forests

Article

Exploring the Spatial and Temporal Changes of Carbon Storage in Different Development Scenarios in Foshan, China

Lihua Chen [1,2] **and Yuan Ma** [1,2,*]

[1] School of Architecture and Urban Planning, Guangdong University of Technology, Guangzhou 510090, China
[2] Landscape Planning and Ecological Restoration Research Center, Guangdong University of Technology, Guangzhou 510090, China
* Correspondence: mayuan0714@163.com

Abstract: Carbon storage (CS) is strongly associated with climate change and ecosystem services. Herein, taking Foshan City, Guangdong Province, China as the study object, analysis was performed upon the potential impacts of the urban–rural relationship of CS by combining the Integrated Assessment of Ecosystem Services and Trade-offs (InVEST) and the Patch Generation Land-use Simulation (PLUS) models. Based on three different development plans under regional policies, land-use/ land-cover (LULC) changes in Foshan City in 2035 were simulated. The results show that (i) Foshan City experienced rapid urban expansion from 2010 to 2020 spreading from the central area to the outer circle in a cascading manner. Urban land use mainly encroached on ecological land during these 10 years. (ii) The CS in Foshan City from 2010 to 2020 showed an increase followed by a decrease, and the simulations estimated a continuous loss of the CS in Foshan City by 2035. (iii) There was spatial heterogeneity in the CS changes in Foshan. From 2010 to 2020, the northern part of Sanshui District and the eastern part of Chancheng District experienced the greatest economic loss of CS. The carbon loss will further increase in future development scenarios. This research can provide vital references for government administrators to formulate valid development patterns and ecological conservation strategies.

Keywords: carbon emission; ecosystem; PLUS model; InVEST model; urban expansion

Citation: Chen, L.; Ma, Y. Exploring the Spatial and Temporal Changes of Carbon Storage in Different Development Scenarios in Foshan, China. *Forests* **2022**, *13*, 2177. https://doi.org/10.3390/f13122177

Academic Editor: Jarosław Socha

Received: 27 October 2022
Accepted: 16 December 2022
Published: 19 December 2022

1. Introduction

Green plants and soil layers can be used to store carbon dioxide in terrestrial ecosystems, which can be effectively reduced in the atmosphere [1,2]. In the midst of rapid urbanization and industrialization, land-use changes have also occurred dramatically [3]. Urban expansion, which mainly encroaches on ecological land, leads to changes in the large amount of ecological land that can provide carbon storage. Urban expansion is not only provided with ecological service functions but also has high density of carbon storage, thereby, causing the reduction of CS [4].

Carbon storage in terrestrial ecosystems has been significantly reduced [5] because of the influence of rapid urban sprawl, which affects the health of the carbon cycle and the further development of urban sustainability. Therefore, studying the interrelationship between urban sprawl and CS not only contributes to discovering the changes of CS in ecosystems but also has important implications for ecosystem conservation, environmental sustainability and the global greenhouse climate.

Ecosystem services are significant for maintaining the stability and healthy development of ecological environment, the economy, and society [6,7]. In recent years, the sustainable development of urban ecosystems is gradually becoming a guarantee for maintaining urban ecological security [8] and improving the health of ecosystems [9,10].

The Integrated Assessment of Ecosystem Services and Trade-offs (InVEST) model [11] assesses CS, using CS modules and carbon density data, which simplifies a complex process and makes it more efficient [12]. In recent years, InVEST has been applied to CS assessment in many fields. The variability of carbon storage in the Yangtze River Delta urban agglomeration [13] has been assessed in two dimensions with the help of the InVEST model. There are also studies on the economic valuation of CS in the Konar Basin in India [14] and on the relationship between ecosystems and carbon storage changes at both the national and provincial levels [15].

However, most studies stay at the national and provincial levels of carbon storage [16,17], and spatial changes to the county-level CS have not been studied in depth, particularly for the developing needs of different townships [18]. To the end, the CS module of the InVEST model was, thereby, chosen to explore the dynamic variations of CS. Policy-makers can select the optimal model for integrated urban–rural development, formulate ecological conservation policies, and protect rural cropland by considering the demands of various townships. The reduction of cropland may cause a food crisis, food security issues, and an increase in food miles, which will, in turn, cause an increase in carbon emissions.

Setting up different scenarios based on different urban construction policies is a more scientific method to explore the future impact of LULC changes on CS, which can provide useful information for future urban planning [19]. Additionally, there are studies with combined land-use simulation models with the assessment of carbon storage, thus, offering the possibility of combining multiple models [20]. Many simulation models, such as the Cellular Automata (CA) model and the Markov and Flus model, have been used to investigate the relationship between LULC change and CS [21–23].

However, these models are subject to the drawbacks of failing to reveal the underlying indicates driving land-use change or easily capture the spatio-temporal evolution of various land-use patches [20]. The patch-generating land-use simulation (PLUS) model [24] is divided into three main panels, of which, the Land Expansion Analysis Strategy (LEAS) panel reveals the expansion potential of each type of land use; and the CA model is based on multi-type random patch seeds (CARS) [25].

The panel allows the addition of different policy constraints to simulate land-use expansion in different future scenarios, and studies the relationship between urban expansion and the impact of CS [26]. Second, in the carbon sink services of ecosystems, their economic value has been recognized and applied by the global market economy system [27]; however, the impact of CS changes on socio-economic values has been rarely studied. Therefore, this study examines the changes in carbon storage and the estimation of the CS economic value under different scenarios at the regional level of development.

The global climate is increasingly worsening, and climate change is affecting the natural environment where humans live. Controlling carbon dioxide emissions has become a major global challenge, and a series of guidelines and targets have been set by countries around the world to address climate issues. The urbanization of China is growing rapidly [28,29], and in 2021, the National People's Congress proposed to include "carbon peaking" and "carbon neutrality" in the government report. Therefore, balancing the urbanization development rate and carbon dioxide emissions becomes an essential issue for healthy regional development [26].

Foshan is in a subtropical climate zone and suffers from a severe greenhouse climate with high summer temperatures. In addition, the city is also undergoing rapid urbanization, making it a typical city in China to study carbon emissions. Considering the rapid urban sprawl, land use in Foshan is being exposed to dramatic changes. The CS of the ecosystem services is significantly decreasing.

To this end, herein, two models, PLUS and InVEST, were combined to examine the changes in CS at the urban and rural scales and explore balancing carbon emissions with human survival and achieving sustainable management of urban and rural ecosystems are the goals of the future regional development of Foshan City, a "low-carbon city" and "resource-saving and environment-friendly" pilot city in China. In the face of climate risks, such as high temperatures and heat, only by actively building a climate-resilient society can urban problems and damage be mitigated.

Herein, Foshan City was selected as a typical area for the assessment of CS, and three different development scenarios explore the LULC changes and CS in conjunction with more appropriate local urban planning and land policies. The study aims to (1) identify land-use changes and analyze the potential relationships between land use and CS from 2010 to 2020; (2) predict the future changes of CS and its economic value with three different scenarios; and (3) analyze the urban–rural relationship and spatial variability of CS, and select appropriate urban land-use scenarios. The research results can allow government departments and planners to obtain helpful suggestions and solutions for improving sustainable urbanization in their areas.

2. Materials and Methods

2.1. Study Area

Foshan City (Figure 1) is situated in the hinterland of the Pearl River Delta, geographically in Guangdong Province, China (between 22°38′–23°34′ N, 112°22′–113°23′ E) and has a subtropical monsoonal humid climate. Its topography is high in the northwest and southwest of the administrative boundary and low in the central and eastern part of the country [30]. The landscape is mainly plain, featuring low mountains and hills.

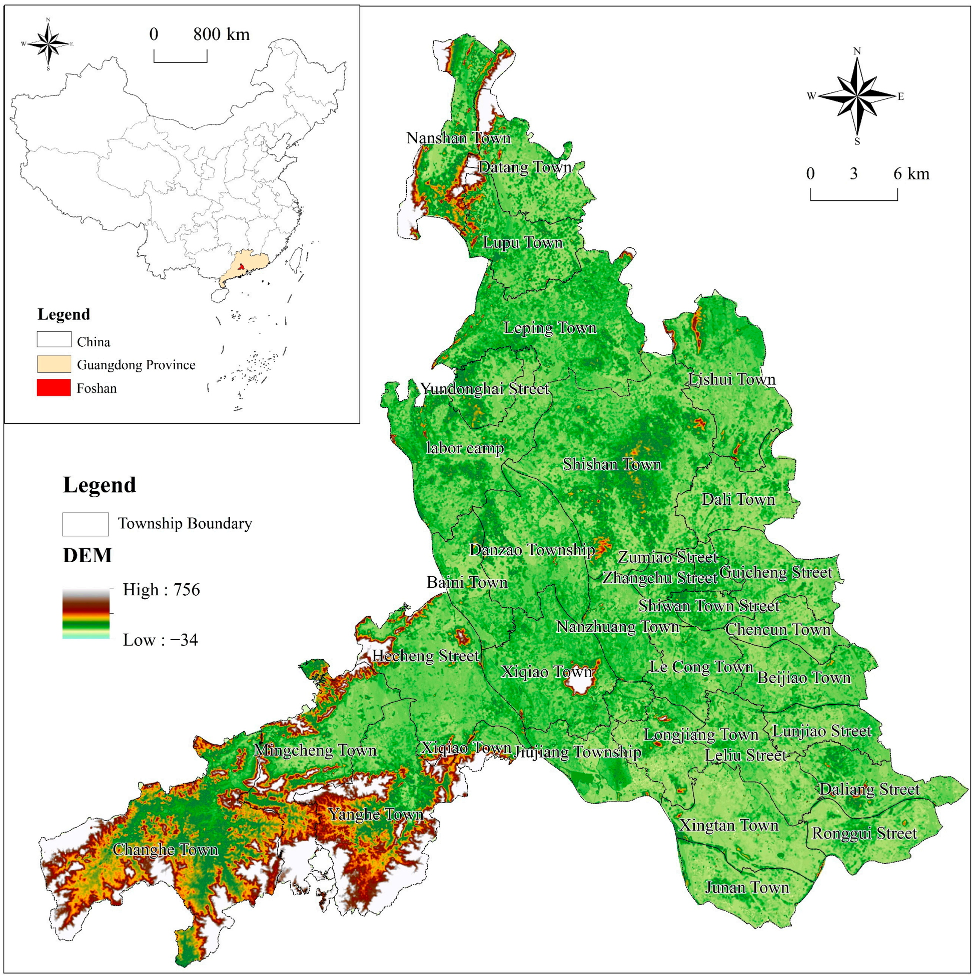

Figure 1. Study area (location and administrative division map of Foshan, China).

