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Spatiotemporal variation and dynamic simulation of carbon stock based on PLUS and InVEST models in the Li River Basin, China

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The watershed is the optimal natural division for ecosystems, playing a crucial role in carbon reduction and sequestration. Exploring the carbon sequestration potential of terrestrial ecosystems under different land use scenarios and enhancing regional carbon storage capacity is of significant importance. In this study, the LUCC in the Lijiang River basin under the scenarios of natural evolution (NE), natural conservation (NC), urban developmentand (UD) and farmland protection (FP) in 2040 was simulated by using grid data, driver grid data and carbon density data, based on the PLUS model and the InVEST model. Then, the effects of land use change on carbon stock in the Lijiang River Basin from 2000 to 2040 were evaluated. The results show that, (1)from 2000 to 2020, the area of arable land significantly increased in the Li River Basin, while forest and grassland areas decreased significantly. The distribution pattern of land use in the Li River Basin is mainly influenced by factors such as economy, population density, topography, and roads. Population growth and economic development require more arable land, forest land, and construction land. (2)Due to land use change, the carbon stock in the Li River Basin decreased by 3.69×10^6 t over the 20-year period, particularly in the northern and southern regions of the basin. (3)Meanwhile, there was a significant change in the land use pattern, with forest carbon stock accounting for a reduced proportion (90.76%) of the total ecosystem carbon stock in 2020. (4)According to the projected natural evolution scenario, the carbon stock in 2040 will decrease by 3.13×10^6 t compared to 2020 in the Li River Basin. Under the scenario of arable land protection, the carbon stock will decrease significantly. Under the ecological protection scenario, the carbon stock of the terrestrial ecosystem will increase by 2.75×10^5 t. Under the urban development scenario, the carbon stock caused by land use change will be uncertain; however, construction land increase will definitely cause the decrease of carbon stock.This study examines the impact of land use change scenarios on carbon storage in the Li River Basin, highlighting the potential carbon gains under the ecological conservation scenario, providing valuable insights for regional land use planning and carbon reduction strategies.

Watershed is considered the optimal natural unit for ecological research[1]. It consists of a series of interconnected water bodies and surrounding lands, forming a relatively independent ecosystem. These watershed ecosystems are vital for mitigating greenhouse gas emissions, as they have the capacity to absorb and store large amounts of carbon[2]. Additionally, they play a key role in carbon sequestration by regulating water circulation and influencing soil quality[3]. Furthermore, watershed ecosystems are integral to the global carbon cycle and contribute significantly to climate regulation[4]. However, deforestation, unsustainable land development, and agricultural land expansion disrupt the integrity of watershed ecosystems, leading to carbon emissions and carbon stock reduction, further exacerbating greenhouse gas emissions and climate change[5]. Therefore, exploring land use patterns and their changes in different scenarios, protecting and restoring watershed ecosystems, and optimizing land use structure have become an important strategy for carbon reduction and sequestration. Land use scenario simulation plays a key role in quantifying the impact of land use change on ecosystem carbon stock[6]. Some scholars use quantitative models to predict future land use demands, but they cannot reveal the causal relationship

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between driving factors and land use changes or identify land use patterns spatially[7–9]. To address these issues, coupling quantitative and spatial predictive models has become a new research tool[10]. However, existing models have some limitations. For example, the Cellular Automaton (CA) model cannot simulate multiple land use types[11], the Conversion of Land Use and its Effects at Small regional extent (CLUE-S) model has prediction errors in the allocation process and limited applicability[12], and the FLUS model, while relatively good, struggles to simulate the spatiotemporal dynamics of multiple land use types at the patch level. However, the PLUS model effectively overcomes the limitations of other models by incorporating the Land Use Elasticity Allocation Strategy (LEAS). LEAS enables the PLUS model to accurately capture the causal relationships between various factors influencing land use changes, such as socio-economic dynamics, population growth, and agricultural demand. By introducing elasticity parameters, the PLUS model is capable of simulating land use allocation responses to these driving factors, ensuring accuracy even under complex, multi-type land use conditions.Moreover, the PLUS model can simulate land use changes at a higher spatial granularity, which is crucial for studying patch-level dynamics and spatiotemporal variations. Its flexibility allows it to predict land use changes effectively in regions with diverse land cover types and complex socio-economic conditions, ensuring that the results are more accurate and reflective of actual land use processes. The model's strong performance in predictive research further supports its suitability for addressing the challenges posed by complex land use dynamics in our study. Therefore, the PLUS model was chosen for this study, because it introduces the LEAS to better explore the causal relationship of land use changes and accurately simulate the changes in multiple land use types, showing good performance in predictive research[13].

Carbon stock assessment is a crucial component of global climate change research and carbon emission management. As the understanding of natural ecosystems' carbon sequestration capacity deepens, accurately estimating carbon stocks under different land use types is of great significance for formulating effective carbon reduction policies and promoting sustainable development. In recent years, with the advancement of GIS technologies, model-based carbon stock assessment methods have gradually become mainstream. Among these, the InVEST model, an integrated ecosystem service evaluation tool, has been widely used for carbon stock calculations. The model, by combining remote sensing data with GIS technology, enables the precise estimation of carbon stocks and their spatial distribution across various land use types, providing a scientific basis for ecological conservation and management.Compared to field survey methods, the InVEST model integrates comprehensive assessment, spatial analysis capabilities, consideration of ecosystem processes, data-driven approaches, and user-friendliness to assess the dynamics of carbon storage under land use changes. It provides researchers with an effective tool to evaluate the impact of different land use types on carbon storage[14–17].

In recent years, human activities have caused significant changes in land use and land cover in the Li River Basin, particularly driven by construction land, urbanization, and tourism development[18]. These changes have directly or indirectly affected the ecosystem. Therefore, the study of carbon stock in the Li River Basin ecosystem has attracted the attention of researchers. Lan et al. explored the spatiotemporal patterns of carbon stocks in forest vegetation in GuangXi[19–21]. Most studies assessed the carbon stocks of individual ecosystems through field survey, focusing on carbon storage of a single ecosystem. However, the carbon stocks of ecosystems are interconnected and mutually influenced[22].

The above results provide a scientific basis for the study of carbon stock in the Li River Basin ecosystem. However, there are still some limitations. Firstly, field survey methods are not suitable for large-scale and long-term time series studies, as they cannot dynamically capture the spatiotemporal patterns and evolution of carbon stock. Additionally, focusing on a single ecosystem or carbon pool cannot comprehensively reflect the current status and development trend of terrestrial ecosystem carbon stock. Secondly, existing studies have not sufficiently emphasized the simulation of future land use scenarios and the resulting changes in carbon stock, making it difficult to provide effective support for optimizing land use structure and decision-making under low-carbon development.The aim of this study is to use the PLUS model and InVEST model to analyze land use changes in the Li River Basin from 2000 to 2020 and their impact on carbon stocks, as well as to predict the changes in carbon stocks under different development scenarios in 2040. Through a systematic dynamic analysis of carbon stocks, this study seeks to provide scientific support for land use planning and ecological protection in the Li River Basin, contributing to the formulation of regional low-carbon development strategies.

