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RESEARCH ARTICLE

Dynamic Assessment of Carbon Storage Function and Forecasting of Its Future Potential in Beijing's Green Belt

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Urban green belts (GBs) have multiple functions of providing ecosystem carbon storage services, improving urban microclimate, and inhibiting urban sprawl. However, there is a paucity of studies to assess the dynamics of the ecosystem carbon storage function of the GB around the city and forecast its future potential. Our study analyzed the dynamic changes of carbon stock in Beijing's GB during 2000 to 2020 and predicted the GB's carbon storage potential in 2035 by coupling the InVEST and FLUS models. Results showed that Beijing's GB carbon storage decreased from 14.45 to 10.59 Mt from 2000 to 2020. The carbon density of the GB in Beijing from 2000 to 2010 was greater than that of the non-GB areas, indicating that the GB had a substantial carbon storage function. The carbon stock in Beijing's GB showed the spatial characteristics that the high carbon stock zones were located in the western part of the GB under 3 scenarios in 2035. The overall carbon stock in 2035 under the economic development scenario was 35.60 Mt, with the largest reduction from 2020, 1.78 Mt. The spatial layout, morphology, and structure of urban GB had a notable effect on carbon storage function, and the protection and spatial regulation of urban GB systems should be strengthened in the future in terms of urban–rural development and planning, the morphology and scale of GB, and institution and public support.

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Introduction

The carbon sink service function, which offsets carbon emissions from urban construction and development by increasing carbon stocks, is a key link in the regulation of the regional climate and the global carbon cycle [1,2]. As a component of green infrastructure and a direct carbon storage element in cities, urban green belt (GB) plays a substantial role in reducing urban CO_2 levels, mitigating the impacts of climate change on cities and maintaining the carbon–oxygen homeostasis, and is an effective means of enhancing urban ecosystem functionality and the pattern of urban ecological security [3,4]. The World Cities Report 2022 identifies the need to help cities adapt and respond to shocks and stresses and to guide the world toward a resilient, green, ecological, and sustainable urban future [5]. The ecosystem carbon storage function of urban GB contributes to the fulfillment of the sustainable development goal (SDG) 11. In 2020, China explicitly stated that it would "strive to peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060" (the "3060" commitment) [1]. Against the background of the "3060" commitment, ecosystem carbon sinks are a necessary option for achieving carbon neutrality, and the larger the carbon sink, the greater the likelihood of reaching carbon neutrality [6,7]. However, one of the most significant factors causing changes in carbon stocks is land-use change. This alteration is a consequence of changes in ecosystem structure, function, and processes [8,9], which is surpassed only by the burning of fossil fuels in terms of its contribution to increases in atmospheric CO_2 levels [10–12]. Frequent encroachment on GB is due to the low level of effectiveness of GB legislation and the complexity of land tenure. Therefore, quantitatively assessing the ecosystem carbon stock of urban GB, predicting the future land use and carbon stocks in the GB through multi-scenario simulation, and exploring the paths to optimize the structure of land use of urban GB are fundamental to the amplification of green infrastructure multifunctionality and the mitigation of climate change [13,14].

In recent years, scholars have explored the impact of land-use change on ecosystem carbon stocks at the global, national, and regional levels, from single or integrated ecosystems, respectively. Studies have shown that at the global scale, deforestation in the tropics is the main cause of the decline in carbon stocks in terrestrial ecosystems [15]. At the national and regional scales, the conversion of cropland to built-up land, which increases carbon emissions, and the return of cropland to forest and grassland, or afforestation programs, which reduces carbon emissions, are the 2 important processes in the change of ecosystem carbon stocks [4]. Other studies have been carried out to model future land-use change scenarios and their impacts on carbon stocks in urban ecosystems [16], and to explore how to optimize the geospatial configuration of land use under the low-carbon perspective [17], achieving the prediction of the carbon stocks and its spatial visual representation. However, there are few studies assessing ecosystem carbon stocks in urban GB and simulating multiple scenarios to predict future carbon stocks in GB. Urban GB is a green open space composed of farmland, forests, water, and additional green spaces in the outskirts of the city [18,19]. It originated from the thinking and reaction to the malignant sprawl of cities under the background of the industrial revolution [13,20,21]. With a full understanding of the functions of GB, an established convergence has emerged among academics that GB is an important component of urban green infrastructure, extending its ecosystem carbon storage and other functions [22,23].

Studies have assessed ecosystem carbon stocks in urban GB and investigated the impacts of land-use dynamics on carbon stocks [13,24], but there is a lack of modeling of the spatial characteristics of urban GB ecosystems' carbon stocks and their future scenarios. Multi-scenario projections of carbon stocks can offer a certain scientific basis for future urban GB planning. Studies have explored the effect of GB in mitigating climate change and constraining urban expansion from the perspective of temporal evolution in carbon storage; e.g., Han et al. [13] investigated the efficacy of 6 counties with GB in the United States in constraining sprawl and storing carbon using land cover data, carbon stock and carbon flux data per unit area, ArcGIS overlay analysis, and the Land Conversion Index; Hwang et al. [3] used the InVEST model for carbon stock analysis in order to explore the effectiveness of GB in Korea in curbing urban sprawl and helping to mitigate climate change. However, previous studies have primarily focused on temporal evolution in carbon stocks within urban GB, lacking the integration of different spatial analysis methods for land use to investigate the spatial heterogeneity of carbon stock variations and their future scenario projections. Among many land-use change models, the FLUS model suggested by Liu and others is appropriate for complicated land-use simulation with multiple scenarios, scales, and high precision [25]. Among many ecosystem service models, the InVEST model is extensively applied to measure carbon stocks in ecosystems and can show the spatial distribution of carbon stocks [26]. When current and future projected land-use data are provided, the InVEST model can estimate current and future carbon stocks or losses. The combination of the 2 approaches, the FLUS model and the InVEST model, can effectively solve the above problems.

Beijing's GBs were first established and have been in place for the longest time in China [18]. Due to the special context of urban development, the GB policy has been in place for more than 50 years, with the "Greening Isolated Area" as the controlling element [19,27]. With the creation and implementation of the massive second GB, the GB policy is gaining increasing attention. In 2023, the Beijing Municipal People's Government officially issued the Planning for Reducing the Quantity and Improving the Quality of Beijing's Second Greening Isolated Area (2021–2035), which promotes the reduction of the quantity, improvement of the quality and increase of the green and the systematic governance of ecological space. The spillover effect of the external effect of ecological space in Beijing's second GB is significant, with a variety of ecological service functions such as carbon storage [3]. However, the results of the implementation of the GB still have a large deviation from the intended objectives, and the urgent issues and contradictions that need to be addressed are still relatively prominent [18]. Evaluating the carbon storage function of Beijing's GB and its future potential can provide useful policy insights for the formulation and implementation of the current Beijing Urban Master Plan and the Beijing Recent Territorial and Spatial Plan (2021–2025), which will also facilitate the theoretical innovation and practical development of GB research in China.

Consequently, this study focuses on the following 2 research questions: (a) How to quantitatively assess the dynamics of carbon storage functions in megacity GB based on multi-source data? (b) How to couple different approaches to predict the carbon storage potential of urban GB under multiple scenarios? The article selected Beijing, the earliest megacity in China with a typical ring GB; explored the features of carbon stock changes in the urban GB during the 2000 to 2020 period using land-use data, Digital Elevation Model (DEM) data, socio-economic data, and carbon density data; adopted the FLUS model to predict the land use under the following 3 scenarios: (a) natural development (ND), (b) ecological protection (EP), and (c) economic development (ED) in 2035; and applied the InVEST model to evaluate the ecosystem carbon storage under the 3 scenarios in the future (Fig. 1). The research can offer decision-making support for the sustainable development of land use in urban GB of Beijing and other similar-sized cities internationally.

Materials and Methods

Study area

Beijing is a world-class metropolis with a residentially anchored urban populace of 21.86 million in 2023, and the built-up area expanded from 488 km^2 in 2000 to 1,469 km^2 in 2022. Beijing's urban layout is circular and radial, and it was the first city in China to start the practice of building GB [28]. The Beijing City Construction Master Planning Programme of 1983, designated the first GB area as 260 km^2, with an urban area of 750 km^2. However, due to the continuous encroachment of urban construction land on GB, the first GB was gradually planned out of control and shrunk in size as the city grew in size. In this study, the second GB of the Beijing Urban Master Planning (2016–2035) and the Beijing 14th Five-Year Planning for the Construction and Development of Green Separated Areas is selected as the study area (Fig. 2), and the second GB is mainly located between the Fifth Ring Road and the Sixth Ring Road [27]. Beijing GB is primarily situated within the urban–rural fringe zones. Within the planning area, urban construction land accounts for over 40%, indicating rapid urbanization and a clear trend toward suburban urbanization. To explore whether the GB has a better carbon storage function, the urban area of Beijing was divided into the urban GB and other areas of the city outside the GB, i.e., the non-GB.