Foshan is governed by five jurisdictions with forty-one towns and streets, covering a total land area of 3798.6 km^2. The rapid population growth and increasing regional inequality between urban and rural areas in Foshan City are more prominent relative to other cities, making it a typical city for the assessment of CS changes under urbanization and the prediction of future CS change. Additionally, studying the changes and influence factors in Foshan City can offer a better reference for the future of CS in developing countries.

2.2. Data Sources

The data in this research cover three main categories, namely land-use data, social and economic data, and climate and environmental data. To be specific, the land-use raster data are for 2010, 2015, and 2020 in Foshan City, classified into six categories: cropland, forest land, grassland, water, construction land, and unused land [31]; the socio-economic data include population and GDP data for 2019, road data for 2018, and distance data to urban centers; and the climate and environmental data include soil type, temperature, precipitation, DEM, and distance to rivers (Table 1).

Table 1. Data used in the study (The specific URL is in the references.).

Type	Data	Resolution	Source	Year
LULC	Land use/land cover	30 m	Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (https://www.resdc.cn, accessed on 15 September 2022) [32]	2010 2015 2020
Socio-economic data	Population (POP)	1 km	Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (https://www.resdc.cn, accessed on 15 September 2022) [32]	2019
	Gross domestic product (GDP)			2019
	Highway	30 m	OpenStreetMap (https://www.openstreetmap.org, accessed on 15 September 2022) [33]	2018
	Road			2018
	Railway			2018
	Urban center		*Foshan City Territorial Spatial Master Plan (2020–2035)* [34]	2020
Climate and Environmental Data	Soil data	1 km	Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (https://www.resdc.cn, accessed on 15 September 2022) [32]	2015
	Temperature			2015
	Precipitation			2015
	Digital elevation model (DEM)	30 m	Geospatial Data Cloud(http://www.gscloud.cn, accessed on 15 September 2022) [35]	2019
	River	30 m	Extracted from Land Use 2020	2020

2.3. Methods

In this research, dynamic modeling and prediction using PLUS and CS change calculation and spatial visualization using the InVEST model were mainly applied. The experimental procedure of this research was divided into two main parts. First, the PLUS model was applied for land-use simulation. In the LEAS panel, land-use data and drivers (socio-economic factors, climatic, and environmental factors) for 2010 and 2015 were input to explore the development potential of every land type.

In the CARS panel, the land-use data for 2020 were simulated based on the above calculated land-use development potential data, land-transfer matrix, land-transfer probability, and future land-demand forecast. The errors with the real 2020 land use were verified using the kappa index and the Fom index. In the case of favorable simulation results of the indices, the 2020 land use was used to simulate the 2035 land use following the above steps. The 2035 land-use demand was derived from the Markov model based on the transfer matrix of 2015 and 2020.

According to the different policies, focus was placed on cropland protection and ecological protection, to pursue multi-scenario simulations. Finally, the InVEST model was applied in the second panel to explore the CS changes. The carbon storage changes from 2010 to 2035 were calculated by inputting the land-use data and carbon-pool density data of each site. The economic value of CS was calculated by inputting three carbon storage price indices (Figure 2).

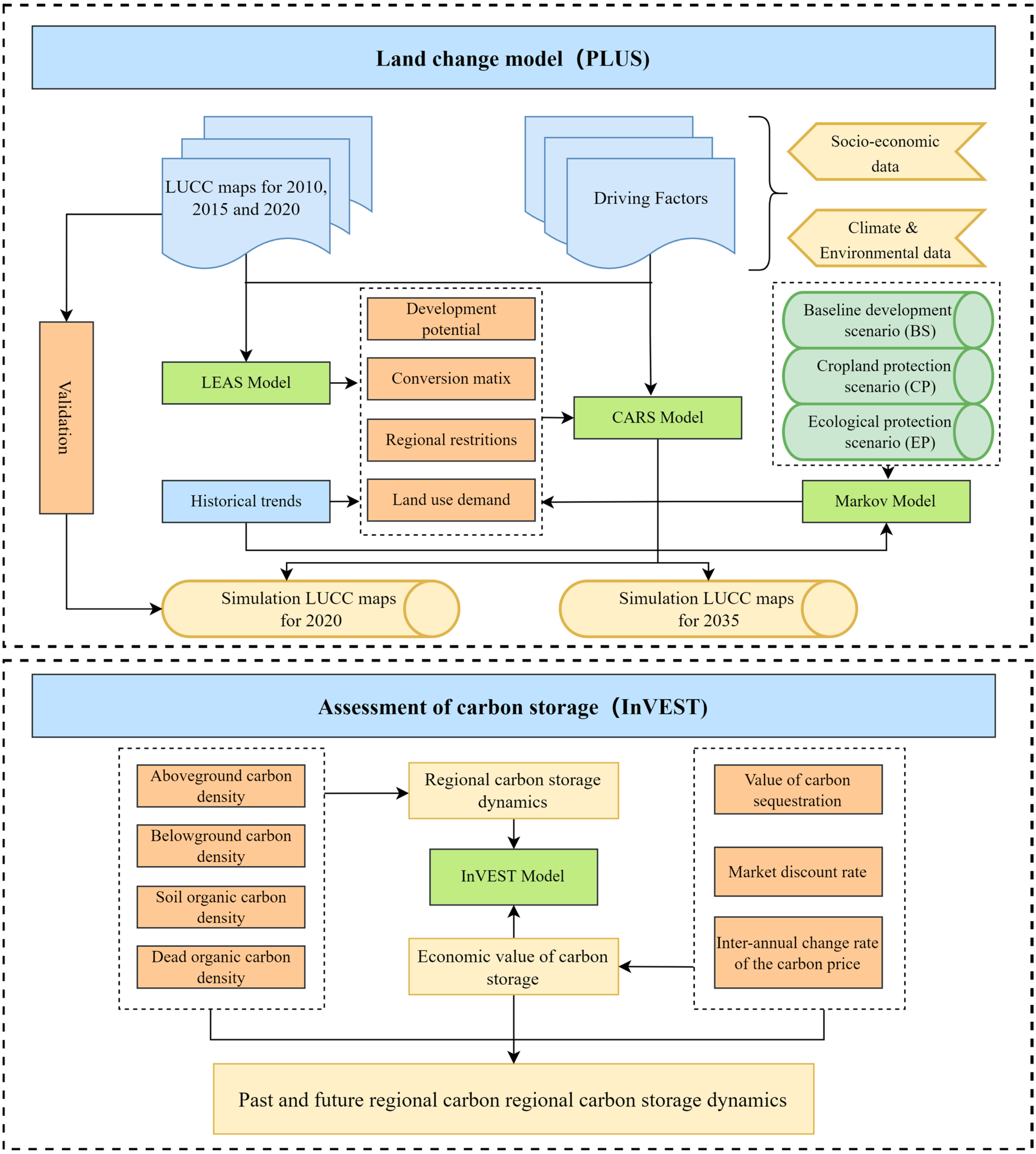

Figure 2. Overall experimental process in this study.

2.3.1. Future City Expansion Simulation

In this research, land-use changes were explored using the PLUS model. The drivers of LULC changes were obtained by drawing the land-use map under future scenarios using the PLUS model. The amount of land-use changes was obtained using the Markov model [25,36]. Additionally, the transfer matrix of various land-use types was used to limit the land use under various future scenarios in conjunction with the development plan of Foshan City.

Combined with the *General Land-Use Plan of Foshan City, Guangdong Province (2006–2020)* and the *General Land Spatial Planning Plan of Foshan City (2020–2035)* [34], the transfer probability matrix from 2015 to 2020 was set by referring to previous studies and suggestions from relevant experts. The demand of the following future land-use scenarios in Foshan City was calculated for spatial simulation of land use using the Markov model.

According to differences among different development scenarios, three development scenarios were set (Table 2).

Table 2. Description of different development scenarios of Foshan in 2035.

Development Scenarios	Description
Baseline development scenario (BS)	Moderate population growth Moderate GDP growth Moderate technological innovation Moderate land policy
Cropland protection scenario (CP)	Low population growth Low GDP growth Slow technological innovation Strict land policy
Ecological protection scenario (EP)	Low population growth Moderate GDP growth Rapid technological innovation Reasonable land policy

(i) Baseline development scenario (BS): This scenario represents the development pattern from 2015 to 2020, and the land-use demand in 2035 under the historical development trend is derived based on its land-use development trend and Markov chain.

(ii) Cropland protection scenario (CP): Based on the baseline development scenario, a strict prohibition on the transformation of basic farmland is added with reference to the *Outline of the China National LULC Master Plan (2006–2020)* [37] and the *Foshan City LULC Master Plan (2006–2020)* [34,38]. The amount of cropland is protected in this scenario, and the encroachment of construction land and other land into basic cropland is strictly controlled.

