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Variation of Net Carbon Emissions from Land Use Change in the Beijing-Tianjin-Hebei Region during 1990–2020

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Abstract: Global increasing carbon emissions have triggered a series of environmental problems and greatly affected the production and living of human beings. This study estimated carbon emissions from land use change in the Beijing-Tianjin-Hebei region during 1990–2020 with the carbon emission model and explored major influencing factors of carbon emissions with the Logarithmic Mean Divisia Index (LMDI) model. The results suggested that the cropland decreased most significantly, while the built-up area increased significantly due to accelerated urbanization. The total carbon emissions in the study area increased remarkably from 112.86 million tons in 1990 to 525.30 million tons in 2020, and the built-up area was the main carbon source, of which the carbon emissions increased by 370.37%. Forest land accounted for 83.58–89.56% of the total carbon absorption but still failed to offset the carbon emission of the built-up area. Carbon emissions were influenced by various factors, and the results of this study suggested that the gross domestic product (GDP) per capita contributed most to the increase of carbon emissions in the study area, resulting in a cumulative increase of carbon emissions by 9.48 million tons, followed by the land use structure, carbon emission intensity per unit of land, and population size. By contrast, the land use intensity per unit of GDP had a restraining effect on carbon emissions, making the cumulative carbon emissions decrease by 103.26 million tons. This study accurately revealed the variation of net carbon emissions from land use change and the effects of influencing factors of carbon emissions from land use change in the Beijing-Tianjin-Hebei region, which can provide a firm scientific basis for improving the regional land use planning and for promoting the low-carbon economic development of the Beijing-Tianjin-Hebei region.

Keywords: carbon emission; carbon neutrality; land use change; Beijing-Tianjin-Hebei; LMDI

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Citation: Yan, H.; Guo, X.; Zhao, S.; Yang, H. Variation of Net Carbon Emissions from Land Use Change in the Beijing-Tianjin-Hebei Region during 1990–2020. *Land* **2022**, *11*, 997. https://doi.org/10.3390/land11070997

Academic Editors: Li Ma, Yingnan Zhang, Muye Gan and Zhengying Shan

Received: 1 June 2022
Accepted: 29 June 2022
Published: 30 June 2022

1. Introduction

The global increasing carbon emission under high carbon emission mechanisms has triggered a series of environmental problems, e.g., global climate anomalies, sea level rise, and frequent extreme weather events, which have greatly affected the production and living of human beings in recent decades [1,2]. Previous studies suggested that the land use system serves as a vital link between the human socio-economic system and the natural ecological environment, and the carbon emissions caused by land use change have been one of the important influencing factors of global warming [1–3]. In fact, various human activities, e.g., social construction, economic development, industrial arrangement, urban expansion, and energy consumption, are all closely related to the carbon emissions, all of which are ultimately implemented in different land use practices [4,5], and relevant land use change has been considered as the second most important influencing factor of the global increasing atmospheric CO_2 content [6,7]. The 14th Five-Year Plan of China proposed to achieve the "peak carbon dioxide emissions" by 2030 and "carbon neutrality" by 2060, that the low-carbon economy should serve as a new economic growth mode in the future, and that new green energy sources should be developed to reduce the dependence of economic growth on the major fossil energy sources such as coal and oil [4]. It is, therefore, of practical significance to explore the regional carbon emissions from land use change to achieve low carbon land use, promote low carbon economic development, and establish a resource-conserving and environment-friendly society in this context [8,9].

Previous studies on carbon emissions from land use change at home and abroad were primarily concentrated on the spatiotemporal variation of different land use types and their relevant effects on carbon emissions, carbon emission accounting, influencing factors of land use change, and carbon emissions [10–13]. The Guidelines for the National Greenhouse Gas Inventories prepared by the Intergovernmental Panel on Climate Change (IPCC) provided a valuable methodological reference for accounting carbon emissions from land use change [13,14]. Besides, some scholars also proposed the emission coefficient method for the carbon emission accounting of cropland, forest land, grassland, and built-up area and explored the effects of land use change on carbon emissions [14–16]. In addition, most scholars have generally explored the influencing factors of carbon emissions with various econometric methods, such as the factor decomposition method [17,18], and some other scholars explored the drivers of carbon emissions with the Laspeyres decomposition method [19–21]. Moreover, more scholars carried out decomposition analyses based on the Logarithmic Mean Divisia Index (LMDI) model to reveal the influencing factors of carbon emissions in various relevant fields, e.g., carbon emissions per capita, carbon emissions due to industrial combustion energy, carbon emissions in the manufacturing industry, and drivers of carbon emissions from energy consumption for different time durations in China [22,23]. The results of these studies provided valuable methodological references for exploring a series of issues related to carbon emissions from land use change [24,25]. However, these existing studies focused more on some major land use types, such as cropland and built-up area, with less consideration of the carbon emissions from some other land use types [25,26]. In particular, there are relatively fewer quantitative studies on the influencing factors of carbon emissions from land use change, especially the studies on the influencing factors of carbon emissions from land use change with the LMDI model [6,27,28].

The Beijing-Tianjin-Hebei region, as one of the major urban agglomerations in China, accounted for 11–12% of the national total carbon emissions, which is higher than the national proportions of both gross domestic product (GDP) and the population of this region [5,12]. In particular, the goal of peak carbon dioxide emissions and carbon neutrality has put forward new and higher requirements for the synergistic development of this region [16,18,29]. This study estimated the net carbon emissions from land use change in the Beijing-Tianjin-Hebei region from the perspective of land use and decomposed the influencing factors of carbon emissions from land use change to quantitatively reveal the effects of these influencing factors on the carbon emissions from land use change, aiming to provide a firm scientific basis for improving the regional land use planning, promoting the low-carbon economic development, and guiding the development of the Beijing-Tianjin-Hebei region into the capital economy circle.