Data sources

The research data consist of 5 components: (a) Land-use data are derived from the China Land Cover Dataset, a dataset with an annual spatial resolution of 30 m [29]. For the study, land-use data at 5-year intervals from 2000 to 2020 were selected. (b) As prescribed by the InVEST model user manual, the carbon storage module assumes that the carbon density of every type of land use is a constant. In this research, the carbon density data were based on prior studies [30,31]. (c) DEM data are from the National Aeronautics and Space Administration Shuttle Radar

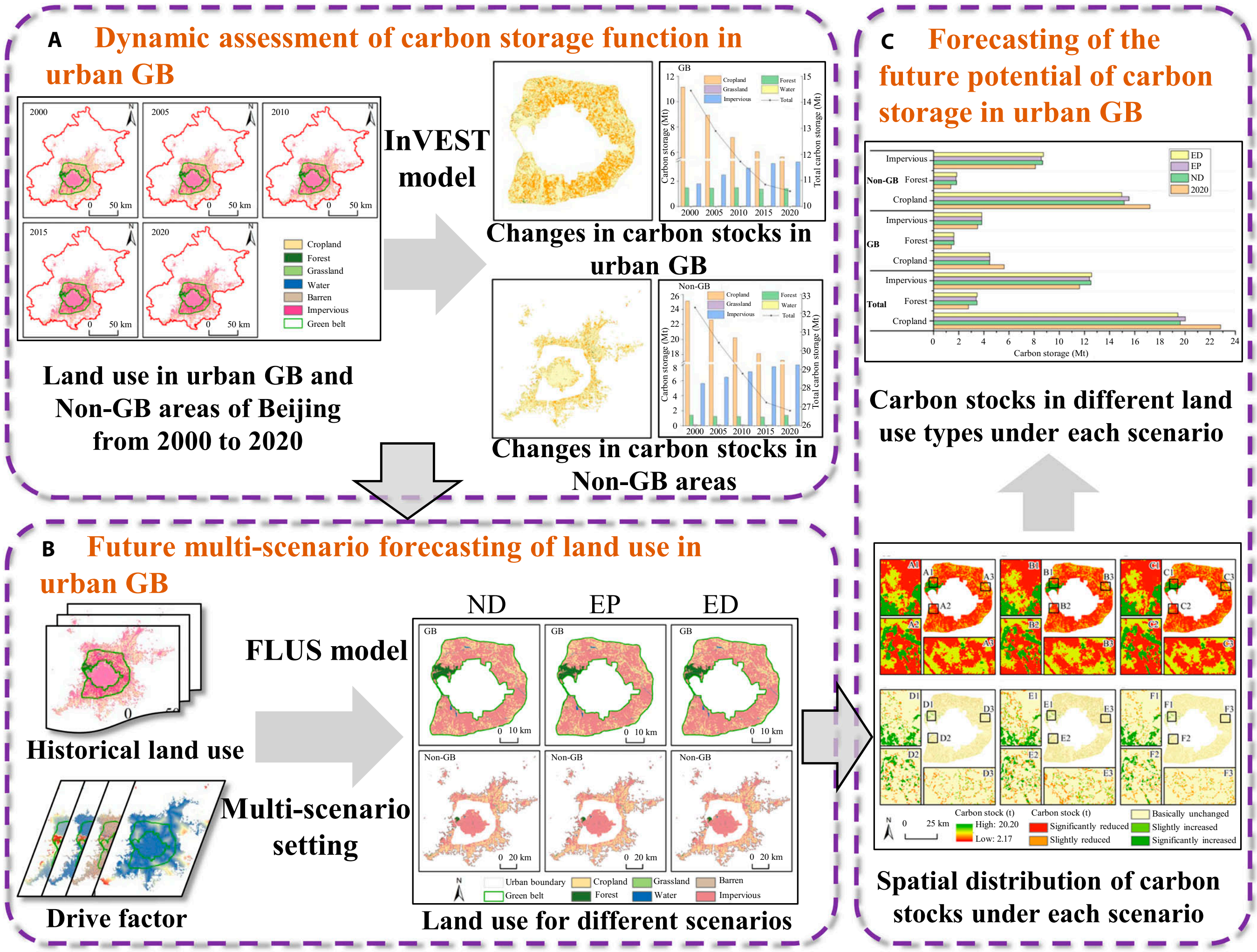

Fig. 1. The framework of our study. (A) Dynamic assessment of carbon storage function in urban green belt (GB). (B) Future multi-scenario forecasting of land use in urban GB, where ND represents the natural development scenario, EP represents the ecological protection scenario, and ED represents the economic development scenario. (C) Forecasting of the future potential of carbon storage in urban GB.

Topography Mission (NASA-SRTM) 30 m DEM data. (d) Socioeconomic data include population data at 100-m grid spatial resolution and Gross Domestic Product (GDP) data at 1-km grid. Population data are taken from Worldpop population data in 2020 (https://hub.worldpop.org/); GDP data come from the Resource and Environment Science Data Centre of the Chinese Academy of Sciences in 2019. (e) This research adopted the 2020 city boundary data from the global city boundary dataset released by Professor Peng Gong's team (http://data.ess.tsinghua.edu.cn/), and the basic geographic information data come from the National Centre for Basic Geographic Information and Open Street Map database, specifically including the city administrative boundaries and the traffic route data.

Methods

InVEST model

1. Calculation of carbon stocks. The calculation of carbon stocks by the InVEST model encompasses the 4 common basic carbon pools (aboveground, belowground, soil, and dead organic matter), but only the 3 major pools are considered in this research because of the difficulty in acquiring data for the dead organic matter carbon pool. The principle of carbon stock calculation is as follows [32], with the inherent limitation that the input carbon pool parameters (aboveground, soil, etc.) are mostly dependent on literature or regional case studies:

$$C_i = C_{i-\text{above}} + C_{i-\text{below}} + C_{i-\text{soil}} \quad (1)$$

$$C_{\text{tot}} = \sum_{i=1}^{n} C_i \times S_i \quad (2)$$

where C_i represents the total carbon density of land-use type i (t/hm^2); $C_{i\text{-above}}$ stands for the aboveground carbon density (t/hm^2); $C_{i\text{-below}}$ represents the belowground biogenic carbon density (t/hm^2); $C_{i\text{-soil}}$ represents the soil carbon density (t/hm^2); C_{tot} represents the total carbon stock (t); S_i stands for the land-use area (hm^2) of land-use type i; n refers to the number of land-use types, n is 6 in the research.

2. Selection of carbon density data. The carbon density database was constructed mainly with reference to measured data from existing literature [30,31], and the following principles were followed in data selection: preference was accorded to the carbon density values derived from field surveys and