(iii) Ecological protection scenario (EP): This scenario adds a policy control area for first-level ecological control with reference to *the Foshan City General LULC Plan (2006–2020)*, which mainly controls the conversion of cropland, grassland, forest land, and water to construction land.

The PLUS model was hereby used to investigate drivers influencing LULC change [24], which can be influenced by internal and external factors, such as own land-use type collision, natural environment, and socio-economics. Twelve drivers were finally screened using the LEAS panel of the model (Figure 3), and the influence of each driver on building land expansion was above 4% (Figure 4).

The application of the Kappa index is a more accurate and simpler test that detects the consistency of the simulation results by comparing the error matrix [39]. The present results show that the Kappa coefficient of this study is 0.87, the Fom index is 0.103, and the overall accuracy (OA) index is 0.904, indicating the high accuracy of the relevant parameter settings and drivers for subsequent simulations of different scenarios.

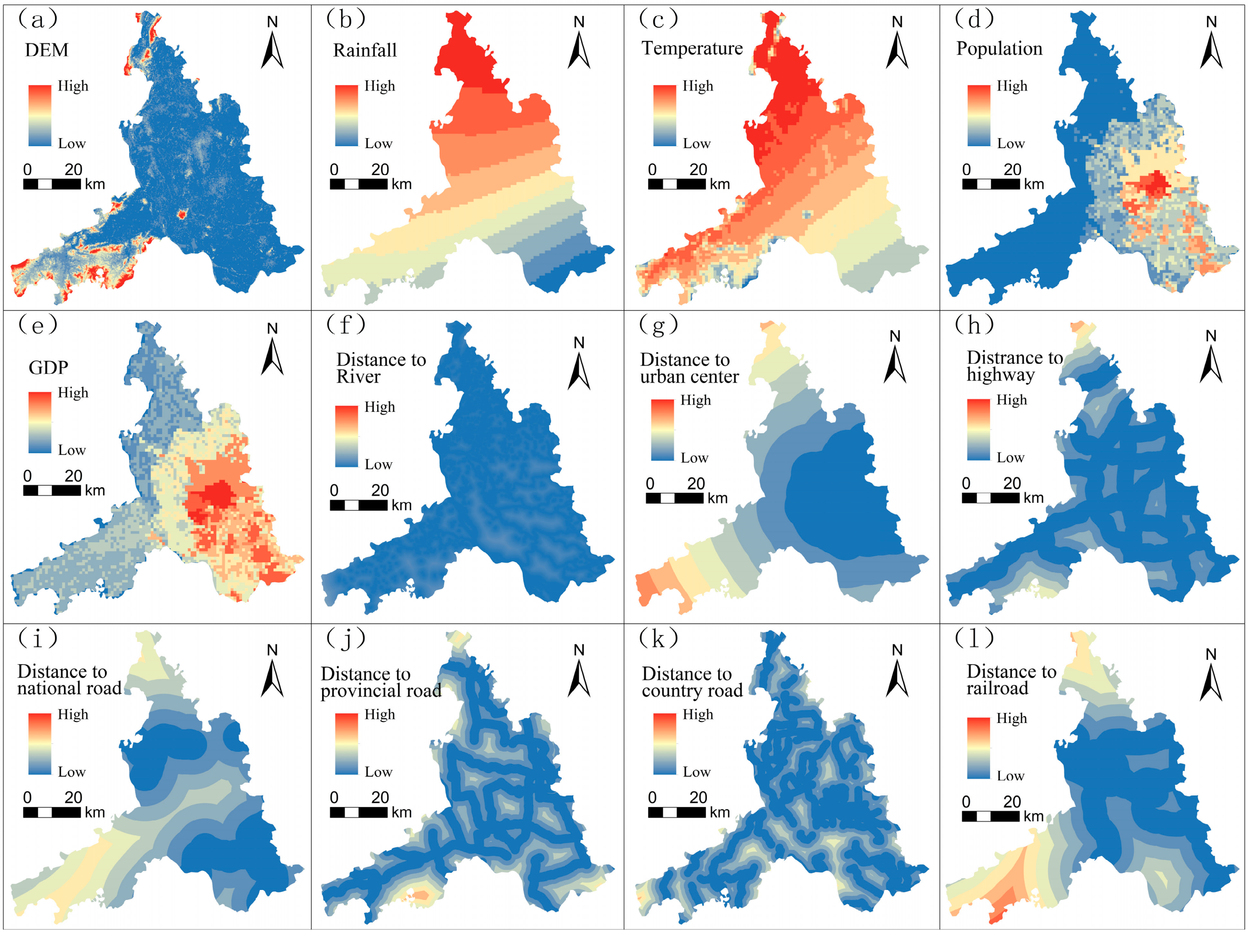

Figure 3. Driving factors of urban expansion. (**a**) DEM; (**b**) Rainfall; (**c**)Temperature; (**d**) Population; (**e**) GDP; (**f**) Distance to river; (**g**) Distance to urban center; (**h**) Distance to highway; (**i**) Distance to national road; (**j**) Distance to provincial road; (**k**) Distance to country road; (**l**) Distance to railroad.

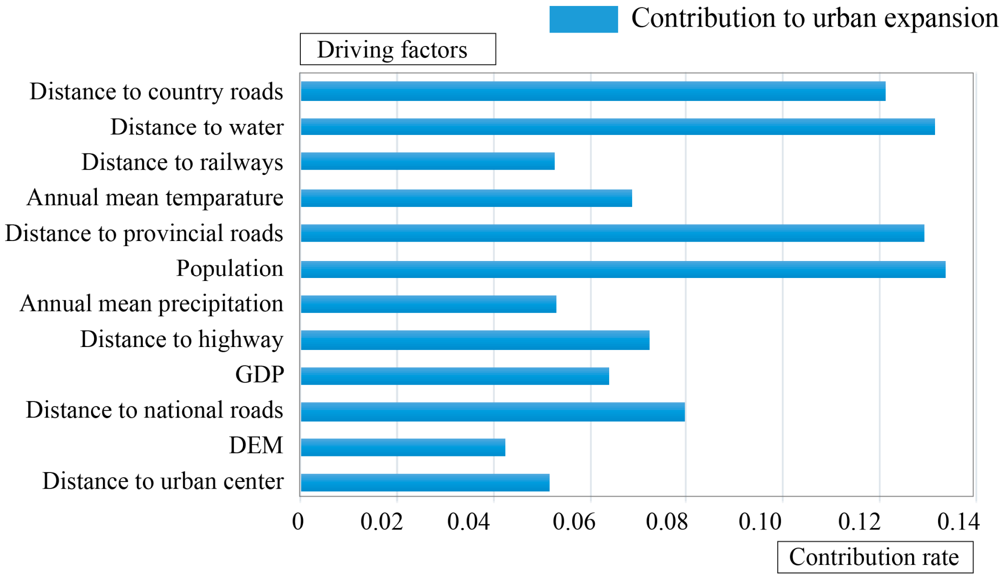

Figure 4. Contribution of each driver to the growth of urban expansion.

2.3.2. Carbon Storage Assessment

The InVEST model can effectively evaluate and visualize the ecosystem (e.g., habitat quality assessment, carbon storage, and biodiversity). Considering its operability and efficiency in avoiding calculation errors, the model has been widely used by many researchers, planners and government departments in recent years.

$$C_{tot} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{1}$$

where, C_{tot}, C_{above}, C_{below}, C_{soil}, and C_{dead} (Table 3) represent the total CS, aboveground CS, belowground CS, soil CS, and dead CS [25]. The hereby-adopted four carbon density data corresponding to different LULC types in the carbon pool were accessed from the Chinese terrestrial ecosystem carbon density dataset [40], and the dead organic CS density mainly refers to the results of previous studies [41] and literature related to carbon density [18,30]. The CS density of every type of land use was mainly based on the carbon-storage density of Guangdong Province in the corresponding area [42].

Table 3. The carbon density of various land-use and land-cover (LULC) types of Foshan (Unit: t/ ha).

LULC	C_{above}	C_{below}	C_{soil}	C_{dead}
Cropland	16.49	10.89	75.82	2.11
Forest land	30.14	6.03	100.15	2.78
Grassland	14.29	17.15	87.05	7.28
Water body	0.09	0	0	0
Construction land	7.61	1.52	34.33	0
Bare land	10.36	2.07	34.42	0.96

The calculation of the economic value of CS requires three important parameters, which are the value of each ton of CS (of which the social cost of carbon is recommended by the InVEST model), the market discount rate (which reflects the phenomena that the current social interests take precedence over future interests), and the interannual variability of carbon price. According to the official website of the InVEST model and references, the economic cost of CS emissions in China was $9.20/t [18,42]; the market discount rate of the social value of CS sinks was 10%; and the inter annual rate of change of the social cost of CS was set to be constant.

3. Results

3.1. Spatial and Temporal Patterns of Urban Expansion

Significant changes in the land use of Foshan resulted from the urban expansion between 2010 and 2020. Urban construction land expanded, going from 103,637.16 ha in 2010 to 124,034.94 ha in 2015. Urban construction land in Foshan City is mainly concentrated in the central urban district of Chancheng District and has a tendency to expand from the center to the periphery while continuing to grow.

During the decade, a total of 20,397.78 ha of construction land was granted for other land-use types. Urban expansion mainly took over cropland, forest land, and water. With an urban expansion area of about 68.84% of the 10-year urban expansion (2010–2020), the fastest phase of construction land urbanization took place between 2010 and 2015, and the cropland and water land of 6355.62 ha made up the majority of the urban construction land flow from 2015 to 2020.