2. Materials and Methods

2.1. Study Area

The Beijing-Tianjin-Hebei region is located in the northern part of China (36°5′–42°40′ N, 113°27′–119°50′ E), which is one of the three major urban agglomerations in China [18,26,30]. There is very complex terrain in this region, where there are mainly higher mountains and plateaus in the northern and western parts and flatter plains in the southern and eastern parts (Figure 1). There is a warm-temperate continental monsoon climate in this region, with higher temperatures and precipitation in the summer. The Beijing-Tianjin-Hebei region is the political, economic, cultural, and scientific center of China and plays a strategically important role in the economic development of China [18]. The Beijing-

Tianjin-Hebei region takes up approximately 2% of the total national land area, but it accounts for approximately 8.1% of the total national population and 9.44% of the total national GDP. However, there is very high energy consumption intensity along with rapid urbanization in the Beijing-Tianjin-Hebei region, leading to very high carbon emission. For example, the carbon emission in the Beijing-Tianjin-Hebei region reached 1.085 billion tons in 2018, accounting for about 1/9 of the total national carbon emissions of China [26,30]. Exploring the long time-series variation of net carbon emissions from land use change can provide valuable information for addressing the pressure of carbon emission reduction in the Beijing-Tianjin-Hebei region, especially in the context of the coordinated development of the Beijing-Tianjin-Hebei region [26,27].

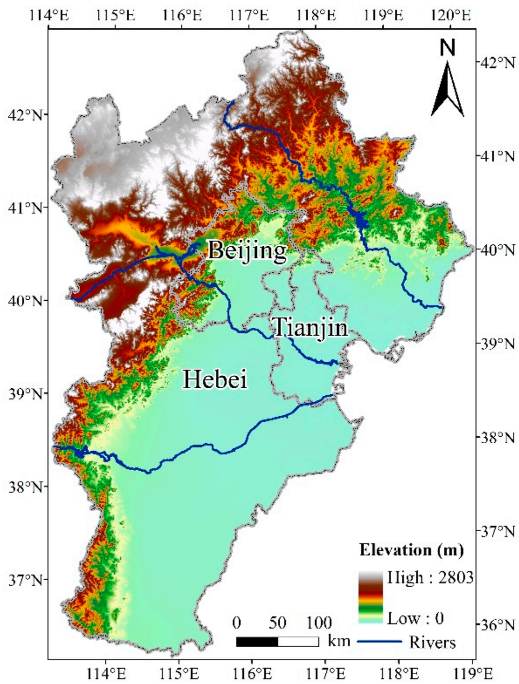

Figure 1. Location of the Beijing-Tianjin-Hebei region.

2.2. Data and Processing

The spatial data used in this study includes the 1-km land use data extracted from the Land Use Remote Sensing Monitoring Data of China in 1990, 1995, 2000, 2005, 2010, 2015, and 2020 (http://www.resdc.cn, accessed on 31 October 2021), which were reverted from Landsat TM/ETM images. The land types were classified into cropland, forest land, grassland, water area, built-up area, and barren land [12,26], based on which this study explored the land use transfer matrix of the Beijing-Tianjin-Hebei region during 1990–2020. Besides, the non-spatial data used in this study mainly included the socioeconomic data (e.g., population and GDP), regional energy consumption data, and carbon emission coefficients of the Beijing-Tianjin-Hebei region, which were obtained from various issues of the China Statistical Yearbook, the China Energy Statistical Yearbook, IPCC reports, and the relevant literature. Finally, these data in different parts of the study area were combined to obtain the regional energy consumption amount and the carbon emission coefficients of different land use types, and these regional data were further summed up to obtain the relevant total data of the whole Beijing-Tianjin-Hebei region.

2.3. Carbon Emission Accounting Model and Carbon Emission Coefficients

The carbon emissions can be categorized into direct and indirect carbon emissions [27]. The former refers to carbon emissions caused by the processes of maintenance and conversion and specific land types, while the latter refers to carbon emissions generated by the land serving as a carrier of production and living processes of human beings [28,29]. A large number of studies have shown that some land use types may be both carbon sources and sinks, and the intensity of carbon sources and sinks generally varies greatly among different land use types [30,31]. This study primarily focused on the carbon emission effects of land use change caused by human activities, i.e., the amounting of carbon emissions and the sequestration of cropland, forest land, grassland, water body, built-up area, and barren land under the influence of human activities, and it finally summarized the carbon emission amount of different land use types. The major crops in the study area include wheat and maize, and these crops on cropland can absorb CO_2 in the air through photosynthesis in general, but most of the crop biomass is then decomposed in the soil and released back into the air in the short term, so there are generally insignificant effects of crop biomass as a carbon sink. Meanwhile, the effects of cropland inputs and soil emissions on the carbon emissions can also be reflected with the carbon emission coefficient of cropland [30]. By contrast, carbon emissions from energy consumption and industrial activities such as housing, mining, and manufacturing and transportation are the main sources of carbon emissions. Thus, the built-up area and cropland generally serve as the carbon sources, with positive carbon emission coefficients, while the forest land, grassland, water body, and barren land generally serve as carbon sinks, which are carbon absorbers with negative carbon emission coefficients. The regional carbon emission can be estimated based on the carbon emission coefficients according to the guidelines of IPCC as follows:

$$E_c = \sum e_i = \sum A_i \times \xi_i \tag{1}$$

where E_c is the total carbon emission (or absorption) amount, e_i is the carbon emission (or absorption) amount from the ith land use type, A_i is the area of the ith land use type, and δ_i is the carbon emission (or absorption) coefficient of the ith land use type.