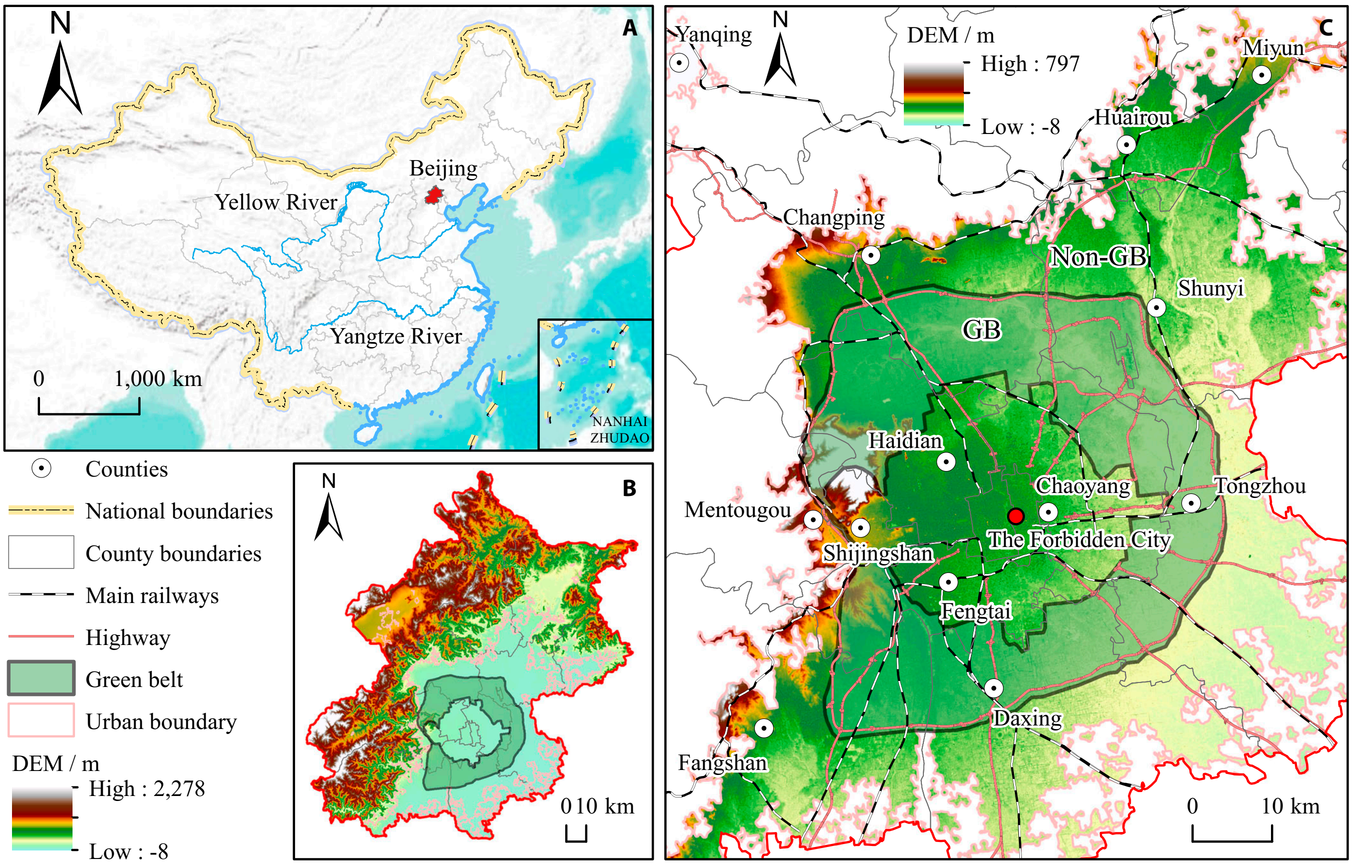

Fig. 2. Study area. (A) Geographic location of Beijing in China. (B) Geographic location of green belt (GB) in Beijing. (C) GB and non-green belt (non-GB).

experiments in the study area, and for some of the data that lacked references, the data were supplemented with data from research literature in the neighboring areas, so that the carbon density values of distinct land-use categories in both the GB and non-GB areas of Beijing were obtained in the end (Table S1).

FLUS model

The FLUS model has been developed for the simulation of future land-use scenarios under the influence of both anthropogenic and natural influences [33]. The model is predicated on the conventional cellular automata model and the artificial neural networks algorithm, according to the needs of different scenarios, combined with Markov Chain, land cost, and so on to measure the quantity demand of various land uses in the future, and integrated the historical land-use data with a variety of driving force factors containing anthropogenic activities and natural effects (temperature, precipitation, soil, topography, traffic, location, policy, etc.) to gain the development suitability probability (Eqs. 3 and 4), and then calculate the total conversion likelihood of the metacells, and simulate the future land-use changes subsequent to the implementation of the roulette competition mechanism [34].

$$P_{p,k}^{t} = \sum_{j} w_{j,k} \times \left[1/\left(1+e^{-N_j(p,q)}\right)\right] \quad (3)$$

$$N_j(p,q) = \sum w_{i,j} \times x_j(p,q) \quad (4)$$

where $P_{p,k}^{t}$ is the suitability likelihood of converting cell p into k-class land at time t; t is the year; $w_{j,k}$ represents the weights of the hidden layer and the output layer; $N_j(p,q)$ is the hidden layer neuron j that receives input layer signals; $x_j(p,q)$ is the input value of cell p for the ith neuron at iteration q; $w_{i,j}$ represents the weights of the input layer and the hidden layer.

The FLUS model is composed of 2 major components. The first part is a module to acquire the probability of land-use suitability predicated upon Artificial Neural Network (ANN) training, and the second part is a module for adaptive inertia and competitive mechanisms. Since land-use change is driven by both natural and human factors, the drivers need to be added to the ANN when producing a land suitability atlas using the ANN. The main part of the adaptive inertia and competition mechanism module is the determination of neighborhood factor parameters for each class (Eqs. 5 and 6) [34], concerning the rules for land transfer in the Beijing GB under ND conditions; a table of neighborhood factor parameters for different scenarios has been obtained after debugging and validation (Table S2). An inherent limitation of the FLUS model is that the setting of the adaptive inertia coefficient priority may be subjective, leading to biased calculation of the conversion probability.

$$\Omega_{p,k}^{t} = \sum\nolimits_{N\times N} \mathrm{con}\left(c_p^{t-1}=k\right)/(N\times N-1)\times w_k \quad (5)$$

$$I_k^t = \begin{cases} I_k^{t-1} & \text{if } |D_k^{t-2}| \le |D_k^{t-1}| \\ I_k^{t-1}\times D_k^{t-2}/D_k^{t-1} & \text{if } D_k^{t-1} < D_k^{t-2} < 0 \\ I_k^{t-1}\times D_k^{t-1}/D_k^{t-2} & \text{if } 0 < D_k^{t-2} < D_k^{t-1} \end{cases} \quad (6)$$

where $\Omega^t_{p,k}$ is the neighborhood influence factor of cell p at time t, representing the total number of cells occupied by land type k within the $N \times N$ Moore neighborhood window during the previous iteration $t-1$; w_k represents the neighborhood factor parameter for each land-use type; I^t_k represents the inertia coefficient of land type k at iteration time t; D^{t-1}_k stands for the discrepancy between the land demand and the actual quantity at time $t-1$.

Employing 2015 land-use data as the training dataset, we predicted the distribution of land-use types in 2020, and the accuracy of the model was detected, with an overall accuracy of 92% and a Kappa coefficient of 85.1%, which indicated that the selected driving factors had a stronger explanatory ability for the land use of Beijing's GB [35].

Multi-scenario setting

To study the effects of future land-use demand on the spatial evolution of urban sprawl under various scenarios, this research established 3 scenarios, namely, ND, EP, and ED, to simulate the land-use changes in the GB and non-GB areas in Beijing [36]. The different scenarios are set up on the basis of land-use conversion probabilities for 2015 to 2020. (a) The ND scenario, in which land-use changes are not influenced by human programs and policies, but evolve only in accordance with the characteristics of land-use conversions under historical circumstances (Table S3). The study made the assumption that the historical development pattern would continue in the following decades, so no constraints were placed on the simulation experiments, and Markov-based calculations were carried out to arrive at the land-use demand in 2035. (b) The EP scenario emphasizes the co-construction and co-insurance of ecological environments. Taking into account the land-use development of the city of Beijing, it increased the likelihood of shifting cropland to forest by 60%, and increased the likelihood of shifting to grassland by 50%, and reduced the likelihood of shifting to impervious by 70%. The likelihood of forest shifting to cropland was reduced by 80%, to grassland by 70%, and to impervious by 90%. The likelihood of grassland shifting to cropland increased by 20%, the likelihood of shifting to forest increased by 50%, and the likelihood of shifting to impervious decreased by 80%; 20% increased in the probability of barren shifting to cropland and 30% increased in the probability of shifting to grassland. (c) The ED scenario highlights the ED objectives of the SDGs and places no limits on urban sprawl. In accordance with the 2015 to 2020 land-use transfer matrix, set the probability of an 80% increase in the transfer of cropland to impervious. The likelihood of forest shifting to impervious increased by 80%. The likelihood of the transfer of grassland to impervious increased by 60%. The likelihood of the transfer of barren to impervious increased by 50%. The likelihood of mutual transfers between the remaining land-use types remained constant. The different scenario settings were tested for model accuracy, and the overall accuracy and Kappa coefficients met the requirements of the study. The overall accuracy of the ND scenario, EP scenario, and ED scenario was 95%, 93%, and 92% respectively, with corresponding Kappa coefficients of 90.2%, 88.5%, and 85.1%.

Results

Dynamic assessment of carbon storage function in urban GB

Beijing's urban expansion occupied 477.93 km^2 of green space in the GB from 2000 to 2020, and the carbon stock in the GB was reduced from 14.45 to 10.59 Mt. Its spatial distribution, in general, showed the characteristics of a low center with a high periphery, a small area of high-value zones, and a large area of medium-value and low-value zones (Fig. 3A to E). High-value zones predominantly clustered within the western part of the GB, and the main land-use type was forest with strong carbon storage capacity. Medium-value zones were mainly located in the outer edge of the GB, and the main land-use type was cropland. Low-value zones were distributed in the center of the GB in patches, and the main land-use type was impervious. To more clearly reflect the changes in the spatial distribution of carbon storage in Beijing GB, the spatial variation values of carbon stocks from 2000 to 2020 were classified into 5 categories, namely, significantly reduced, slightly reduced, basically unchanged, slightly increased, and significantly increased. The carbon stock in Beijing's GB as a whole showed a trend of basically unchanged and slightly reduced from 2000 to 2020 (Fig. 3F), and the area of carbon stock decrease was distributed in the GB in a piecemeal manner, accounting for 32.92%, and the reduction of carbon stock was mainly driven by converting cropland to impervious. The area of carbon stock increase was distributed in a point-like manner in the western, northern, and southwestern parts of the GB, accounting for 1.81%, and the increase of carbon stock was mainly driven by converting cropland and barren to forest and grassland.

