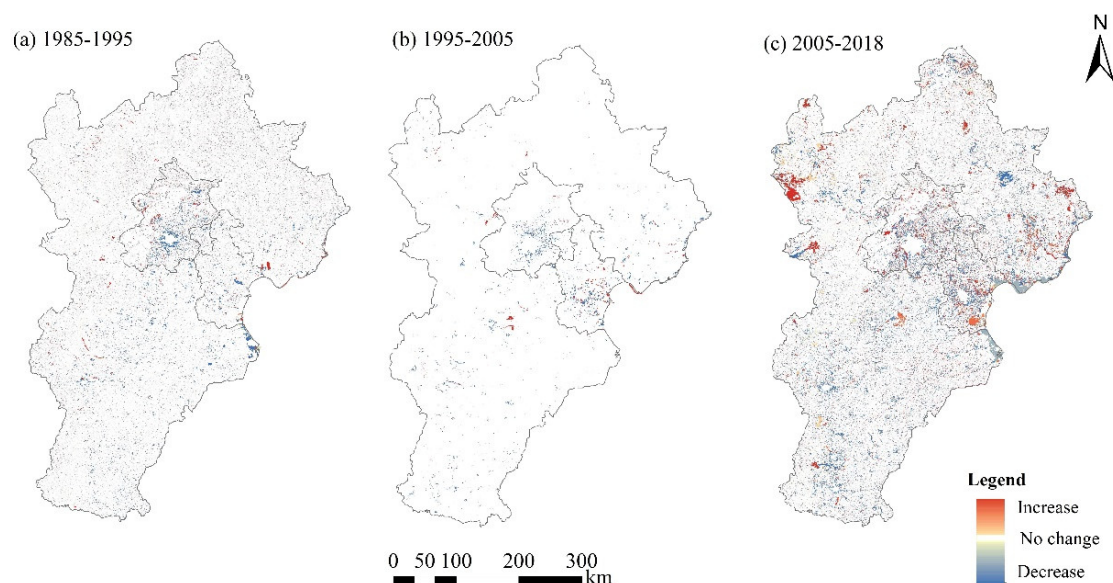
Figure 8. Spatial distribution of the changes in carbon storage from (**a**) 1985 to 1995, (**b**) 1995 to 2005, and (**c**) 2005 to 2018.

4. Discussion

Different interactions between humans and the environment shape different regional functions and functional spaces [50]. Land use is an intuitive reflection of the relationship between humans and the environment. The products and services provided by different land use types are quite different, which forms the spatial differences in land use functions. Land use functions refer to the attribute and state in which various products and services are directly or indirectly provided to human beings by different land use types [79], including production function (economic function), living function (social function), and ecological function [52]. The production–living–ecological (PLE) space is an effective means to realize the optimization of China's spatial development pattern under the strategic background of ecological civilization construction, and is also a more comprehensive zoning mode [80]. In this study, the PLE spaces are classified based on the dominant land use functions, which are defined from land use multifunctions.

The BTH region has a clear spatial distribution pattern of PLE space. The production space is mainly distributed in the southeast plain area; the living space is primarily located in metropolitan areas including Beijing, Tianjin, Shijiazhuang, Tangshan, and Langfang; and the ecological space is concentrated in the Yanshan-Taihang Mountain areas. With the continuous advancement of urbanization and industrialization, the BTH urban agglomeration has undergone a dramatic transformation of land use in the past 33 years, which has mainly manifested in the decrease of agricultural production land and the increase of living land. The overall regional quality of the eco-environment is deteriorating, which is mainly being caused by the transformation of agricultural production land into urban and rural living land, and is consistent with the current research conclusions in the economically developed urbanization areas such as the Yangtze River Delta and the eastern coast [81,82]. With the rapid advancement of the urbanization level, the demand for urban living land in the BTH region is increasing, and the contradiction between land supply and demand is being further intensified. Due to the influence of regional natural conditions, traffic, economic policies, development strategies, and other factors, the change degree of construction land varies significantly in different regions [63]. Meanwhile, attention should also be paid to the increasing scale of rural residential land, with an increase of 5043.24 km^2 from 1985 to 2018, which is 1.06 times the increased area of urban living land, reflecting the serious vacancy of rural residential land in the region. In recent years, the decline of rural areas has caused widespread concern among scholars. The nonagriculturalization of the rural population has caused the phenomenon that "people leave uninhabited houses", as well as "building new but not demolishing the old" in homesteads. Rural