The carbon emission (or absorption) coefficients of different land use types, which were assumed to keep stable during the study period, were determined as follows. The cropland that provides both carbon emission and carbon absorption serves as both a carbon source and carbon sink [29,30]. It is therefore necessary to take into account the greenhouse gas produced during the crop production and CO_2 absorption of crops during the reproductive period, and the difference between the two can be used to estimate the net carbon emission coefficient of the cropland [22,24]. Previous studies have shown that the carbon emission coefficient and carbon sequestration coefficient of cropland are approximately 0.422 t/hm^2 and 0.007 t/hm^2, respectively [31,32], so this study took the difference between the two as the net carbon emission coefficient of cropland, i.e., 0.415 t/hm^2. In addition, the forest land and grassland are the most important carbon sink and carbon sequestration systems in the terrestrial ecosystem, and previous studies have shown that the carbon emission coefficients of the forest land and grassland were −0.623 t/hm^2 and −0.144 t/hm^2, respectively [33,34], which were also adopted in this study. In addition, previous studies showed that there is very limited carbon absorption of the water body and barren land, generally with very weak impacts on the regional net carbon emissions [27,32]. However, the water body and barren land accounted for 4% of the total area in the Beijing-Tianjin-Hebei region, so this study still considered the carbon emission coefficients of the water body and barren land, which were approximately −0.03 t/hm^2 and −0.05 t/hm^2, respectively, according to the literature survey results [35–37]. Moreover, there are various types of built-up area, e.g., urban land, rural settlements, traffic roads, factories and mines, industrial areas, oil fields, salt fields, and quarries. The built-up area carries a large amount of the energy consumed in the production and living of human beings, and it is unfeasible to calculate the carbon emissions of the built-up area according to only the area share of built-up area [38,39]. It is necessary to estimate the carbon emissions from the built-up area based on the carbon emissions generated by the energy consumption of human beings on the built-up area [40,41], which can be estimated according to the carbon emission coefficient method of the IPCC as follows:

$$EC = \sum m_i \times \beta_i \times \theta_i \tag{2}$$

where EC is the carbon emission from energy consumption on the built-up area, m_i is the consumption amount of various fossil energy sources, β_i is the standard coal conversion coefficient of each energy resource, and θ_i is the carbon emission coefficient of each energy resource. This study used the standard coal conversion coefficient and carbon emission coefficient of each energy resource published by the IPCC guidelines [32,42,43], which are shown in Table 1.

Table 1. Standard coal conversion coefficients and carbon emission coefficients of various energy sources.

Energy Sources	Standard Coal Conversion Coefficient	Carbon Emission Coefficient
Coal	0.7143 (kgce/kg)	0.7559
Coke	0.9714 (kgce/kg)	0.8550
Crude oil	1.4286 (kgce/kg)	0.5857
Gasoline	1.4714 (kgce/kg)	0.5538
Kerosene	1.4714 (kgce/kg)	0.5714
Diesel oil	1.4571 (kgce/kg)	0.5921
Fuel oil	1.4286 (kgce/kg)	0.6185
Natural gas	1.3301 (kgce/m^3)	0.4483
Electric power	0.1229 kg (kgce/kWh)	0.7476

2.4. Decomposition Analysis of Influencing Factors of Carbon Emissions

This study explored the influencing factors of carbon emissions with the LMDI model, which is one of the most widely used methods to explore the influencing factors of energy consumption in the field of low carbon economy due to its advantages such as high operability, full decomposition, no residuals, and unique results [36,37]. Specifically, this study analyzed the effects of different influencing factors on carbon emissions from land use change according to the Kaya identity by introducing the land use factor and establishing the formula of influencing factors of regional carbon emissions from five aspects, i.e., energy consumption structure, land output intensity, land use structure, economic growth, and population scale effect, as follows [41,42]:

$$C = \sum \frac{C_i}{L_i} \times \frac{L_i}{L} \times \frac{L}{G} \times \frac{G}{P} \times P \tag{3}$$

where C is the total carbon emissions from land use change (million tons), C_i is the carbon emission amount of the ith land use type (million tons), L_i is the area of the ith land use type (km^2), L is the total land area of the study area (km^2), G is the GDP (10^8 CNY), and P is the regional population size (10^4 persons).

Then, the regional total carbon emissions can be expressed as follows [40,42]:

$$f_i = \frac{C_i}{L_i};\ S_i = \frac{L_i}{L};\ q = \frac{L}{G};\ g = \frac{G}{P} C = \sum f_i \times S_i \times q \times g \times P \tag{4}$$

where f_i, S_i, q, g, and P refer to the carbon emission intensity per unit of the ith land use type, the effect of the land use structure, land use intensity per unit of GDP, GDP per capita, and population size, respectively. According to this formula, the contribution value and contribution rate of each factor can be further analyzed with the LMDI model. Assuming the carbon emission in the base period and the Tth period are C^0 and C^T, respectively, then the carbon emission change during the study period (0–T) can be expressed as follows [40,43]:

$$\begin{aligned} \Delta C = C^T - C^0 &= \sum_{i=1,2,\ldots\ldots 6} f_i^T \times s_i^T \times q^T \times g^T \times P^T - \sum_{i=1,2,\ldots\ldots 6} f_i^0 \times s_i^0 \times q^0 \times g^0 \times P^0 \\ &= \Delta C_{f_i} + \Delta C_{s_i} + \Delta C_q + \Delta C_g + \Delta C_P + \Delta C_{rsd} \end{aligned} \tag{5}$$

$$D = \frac{C^T}{C^0} = D_f D_s D_q D_g D_P D_{rsd} \tag{6}$$

where ΔC is the carbon emission change during the study period, ΔC_{f_i}, ΔC_{s_i}, ΔC_q, ΔC_g, and ΔC_P are the contribution values of f_i, S_i, q, g, and P, respectively, and ΔC_{rsd} is the decomposition residual. If the obtained contribution value is >0, then the factor has a pulling effect on the carbon emissions during the study period; otherwise, the factor has a suppressing effect on carbon emissions. D is the carbon emission change percentage between the base period and the Tth period; D_f, D_s, D_q, D_g, D_p, and D_{rsd} are the contribution rates of f_i, S_i, q, g, and the residual error, respectively.