Data sources and research methods
Over of the study area
The Li River Basin is located between 24°38'10" N and 25°53'59" N latitude, and 110°07'39" E and 110°42'57" E longitude. The basin covers an area of 5831.50 square kilometers and includes the entire territory of DieCai District, XiuFeng District, QiXing District, XiangShan District, and YanShan District of GuiLin Counties in GuangXi, as well as parts of Resource Counties, Xing'an Counties, LingChuan Counties, LingShan Counties, YangShuo Counties, and PingLe Counties (Fig. 1). The Li River is the upper reaches of the Li River Basin and serves as the mother river of GuiLin. The Li River Basin is rich in historical relics, beautiful natural landscapes, and a good ecological environment. It is particularly known for its karst landform landscapes, which have the largest global distribution, the highest aesthetic value, and are the most typical and irreplaceable. These landscapes are the soul and essence of GuiLin's scenery. The upstream areas of the Li River, including Mao'er Mountain, QingShi Pool, and HaiYang Mountain, have a relatively high forest coverage rate, and the forest vegetation in high-altitude areas is well-preserved. These vegetation, especially the evergreen broad-leaved forests, serve as the "green reservoir" of the Li River source. The two main land cover types within the basin are arable land and forest land.The socio-economic development of the Li River Basin in Guilin, Guangxi, is primarily driven by agriculture, tourism, and the service industry, with tourism being particularly prominent, attracting a large number of visitors. As urbanization accelerates, infrastructure and transportation networks in the basin have gradually improved, but challenges related to land use changes and environmental protection remain.
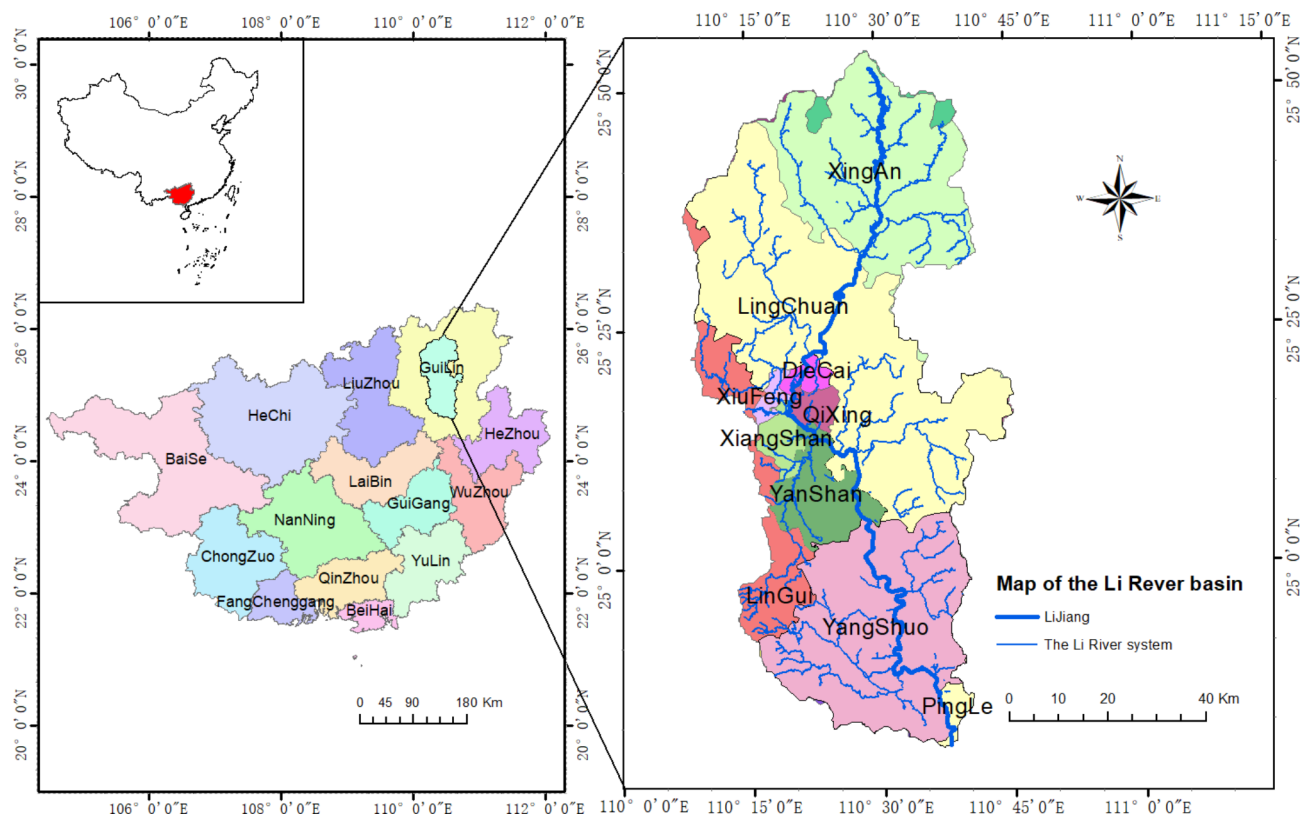
Fig. 1. Map of the Li River Basin.

Data Category	Data Subcategory	Data Name	Data source	Unit/ Interval
Land use	Land use maps in 2000, 2010, 2020		CERN	30 m
Natural	Topography	Elevation	Geospatial data cloud platform	30 m
		Slope		30 m
	Climate	Average annual precipitation	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences	1 km
		Average annual temperature		1 km
	Soil	Soil type		1 km
	River system	Distance to river		30 m
Socioeconomic factors	Population	Population density		1 km
	Economic development	GDP		1 km
	Traffic accessibility	Distance from the primary road		30 m
		Distance from the secondary road		30 m
		Distance from the tertiary road		30 m
		Distance from the rallway		30 m
	Government accessibility	Distance from a prefecture-level city and the county seat		30 m
Limiting factor	Nature Reserve	Vector Map of the Li River Basin Nature Reserves		30 m

Table 1. Source of data.