hollowing is essentially an undesirable evolutionary process that leads to the "external expansion and internal hollowing" of a village during the process of urban–rural transformation and development, which is a special form of rural territorial system evolution [83]. There is an urgent need to solve rural problems, such as the increasing vacancy of rural houses, waste of construction land, and the rapid loss of agricultural production factors, to promote rural revitalization [84,85]. During the study period, it can be seen that the urbanization process was relatively slow from 1985 to 2005; however, from 2005 to 2018, agricultural production land dramatically decreased by 8064.89 km^2, which reflects large-scale occupation of cultivated land due to the rapid development of urbanization and industrialization.

An unbalanced economic development and industrial structure have led to significant differences in the transformation direction of regional land use, which has had a significant effect on eco-environment quality and terrestrial carbon sequestration. In this study, by constructing the eco-environmental quality index and adopting the InVEST model, we found that the overall quality of the eco-environment in the BTH urban agglomeration has deteriorated, and the carbon sequestration, as a regulation function for ecosystem services, decreased during this period because of the unprecedented land use transitions from 1985 to 2018 in this region. Figure 9 reveals the driving mechanism of the major eco-environment effects of land use transitions in the BTH region. The expansion of construction land, such as urban and rural living land and industrial production land, caused the reduction of carbon storage. Relevant studies show that there is a significant negative correlation between county urbanization level and carbon storage in the BTH region, and the land use transition caused by urbanization resulted in the reduction of carbon storage in this region [76], which is consistent with the conclusion of this study.

During the study period, the area experiencing the greatest loss of carbon storage was mainly distributed in the center of each economic circle. It can be seen from Figure 8 that carbon stock reduction appears in the periphery of the city centers of Beijing and Tianjin, which is closely related to the urban sprawl. Current research shows that the loss of cultivated land and the expansion of construction land in Beijing are concentrated in the area between the Fourth Ring Road and the Fifth Ring Road [64]. Around the highly urbanized core, the urban–rural interface has experienced many residential and industrial activities, with a profound impact on carbon storage. This result confirmed that the BTH region is currently under the rapid development of industrialization and urbanization, which has transformed a large area of agricultural production land, such as cultivated land, into urban built-up area. Moreover, it should be noted that there was a significant reduction of carbon storage in an area in the northeast of the region from 2005 to 2018, which was mainly caused by the conversion from forestland to grassland.

Commonly, the disorder of the land use structure leads to an unsustainable land use pattern and conflict among landscape functions [86]. Land use planning is crucial to successfully reconcile land use conflicts in the context of approving policies and plans, and in individual planning decisions [87,88]. On the whole, during the process of rapid economic development and urbanization, the BTH region has also suffered from the huge pressure brought about by the deterioration of the eco-environment, resulting in regional environmental problems such as ecological imbalances and environmental pollution. To solve the spatial contradiction of the PLE space, the BTH metropolitan area should utilize coordinated development that can balance economic construction and eco-environment protection, and optimize the layout of the PLE space under the idea of "global optimization", as follows: (1) For the production space, we should establish an industrial space layout system suitable for world-class urban agglomeration, and build an intensive and efficient production space according to the concept of a centralized layout, intensive land use, and eco-friendly development. Specifically, we should strictly control the population and the amount of incremental urban land, delimit the bottom line of cultivated land, adjust the agricultural production structure in plain areas, develop water-saving agriculture and forestry, and strengthen farmland protection. (2) For the living space, we should adhere to the principles of green, low-carbon, and multifunctional. First, we should vigorously promote the construction of public green space and open space in urban built-up areas; second, we should improve the living environment in rural areas and build a livable