The following are the relationships in the additive decomposition mode according to the LMDI model [40,44,45]:

$$\begin{aligned}
\Delta C_{f_i} &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{f_i^T}{f_i^0} \\
\Delta C_{s_i} &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{S_i^T}{S_i^0} \\
\Delta C_q &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{q^T}{q^0} \\
\Delta C_g &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{g^T}{g^0} \\
\Delta C_P &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{P^T}{P^0}
\end{aligned} \tag{7}$$

The following are the relationships in the multiplicative decomposition mode according to the LMDI model [40,45]:

$$\begin{aligned}
&D_f = \exp(W\Delta C_{f_i}); D_s = \exp(W\Delta C_{s_i}) \\
&D_q = \exp(W\Delta C_q); D_g = \exp(W\Delta C_g) \\
&D_P = \exp(W\Delta C_P); D_{rsd} = 1 \\
&W = \frac{\ln D}{\Delta C}
\end{aligned} \tag{8}$$

3. Results

3.1. Land Use Change in the Beijing-Tianjin-Hebei Region

There was remarkable land use change in the Beijing-Tianjin-Hebei region during 1990–2020. There is mainly cropland and forest land in the Beijing-Tianjin-Hebei region, where the cropland is mainly distributed in the central and southeast parts of the study area, and the forest land as well as grassland are mainly distributed in the northeast and western parts (Figure 2). The built-up area is concentrated in the central part and the peripheral zone of the central towns in the study area. The water body is very limited in the study area, which mainly includes rivers near towns and lakes in the northwest. More specifically, cropland as the main land use type accounted for approximately 51.92% of the entire area in 1990. The forest land and grassland ranked second and third, accounting for about 20.65% and 16.49% of the entire area, respectively, while the built-up area, water body and barren land accounted for 10.94% of the entire area in total. There was a decreasing trend of cropland, forest land, grassland, and barren land from 2000–2015, while the built-up area increased significantly due to the accelerated urbanization process. In particular, the cropland decreased significantly from 2015–2020, while the built-up area continued to increase, and other land types only changed slightly.

Table 2 shows the land use transfer in the Beijing-Tianjin-Hebei region from 1990–2020. A total of 73,072 km^2 of land was transferred during 1990–2020, among which the transfer-out area of the cropland ranked first, accounting for about 91.2% of the total transfer-out area. The cropland was mainly transferred into built-up area, grassland, and forest land, with the converted areas of which reaching 6726 km^2 and 4705 km^2 and 17,621 km^2, respectively. Meanwhile the transfer-in area of cropland reached 19,880 km^2, which was mainly converted from grassland and built-up area, accounting for about 69.4% of the total transfer-in area of cropland. The transfer-in area of built-up area increased most significantly during the study area, reaching 20,837 km^2, 84.6% of which was transferred from the cropland. By contrast, watershed and barren land only changed slightly, most of which was converted to cropland, accounting for 49% and 51% of their transfer-out area, respectively.

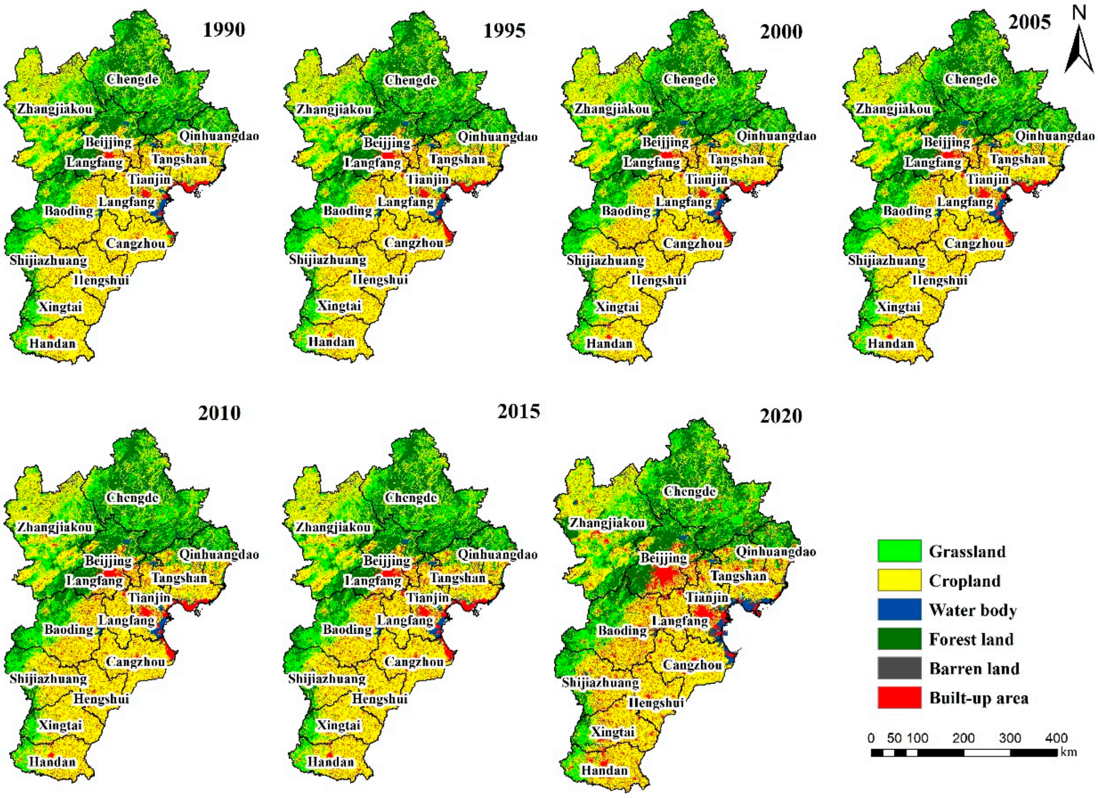

Figure 2. Spatial pattern of land use in the Beijing-Tianjin-Hebei region from 1990–2020.