High-carbon-storage zones in Beijing's urban non-GB areas from 2000 to 2020 predominantly clustered within the western part of the non-GB areas, where the dominant land-use class was forest, with a strong carbon storage capacity (Fig. 4A to E). Medium-carbon-storage zones predominantly clustered within the non-GB periphery, and the main land type was cropland. Low-value zones were located in the central region of the non-GB zones, and the main land type was impervious. The carbon storage reduction areas in the non-GB areas of Beijing from 2000 to 2020 were distributed in patches in various directions (Fig. 4F), and the reduction of carbon stock was mainly driven by converting cropland to impervious, with the areas of significantly reduced and slightly reduced representing 0.24% and 19.64% of the non-GB areas, respectively. The areas of carbon stock increase were located in the north, east, and southeast of the non-GB areas in a point-like manner, and the areas of slightly increased and significantly increased accounted for 0.34% and 2.12% of the non-GB areas, respectively. The increase in carbon stock was mainly driven by converting cropland and barren to forest and grassland.

The carbon density of the GB and non-GB areas in Beijing showed a progressive decreasing tendency from 2000 to 2020, the carbon density of the GB in Beijing was greater than that of the non-GB areas in 2000 to 2010 (Table 1), and the carbon storage capacity of the GB in 2000 and 2010 was 941.26 and 92.99 t/km^2 more than that of the non-GB areas, respectively. Carbon density in Beijing's GB decreased from 9,399.95 t/km^2 in 2000 to 6,888.15 t/km^2 in 2020, and that in the non-GB areas decreased from 8,458.69 t/km^2 in 2000 to 7,017.41 t/km^2 in 2020, suggesting that rapid urban expansion has caused a drastic decrease in carbon density in Beijing's GB and non-GB. The carbon density of the Beijing GB in 2000, 2005, and 2010 was 9,399.95, 8,390.02, and 7,627.88 t/km^2, respectively, which was greater than that of the non-GB areas in the same period, indicating that Beijing GB had a substantial carbon storage function compared to the non-GB areas in this period. However, the carbon density of the GB in 2015 and 2020 was smaller than

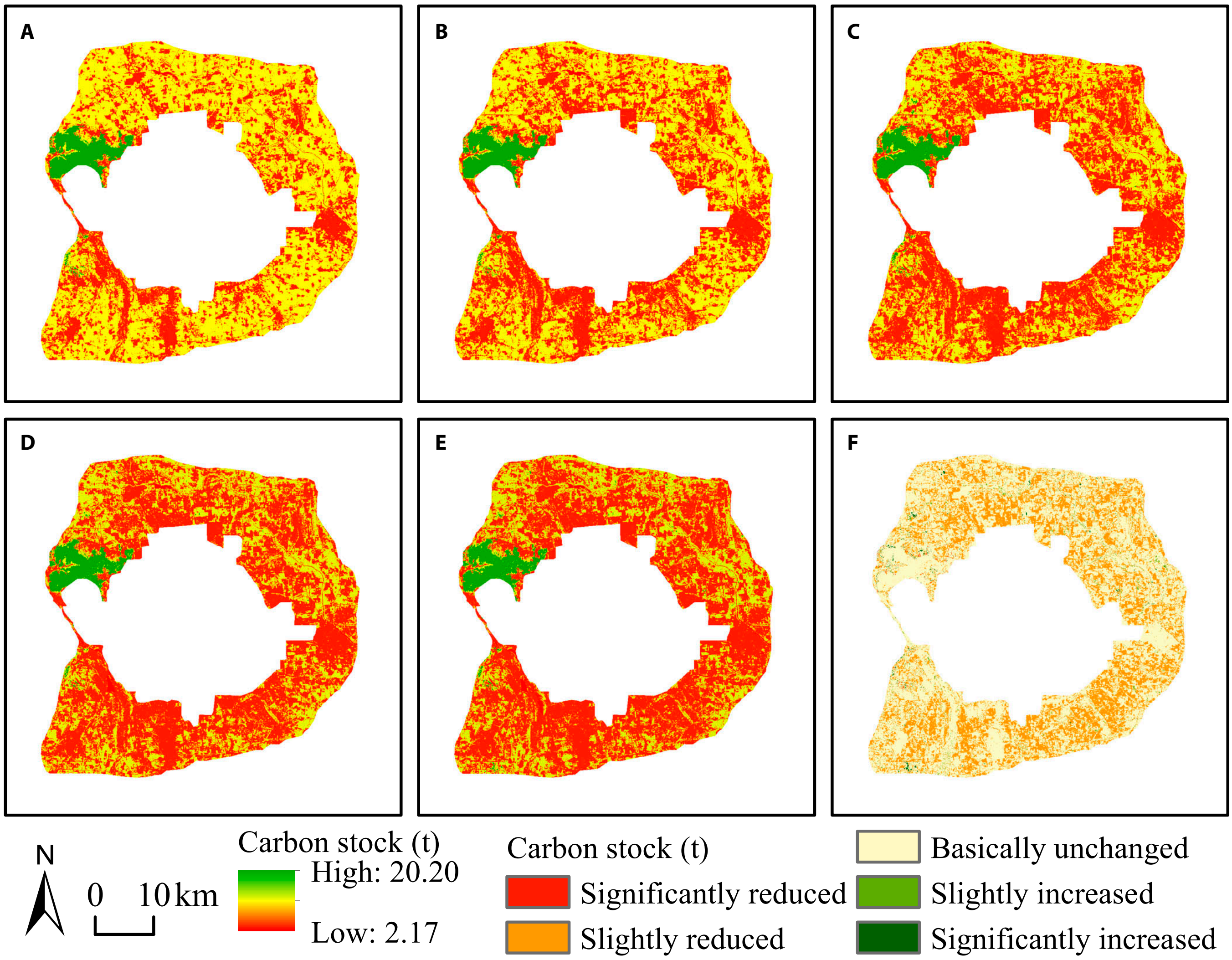

Fig. 3. Spatial distribution of carbon stocks in Beijing's urban GB in 2000 (A), 2005 (B), 2010 (C), 2015 (D), 2020 (E), and its changes from 2000 to 2020 (F).

that of the non-GB areas, indicating that the GB did not fulfill its carbon storage function in that period, which was due to the significant decline in carbon density of the urban GB as a result of urban sprawl, which resulted in the encroachment of a great deal of ecological land, including cropland, by construction land.

The carbon stocks in the GB and non-GB areas of Beijing revealed a gradual downward tendency during the 2000 to 2020 period, and the carbon storage of heterogeneous land-use categories showed significantly different nonlinear trends (Fig. S1). In terms of the carbon storage of each land-use class (Fig. S1A), the carbon stock of cropland revealed a gradual downward tendency. Carbon stocks in forest, grassland, and water showed slightly fluctuating trends. Carbon stocks on impervious showed a gradual upward trend, from 1.79 to 3.51 Mt, an increase of 1.72 Mt, which was caused by the large increase in the area of built-up land owing to the demands of urban development. The carbon stock in the non-GB areas of Beijing decreased from 32.31 Mt in 2000 to 26.80 Mt in 2020 (Fig. S1B). Among them, the 2000 to 2005 period saw the largest decrease of 1.88 Mt. In terms of carbon storage of land-use type, cropland carbon stocks revealed a gradual downward tendency from 2000 to 2020. Carbon stocks in forest revealed a decreasing and then increasing tendency. Impervious showed a gradual upward trend, from 5.63 Mt in 2000 to 8.10 Mt in 2020, which was 1.43 times higher than that of the GB.

Future multi-scenario forecasting of land use in urban GB

According to the FLUS model prediction results (Fig. S2), the overall land-use change trends in Beijing's GB and non-GB areas under different scenarios in 2020 to 2035 were roughly the same, with the areas of cropland, water, grassland and barren decreasing, and the areas of impervious and forest increasing (Table 2). Under the ND scenario, cropland decreased by 276.79 km^2. Forest increased by 30.41 km^2. Impervious increased by 250.98 km^2, which represented 4.69% of the total regional coverage, and the large amount of cropland transferred out was the dominant type of land-use conversion under the ND scenario, and the direction of the transfer was mainly to forest and impervious (Fig. S3). Under the EP scenario, cropland decreased to 1,720.87 km^2, a reduction of 240.82 km^2. The growth of construction land was constrained as a whole, with a significantly lower increase compared to the ND scenario, and impervious increased by 217.83 km^2 from 2020 to 2035.