Source of data

Land use data is sourced from the CERN (European Organization for Nuclear Research) Data Center (https://zenodo.org/records). Digital Elevation Model (DEM) data is obtained from the Geospatial Data Cloud Platform (http://www.gscloud.cn). Other data is sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn), including natural factors, socio-economic factors, and constraint factors (Table 1; Fig. 2). Subsequently, ArcGIS is used to process the acquired data and obtain 13 types of land use change driving factors.
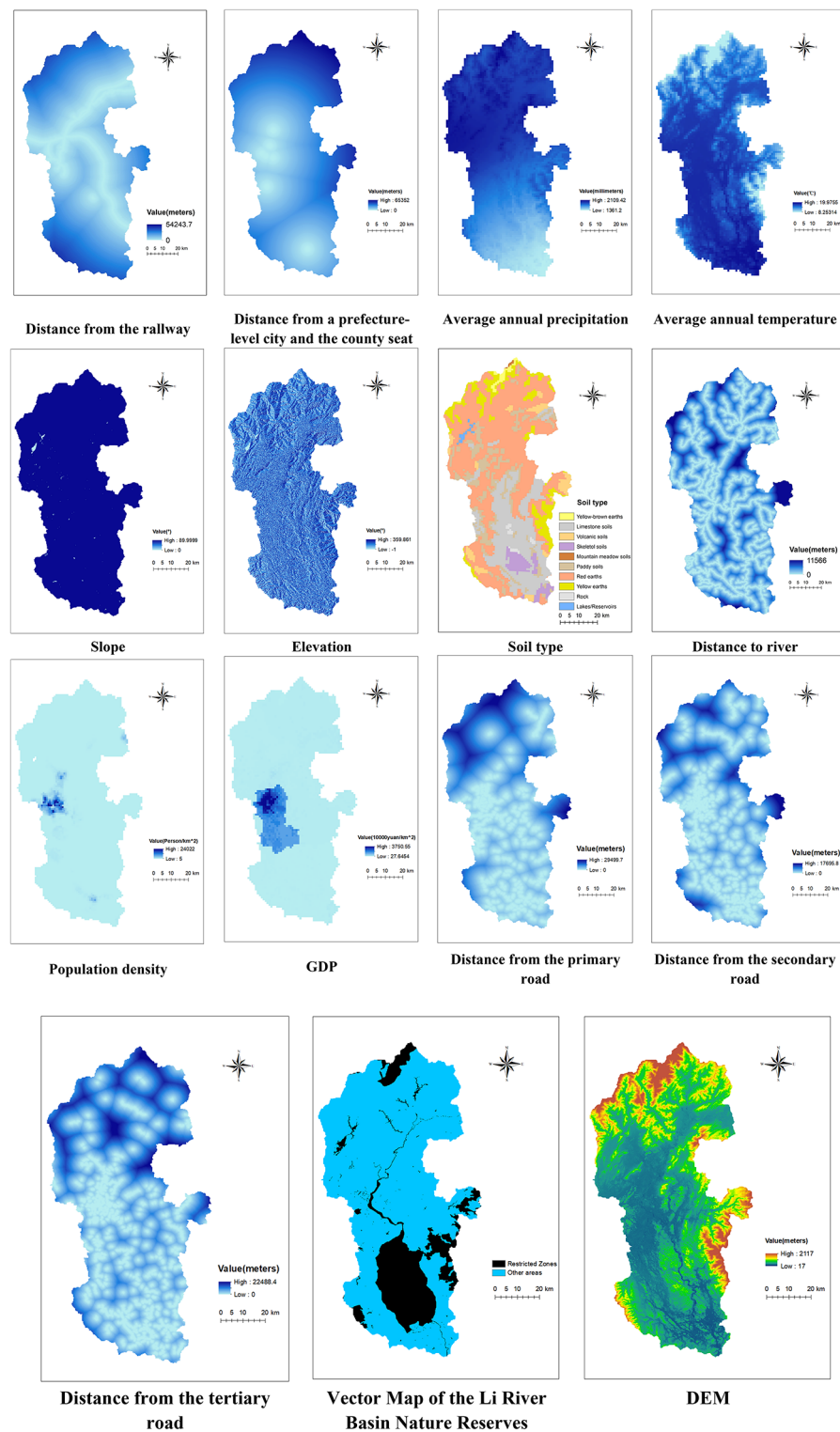
Fig. 2. Driver Factor and Restricted Zones Details.

Research Method

Land Use Change Prediction based on the PLUS Model

The PLUS (Patch-Generating Land Use Simulation) model is a grid-based land use change simulation model. This model employs a novel analytical strategy to identify the drivers of land use change. It utilizes a multi-class seed growth mechanism to simulate changes at the patch level for different land use types. Additionally, it is coupled with a multi-objective optimization algorithm to support sustainable development in planning policies[23].

Scenario	Cropland	Forest	Grassland	Waters	Construction land	Unused land
Natural evolution	0.243019	0.571009	0.141058	0.015021	0.029640	0.000252
Farmland protection	0.385483	0.456808	0.112847	0.015021	0.029640	0.000201
Natural conservation	0.194415	0.598301	0.168350	0.015021	0.023712	0.000201
Urban development	0.241903	0.570522	0.140782	0.014995	0.031547	0.000251

Table 2. LEAS values of land use types under different scenarios.

Scenario	Farmland protection						Natural conservation						Urban development						natural evolution					
Land-Use	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F
A	1	0	0	0	0	0	1	0	1	1	0	1	1	0	1	0	1	1	1	0	1	0	0	1
B	1	1	1	0	0	1	0	1	1	1	0	0	1	1	1	0	1	1	0	1	1	0	0	1
C	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	0	1	1
D	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0
E	1	0	0	0	1	1	0	1	0	0	1	1	0	0	0	0	1	0	0	0	0	0	1	1
F	1	1	1	0	1	1	0	1	1	1	0	1	1	1	1	0	1	1	1	0	1	0	1	1

Table 3. Land Use Type Transition Matrix for different Scenarios.A ~ F correspond to cultivated land, forest, grassland, water area, built-up land, and unused land.

The Land Expansion Analysis Strategy (LEAS) is a method and strategy for evaluating land use expansion. In this study, land use data from 2000 to 2010 were input into the LEAS module to extract areas of change for each land use type. The extracted factors and drivers were sampled together, and the Random Forest algorithm was used to individually analyze the expansion of each land use type and the contributing factors. This approach provided the development probabilities for each land use type and quantified the contribution of each driver to the expansion of land use during the specified period, thereby predicting the land use patterns for 2020. Following accuracy validation, land use data from 2000 to 2020 were re-entered into the LEAS module, and the same algorithm was used to determine the development probabilities for each land use type. Subsequently, the land use patterns for 2040 under different scenarios were predicted (Table 2).

Based on the ratio of land use expansion area and transfer probability, combined with the accuracy and kappa coefficient of the land use simulation in 2020, the simulation results are optimized through multiple rounds of calibration. Finally, the land use type transition matrix is determined.

According to the needs of conservation and development in the Li River Basin, this study sets four different scenarios: natural evolution, farmland protection, natural conservation, and urban development. Based on the land use transition matrix from 2000 to 2020 and using the Markov model, the land use pattern in the Li River Basin for the year 2040 is predicted (Table 3).Natural Evolution Scenario: In this scenario, future land use demands are predicted based on the results of the Markov model. The neighborhood weight coefficients are set according to the proportional expansion of land use types in the Pearl River Basin from 2000 to 2020.Farmland Protection Scenario: This scenario builds upon the natural evolution scenario by restricting the conversion of farmland to other land types, thereby ensuring the preservation of farmland area and achieving farmland protection.Natural Conservation Scenario: This scenario primarily focuses on the development of ecological environments. Based on the ecological protection planning goals of the Pearl River Basin, and using the natural evolution scenario as a foundation, ecological land is restricted from being converted to other land types, while water bodies are designated as restricted zones.Urban Development Scenario: This scenario prioritizes the sustainable development of urban areas and rational land use planning. It is based on the natural evolution scenario, allowing the conversion of land for urban development to other land uses in order to meet the demands of urban growth.

Assessment of Ecosystem Carbon Stock based on the InVEST Model

1.Carbon Stock calculation

The carbon stock is calculated based on the InVEST model. The InVEST carbon pool includes four carbon stocks: above ground biomass carbon (C_{i_above}), below ground biomass carbon (C_{i_below}), soil carbon (C_{i_soil}), and dead organic carbon (C_{i_dead}). The model simulates carbon stock based on land use data for each period and the corresponding carbon density, using the following formula:

$$C_{tot} = \sum\nolimits_{i=1}^{n} \left(C_{i\_above} + C_{i\_below} + C_{i\_soil} + C_{i\_dead} \right) * A_i \tag{1}$$

In Eq. (1), C_{tot} represents the total carbon stock of the ecosystem, C_{i_above}、 C_{i_below}、 C_{i_soil} and C_{i_dead} represent the above ground biomass carbon density, below ground biomass carbon density, soil carbon density, and dead organic carbon density of land use type i, respectively. *Ai* represents the area of land use type i, and *n*is the number of land use types[24].