Table 2. Land use transfer matrix in the Beijing-Tianjin-Hebei region during 1990–2020 (km^2).

1990	2020						
	Grassland	**Cropland**	**Built-up Area**	**Forest Land**	**Water Body**	**Barren Land**	**Total Decrease**
Grassland	19,377	7016	1425	6858	538	223	16,060
Cropland	6726	79,738	17,621	4705	2512	302	31,866
Built-up area	314	6777	6821	190	996	43	8320
Forest land	6713	3454	836	33,103	251	29	11,283
Water body	486	1778	768	361	2288	489	3882
Barren land	320	855	187	75	224	547	1661
Total increase	14,559	19,880	20,837	12,189	4521	1086	73,072
Overall change	−1501	−11,986	12,517	906	639	−575	—

3.2. Evolution of Net Carbon Emissions in the Beijing-Tianjin-Hebei Region

The average annual net carbon emission during 1990–2020 was 313.93 million tons, and the net carbon emissions of Hebei Province changed most significantly, increasing by 317.71 million tons during the study period, followed by Tianjin and Beijing. From the perspective of regions within the study area, the changing trend of net carbon emissions of Hebei Province is similar to that of Beijing and Tianjin. Besides, the evolution of carbon emissions in the Beijing-Tianjin-Hebei region over these 30 years was divided into three stages, according to the change of net carbon emissions, the industrial development status, and energy consumption status in the study area, as shown in Figure 3.

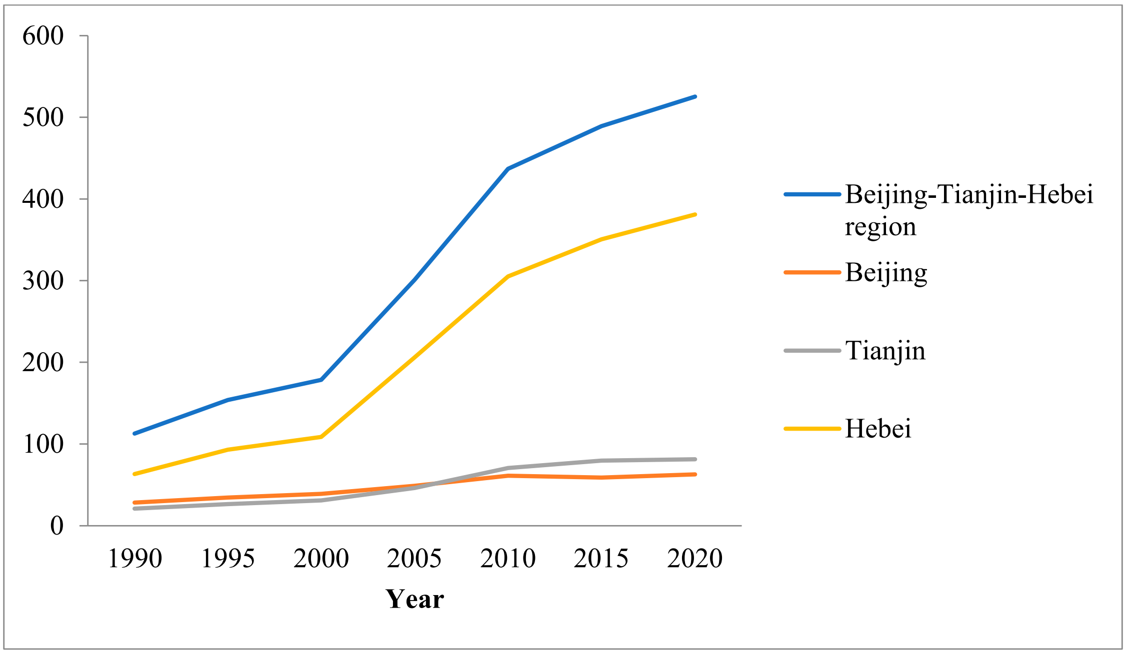

Figure 3. Changing trends of net carbon emissions in the Beijing-Tianjin-Hebei region from 1990–2020 (million tons).

Phase I (1990–2000) is the stage of slow increase in net carbon emissions, which increased from 112.86 million tons to 178.54 million tons but was still significantly lower than the average level of the whole study period. This is mainly due to the fact that the study area was still in the early industrialization stage during this phase, with a low urbanization level and low consumption of various energy sources, which led to relatively lower net carbon emissions.

Phase II (2000–2010) is the stage of rapid growth of net carbon emissions, which rapidly increased from 178.54 million tons to 436.83 million tons, with the average annual growth rate reaching 144.66%. This is mainly due to the national focus on the development of heavy industries and the relatively loose macro production capacity policies during this period, which led to the lower entry requirement of high energy-consuming, high-emission, and low-efficiency enterprises into the study area, thus resulting in the rapid increase of the net carbon emissions.

The third phase (2010–2020) is the stage of steady increase of net carbon emissions, with the total carbon emissions increasing steadily from 436.83 million tons to 525.31 million tons. The average carbon emission level during this phase was 1.58 times that of the second phase, but the average annual growth rate was only 20.25%, which is much lower than that of the second phase. This is mainly due to the improvement of energy efficiency under the influence of the national policies on energy saving and emission reduction and application of advanced technologies. In particular, the implementation of the policies of "peak carbon dioxide emissions" and "carbon neutrality" imposed important limitations on the increase of carbon emissions.