According to the land-use policy for setting different constraints, three different simulation scenarios were set up using the PLUS model. Under the BS scenario, all types of land present a natural development state. By 2035, both cropland and forest land will have decreased to 113,335.92 and 80,308.17 ha, respectively, while grassland will have increased. In contrast to the other two scenarios, the EP scenario has the smallest urban expansion (130,959.99 ha), which occupies less forest and cropland. Additionally, the CP scenario indicates the largest urban expansion area (133,437.24 ha), occupying forest land but maintaining cropland and grassland (Table 4 and Figure 5).

Table 4. Land-use change in Foshan from 2010 to 2035 (Unit: ha).

LUCC	2010	2015	2020	2035_BS	2035_EP	2035_CP
Cropland	95,214.06	125,475.39	121,643.91	113,335.92	113,335.92	121,191.75
Forest land	85,210.20	84,411.27	80,308.17	78,076.26	80,171.28	70,613.37
Grassland	1012.86	928.44	2105.91	3577.23	2055.24	2100.96
Water	94,347.36	50,993.55	51,401.16	51,967.71	51,967.71	51,146.82
Construction land	103,637.16	117,679.32	124,034.94	131,533.02	130,959.99	133,437.24
Unused land	209.88	146.61	143.82	136.89	136.89	136.89

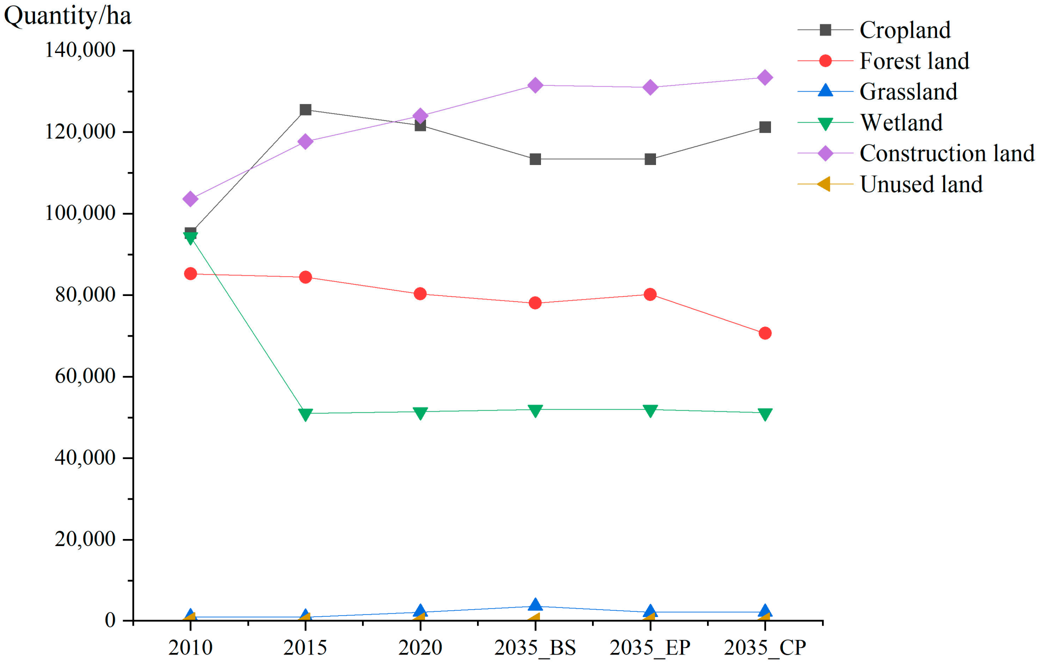

Figure 5. Changes in land use by type for Foshan from 2010 to 2035.

In terms of spatial distribution, the urban expansion in Foshan will spread to the countryside areas in 2035. However, compared with the other two scenarios, the BS scenarios show that the construction land use will extend more to rural land and ecological land use. The CP scenario has the least urban expansion and mainly encroaches on grassland. This scenario strictly controls the amount of retained cropland and also protects forest land. The EP scenario has limited urban construction land expansion as forest land is strictly protected.

The results reveal a continuous growth of urban construction land under different scenarios. According to the three scenario simulations, construction land will further expand in 2035, which will mainly erode ecological land. However, the encroachment of construction land can be effectively controlled using the basic cropland control and ecological protection policy of government travel (Figure 6).

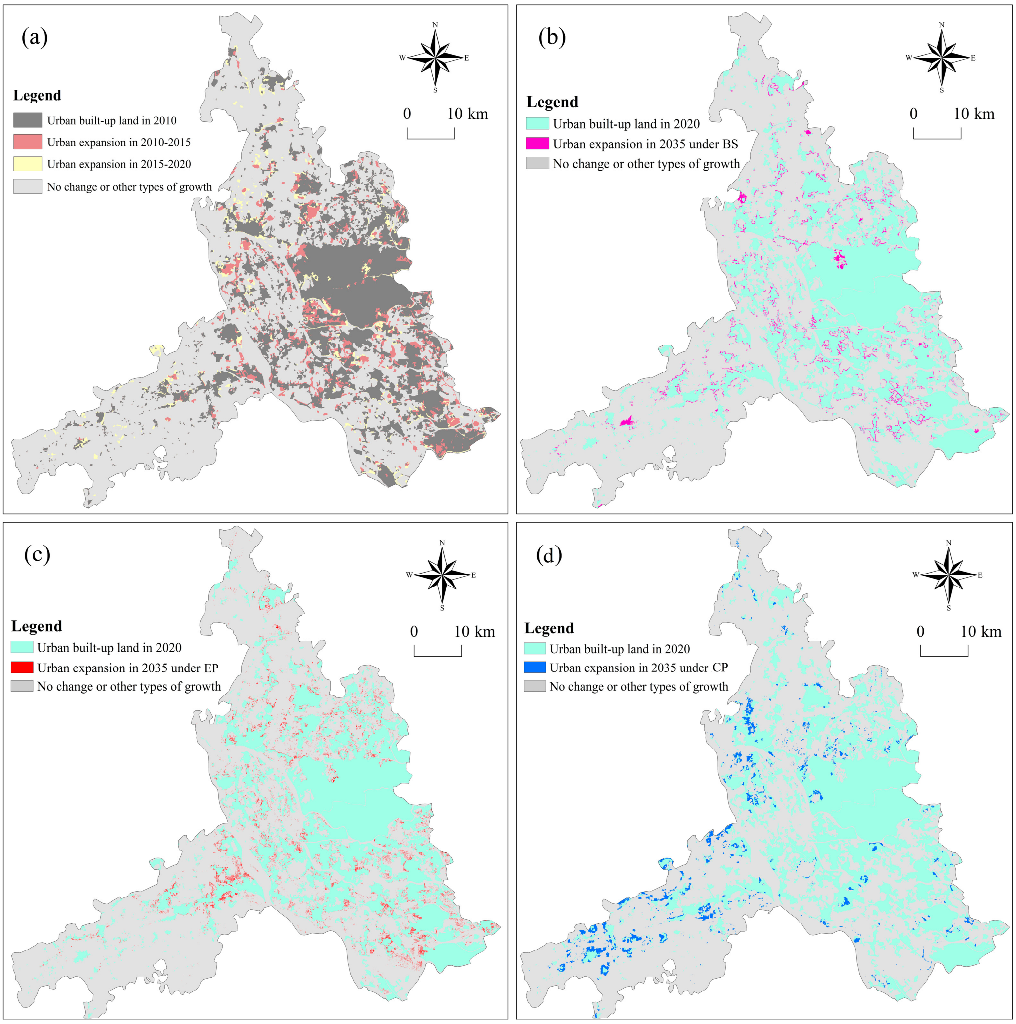

Figure 6. Urban expansion of Foshan from 2020 to 2035. (**a**) Urban expansion from 2010 to 2020; (**b**) Projected urban expansion from 2020 to 2035 according to BS; (**c**) Projected urban expansion from 2020 to 2035 under EP; (**d**) Projected urban expansion from 2020 to 2035 under CP.

3.2. Carbon Storage Dynamics in Terrestrial Ecosystems

The carbon storage in Foshan City has changed drastically as a result of its rapid outward expansion. In 2010, 2015, and 2020, the total terrestrial ecosystem carbon storage was 26.53×10^6, 30.20×10^6 and 29.65×10^6 t, and the average CS density was 69.88, 79.55 and 78.10 t/ha, respectively. The overall trend of terrestrial ecosystem CS in Foshan City increased from 2010 to 2015. However, it was statistically derived that the carbon storage declined rapidly during the period of 2015–2020. According to the projected 2035, the BS scenario carbon storage decline rate will continue with the decline rate of 2015–2020; while the EP scenario will decline slower than that under the BS scenario; and the CP scenario will decline slower than that under the EP scenario, presenting a carbon storage decline rate c CP > BS > EP (Figure 7).

From 2010 to 2015, CS showed an increasing trend due to the conversion of most of the waters of Foshan into agricultural land for pond fields, mainly concentrated in Shunde District, Foshan City. The area of carbon loss was expanding quickly as a result of construction land encroaching on cropland and forest land from 2015 to 2020, which led to the decline of carbon storage at the fastest rate in the previous 5 years. By directly occupying cropland and forest land, the urban extension of Foshan City has resulted in the ecosystem carbon storage of 403,493.16 and 570,741.21 t.