Land use types	C_{i_above}	C_{i_below}	C_{i_soil}	C_{i_dead}
Cropland	13.49	2.68	47.4	1
Forest	105	25.5	96	29
Grassland	3.01	13.53	60	1
Waters	2.8	2.4	0	0
Construction land	11.45	0.93	1	0
Unused land	3.40	0.211	31.4	34.8

Table 4. Carbon Density table for different land types (t/hm^2).
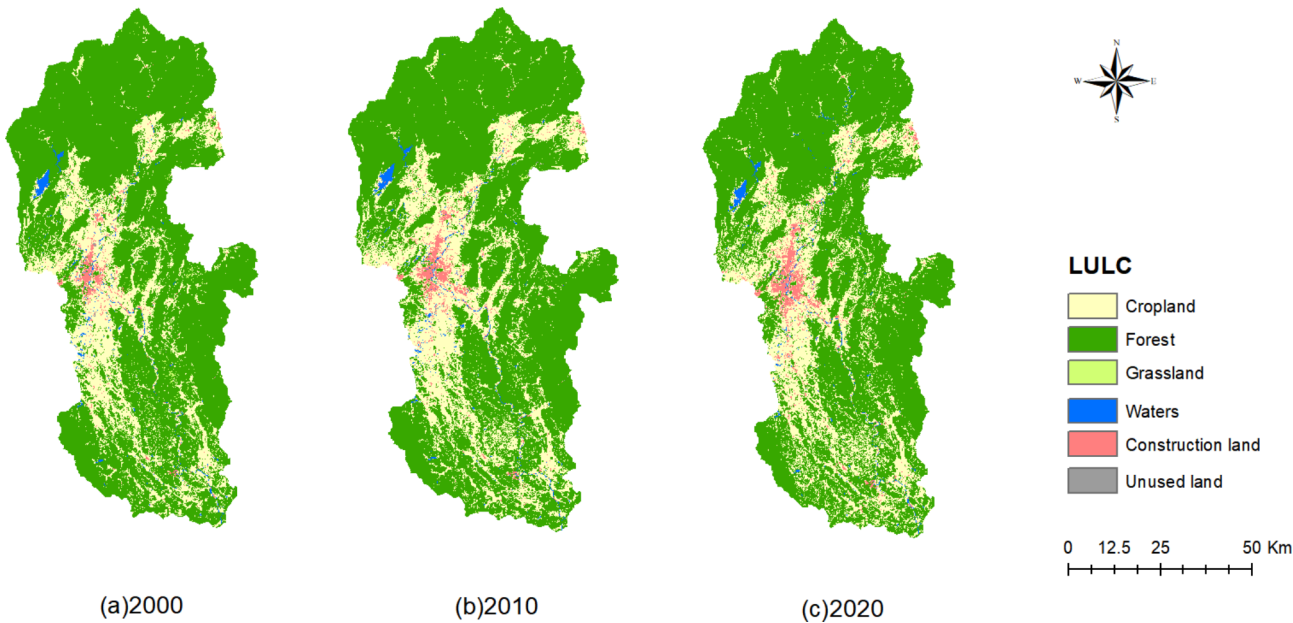
Fig. 3. Land Use Changes in the Li River Basin.

2. Carbon Density Adjustment

Different land cover types require carbon density data for the InVEST model. Based on relevant research in the Li River Basin and the Carbon Density Dataset of Terrestrial Ecosystems in China, carbon density data for the Li River Basin are adjusted, resulting in a carbon density table for the Li River Basin[25,26] (Table 4).

Methodology

Firstly, the study established a simulation framework based on the PLUS and InVEST models by collecting and organizing grid data, driving factor grid data, and carbon density data. Next, these data were used to simulate land use changes (LUCC) in the Li River Basin from 2000 to 2040, considering four scenarios: Natural Evolution (NE), Nature Conservation (NC), Urban Development (UD), and Farmland Protection (FP). Subsequently, the impact of land use change on carbon storage was assessed. Finally, by comparing carbon storage changes across different scenarios, the long-term effects of land use changes on basin carbon storage and the predicted outcomes were analyzed.

Results

Land use change and spatial-temporal characteristics of carbon stock in the li river basin

Land use distribution and change

The Li River Basin is one of the most important basins in GuangXi and a significant factor in the agricultural and tourism development of GuiLin City. As shown in Fig. 3, the area of cultivated land in this region has significantly increased. However, due to human activities such as deforestation, land development, and urbanization, the forest area in the Li River Basin has decreased by 148.13 km^2 over the past twenty years, resulting in considerable damage and reduction in forest resources. The Li River Basin consists of a wide range of water bodies, including major rivers, lakes and reservoirs, estuaries, and wetlands. The water area in the Li River Basin has decreased by 0.17 km^2 during the same period, which can be attributed to various factors including natural processes and human activities such as climate change, reservoir construction, and river channel regulation. From 2000 to 2020, the built-up area in the Li River Basin increased by 0.97 km^2, which has had a certain impact on the carbon

Land use types	Cropland	Forest	Grassland	Waters	Construction land	Unused land	Total Areas
Cropland	1244.4381	55.6794	0.1917	1.6659	4.644	31.0248	1337.6439
Forest	217.9791	4159.0431	3.4515	0.3303	0.2619	2.7396	4383.8055
Grassland	2.6154	20.2707	7.758	0.27	0	0.0018	30.9159
Waters	1.2213	0.3537	0.1386	1.6011	0.2529	0.5859	4.1535
Construction land	4.0653	0.3231	0.0009	0.1107	50.1885	0.7857	55.4742
Unused land	0.0513	0.0018	0	0.0009	1.098	86.499	87.651
Total Areas	1470.3705	4235.6718	11.5407	3.9789	56.4453	121.6368	
Change in area	−132.7266	148.1337	19.3752	0.1746	−0.9711	−33.9858	

Table 5. Land Use Type Transition Matrix from 2000 to 2020 (km^2).
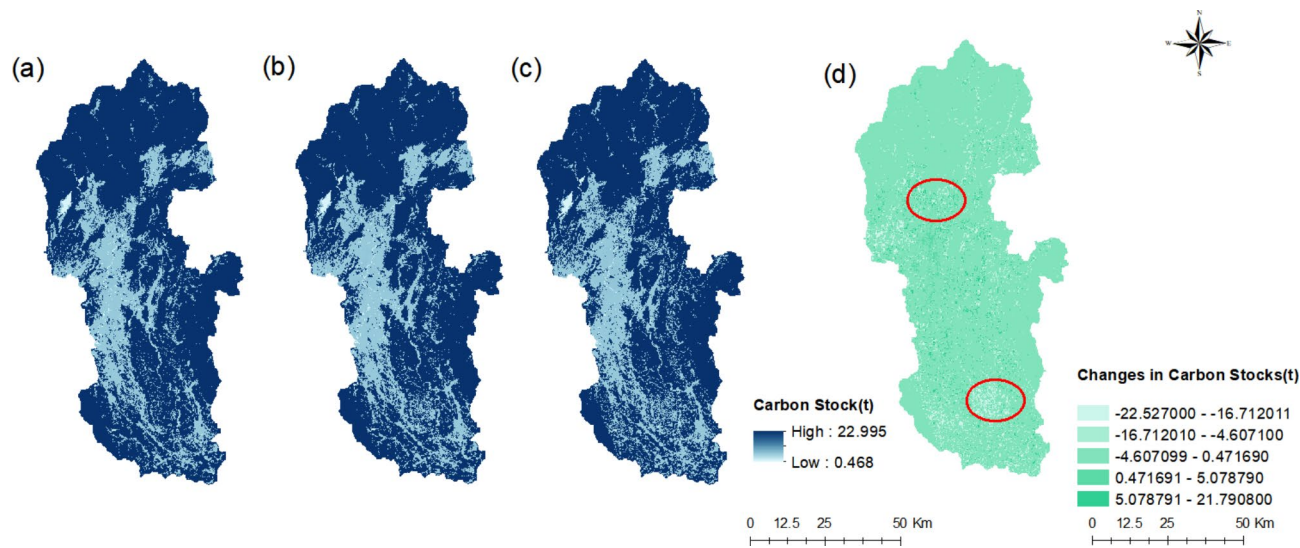
Fig. 4. Carbon Stock Changes from 2000 to 2020.(**a**) Spatial Distribution of Carbon Stock in 2000;(**b**) Spatial Distribution of Carbon Stock in 2010;(**c**) Spatial Distribution of Carbon Stock in 2020;(**d**) Spatial Changes in Carbon Stock from 2000 to 2020.