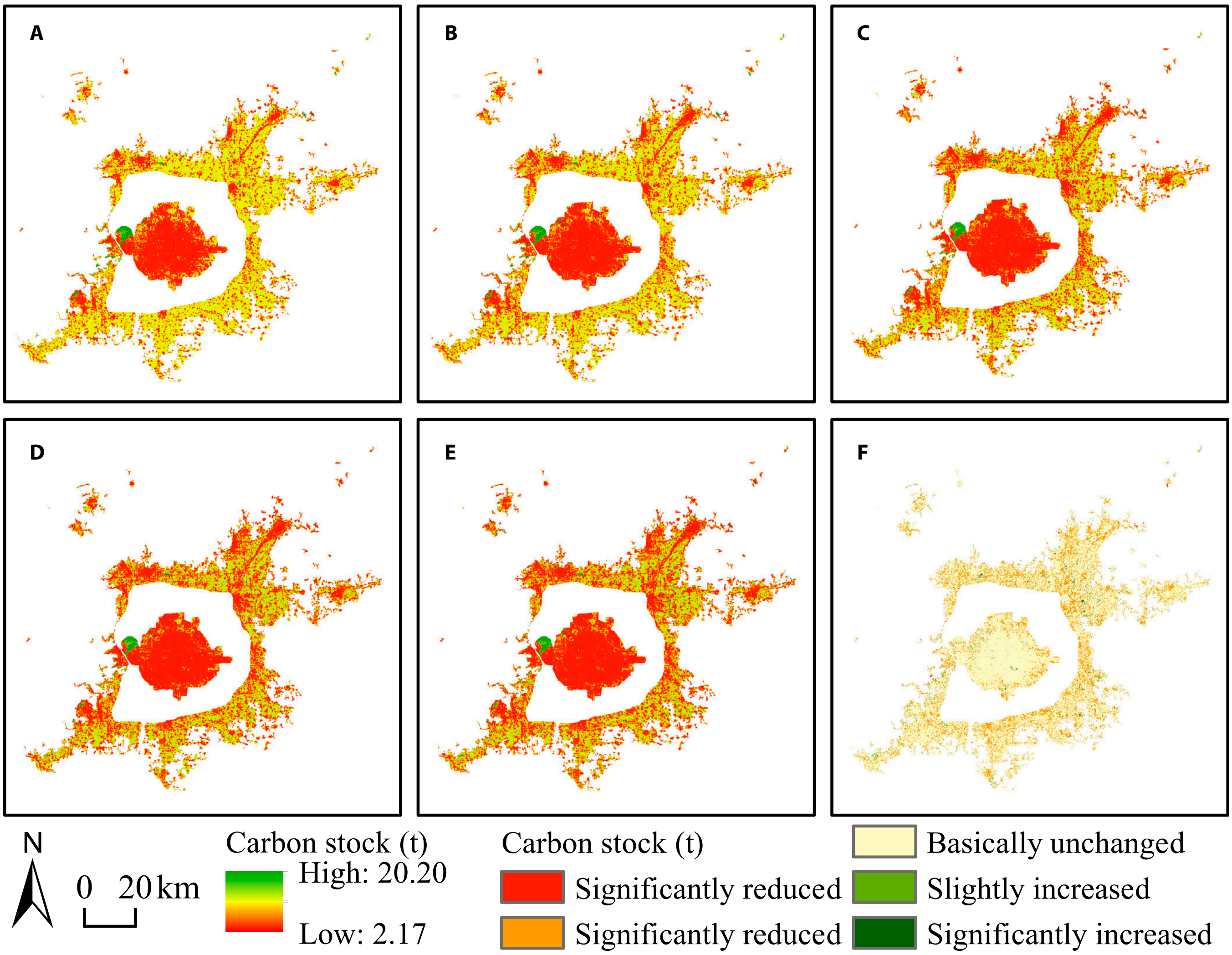

Fig. 4. Spatial distribution of carbon stocks in non-GB areas of Beijing in 2000 (A), 2005 (B), 2010 (C), 2015 (D), 2020 (E), and its changes from 2000 to 2020 (F).

Table 1. Carbon density in urban GB, non-GB, and the city as a whole in Beijing from 2000 to 2020 (t/km^2)

Different regions	2000	2005	2010	2015	2020
GB	9,399.95	8,390.02	7,627.88	7,053.06	6,888.15
Non-GB	8,458.69	7,966.06	7,534.89	7,131.41	7,017.41
Total	8,728.79	8,087.72	7,561.58	7,108.93	6,980.32

The ED scenario saw the largest increase in the area of impervious, which increased by 265.69 km^2, or 4.96% of the total area, and the large increase in impervious led to the largest decrease in cropland, which decreased by 292.18 km^2.

Different land uses in the GB and non-GB areas of Beijing from 2020 to 2035 showed different trends under each scenario (Table 2). In the GB, cropland, grassland, water, and barren showed a decreasing trend in all 3 scenarios, with the smallest decrease in cropland in the EP scenario, with a decrease of 97.60 km^2; Forest and impervious showed an increasing tendency, whereby the most pronounced expansion occurred in impervious under the ED scenario, with an increase of 91.37 km^2. In the non-GB areas, cropland, grassland, water, and barren under the 3 scenarios showed the same decreasing trend, with the ED scenario showing the largest decrease in cropland, with a decrease of 193.22 km^2, which was 50.00 km^2 more than that of the EP scenario. Forest and impervious showed an increasing tendency, and the increase in impervious was ED scenario > ND scenario > EP scenario, and the impervious under the ED scenario increased by 175.54 km^2, which accounted for 4.60% of the area of the non-GB areas.

Table 2. Comparison of the area of various land-use categories under the 3 scenarios in 2035 with the current situation in 2020 (km^2)

Land-use types		2020	2035			2020–2035		
			ND	EP	ED	ND	EP	ED
Total	Cropland	1,961.69	1,684.90	1,720.87	1,669.51	−276.79	−240.82	−292.18
	Forest	123.72	154.13	151.06	154.47	30.41	27.34	30.75
	Grassland	6.38	2.51	2.65	2.63	−3.87	−3.73	−3.75
	Water	46.20	44.91	45.02	45.13	−1.29	−1.18	−1.07
	Barren	0.48	0.25	0.25	0.25	−0.23	−0.23	−0.23
	Impervious	3,217.88	3,468.86	3,435.71	3,483.57	250.98	217.83	265.69
GB	Cropland	482.74	383.79	385.15	382.48	−98.96	−97.60	−100.26
	Forest	62.79	72.50	71.66	72.32	9.71	8.87	9.53
	Grassland	0.30	0.04	0.03	0.03	−0.26	−0.27	−0.26
	Water	17.93	17.50	17.48	17.61	−0.43	−0.44	−0.32
	Barren	0.24	0.10	0.10	0.11	−0.14	−0.14	−0.14
	Impervious	973.06	1,063.21	1,062.65	1,064.43	90.15	89.59	91.37
Non-GB	Cropland	1,478.95	1,302.42	1,335.73	1,285.72	−176.53	−143.22	−193.22
	Forest	60.93	81.62	79.40	82.15	20.69	18.47	21.21
	Grassland	6.09	2.48	2.63	2.60	−3.61	−3.46	−3.48
	Water	28.27	27.41	27.53	27.52	−0.86	−0.74	−0.75
	Barren	0.23	0.14	0.15	0.14	−0.09	−0.08	−0.09
	Impervious	2,244.82	2,404.43	2,373.07	2,420.36	159.60	128.24	175.54

Forecasting of the future potential of carbon storage in urban GB

The geospatial distribution of carbon stocks in the Beijing GB under the 3 scenarios in 2035 would not change much compared with that in 2020, with the overall geospatial distribution of high values distributed in the western part of the GB in areas such as the West Mountain national forest park and Fragrant Hills Park, medium values distributed in the periphery of the GB in the inner part of the Sixth Ring Road, and low values distributed in the center of the GB in the outer part of the Fifth Ring Road (Fig. 5A to C). From 2020 to 2035, the carbon stock in Beijing's GB would be slightly reduced and basically unchanged (Fig. 5D to F). The carbon stock decreasing areas were distributed in all directions of the GB in a point-like manner, and the reduction of carbon stock was mainly driven by converting cropland to impervious. The carbon stock increasing areas were scattered in the western part of the GB in a point-like manner, and the increase of carbon stock was mainly driven by converting cropland and barren to forest.