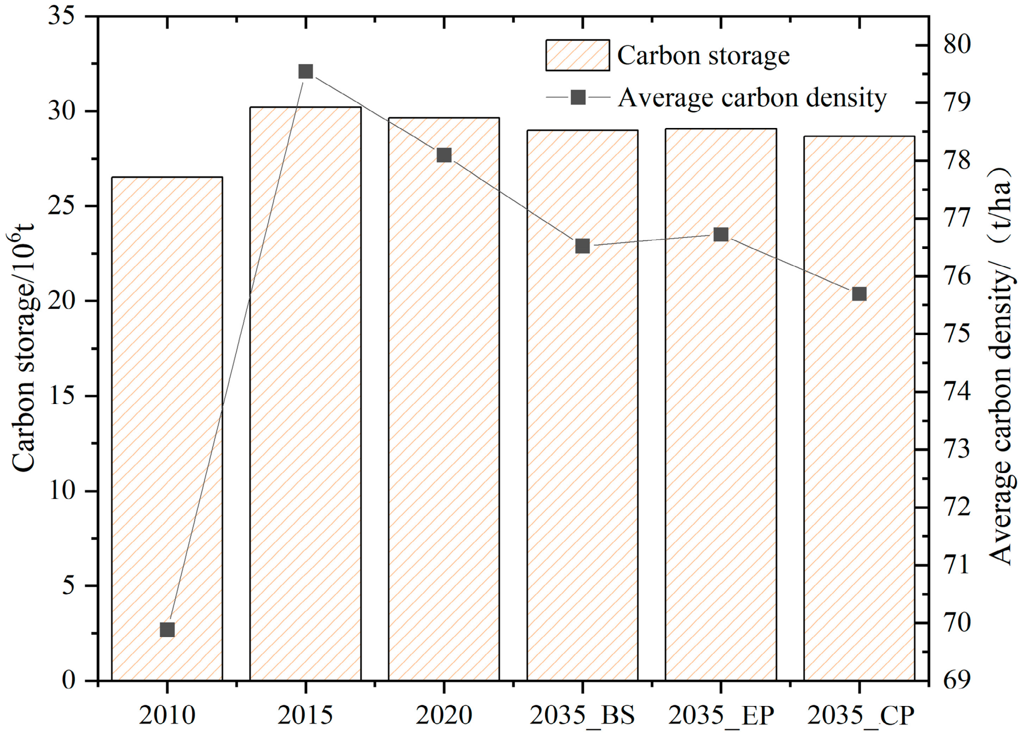

Figure 7. Change of carbon storage and carbon density in Foshan from 2010 to 2035.

By 2035, it is estimated that the CS in Foshan City will have further decreased with more than 75% of the city's total carbon sink coming from cropland and forest land—two types of Foshan's most significant carbon pools. Cropland among them sequestered the most carbon in 2015, which was 13.21 × 10^6 t, or 44% of the total carbon sequestered in 2015. According to 2035 simulations and projections, CS will continue to decline; however, the decline rate can be slowed by policy protection (Table 5).

Table 5. Change of carbon storage and carbon density data in Foshan from 2010 to 2035.

LUCC (10^6 t)	2010	2015	2020	2035_BS	2035_EP	2035_CP
Cropland	10.03	13.21	12.81	11.94	11.94	12.76
Forest land	11.85	11.74	11.17	10.86	11.15	9.82
Grassland	0.13	0.12	0.26	0.45	0.26	0.26
Water	0.01	0.00	0.00	0.00	0.00	0.00
Construction land	4.50	5.11	5.39	5.72	5.69	5.80
Unused land	0.01	0.01	0.01	0.01	0.01	0.01
Total carbon storage	26.53	30.20	29.65	28.97	29.05	28.66
Average carbon density/(t/ha)	69.88	79.55	78.10	76.52	76.72	75.69

Under all these three scenarios, the CS capacity of terrestrial ecosystems shows a decreasing trend in 2020–2035. The CS capacity of ecosystem is expected to reach 28.97 × 10^6 (BS), 29.05 × 10^6 (EP), and 28.66 × 10^6 t (CP) in the three scenarios. The CS will decrease by 0.67 × 10^6 (BS), 0.60 × 10^6 (EP), and 0.99 × 10^6 t (CP), with decreases of 2.28%, 2.02%, and 3.33%, respectively, compared to 2020. In 2035, the CS sink capacity of Foshan ecosystem will decrease under the different scenarios (Table 6).

Table 6. Change of carbon storage loss in Foshan from 2010 to 2035. (unit: t).

LUCC	2010–2015	2015–2020	2010–2020	2020–2035_BS	2020–2035_EP	2020–2035_CP
Cropland	+3,186,820.66	−403,493.16	+2,783,327.50	−874,914.43	−874,914.43	−47,616.97
Forest land	−111,131.16	−570,741.21	−681,872.37	−310,458.68	−19,041.40	−1,348,546.68
Grassland	−10,617.50	+148,090.40	+137,472.90	+185,047.92	−6372.77	−622.56
Water	−3901.84	+36.68	−3865.16	+50.99	+50.99	−22.89
Construction land	+610,272.27	+276,215.25	+886,487.52	+325,866.56	+300,962.67	+408,623.96
Unused land	−3024.94	−133.39	−3158.33	−331.32	−331.32	−331.32
Total	+3,668,417.49	−550,025.43	+3,118,392.06	−674,738.97	−599,646.25	−988,516.47

Comparing the other two scenarios, the EP scenario has the highest average carbon density of 76.72 t/ha, proving the efficiency of the forest land conservation in this scenario in maintaining carbon storage. Additionally, the lower CS density is 75.69 t/ha for CP, which has a weaker carbon sequestration capacity. Conservation of ecological land can effectively maintain CS, and the primary cause of carbon loss is urban expansion. Under the three scenarios, the CS loss brought by the loss of cropland is 874,914.42 (BS), 874,914.42 (EP), and 47,616.96 t (CP), 1.29, 1.45, and 0.05 times the total CS loss (Figure 8).

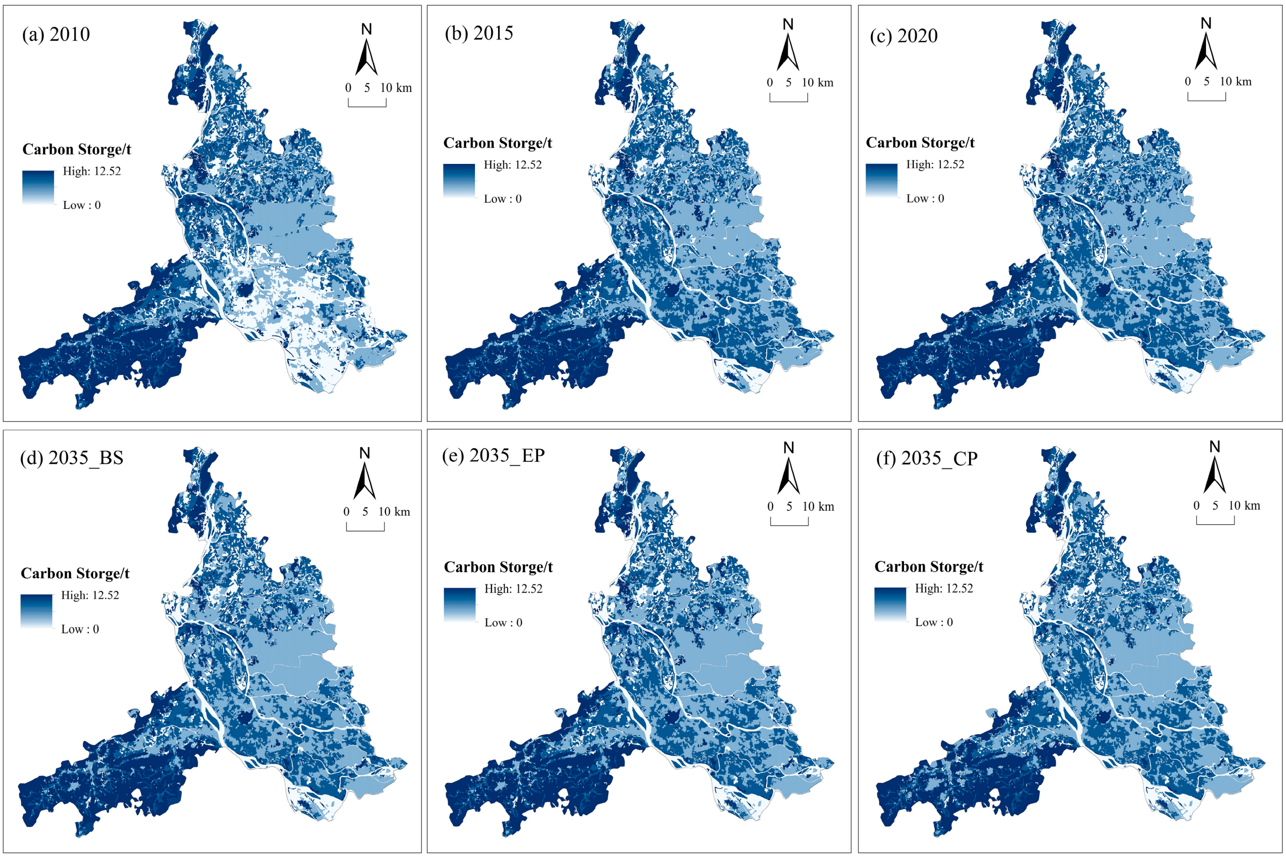

Figure 8. Carbon storage changes in Foshan from 2010 to 2035. (**a**–**c**) Carbon storage from 2010 to 2020 in Foshan; (**d**–**f**) Carbon storage of three scenarios in 2035.