3.3. Variation of Carbon Emissions from Land Use Change

The carbon emissions from land use change are shown in Table 3, which were estimated on the basis of the land use data and energy consumption data of the Beijing-Tianjin-Hebei region during 1990–2020. The carbon emissions from land use change in the Beijing-Tianjin-Hebei region showed an overall increasing trend during 1990–2020, with the total carbon emissions increasing from 112.86 million tons in 1990 to 525.30 million tons in 2020, with an overall growth rate of 365.46% during these 30 years (Table 3). Among the major sources of carbon emissions, the carbon emissions from cropland decreased slowly from 4.66 million tons in 1990 to 4.15 million tons in 2020, with a total decrease of 0.52 million tons and an average annual decrease of 17.12 thousand tons in these 30 years, which is mainly due to the slowly decreasing trend of cropland area in the study area during the study period. However, the carbon emissions from built-up area as another major source of carbon emissions increased rapidly from 111.51 million tons in 1990 to 524.51 million tons in 2020, with an overall growth rate of 370.37% during the study period. In particular, carbon emissions from built-up area accounted for 95.99–99.22% of the total carbon emissions, so built-up area served as the main carbon emission source in the Beijing-Tianjin-Hebei region during the study period. The carbon sinks included the forest land, grassland, water area, and barren land, the effects of which on the carbon absorption shoed a descending order. Specifically, the carbon absorption effect of the forest land was the most significant, accounting for 83.58–89.56% of the total carbon absorption amount of the study area, while the grassland and water body accounted for 9.62–15.49% and 0.47–0.59% of the total carbon absorption amount of the study area, respectively. By contrast, the carbon sequestration effect of barren land was the least significant, accounting for only 0.24–0.35% of the total carbon absorption amount of the study area. It is particularly notable that the ratio of the carbon emissions from the built-up area to the carbon absorption from the forest land ranged between 40.26 and 185 during 1990–2020. In other words, the carbon emissions from the built-up area were so large that the carbon absorption effect of the forest land failed to offset the carbon source effect of built-up area, which is the underlying reason for the continuous increase of the total carbon emissions in the study area during the study period.

Table 3. Carbon emissions from land use change in the Beijing-Tianjin-Hebei region during 1990–2020 (million tons).

Year	1990	1995	2000	2005	2010	2015	2020
Forest land	−2.77	−3.72	−2.79	−2.79	−2.79	−2.78	−2.84
Grassland	−0.51	−0.4	−0.51	−0.5	−0.5	−0.5	−0.49
Water body	−0.02	−0.02	−0.02	−0.02	−0.02	−0.02	−0.02
Barren land	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01
Cropland	4.66	4.22	4.55	4.51	4.49	4.46	4.15
Built-up area	111.51	153.74	177.33	299.91	435.66	487.95	524.52
Carbon sink	−3.31	−4.16	−3.32	−3.32	−3.32	−3.31	−3.36
Carbon Source	116.17	157.96	181.87	304.42	440.15	492.41	528.66
Total carbon emissions	112.86	153.8	178.55	301.1	436.83	489.1	525.31

3.4. Effects of Influencing Factors of Carbon Emissions from Land Use Change

The decomposition of the variation of carbon emissions in the Beijing-Tianjin-Hebei region during 1990–2020 with the LMDI model revealed the contribution value and contribution rate of five influencing factors of carbon emissions, i.e., carbon emission intensity per unit of land, land use structure, land use intensity per unit of GDP, GDP per capita, and population size in Figure 4. The results showed that there was obvious annual variation trends of these influencing factors of carbon emissions from land use change in the study area (Figure 4). Besides, Figure 5 shows the cumulative contribution rate of these influencing factors. There were remarkable differences in the contribution value between various influencing factors of the carbon emissions from land use change (Figure 5). The absolute contribution values of each influencing factor to the variation of carbon emissions from land use change during 1990–2020 in a descending order were land use intensity per unit of GDP > GDP per capita > land use structure > carbon emission intensity per unit of land > population size. The land use intensity per unit of GDP was the biggest restraining factor of the increase of carbon emissions, and the remaining four factors all had positive effects on the increase of carbon emissions, among which GDP per capita had the greatest promotion effects on the increase of carbon emissions (Figure 5).

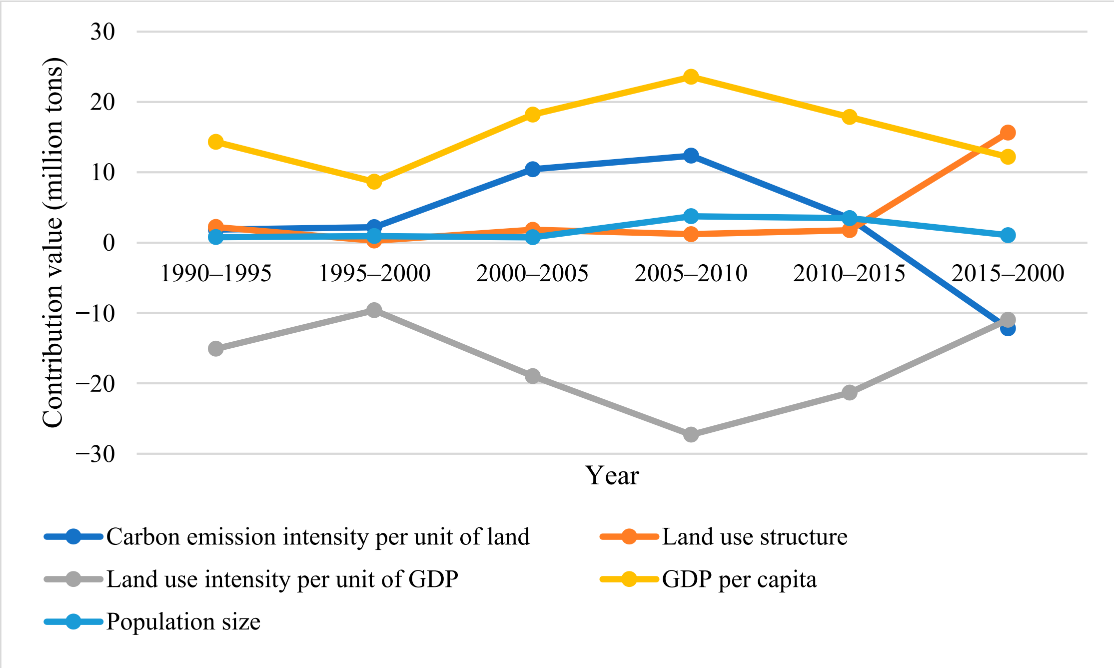

Figure 4. Contribution value of the influencing factors to variation of carbon emissions from land use change in the Beijing-Tianjin-Hebei region.