	2000		2010		2020	
Type of land use	Carbon/tC	Proportion	Carbon/tC	Proportion	Carbon/tC	Proportion
Cropland	8.49×10^6	7.114%	9.33×10^6	8.007%	9.46×10^6	8.181%
Forest	1.10×10^8	92.122%	1.06×10^8	91.137%	1.05×10^8	90.755%
Grassland	2.36×10^5	0.198%	8.76×10^4	0.075%	4.67×10^4	0.040%
Waters	2.11×10^3	0.002%	2.03×10^3	0.002%	1.01×10^3	0.001%
Construction land	7.28×10^4	0.061%	7.41×10^4	0.064%	6.92×10^4	0.060%
Unused land	6.01×10^5	0.503%	8.34×10^5	0.716%	1.11×10^6	0.963%
Total	1.19×10^8	1	1.17×10^8	1	1.16×10^8	1

Table 6. Carbon Stock Changes in different land uses in the Li River Basin from 2000 to 2020.

stock in the basin. Moreover, during the same period, the grassland area in the Li River Basin decreased by 19.38 km^2, while the unused land area increased by 33.99 km^2 (Table 5; Fig. 4).

Carbon stock changes
Using the InVEST model, calculations were conducted to assess the spatial distribution of carbon stocks in the Li River Basin for the years 2000, 2010, and 2020 (Fig. 4; Table 6). From 2000 to 2020, the carbon stock in the Li River Basin decreased from 1.19×10^8 t to 1.16×10^8 t, a reduction of 3.69×10^6 t. In 2000, forest carbon accounted for 92.12% of the total ecosystem carbon stock in the basin, while in 2020, forest carbon accounted for 90.76% of the total ecosystem carbon stock. Forests are generally considered to be one of the largest carbon reservoirs in terrestrial ecosystems, indicating significant land use changes over the two-decade period. Changes

in land use have led to the conversion of natural carbon sinks, such as forests and grasslands, into carbon sources. Natural ecosystems like forests accumulate carbon through photosynthesis and the organic matter stored in vegetation and soil, exhibiting high carbon storage capacity. When these ecosystems are transformed into agricultural land or urban areas, the carbon stored in vegetation and soil is often released into the atmosphere in the form of carbon dioxide (CO_2), resulting in a decrease in carbon stocks in terrestrial ecosystems[27,28]. Land use changes also impact soil carbon storage. Natural ecosystems such as forests and grasslands have higher soil organic carbon content, while soils in agricultural or urban areas typically have lower organic carbon content. For example, when land is converted from forests or grasslands to cropland or developed areas, soil carbon stocks tend to decrease.

Future land use scenarios and carbon stock predictions

The PLUS model was validated using overall accuracy (OA) and kappa coefficient to ensure its applicability in the study area. Both OA and kappa coefficient range from 0 to 1, with values closer to 1 indicating higher simulation accuracy. When the value exceeds 0.75, the simulation accuracy is considered reliable[29]. The accuracy verification of the 2020 land use status and predicted results showed an OA value of 87.95% and a kappa coefficient of 0.7871, indicating a high simulation accuracy that meets the research requirements.

Future land use predictions
Based on the PLUS model and 2020 land use data, scenario simulations were conducted to obtain land use predictions for the year 2040 under the following scenarios: natural evolution, farmland protection, natural conservation, and urban development (Figs. 5 and 6).

In the natural evolution scenario, the area of farmland in the Li River Basin is projected to decrease by 103.60 km^2 in 2040 compared to 2020, accompanied by an increase of 297.63 km^2 in forested areas. The reduction in forests and grasslands leads to ecosystem degradation, loss of biodiversity, degradation of soil quality, soil erosion, and excessive water resource utilization, ultimately impacting the carbon stock in the Li River Basin.

In the farmland protection scenario, the area of built-up land in the Li River Basin is projected to reach 51.38 km^2 in 2040, increasing by 5.06 km^2 compared to 2020. With economic development and urbanization, the level of urbanization in the Li River Basin will continue to rise, requiring more land for construction to meet the demands of urban development. Assuming the current macro-control policies and land use regulations remain unchanged, the area of farmland in the Li River Basin will reach 1451.29 km^2, increasing by 19.08 km^2 compared to 2020. The forested area will reach 4033.93 km^2, with respective increases of 201.74 km^2.

In the natural conservation scenario, the forested and grassland areas in the Li River Basin are projected to increase by 117.77 km^2 and 4.63 km^2, respectively. The improvement of the ecological environment will also lead to an increase in water area by 2.08 km^2. The increase in forested and grassland areas has a positive impact on carbon stock, contributing to mitigating climate change to some extent.