3.3. Spatial Variability of CS and Economic Losses

The InVEST model was used to assess the economic value changes on ecosystem CS in Foshan City, and the carbon loss was implemented at the township level. From 2010 to 2020, the highest carbon losses were concentrated in Southwest Street in Sanshui District and Nanshan Town in Sanshui District, with losses of 122,422.57 and 51,144.6 t, respectively. In contrast, the CP scenario retained the largest amount of farmland, and the reduction of carbon storage was concentrated in Genghe Town and Mingcheng Town of Gaoming District, with losses of 213,442.69 and 102,017.29 t.

Under the EP scenario, some of the cropland in northern Foshan would be further transformed into forest land, generating CS sinks. Additionally, the reduction of carbon storage was concentrated in Xiqiao Town and Shishan Town of Nanhai District, with losses of 44,809.05 and 42,420.17 t. The most serious loss of CS in the ecosystem of Foshan was in Sanshui District, followed by Shunde District and Gaoming District, where the economic development and urban expansion were obvious (Figure 9).

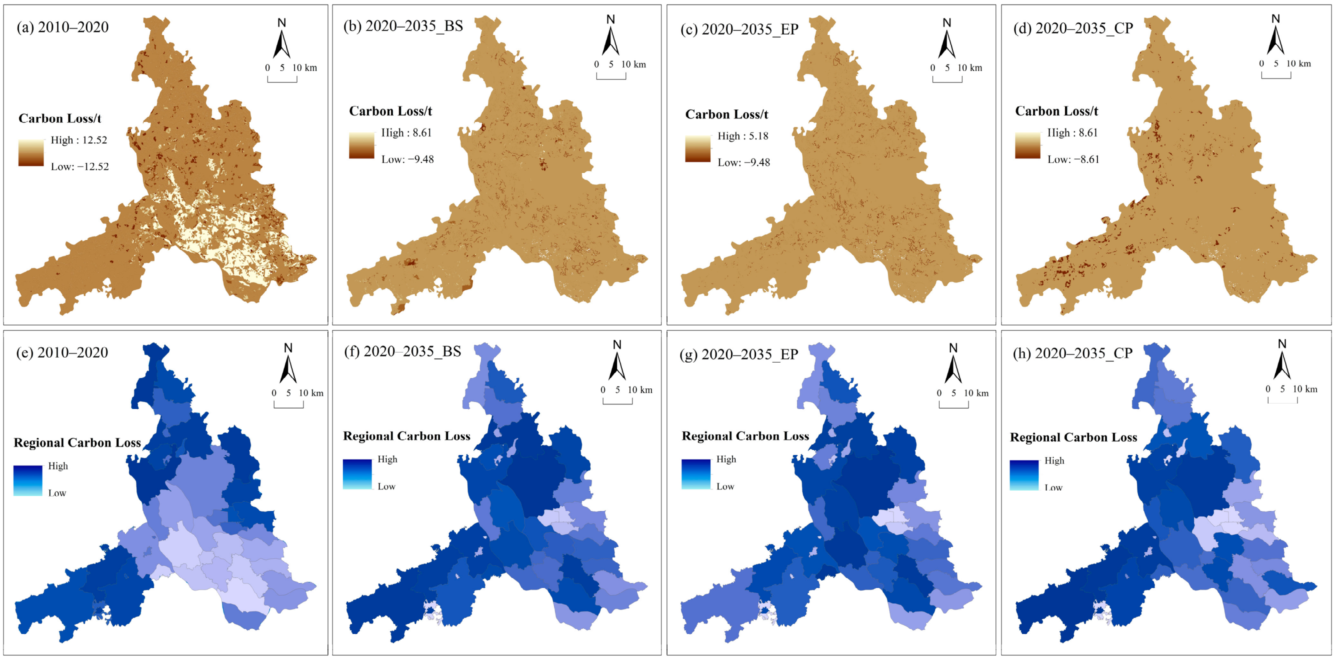

Figure 9. Carbon storage losses under different scenarios in Foshan from 2010 to 2035. (**a**–**d**) Carbon losses from 2010 to 2035 in Foshan; (**e**–**h**) Regional carbon losses from 2010 to 2035.

This was a critical period for the development and transformation of urbanization in Foshan, with its population, social, economic and cultural level, and market circulation increasing. However, the urban–rural conflict was further intensified [8]. The carbon value valuation module of the InVEST model was, thereby, used to calculate the economic losses brought on by the loss of CS. According to the findings, carbon sequestration totaled 28,757,080 USD between 2010 and 2020, with a loss of 4,889,513 USD between 2015 and 2020. Under the three simulated scenarios, the predicted value of carbon storage will be reduced by 5,447,538 (BS), 4,799,589 (EP), and 8,293,614 (CP) USD over the course of the next 15 years.

In the regional distribution, the highest loss of carbon storage value during 2010–2020 was in Southwest Street and Nanshan Town of Sanshui District, with a loss value of 1,116,220 and 466,324 USD, respectively; the highest economic value of carbon sequestration was in Xingtan Town of Shunde District of Foshan City, with a loss value of 7,185,766 USD. Under the BS and EP scenarios, the highest economic value of CS loss is in Shishan Town, Southern District, with losses valued at about 633,825 and 409,372 USD, respectively. In the CP scenario, the economic value of CS loss was as high as 1,936,458 USD in Genghe Town, Gaoming District (Figure 10).

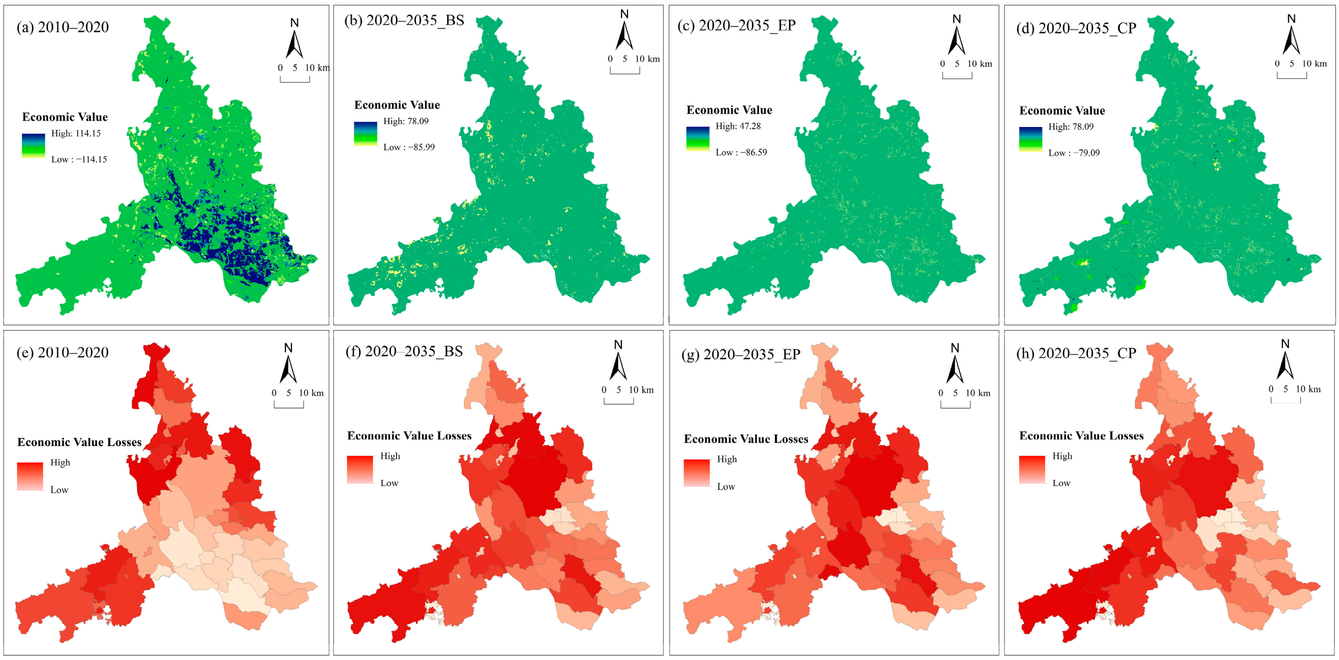

Figure 10. Spatial heterogeneity of economic losses of carbon storage in Foshan. (**a**–**d**) Economic value from 2010 to 2035 in Foshan; (**e**–**h**) Economic value losses from 2010 to 2035 in Foshan.

4. Discussion

4.1. Impact of Urban Expansion on CS

The land amount used for construction continues increasing, encroaching on cropland, forest land, and water, thus, reducing the CS amount. The construction land growth of Foshan City has severely encroached on rural cropland and water, with Chancheng District as its central urban area, and Shunde District occupying the highest proportion of encroachment on ponds and paddy fields. In Foshan City, the period from 2010 to 2020 witnessed both the fastest rates of urban sprawl and the fastest rates of decline in the amount of carbon sequestered by the terrestrial ecosystem.

From 2010 to 2015, Foshan City expanded its construction land area by 14,042.16 ha, resulting in a decrease of 10,226.27 t in CS of cropland and 385,956.88 t in CS of ecological land. From 2010 to 2020, the area of urban construction land increased by 6355.62 ha, resulting in a decrease of 2,959,201.39 t in CS of cropland and a loss of 482,026.03 t in CS of ecological land (Table 7). Urbanization has a gradually increasing and decreasing effect on the carbon-storage ability of Foshan. The expansion of urban construction land has, however, slowed down when compared to the previous phase, which is closely related to a series of ecological protection policies in Foshan.

Table 7. Relationship between urban expansion and carbon storage.