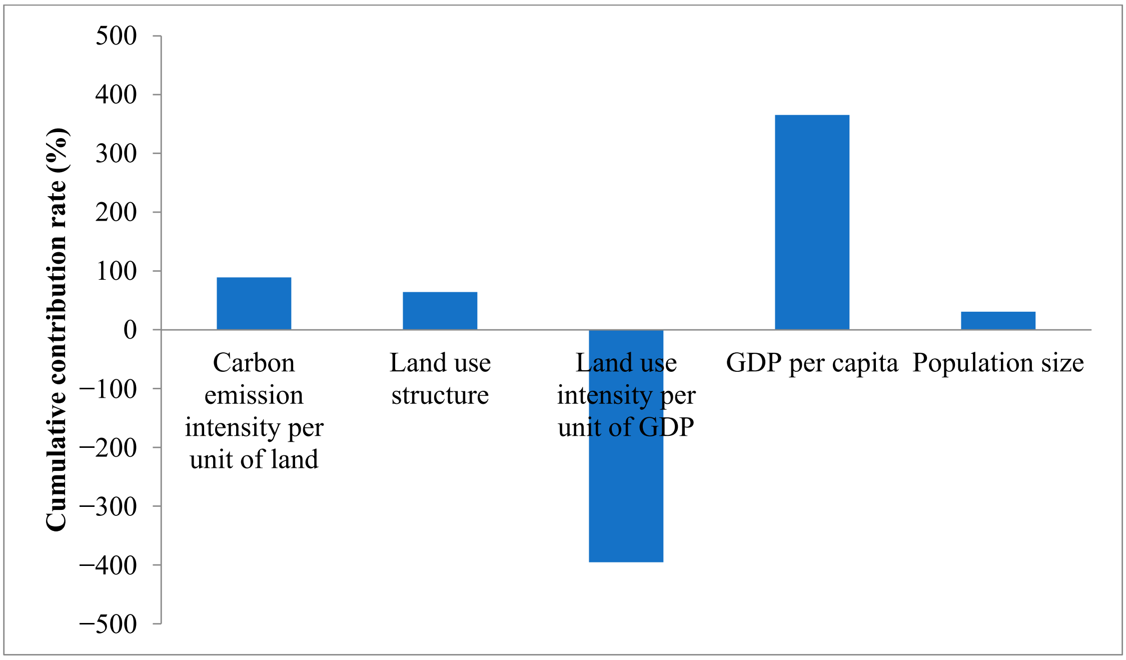

Figure 5. Cumulative contribution rate of influencing factors to the variation of carbon emissions from land use change in the Beijing-Tianjin-Hebei region.

This study suggested that the land use factors played an important role in influencing the carbon emissions. For example, there were extremely unstable effects of the carbon emission intensity per unit of land on the carbon emissions, which showed a promoting effect during 1990–2015 and a restraining effect during 2015–2020, indicating uncertainties of the role of carbon emission intensity per unit of land in influencing the carbon emissions from land use change. Nevertheless, the cumulative contribution rate of the carbon emission intensity per unit of land was 89.06% during the study period. Besides, the land use structure had an overall positive effect on the carbon emissions from land use change during the study period, with a cumulative contribution rate of 64.3%. It is notable that the contribution value of the land use structure showed a significant increase during 2015–2020, which is mainly because the built-up area expanded rapidly during this period, which led to the remarkable increase of carbon emissions from land use change. It is therefore of great significance to the control of carbon emissions to carry out the reasonable layout of land use structure. By contrast, the land use intensity per unit of GDP was the primary restraining factor of the carbon emissions from land use change in the study area, which had a suppressive effect on the net carbon emissions throughout the study period, with a cumulative contribution reaching −385.47%. This indicates that it is feasible to achieve a sustainable development status of the land use by promoting the economic development and adopting some reasonable means.

There was always a positive contribution value of GDP per capita to the increase of carbon emissions, i.e., GDP per capita had played a positive role in promoting the increase of carbon emissions from land use change during the study period. In particular, the cumulative contribution of GDP per capita was the highest among these influencing factors, indicating that GDP per capita played the most important role in promoting the increase of carbon emissions from land use change. In fact, GDP per capita represents the regional economic development level as well as the affluence level, and the rapid economic development not only brings abundant material achievements but also generates a large amount of carbon emissions; it is therefore necessary to pay more attention to the factors of economic development in future research and the practice of carbon emission reduction. Additionally, the population size always had a promoting effect on the increase of carbon emissions during 1990–2015, which is similar to GDP per capita. The cumulative contribution value and cumulative contribution rate of population size reached 1.05 million tons and 30.61%, respectively, indicating that the population size is also one of the most important factors promoting the increase of carbon emissions from land use change. This is primarily because the population growth leads to the increase in energy consumption and further results in more carbon emissions from energy consumption on the land.