and moderate living space [89]. In addition, in the process of Beijing–Tianjin–Hebei regional integration, we should narrow the gap between urban and rural areas, coordinate urban and rural construction land, highlight the goal of eco-environment protection, and lay a solid foundation for urban–rural integration. (3) For the ecological space, we must strictly delimit the ecological bottom line and implement the strictest ecological protection policies. In addition, we should further expand ecological space through land reclamation and afforestation, in order to provide a solid ecological barrier for the urban development of Beijing and Tianjin. Currently, the BTH region proposes to build a production–living–ecological spatial pattern of "one pole, two wings, three screens" [90]. "One pole" refers to the construction of the core production and living area of the international urban agglomeration of Beijing, Tianjin, and Northern Hebei, with Beijing and Tianjin as the core. "Two wings" means that Baoding, Langfang, and Shijiazhuang are taken as the left wing to construct the auxiliary production and living areas of the national urban agglomeration in central and southern Hebei; and Tangshan, Qinhuangdao and Chengde are taken as the right wing, to construct the auxiliary production and living areas of the BTH urban agglomeration in east and northeast Hebei. "Three screens" refers to the ecological barrier for water conservation of Yanshan Mountain in Zhangjiakou and Chengde, the ecological barrier for soil and water conservation of the Taihang Mountains in Shijiazhuang and Handan, and the coastal ecological barrier along the Bohai Sea in Tianjin and Qinhuangdao. This will provide a scientific reference for the further spatial optimization of PLE space in the BTH region.
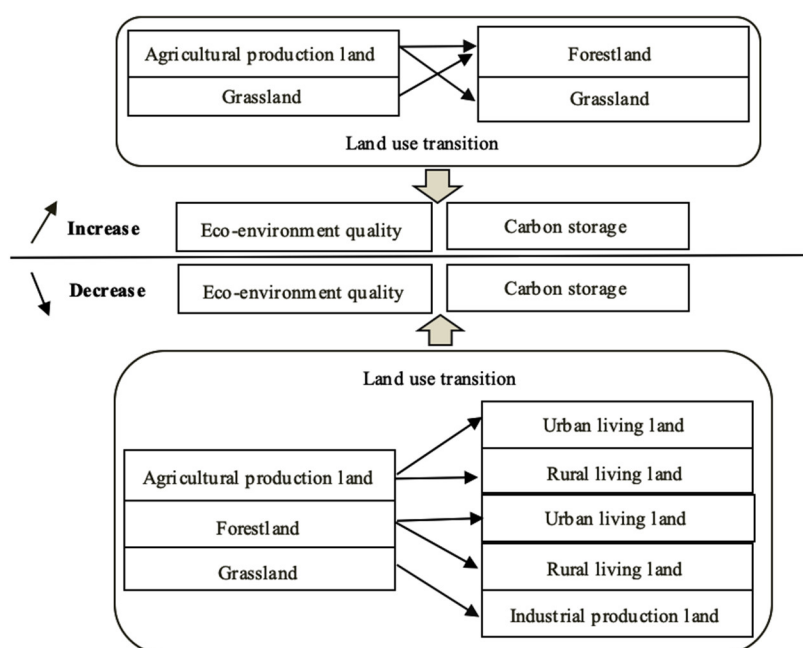
Figure 9. The driving mechanism of land use transition on eco-environment effects in the BTH region.

5. Conclusions

This paper adopted the land use transfer matrix to analyze the dynamic changes of land use, and then constructed an eco-environmental quality index and used InVEST-based carbon storage analysis to quantitatively study the related eco-environmental effects in the BTH region from the perspective of the production–living–ecological space. The results show that: (1) From 1985 to 2018, the land use pattern of the study area has changed significantly, presenting characteristics of rapid expansion of living spaces, shrinking production space, and relatively stable ecological land, and the living land is mainly being converted from agricultural production land. (2) Overall, the eco-environmental quality index is "high in the northwest and low in the southeast", with obvious regional differences. There are two simultaneous trends of ecological improvement and deterioration, but the overall eco-environmental quality of the BTH region demonstrated a deteriorating trend over the past 33 years. Moreover, the main types of eco-environment deterioration are the conversion from

production land to living land, and from ecological land to production land. (3) The distribution of the carbon density demonstrates a decreasing trend from the northwest to southeast. Furthermore, the expansion of construction land, such as urban and rural living land and industrial production land, is the main process causing carbon storage changes. We suggest that the BTH metropolitan area should take the path of coordinated development of economic construction and eco-environment protection. At this critical stage of BTH regional integration, guided by the idea of "global optimization", the region should optimize the layout of the production–living–ecological space and promote land multifunctional transformation, in order to realize the goal of high-quality and efficiency of the production space, moderate livability of the living space, and beautiful scenery of the ecological space.

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