	2010–2015	2015–2020	2020–2035 BS	2020–2035 EP	2020–2035 CP
Urban expansion/ha	+14,042.16	+6355.62	+7498.08	+6925.05	+9402.3
Carbon loss caused by urban expansion encroaching on cropland/t	−1,096,991.10	−959,201.39	−700,208.30	−740,953.79	0
Carbon loss caused by urban expansion encroaching on ecological land/t	−385,956.88	−482,026.03	−161,056.35	−26,996.53	−1,333,649.07
Total carbon loss/t	+3,668,417.49	−550,025.43	−674,738.97	−599,646.25	−988,516.47
Economic value of total carbon loss/USD	+33,646,592.76	−4,889,512.70	−5,447,537.81	−4,799,589.01	−8,293,613.91

Foshan introduced the "*Foshan City Work Plan for Building a High-Quality Forest City in the Greater Bay Area (2018–2022)*" and the "*Special Plan for the Construction of Natural Ecological Civilization in Foshan City*" since receiving the designation of "National Forest City" in 2017. It is actively engaged in ecological protection and seeks to develop a sustainable urban environment. A new ecological pattern of blue-green integration has been built, creating a high-quality urban and rural space. This pattern has been achieved in three ways, i.e., forestation on the mountain, forests in the city, and greening at the seams.

Recently, several studies have attempted to analyze the changes of carbon storage under different urban development scenarios through the urban expansion model [43–45]. For example, Jiang and Deng (2017) [46] analyzed the potential impacts of urban expansion on carbon storage through the Conversion of Land Use and its Effects modeling framework (CLUE-S) model and the Integrated Valuation of Environmental Services and Tradeoffs (InVEST) model, and the results indicated that carbon storage has experienced varying degrees of loss due to urban expansion.

Externally, the change of CS in the region is affected by the expansion of urban construction land, while internally, it is influenced by the urban policies and plans implemented by the government, making it necessarily important to study the spatial and temporal patterns of urban expansion under different policies. To this end, this research predicted three different scenarios, including the BS scenario, CP scenario, and EP scenario.

According to the simulation results, under the BS scenario, the average annual CS loss caused by construction land enlargement in 2020–2035 is projected to be 0.41-times higher than that in 2015–2020. The EP scenario shows that protecting ecological lands can mitigate the reduction of CS and that the loss of CS caused by ecological land occupied by urban sprawl is the lowest. In contrast to the CP scenario, there is less loss of CS caused by the urban enlargement in the development of the EP scenario, compared to the overall loss of CS, which is relatively mild. This indicates that ecological protection policies mitigate and limit urban expansion and reduce carbon losses and are, thus, beneficial to mitigating greenhouse gas (GHG) emissions and global warming.

4.2. Value Loss and Spatial Heterogeneity on CS

Overall, there are essential regional differences in the endowment of ecological land resources, economic levels, and urban expansion in different regions of Foshan City, which are primarily attributed to regional differences in the ecological land resource endowment, economic levels, and urban expansion [47].

According to the present findings, the type of land most susceptible to the encroachment of urban growth is rural production, ecological, and living land, which will exacerbate the already severe urban–rural fragmentation. Although urban construction land expansion will inevitably encroach on forest land and cropland that can be used for carbon sequestration in rural towns, rural towns still have an advantage over urban construction land in terms of spatial distribution. The urban growth in Foshan primarily encroaches on rural cropland, although it also significantly affects forest land. The conversion of ecological land with higher carbon density into urban construction land with lower carbon density leads to the reduction and loss of ecosystem CS [16].

In this case, China launched a program to turn cropland back into forests starting in 1999 [41], and the national policy has contributed considerably in certain ways to the restraint and management. With the proposal of the carbon neutrality goal of China [2], the future development of government policy and planning implementations of China are inevitable for ecological protection and climate environment preservation.

We suggest promoting large-scale greening of the national territory, biodiversity conservation, system management, further optimization of the spatial pattern of carbon sinks, implementation of green carbon sink ecological restoration and synergistic efficiency using nature-based solutions, and enhancing the carbon sequestration capacity of ecosystems. Other rapidly urbanizing cities can draw inspiration from Foshan City to formulate corresponding ecological protection policies, deepen greening construction at multiple levels, diversify, and rely on the proposed “forest city”, “ecological city”, and “park city” plans of China. For instance, “park cities” were proposed to improve the quality of ecological space, promote the efficiency of carbon sequestration, and reduce the loss of the CS value.

4.3. Limitations and Future Directions

Herein, the land use and carbon sink data of Foshan City are substituted into the CS module of the INVEST model to study the CS changes in Foshan City. However, given that carbon storage is usually affected by environmental hydrothermal factors, anthropogenic factors, plant species, and patch size and that many land-use types in the research region are currently changing, these changes will also lead to a gradual increase in CS. Therefore, the data from the model may be inaccurate to an extent.

The future construction of land-use space was also simulated using the PLUS model. Undoubtedly, the three future land-use scenarios described in this model fail to cover all land-use conditions. Hence, the use of the model in the future scenarios needs to be close to the reality and to focus on the relationship between natural and social environment systems in the research region so that the data can better match the actual situation. In addition, the purpose of using this model is to better reveal the trending patterns rather than the data evaluation.

5. Conclusions

Terrestrial ecosystem CS matters considerably in the ecosystem and is subject to the vital impact of LULC changes. Herein, the influence of land-use changes on ecosystem CS was discussed primarily from the perspective of coupling urban expansion and ecological land conservation, and the ecosystem carbon storage in Foshan City was simulated using the InVEST model.

(i). From 2010 to 2020, Foshan City experienced rapid urban expansion, spreading from the central area to the outer circle in a cascading manner. The main land-use types for urban expansion were cropland, forest land, and water during these 10 years. The most influential factors on urban expansion were road and population factors, and the majority of the new urban land was expanded by county road extensions.

(ii) The overall trend of CS in Foshan City was rising and then declining from 2010 to 2020, with a growth trend from 2010 to 2015. However, the CS showed a sharp decline during the period of rapid urban expansion from 2015 to 2020. According to scenario simulations, CS is projected to show a declining trend by 2035; however, the implementation of relevant policies could slow down the decline rate of CS.

(iii) The urbanization of Foshan City directly results in less cropland, which affects the spatial heterogeneity of CS changes in the city. From 2010 to 2020, the northern part of Sanshui District and the eastern part of Chancheng District experienced the greatest economic CS loss, while the central and southern parts of Foshan City experienced the greatest economic growth of carbon storage. The main land types were cropland and construction land. Sanshui District is expected to experience the highest carbon loss in 2035, followed by Shunde District and Gaoming District, and the carbon loss will be further increased under future development scenarios.

Author Contributions: Conceptualization, L.C. and Y.M.; methodology, L.C. and Y.M.; theoretical analysis, L.C.; data analysis, L.C.; writing—original draft preparation, L.C.; writing—review and editing, L.C. and Y.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by GuangDong Basic and Applied Basic Research Foundation–Natural Science Foundation in 2023 (Study on the characteristics identification and regulation optimization of blue-green landscape around the city based on the coupling and coordination of ecological and recreational functions—take Pearl River Delta cities with water network as an example), the National Natural Science Foundation of China (No. 51708127), and Program of Study Abroad for Excellent Teachers at Guangdong University of Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: We would like to thank the Natural Science Foundation of Guangdong Province and National Natural Science Foundation of China.