In the urban development scenario, the area of built-up land in the Li River Basin is projected to reach 56.71 km^2 in 2040, while the farmland area is expected to decrease by 103.69 km^2 compared to 2020. Guilin City is one of the relatively economically developed areas in Guangxi. With economic development
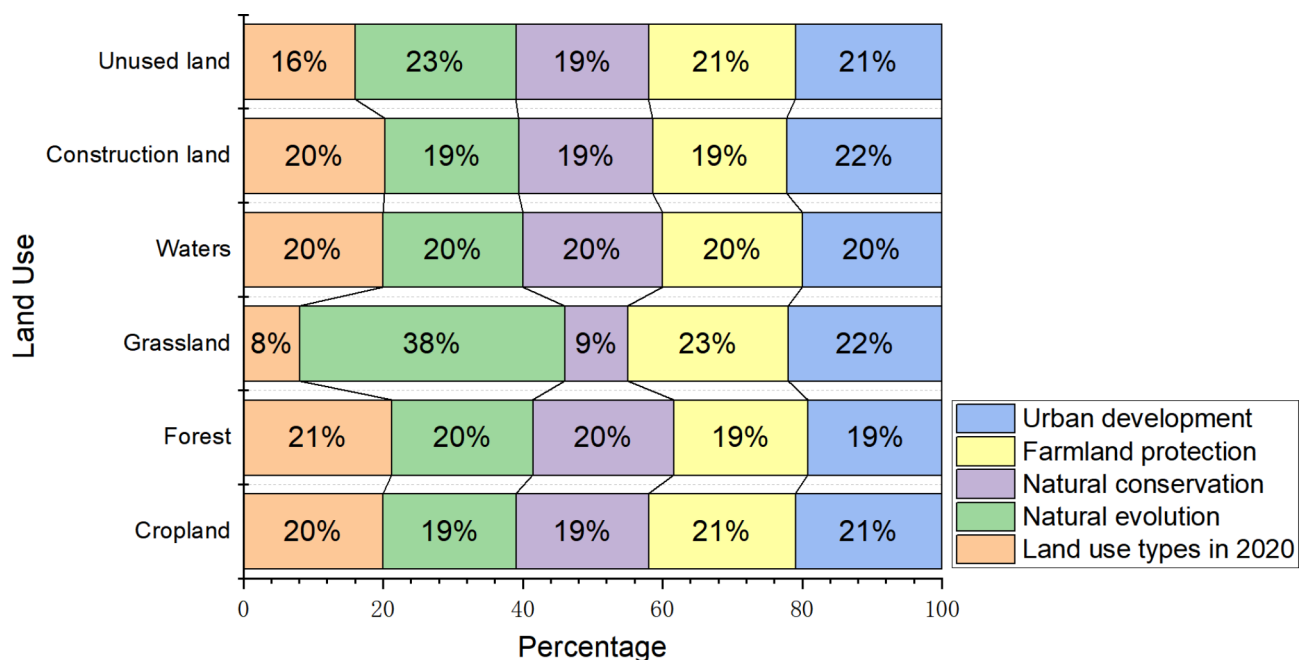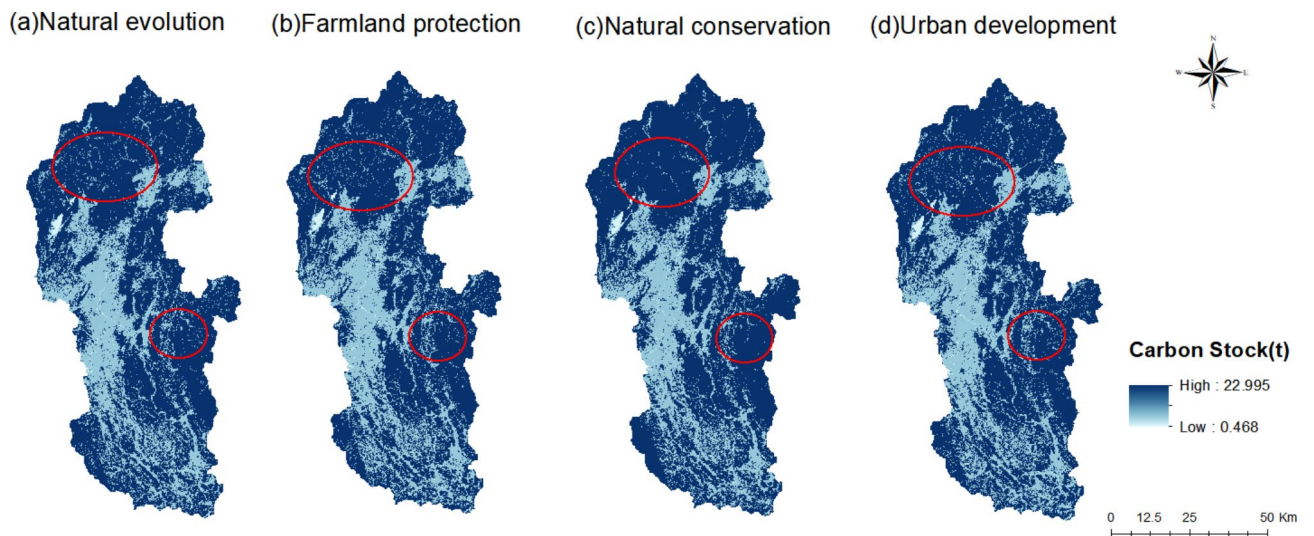

Fig. 5. the Predicted Proportion of Land Use In the Li River Basin.

(a)Natural evolution   (b)Farmland protection   (c)Natural conservation   (d)Urban development
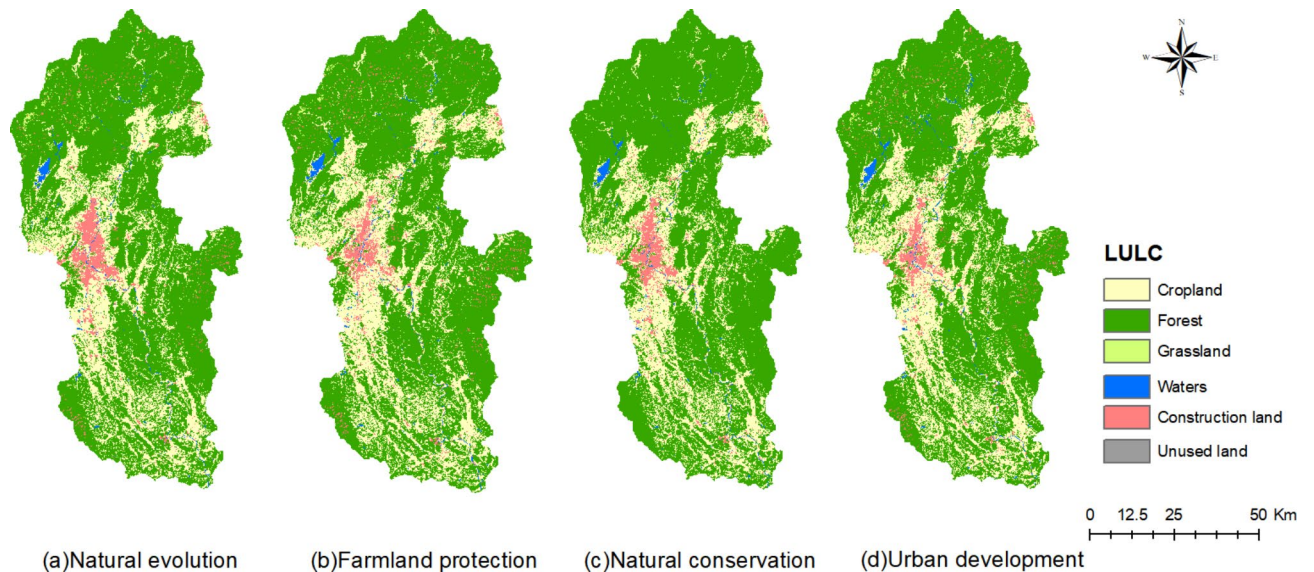
Fig. 6. Displays the Predicted Land Use In the Li River Basin.

Fig. 7. Spatial Variation Characteristics of Carbon Storage in Different Land Uses in the Li River Basin under Different Scenarios.

and a growing urban population, the urbanization process is likely to accelerate more in the urban areas of Guilin City compared to other areas in the Li River Basin.

Future carbon storage prediction

From Fig. 7; Table 7, it can be observed that under the natural evolution scenario, the grassland carbon storage in the Li River Basin is projected to increase by 1.83×10^5 t in 2040, while the forest carbon storage is expected to decrease by 1.92×10^6 t. Compared to the total terrestrial ecological carbon stock in the basin in 2020, there is a reduction of 1.28×10^6 t. The significant decrease in carbon storage is mainly distributed in the northern and southern parts of the Li River Basin. This implies that the increase in grassland carbon storage cannot compensate for the decrease in carbon storage in other regions, especially in the significantly affected northern and southern parts of the Li River Basin. Factors such as land use change, deforestation, and land degradation contribute to the decrease in carbon storage in these areas, resulting in carbon emissions and losses.