All 3 scenarios showed a decreasing tendency in carbon stocks in 2035 compared to 2020 (Table 3). The carbon stock of the Beijing GB in 2035 under the ND scenario was 9.97 Mt, which was 0.62 Mt less than that in 2020. Under the EP scenario, the carbon stock was 9.97 Mt, and the carbon storage was 9.96 Mt under the ED scenario. From 2020 to 2035, the carbon stock in the non-GB areas of Beijing decreased from 26.80 Mt to 25.76 Mt under the ND scenario, a reduction of 1.04 Mt. The ED scenario decreased the most, with a decrease of 1.17 Mt, and the EP scenario decreased the least, with a decrease of 0.82 Mt. The reduction of carbon stocks in the GB was smaller than the reduction of carbon stocks in the non-GB areas under all 3 scenarios. This was due to different land-use policies, with the GB areas implementing policies that reduced built-up land and increased green space, which required enhanced ecological restoration work, and their development pressures were also lower.

In regard to the changes in carbon stocks of individual land-use categories, the carbon stocks of cropland, barren, water, and grassland in Beijing's GB and non-GB areas and the whole region under the 3 scenarios decreased in 2020 to 2035, while the carbon stocks of forest and impervious increased (Fig. 6). For the region as a whole, the ED scenario had the largest loss of carbon stocks in cropland at 3.40 Mt, followed by the ND scenario at 3.22 Mt, and the EP scenario exhibited a minimal reduction of cropland at 2.80 Mt. Carbon stocks in forest increased under all 3 scenarios, which was consistent with the tendency of increasing carbon stocks in forest over the period 2015 to 2020. The largest increase in carbon stock in impervious was 0.96 Mt due to the large growth in built-up areas in the ED scenario.

The carbon stock of Beijing's GB cropland in 2020 to 2035 decreased the most under the ED scenario, 1.16 Mt, and the least under the EP scenario, 1.14 Mt. Carbon stocks in forest increased under all 3 scenarios, while carbon stocks in grassland, water, and barren showed slight fluctuations to a lesser extent. Under the ED scenario, carbon stock in impervious increased the most, increasing by 0.33 Mt. From 2020 to 2035, the carbon stock of cropland in Beijing's non-GB areas decreased the most under the ED scenario, with 2.25 Mt, and decreased the least under the EP scenario, with 1.67 Mt. Similarly, the carbon stocks of forest increased under all 3 scenarios, and the carbon stocks of grassland, water, and barren showed slight fluctuations to a lesser extent. Impervious increased the most under the ED scenario, at 0.63 Mt.

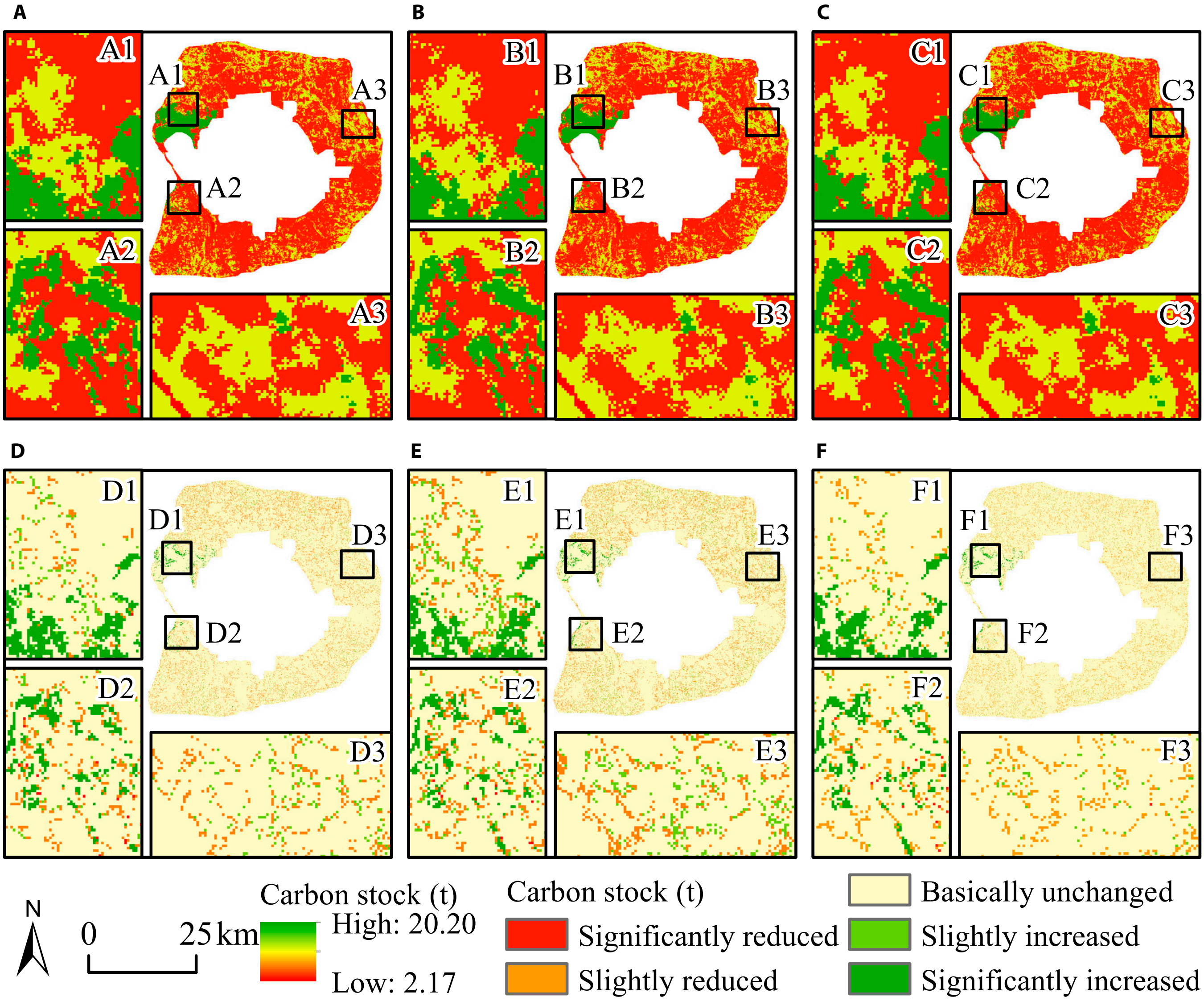

Fig. 5. Geospatial distribution of carbon stocks under 3 scenarios in Beijing GB in 2035 and spatial changes in carbon stocks from 2020 to 2035. (A) 2035 ND; (B) 2035 EP; (C) 2035 ED; (D) 2020 to 2035 ND; (E) 2020 to 2035 EP; (F) 2020 to 2035 ED.

Table 3. Comparison of GB, non-GB areas, and overall carbon stocks in 2035 and 2020 under the 3 scenarios (Mt)

		2035			2020–2035		
Different regions	2020	ND	EP	ED	ND	EP	ED
Total	37.39	35.72	35.95	35.60	−1.67	−1.44	−1.78
GB	10.59	9.97	9.97	9.96	−0.62	−0.62	−0.63
Non-GB	26.80	25.76	25.98	25.63	−1.04	−0.82	−1.17

Discussion

Comparison of spatial and temporal heterogeneity of carbon stocks between GB and non-GB areas

The carbon stocks in the GB and non-GB areas of Beijing exhibited a progressive downward tendency during the 2000 to 2020 period, and the carbon storage of diverse land-use categories showed significantly different nonlinear trends. Beijing's GB carbon stock decreased by 26.72%. The largest reduction of 1.17 Mt occurred between 2005 and 2010, a period of rapid urban expansion in which considerable quantities of urban green space was encroached upon by construction land. However, the carbon stock in the non-GB areas of Beijing decreased by 17.04%. The largest decrease was 1.88 Mt from 2000 to 2005. Since there was