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

References

1. Dorendorf, J.; Eschenbach, A.; Schmidt, K.; Jensen, K. Both tree and soil carbon need to be quantified for carbon assessments of cities. *Urban For. Urban Green.* **2015**, *14*, 447–455. [CrossRef]
2. Tang, R.; Zhao, J.; Liu, Y.; Huang, X.; Zhang, Y.; Zhou, D.; Ding, A.; Nielsen, C.P.; Wang, H. Air quality and health co-benefits of China's carbon dioxide emissions peaking before 2030. *Nat. Commun.* **2022**, *13*, 1008. [CrossRef]
3. Privitera, R.; Palermo, V.; Martinico, F.; Fichera, A.; La Rosa, D. Towards lower carbon cities: Urban morphology contribution in climate change adaptation strategies. *Eur. Plan. Stud.* **2018**, *26*, 812–837. [CrossRef]
4. Sallustio, L.; Quatrini, V.; Geneletti, D.; Corona, P.; Marchetti, M. Assessing land take by urban development and its impact on carbon storage: Findings from two case studies in Italy. *Environ. Impact Assess. Rev.* **2015**, *54*, 80–90. [CrossRef]
5. Dong, L.; Sun, Y.; Ran, J.; Hu, W.; Ji, M.; Du, Q.; Xiong, J.; Gong, H.; Yao, S.; Adnan Akram, M.; et al. Ecosystem organic carbon storage and their drivers across the drylands of China. *Catena* **2022**, *214*, 106280. [CrossRef]
6. Costanza, R.; de Groot, R.; Sutton, P.; van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the global value of ecosystem services. *Glob. Environ. Change* **2014**, *26*, 152–158. [CrossRef]
7. Tscharntke, T.; Klein, A.M.; Kruess, A.; Steffan-Dewenter, I.; Thies, C. Landscape perspectives on agricultural intensification and biodiversity-ecosystem service management. *Ecol. Lett.* **2005**, *8*, 857–874. [CrossRef]
8. Eigenbrod, F.; Bell, V.A.; Davies, H.N.; Heinemeyer, A.; Armsworth, P.R.; Gaston, K.J. The impact of projected increases in urbanization on ecosystem services. *Proc. R. Soc. B Biol. Sci.* **2011**, *278*, 3201–3208. [CrossRef]
9. Seppelt, R.; Dormann, C.F.; Eppink, F.V.; Lautenbach, S.; Schmidt, S. A quantitative review of ecosystem service studies: Approaches, shortcomings and the road ahead. *J. Appl. Ecol.* **2011**, *48*, 630–636. [CrossRef]
10. Zhang, Z.; Peng, J.; Xu, Z.; Wang, X.; Meersmans, J. Ecosystem services supply and demand response to urbanization: A case study of the Pearl River Delta, China. *Ecosyst. Serv.* **2021**, *49*, 101274. [CrossRef]
11. Tang, L.; Ke, X.; Zhou, Q.; Wang, L.; Koomen, E. Projecting future impacts of cropland reclamation policies on carbon storage. *Ecol. Indic.* **2020**, *119*, 106835. [CrossRef]
12. Posner, S.; Verutes, G.; Koh, I.; Denu, D.; Ricketts, T. Global use of ecosystem service models. *Ecosyst. Serv.* **2016**, *17*, 131–141. [CrossRef]
13. Gao, J.; Wang, L. Embedding spatiotemporal changes in carbon storage into urban agglomeration ecosystem management—A case study of the Yangtze River Delta, China. *J. Clean. Prod.* **2019**, *237*, 117764. [CrossRef]
14. Rajbanshi, J.; Das, S. Changes in carbon stocks and its economic valuation under a changing land use pattern—A multitemporal study in Konar catchment, India. *Land Degrad. Dev.* **2021**, *32*, 3573–3587. [CrossRef]
15. Zhang, M.; Huang, X.; Chuai, X.; Yang, H.; Lai, L.; Tan, J. Impact of land use type conversion on carbon storage in terrestrial ecosystems of China: A spatial-temporal perspective. *Sci. Rep.* **2015**, *5*, 10233. [CrossRef]
16. Nie, X.; Lu, B.; Chen, Z.; Yang, Y.; Chen, S.; Chen, Z.; Wang, H. Increase or decrease? Integrating the CLUMondo and InVEST models to assess the impact of the implementation of the Major Function Oriented Zone planning on carbon storage. *Ecol. Indic.* **2020**, *118*, 106708. [CrossRef]
17. Wang, J.; Zhang, Q.; Gou, T.; Mo, J.; Wang, Z.; Gao, M. Spatial-temporal changes of urban areas and terrestrial carbon storage in the Three Gorges Reservoir in China. *Ecol. Indic.* **2018**, *95*, 343–352. [CrossRef]
18. Tian, L.; Tao, Y.; Fu, W.; Li, T.; Ren, F.; Li, M. Dynamic Simulation of Land Use/Cover Change and Assessment of Forest Ecosystem Carbon Storage under Climate Change Scenarios in Guangdong Province, China. *Remote Sens.* **2022**, *10*, 2330. [CrossRef]
19. Yang, J.; Gong, J.; Tang, W.; Liu, C. Patch-based cellular automata model of urban growth simulation: Integrating feedback between quantitative composition and spatial configuration. *Comput. Environ. Urban Syst.* **2020**, *79*, 101402. [CrossRef]
20. Yang, H.; Huang, J.; Liu, D. Linking climate change and socioeconomic development to urban land use simulation: Analysis of their concurrent effects on carbon storage. *Appl. Geogr.* **2020**, *115*, 102135. [CrossRef]
21. Lauf, S.; Haase, D.; Hostert, P.; Lakes, T.; Kleinschmit, B. Uncovering land-use dynamics driven by human decision-making—A combined model approach using cellular automata and system dynamics. *Environ. Model. Softw.* **2012**, *27–28*, 71–82. [CrossRef]
22. Liu, X.; Liang, X.; Li, X.; Xu, X.; Ou, J.; Chen, Y.; Li, S.; Wang, S.; Pei, F. A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects. *Landsc. Urban Plan.* **2017**, *168*, 94–116. [CrossRef]
23. Meentemeyer, R.K.; Tang, W.; Dorning, M.A.; Vogler, J.B.; Cunniffe, N.J.; Shoemaker, D.A. Shoemaker. FUTURES: Multilevel Simulations of Emerging Urban-Rural Landscape Structure Using a Stochastic Patch-Growing Algorithm. *Ann. Assoc. Am. Geogr.* **2013**, *103*, 785–807. [CrossRef]

24. Liang, X.; Guan, Q.; Clarke, K.C.; Liu, S.; Wang, B.; Yao, Y. Understanding the drivers of sustainable land expansion using a patch-generating land use simulation (PLUS) model: A case study in Wuhan, China. Computers. *Environ. Urban Syst.* **2021**, *85*, 101569. [CrossRef]
25. Zhang, X.; Wang, J.; Yue, C.; Ma, S.; Wang, L. Exploring the spatiotemporal changes in carbon storage under different development scenarios in Jiangsu Province, China. *PeerJ* **2022**, *10*, e13411. [CrossRef]
26. Piao, S.; Yue, C.; Ding, J.; Guo, Z. Perspectives on the role of terrestrial ecosystems in the 'carbon neutrality' strategy. *Sci. China Earth Sci.* **2022**, *65*, 1178–1186. [CrossRef]
27. Tian, L.; Ye, Q.; Zhen, Z. A new assessment model of social cost of carbon and its situation analysis in China. *J. Clean. Prod.* **2019**, *211*, 1434–1443. [CrossRef]
28. Wang, J.; Lin, Y.; Glendinning, A.; Xu, Y. Land-use changes and land policies evolution in China's urbanization processes. *Land Use Policy* **2018**, *75*, 375–387. [CrossRef]
29. Xu, H.; Song, Y.; Tian, Y. Simulation of land-use pattern evolution in hilly mountainous areas of North China: A case study in Jincheng. *Land Use Policy* **2022**, *112*, 105826. [CrossRef]
30. Li, T.; Li, M.; Tian, L. Dynamics of Carbon Storage and Its Drivers in Guangdong Province from 1979 to 2012. *Forests* **2021**, *12*, 1482. [CrossRef]
31. Zhou, R.; Lin, M.; Gong, J.; Wu, Z. Spatiotemporal heterogeneity and influencing mechanism of ecosystem services in the Pearl River Delta from the perspective of LUCC. *J. Geogr. Sci.* **2019**, *29*, 831–845. [CrossRef]
32. Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences. Available online: https://www.resdc.cn/ (accessed on 15 September 2022).
33. OpenStreetMap. Available online: https://www.openstreetmap.org/ (accessed on 15 September 2022).
34. Foshan Natural Resources Bureau. Foshan City Territorial Spatial Master Plan (2020–2035). Available online: https://fszrzy.foshan.gov.cn/ (accessed on 15 September 2022).
35. Geospatial Data Cloud. Available online: http://www.gscloud.cn/ (accessed on 15 September 2022).
36. Wang, Z.; Zeng, J.; Chen, W. Impact of urban expansion on carbon storage under multi-scenario simulations in Wuhan, China. *Environ. Sci. Pollut. Res.* **2022**, *29*, 45507–45526. [CrossRef]
37. The Central Government of the People's Republic of China. The China National LULC Master Plan (2006–2020). Available online: https://www.gov.cn/ (accessed on 15 September 2022).
38. Zhuang, Z.; Li, K.; Liu, J.; Cheng, Q.; Gao, Y.; Shan, J.; Cai, L.; Huang, Q.; Chen, Y.; Chen, D. China's New Urban Space Regulation Policies: A Study of Urban Development Boundary Delineations. *Sustainability* **2017**, *9*, 45. [CrossRef]
39. Chen, Y.; Li, X.; Liu, X.; Ai, B. Modeling urban land-use dynamics in a fast developing city using the modified logistic cellular automaton with a patch-based simulation strategy. *Int. J. Geogr. Inf. Sci. IJGIS* **2014**, *28*, 234–255. [CrossRef]
40. Xu, L.; He, N.P.; Yu, G.R. 2010s dataset on carbon density in terrestrial ecosystems of China. *Chin. Sci. Data* **2019**, *4*, 90–96.
41. Zhang, K.; Dang, H.; Tan, S.; Cheng, X.; Zhang, Q. Change in soil organic carbon following the 'Grain-for-Green' programme in China. *Land Degrad. Dev.* **2010**, *21*, 13–23. [CrossRef]
42. Wang, Z.; Li, X.; Mao, Y.; Li, L.; Wang, X.; Lin, Q. Dynamic simulation of land use change and assessment of carbon storage based on climate change scenarios at the city level: A case study of Bortala, China. *Ecol. Indic.* **2022**, *134*, 108499. [CrossRef]
43. He, C.; Zhang, D.; Huang, Q.; Zhao, Y. Assessing the potential impacts of urban expansion on regional carbon storage by linking the LUSD-urban and InVEST models. *Environ. Model. Softw.* **2016**, *75*, 44–58. [CrossRef]
44. Kukkonen, M.; Khamis, M.; Muhammado, M.J.; Käyhkö, N.; Luoto, M. Modeling direct above-ground carbon loss due to urban expansion in Zanzibar City Region, Tanzania. *Land Use Policy* **2022**, *112*, 105810. [CrossRef]
45. Xiang, S.; Wang, Y.; Deng, H.; Yang, C.; Wang, Z.; Gao, M. Response and multi-scenario prediction of carbon storage to land use/cover change in the main urban area of Chongqing, China. *Ecol. Indic.* **2022**, *142*, 109205. [CrossRef]
46. Jiang, W.; Deng, Y.; Tang, Z.; Lei, X.; Chen, Z. Modelling the potential impacts of urban ecosystem changes on carbon storage under different scenarios by linking the CLUE-S and the InVEST models. *Ecol. Model.* **2017**, *345*, 30–40. [CrossRef]
47. Zheng, H.; Wang, L.; Peng, W.; Zhang, C.; Li, C.; Robinson, B.E.; Wu, X.; Kong, L.; Li, R.; Xiao, Y.; et al. Realizing the values of natural capital for inclusive, sustainable development: Informing China's new ecological development strategy. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 8623–8628. [CrossRef] [PubMed]