Under the farmland protection scenario, the carbon storage in croplands is projected to increase by 1.67×10^6 t in 2040, while the carbon storage in forests and grasslands is expected to decrease by 9.35×10^6 t and 1.0×10^4 t, respectively. The water bodies and construction land are projected to decrease by 1.1×10^3

Type of land use	Natural evolution		Farmland protection		Natural conservation		Urban development	
	Carbon/tC	proportion	Carbon/tC	Proportion	Carbon/tC	Proportion	Carbon/tC	Proportion
Cropland	1.02×10^7	9.03%	9.37×10^6	8.191%	9.23×10^6	7.962%	1.02×10^7	9.033%
Forest	1.01×10^8	89.40%	1.03×10^8	90.092%	1.05×10^8	90.735%	1.01×10^8	89.421%
Grassland	1.37×10^5	0.12%	2.30×10^5	0.201%	5.36×10^4	0.046%	1.34×10^5	0.119%
Waters	1.01×10^3	0.00%	1.01×10^3	0.001%	9.86×10^2	0.001%	1.01×10^3	0.001%
Construction land	6.88×10^4	0.06%	6.88×10^4	0.060%	6.88×10^4	0.059%	7.59×10^4	0.067%
Unused land	1.56×10^6	1.39%	1.67×10^6	1.456%	1.39×10^6	1.197%	1.53×10^6	1.358%
Total	1.13×10^8	1	1.14×10^8	1	1.16×10^8	1	1.13×10^8	1

Table 7. Shows the changes in carbon storage for different land uses in the Li River Basin under various scenarios.

t and 4.03×10^3 t, respectively. Compared to the total terrestrial ecological carbon stock in the basin in 2020, there is a decrease of 6.82×10^6 t. The increase in cropland carbon storage indicates that existing government policies and land systems have an impact on agricultural carbon storage. The decrease in forest and grassland carbon storage indicates intensified deforestation and land conversion, leading to carbon emissions and reduction.

Under the natural conservation scenario, the total terrestrial ecological carbon stock in the Li River Basin is projected to increase by 2.75×10^5 t in 2040 compared to 2020. Specifically, the carbon storage in forests and grasslands is expected to increase by 2.26×10^5 t and 6.92×10^3 t, respectively. In the natural conservation scenario, the restoration and protection of forests and grasslands play a positive role in increasing carbon storage in the Li River Basin.

Under the urban development scenario, the total terrestrial ecological carbon stock in the Li River Basin is projected to decrease by 3.17×10^5 t in 2040 compared to 2020. Urban development is usually accompanied by land development, construction, and population growth, resulting in ecosystem degradation and carbon emissions. Large-scale land conversion and construction activities can disrupt the original vegetation cover and reduce carbon absorption capacity. In addition, urbanization increases energy consumption and carbon emissions, further exacerbating the decrease in carbon storage.

## Impact of land use conversion on carbon storage

Land utilization/land cover significantly affects vegetation cover and biomass. It is also the primary purpose for distributing and changing carbon stock in regional terrestrial ecosystems. The dynamic changes in carbon stock induced by the changes in main land use types in The Li River Basin from 2000 to 2040 are shown in Fig. 8 From 2000 to 2040, under the natural evolution scenario, the primary cause of carbon storage reduction is the conversion of forest land to other land use types. The expansion of construction land encroaches on forest land, leading to a decrease in ecosystem carbon storage. In the farmland protection scenario, the increase in cultivated land carbon storage is promoted. Due to Guangxi's cultivation of small trees and shrub crops such as citrus, mangoes, and lychees, there is an increase in cultivated land area and a decrease in forest land area. However, farmland carbon storage decreases while forest land carbon storage increases. Under the natural conservation scenario, the conversion of cultivated land to forest land is promoted to a certain extent through the policy of returning farmland to forest, and the carbon density of forest land is much higher than that of cultivated land, resulting in a significant increase in ecosystem carbon storage. In the urban development scenario, the expansion of construction land restricts the development of cultivated and forest land, leading to a sharp decline in ecosystem carbon storage.

Expansion factor contribution analysis

This paper evaluates the land use distribution pattern in the Lijiang River Basin from 2000 to 2020. (Fig. 9) shows the contribution of the driving factors of land use distribution pattern change in the Lijiang River Basin from 2000 to 2020.

The driving factors that contributed the highest to the change of the spatial distribution pattern of cultivated land were GDP and temperature. Economic growth will increase investment in arable land, improve farming techniques and equipment, and thus affect the distribution and efficiency of arable land, rapid economic growth will require more arable land to support agricultural production and food supply, and more forest land will be needed to provide timber and other forest products[30]. Moderate temperatures can promote crop growth and increase the agricultural production potential of the land.

The driving factors that had the highest contribution to the change of the spatial distribution pattern of forest land were distance from first-class roads, temperature and district and county station. The construction and expansion of roads often results in the deforestation of nearby woodland for road construction and its associated facilities. At the same time, the development of transport infrastructure will also promote human use of the surrounding woodland[31]. Changes in temperature can also affect the
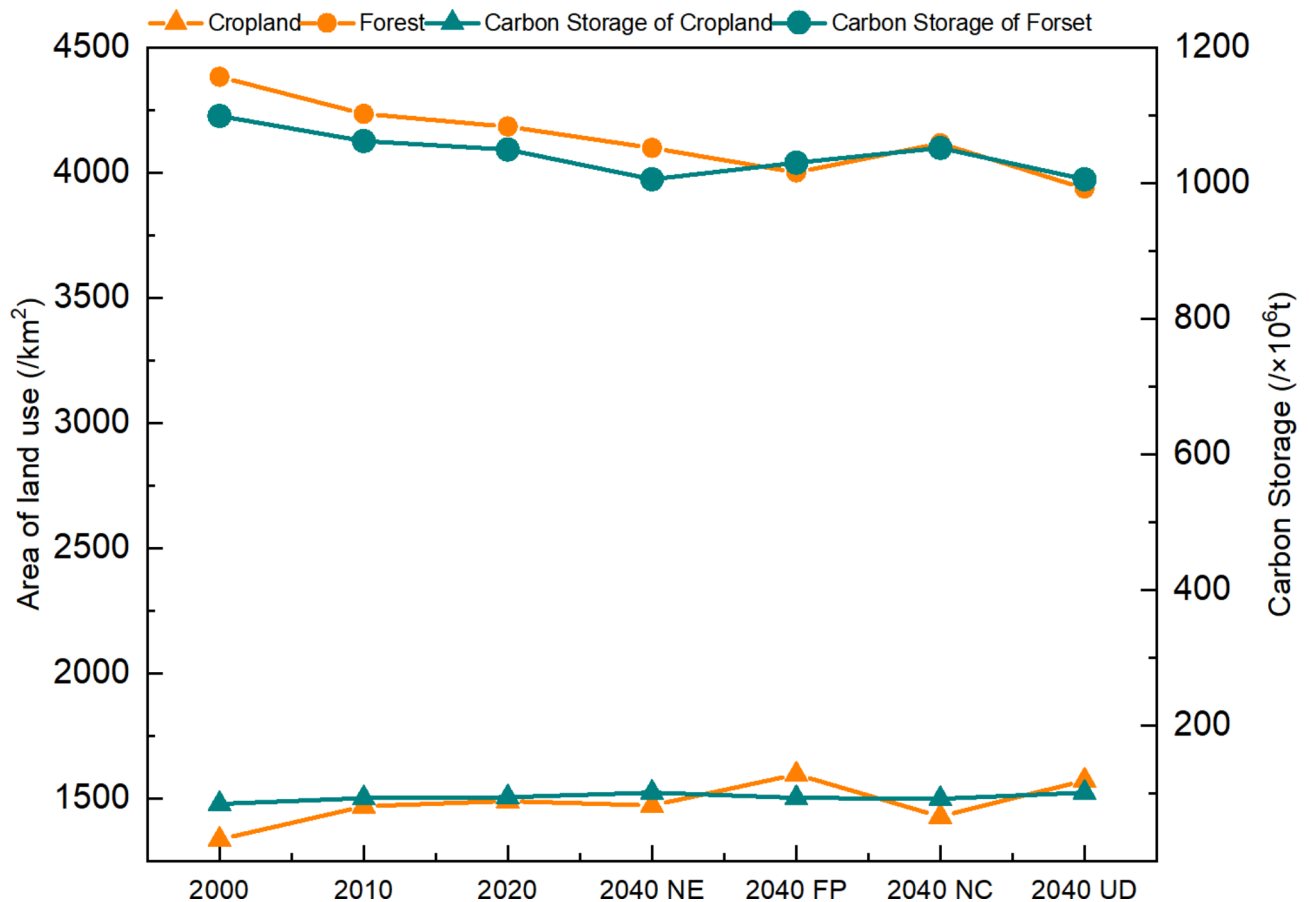
Fig. 8. Changes of main land types and carbon storage in the Lijiang River Basin from 2000 to 2040.

reproduction of woodland pests, which in turn affects woodland health and distribution. District and county stations are often the centres of local economic and social activities. The distribution pattern of forest land is affected by the development level and policy orientation of districts and counties, which is mainly reflected in the process of urbanization.