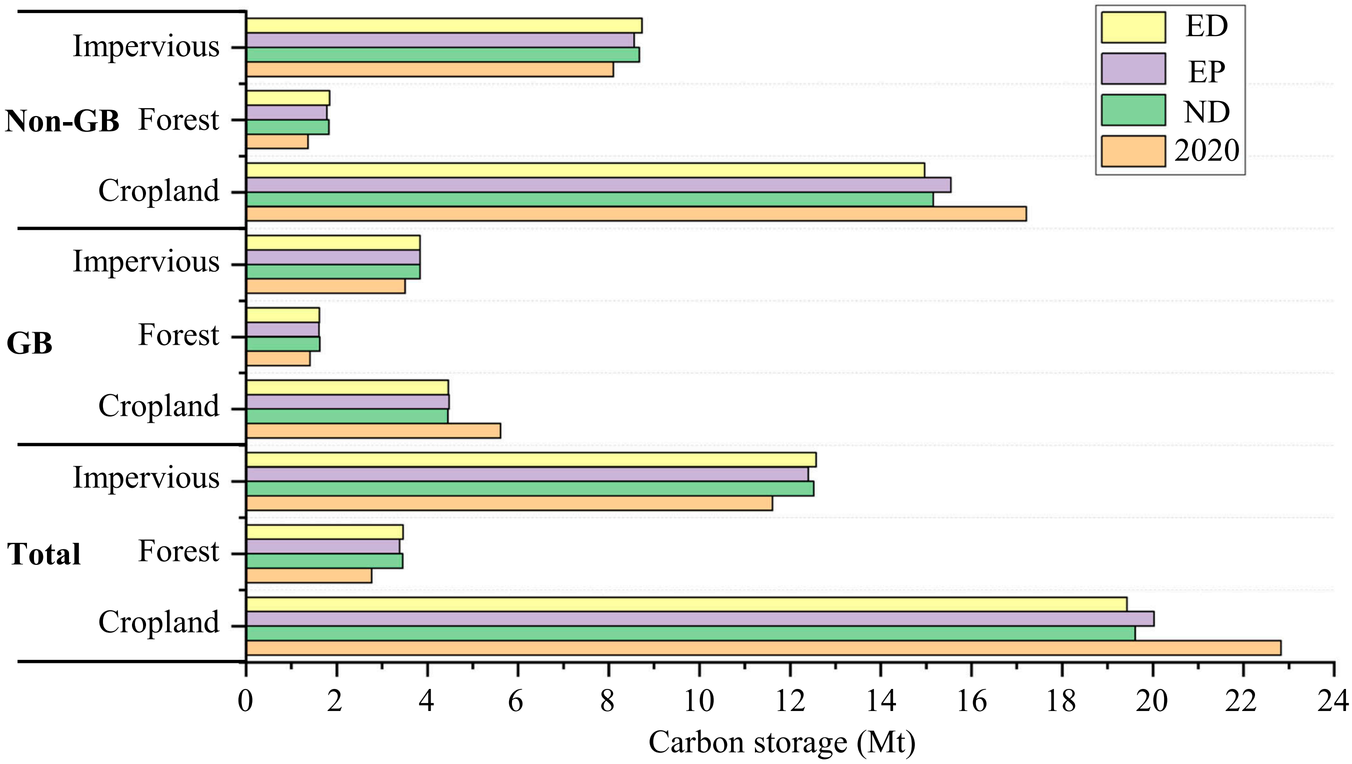

Fig. 6. Comparison of carbon stocks in various land-use types in urban green belt (GB) and non-green belt (non-GB) areas and the city as a whole in Beijing in 2035 and 2020 under economic development (ED), ecological protection (EP), and natural development (ND) scenarios (grassland, water, and barren with values below 0.12 are not shown in the figure).

a large amount of cropland on the periphery of the urban GB, and the further it was from the city center, the less it was affected by urban development; the rate of decline in carbon stock in the non-GB areas was lower than that in the GB [19].

According to the results obtained from the simulation, in the GB, the carbon stock reductions varied among the 3 scenarios, with the ED scenario showing the largest reduction of 0.62 Mt, trailed by the ND scenario and the EP scenario. In the non-GB areas, the reduction of carbon stocks under the 3 scenarios was ED scenario > ND scenario > EP scenario. In terms of changes in carbon stocks by land-use types, the EP scenario had the least loss of cropland and the least increase in impervious, while the ED scenario had the greatest loss of cropland and the greatest increase in impervious [36,37]. In summary, the EP scenario under the 3 scenarios was superior to the remaining 2 scenarios and should be further investigated to achieve optimal ecological and economic benefits.

Influence of spatial morphology and structure of urban GB on carbon storage function

Urban GB and urban fringe have geospatial consistency, but the urban fringe is much larger than the urban GB in width, and a rational spatial layout will reduce the encroachment of urban sprawl on the GB, which in turn will reduce the impact on the carbon storage function of the GB (Fig. 7). The failure of the Sydney urban GB project suggested that permanent urban GB should be spatially laid out to allow appropriate space for the proximate advancement of the city; otherwise, it would constrain the rational development of the city and can easily lead to the encroachment of the urban GB itself, or the spread of the city across the GB [38], which in turn affected its carbon storage function. Therefore, scientific analyses of the spatial layout of urban GB in marginal zones are still needed [39], and the GB carbon storage function can be truly realized through the reasonable spatial layout of urban GB in marginal zones. In addition, urban GB, with its nature-oriented attributes, may optimize the landscape ecological pattern and achieve the function of carbon storage by improving the ecological conditions in the urban fringe, thus reversing the ecological vulnerability of the urban fringe. The realization of this ecological function needs to be guaranteed by the reasonable form and scale of the urban GB [18]. From the practice of cities in various countries, there are 2 major types of urban GB: closed ring and noncyclic [13,40]. For urban fringe areas, a closed ring GB is more conducive to the formation of ecological corridors in the urban landscape ecosystem, which helps to improve the urban landscape ecosystem and realize its ecosystem carbon storage function [41]. The structure of the urban GB determines its landscape type and quantity. Thus, GB structure directly affects the ecological functions provided by GB [42], including carbon storage. For example, the "low center and high periphery" spatial pattern of carbon stock is due to the fact that the center of the GB is mainly impervious, while the periphery is dominated by cropland and forest. The greater the amount of green space in an urban GB, the greater the GB carbon stock. Since the carbon density of forest is the largest among green spaces, the larger the area of forest, the larger the carbon stock; thus, the carbon storage function of the GB is also stronger.

Conservation and spatial regulation of urban GB systems

The Beijing Action Plan for Adapting to Climate Change emphasizes the construction of a climate-friendly ecosystem, and by

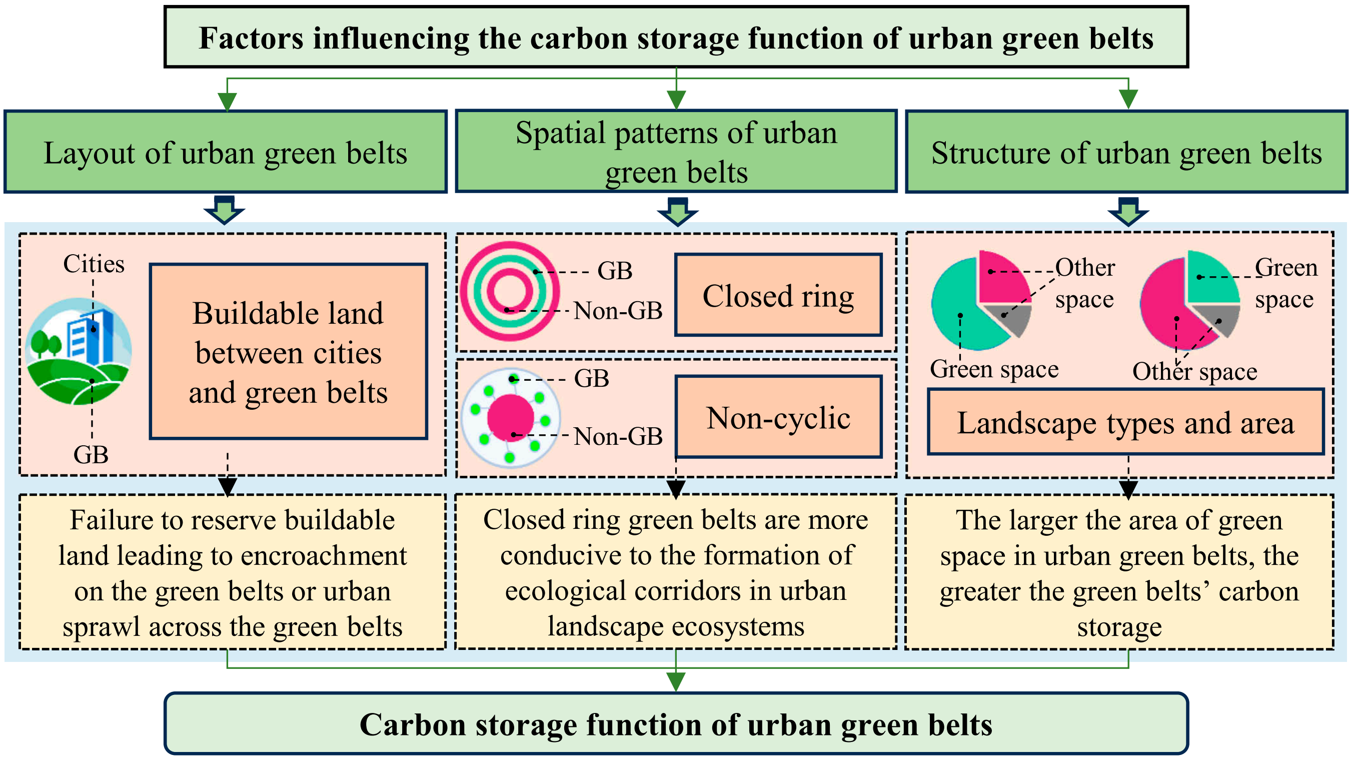

Fig. 7. Structural diagram of the influence of spatial morphology and structure of urban green belt (GB) on the function of carbon storage.