4. Discussion

There is an overall high reliability of the results of this study, which were generally consistent with previous studies. For example, some previous studies suggested that the growth of GDP per capita resulting from expansion of coal intensive industries was a major factor driving carbon emissions in China [44,46], and this study also suggested that GDP per capita played a dominant role in promoting the increase of carbon emissions in the Beijing-Tianjin-Hebei region, indicating there was a consistent major driving factor of the Beijing-Tianjin-Hebei region and the whole of China. On the one hand, the Beijing-Tianjin-Hebei region and other parts of China both used to heavily depend on coal, with a slight difference in the technological level of energy utilization among these regions, which led to a similar pattern of carbon emissions of the Beijing-Tianjin-Hebei region and other parts of China. On the other hand, the Beijing-Tianjin-Hebei region, as one of the three major urban agglomerations in China, generally kept pace with the rapid economic development of the whole of China, leading to a similar change of GDP per capita and subsequently carbon emissions. More importantly, this study estimated the carbon emissions with the data extracted from the authoritative statistical yearbooks and carried out a decomposition analysis of influencing factors of carbon emissions with the relatively mature LMDI model, which were both generally consistent with previous studies and therefore guaranteed the reliability of the results of this study.

There are still some uncertainties in the results of this study due to the limitation of data accuracy, and it is especially necessary to further improve the estimation of the carbon emission (or absorption) coefficients based on dynamic observation data in the future. For example, the carbon emission coefficient of the State Grid Corporation of China has been adjusted from 0.6101 tCO_2/MWh to 0.5810 tCO_2/MWh in 2022, according to the latest "Corporate Greenhouse Gas Emissions Accounting Methodology and Reporting

Guidelines for Power Generation Facilities (2022 Revised Edition)". This carbon emission coefficient has declined slightly by only 4.77% after years of technical progress; it is therefore still feasible to assume that the carbon emission coefficient of electricity kept constant in past decades. Nevertheless, it is still necessary to use some dynamic carbon emission coefficients, according to the specific conditions, to more accurately reveal the effects of technical progress and other factors on carbon emissions in the future.

Although there are still some uncertainties, this study still successfully revealed the effects of various influencing factors of carbon emissions from land use change. This study has accordingly proposed the following policy recommendations, which can contribute to promoting the improvement of the lower carbon emission of land use and support the synergetic development of the Beijing-Tianjin-Hebei region.

(1) Optimization of the land use structure and the spatial layout of land use

It is necessary to carry out land use in a more economical and intensive way, making full use of the barren land and a large amount of idle land by giving priority to turning the barren land and idle land into cropland, forest land, and grassland. It is also necessary to carry out a moderate return of cropland to forest land and grass land. It is particularly urgent to control the proportion of built-up area and increase the area of carbon sinks by planting trees and optimizing the spatial layout of public green space, which can contribute to achieving environmental improvement and low-carbon development in the Beijing-Tianjin-Hebei region.

(2) Adjustment of the energy structure and development of new cleaner energy sources

The current energy consumption of the Beijing-Tianjin-Hebei region dominantly depends on fossil energy, especially coal, while the proportion of cleaner energy is still very low, and it is therefore very necessary to adjust the energy structure and reduce the dependence on fossil energy. To achieve this end, it is necessary to promote the development of new cleaner energy sources and to encourage the development of advanced energy-saving technologies, e.g., the Carbon Capture and Storage technologies, which can effectively reduce carbon emissions.

(3) Optimization of the industrial structure and promotion of the development of the tertiary industry

The increase of GDP of the Beijing-Tianjin-Hebei region still heavily depends on the secondary industry, which plays an important role in the increasing the carbon emissions. By contrast, the primary and tertiary industries have relatively small carbon emissions. It is therefore necessary to carry out optimization of the industrial structure by "retreating from secondary industry and developing the tertiary industries", which can make a considerable contribution to the energy saving and carbon emission reduction in the Beijing-Tianjin-Hebei region.

5. Conclusions

This study estimated the carbon emissions in the Beijing-Tianjin-Hebei region during 1990–2020 based on the carbon emission coefficients, and it revealed the quantitative relationship between land use change and carbon emissions with the decomposition analysis of the main influencing factors of carbon emissions from land use change. The major conclusions are as follows: (1) the cropland, forest land, grassland, and barren land in the study area all showed a decreasing trend during 1990–2020, among which the cropland decreased most significantly and the built-up area increased significantly due to the accelerated urbanization. (2) The total carbon emissions in the study area increased from 112.86 million tons in 1990 to 525.31 million tons in 2020, with a growth rate of 365.46%. Built-up area was the main carbon source, the carbon emissions of which increased rapidly from 111.51 million tons in 1990 to 524.52 million tons in 2020, with a growth rate of 370.37%. The forest land accounted for 83.58–89.56% of the total carbon absorption, but it still failed to offset the carbon emissions of the built-up area. (3) GDP per capita contributed most to the increase of the carbon emissions, resulting in a cumulative increase of carbon emissions by 94.78 million tons. While the land use structure, carbon emission intensity per unit of land, and population size led to the increase of carbon emissions by 18.11 million tons, 22.95 million tons, and 8.67 million tons, respectively. By contrast, the land use intensity per unit of GDP had a restraining effect on the carbon emissions, making the carbon emissions decrease by 103.26 million tons in total. This study accurately revealed the variation of net carbon emissions from land use change and the effects of influencing factors of carbon emissions from land use change in the Beijing-Tianjin-Hebei region, and all the conclusions of this study can provide a firm scientific basis for improving the regional land use planning and for promoting the low-carbon economic development of the Beijing-Tianjin-Hebei region.

Author Contributions: H.Y. (Haiming Yan) and S.Z.: investigation, data curation, writing—original draft preparation, writing—review and editing, and funding acquisition; H.Y. (Huicai Yang): conceptualization, methodology, supervision, and project administration; H.Y. (Haiming Yan) and X.G.: software, validation, and visualization. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Major Project of Humanities and Social Science Research of Hebei Education Department (ZD201907), the Science and Technology Project of Hebei Education Department (BJ2019045), and the National Natural Science Foundation of China (51909052).

Data Availability Statement: Not applicable.

Acknowledgments: We are very grateful for the helpful inputs from the editor and anonymous reviewers.

Conflicts of Interest: The authors declare no conflict of interest.

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