2035, the proportion of green open space in the second GB will increase to about 70%, enhancing the ecological service value of the GB. We quantified the potential carbon offsets of the GB by calculating the ratio of GB CO_2 uptake to urban CO_2 emissions [43]. We have calculated that the carbon stock of the urban GB in 2020 is 10.59 Mt, and we have determined that the total carbon emission of Beijing is 240.12 Mt based on other literature [43]. Therefore, the carbon offsetting capacity of the GB is 4.41%, indicating that the carbon storage in the GB plays an important role for Beijing to achieve the carbon neutrality targets. With the aim of improving the ecosystem carbon storage function of urban GB, the study puts forward recommendations on the protection and spatial regulation of GB systems from 3 aspects: urban–rural development and planning, GB form and scale, and institution and public support:

1. Ensure a rational spatial layout of urban GB in terms of urban–rural development and planning. Firstly, the layout of urban GB is reasonably determined in terms of urban development. As cities need to develop continuously, the process leads to the continuous enlargement of impervious, and it is hard to avoid expanding to the edge of the city within a certain period. Therefore, a certain amount of land should be reserved for future development between the built-up areas of the city and the urban GB. The size, shape, and location of the reserved land should be determined on the basis of the urban development strategy, the scale of urban land use and population, and the natural geographical conditions. Secondly, the planning of urban GB should be coordinated with relevant plans. The spatial layout of urban GB on the urban fringe needs to be examined in coordination with the spatial structure of cities, special plans at the city or regional level, and the requirements of territorial spatial master plans. Finally, when planning urban GB, it is necessary to have a broad and deep knowledge of the laws of urban green development [44]. Large-scale construction in GB is prohibited during the planning and construction stages. Misconceptions in the planning and designation of urban GB, such as regarding the GBs on either side of highways as GB, should be discarded, taking into account the need to make urban sprawl more resistant to natural factors, such as rivers and mountains, with the purpose of reducing the impacts of urban sprawl on the GB and increasing their carbon storage capacity [41,45].

2. Ensure the ecosystem carbon storage function of urban GB in terms of form and scale. The achievement of the carbon storage function of urban GB requires a reasonable form and scale of the GB as a guarantee. In terms of the form of the urban GB, a circular urban GB is more conducive to the construction of species habitats and the formation of ecological corridors, so as to make the urban landscape ecological system more complete. Therefore, urban GB should be planned so that, as far as possible, they form a basically continuous and closed ring. In terms of the scale of urban GB, the scale of GB varies in different countries and cities. The width of urban GB in London, UK, ranges from 10 to 30 km [41], the width of urban GB in Shanghai is 500 m with a length of 97 km [46], and the planned area of GB in Beijing was 297.2 km^2 in 2005 [19]. The scale of urban GB will have an impact on its ecological functions, and urban GB with too small a scale is difficult to realize ecosystem service functions and cannot be coupled with internal and external green space systems in the city.

3. Ensure the permanent effectiveness of urban GB in terms of institution and public support. Firstly, legislation on urban GB should be carried out, while the planning and management of urban GB should be strengthened. Countries such as France, Germany, and the United Kingdom have ensured the permanence

of urban GB through the enactment of relevant laws, and strengthened the planning and management of urban GB. Secondly, a long-term mechanism should be established. The construction of urban GB, as a long-lasting project with a long construction cycle, requires the strengthening of continuous post-construction management. Finally, public support is actively sought [47], making full use of the rich open space and tourism resources within the GB, realizing the recreational and leisure functions of the urban GB, making the public think that the GB is of great benefit and participate in the planning and construction of the GB, and formulating a more scientific and detailed planning program [48].

Limitations and perspectives

The 2 models used in this study have the benefits of easy access to data and easy implementation of calculations [49]. Nevertheless, this research simulated the carbon stock in Beijing's GB under 3 scenarios in 2035 based on 2 models, and there were certain uncertainties in the simulation process that may affect the results of the simulation [50]. Firstly, the carbon density data used to calculate carbon stocks with the InVEST model did not take into account the variability of vegetation types and growth conditions on the identical land category, and changes in carbon stocks were only shifted by land-use type. For example, forest can be categorized as woodland, shrub, open woodland, and other forestland, and grassland can be categorized as high-coverage grassland, mid-coverage grassland, and low-coverage grassland. Although they are the same land-use type, their aboveground carbon density, belowground carbon density, and soil carbon density all differ significantly, which may cause the estimated carbon stock to deviate from the actual carbon stock. Secondly, when using the FLUS model to predict the spatial distribution of land-use types, due to the more difficult data acquisition, there are fewer motivating factors for the conversion of each land-use type to each other, which will have a certain impact on the results of the prediction of the conversion of land-use types. Therefore, the following 2 aspects should also be strengthened in future studies: (a) Determine more realistic carbon densities for varying land-use categories, considering the features of the study area. (b) Strengthen multidisciplinary and cross-field investigations related to carbon storage services, and optimize the existing models of ecosystem services, so as to offer technical support for the further prediction of the effects of land-use changes on ecosystem services.

Conclusion

Our research compared and analyzed the dynamics of carbon stocks in the GB around the city and non-GB areas of Beijing during the 2000 to 2020 period to explore the ecosystem carbon storage function of the urban GB, and predicted the carbon storage of the urban GB under 3 scenarios in 2035 to explore its future carbon storage potential based upon land-use data, DEM data, socio-economic data and carbon density data, coupled with InVEST and FLUS models. The main findings are as follows: (a) The carbon stock in Beijing's GB from 2000 to 2020 decreased from 14.45 to 10.59 Mt, and its spatial distribution generally showed the characteristics of low center and high periphery. The carbon density of the GB in Beijing from 2000 to 2010 was greater than that of the non-GB areas, indicating that the GB had a substantial carbon storage function. (b) The carbon stock in Beijing's GB showed the spatial characteristics that the high-value zones were concentrated in the western part of the GB under 3 scenarios in 2035, such as the West Mountain National Forest Park and Fragrant Hills Park, the medium-value zones were distributed in the periphery of the GB in the inner side of the Sixth Ring Road, and the low-value zones were located in the center of the GB in the outer side of the Fifth Ring Road. The overall carbon stock in 2035 under the ED scenario was 35.60 Mt, with the largest reduction from 2020, 1.78 Mt. (c) The spatial layout, morphology, and structure of urban GB exerted pronounced effects on the carbon storage function, and the protection and spatial regulation of urban GB systems should be strengthened in the future in terms of urban and rural development and planning, GB morphology and scale, and institution and public support. The research quantitatively assessed the ecosystem carbon stock of urban GB, and predicted the future carbon stock in the GB through multi-scenario simulation, so as to investigate ways to enhance the land-use structure of urban GB to increase ecosystem carbon storage, which is substantial for ecosystem service improvement and climate change mitigation.

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Competing interests: The authors declare that they have no competing interests.

Data Availability

Data will be made available on request.

Supplementary Materials

Tables S1 to S3
Figs. S1 to S3

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Dynamic Assessment of Carbon Storage Function and Forecasting of Its Future Potential in Beijing's Green Belt

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Urban green belts (GBs) have multiple functions of providing ecosystem carbon storage services, improving urban microclimate, and inhibiting urban sprawl. However, there is a paucity of studies to assess the dynamics of the ecosystem carbon storage function of the GB around the city and forecast its future potential. Our study analyzed the dynamic changes of carbon stock in Beijing's GB during 2000 to 2020 and predicted the GB's carbon storage potential in 2035 by coupling the InVEST and FLUS models. Results showed that Beijing's GB carbon storage decreased from 14.45 to 10.59 Mt from 2000 to 2020. The carbon density of the GB in Beijing from 2000 to 2010 was greater than that of the non-GB areas, indicating that the GB had a substantial carbon storage function. The carbon stock in Beijing's GB showed the spatial characteristics that the high carbon stock zones were located in the western part of the GB under 3 scenarios in 2035. The overall carbon stock in 2035 under the economic development scenario was 35.60 Mt, with the largest reduction from 2020, 1.78 Mt. The spatial layout, morphology, and structure of urban GB had a notable effect on carbon storage function, and the protection and spatial regulation of urban GB systems should be strengthened in the future in terms of urban–rural development and planning, the morphology and scale of GB, and institution and public support.
Image

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