The driving factors that contributed the highest to the change of grassland spatial distribution pattern were temperature, slope and precipitation[32]. Temperature is a key factor in determining plant growth cycles, species distribution, and biodiversity. It directly affects the photosynthesis and respiration processes of grassland plants, as well as the germination and maturation of seeds. Slope is an important property of topography, affecting water loss and soil erosion. The slope also affects the reception of solar radiation, which in turn affects the temperature and humidity conditions of the grass. Water is one of the essential elements of plant growth, and different land types require different levels of precipitation.

The driving factors with the highest contribution to water bodies are mainly district government, population, slope and other factors[33]. Local government policies on the management of resources in a region can have a significant impact on water bodies. Population growth is often accompanied by an increased demand for water resources. As an important topographic factor, slope directly affects hydrological flow and soil erosion, thus indirectly affecting the distribution of water bodies.

For construction land, population, distance from tertiary roads, and aspect are the driving factors with the highest contribution, mainly because the difficulty of urban construction is closely related to traffic flow and connectivity, as well as the availability and suitability of land[34,35].

The spatial pattern of unused land is mainly affected by factors such as distance from secondary roads, population density, and district and county locations. The closer the land is to the main transportation routes, the higher its development value, and the more likely it is that unused land will attract developers to convert it to other sites. The high population density has led to a high demand for housing and services in the region. District and county locations are often hubs for public transportation, medical care, education, and cultural activities, and are a strong driving force for the conversion of unused land.
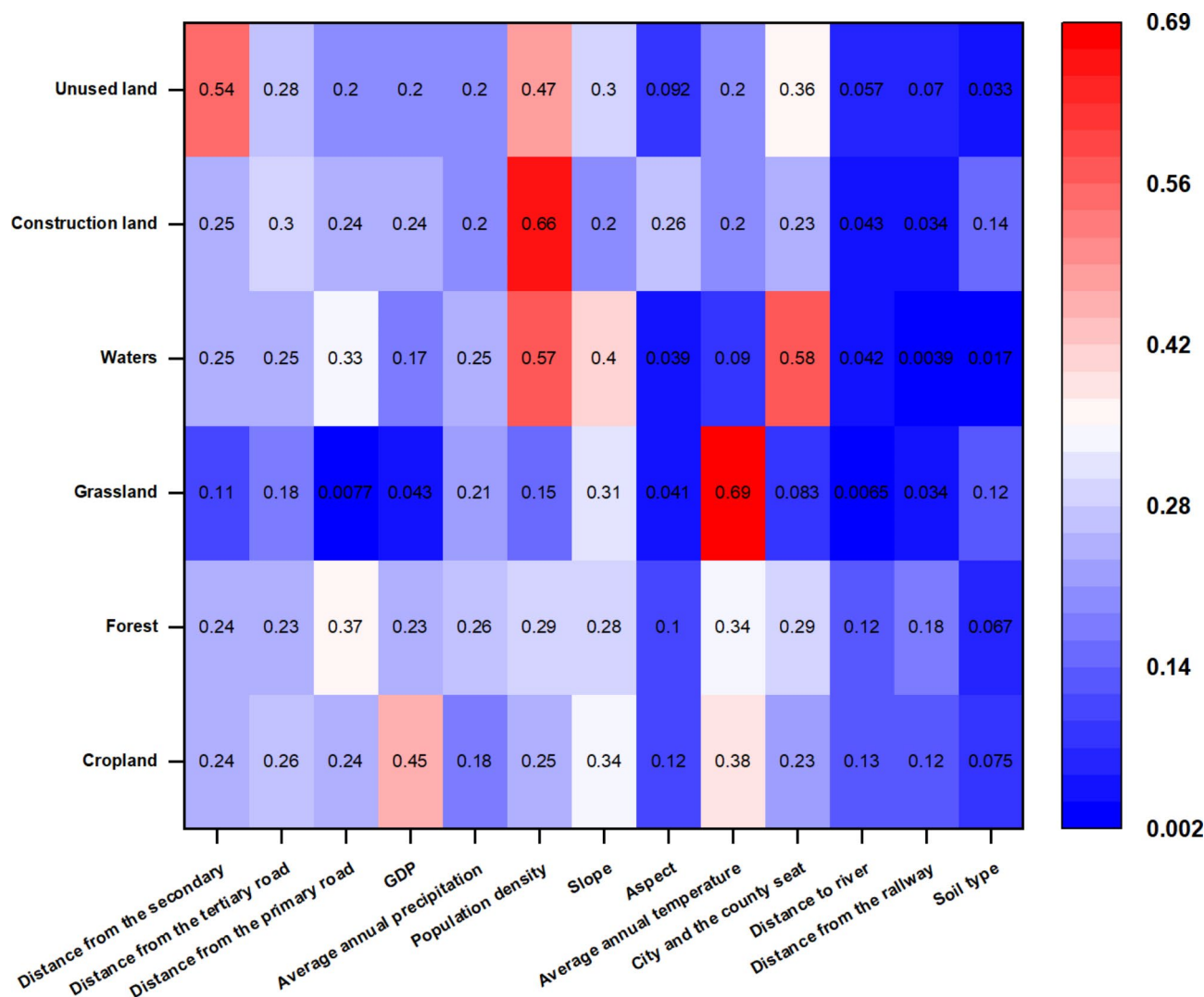
Fig. 9. Driver Contribution Distribution.

Discussion
Impact of land use change on ecosystem carbon storage in the basin

Land use change and its impact on ecosystem carbon storage is a complex and multifaceted issue, involving factors such as land use practices, ecosystem characteristics, climate conditions, and socio-economic factors. According to studies on the Li River Basin, land use change has significantly affected the region's carbon storage capacity[36]. Specifically, the conversion of forests to cropland and construction land has not only reduced forest cover but also exacerbated the loss of soil carbon, further diminishing the carbon sequestration effect. This process aligns with existing research, which highlights the negative impact of land use change, especially deforestation, agricultural expansion, and urbanization, on carbon storage.

Moreover, socio-economic factors play a critical role in land use changes. Population growth and increased agricultural demand have driven the expansion of cropland, while urbanization has accelerated the growth of built-up land. Deforestation is often closely linked to land development, infrastructure construction, and policy support. The interaction of these factors has led to the gradual release or loss of carbon stocks from natural ecosystems, thus affecting the overall carbon storage capacity of the region. At the same time, the increase in unused land, while potentially easing ecological pressures in certain areas, has much lower carbon storage than natural ecosystems such as forests or grasslands, and thus cannot effectively offset the carbon stock loss resulting from land use change.

Compared to similar studies, research in the Li River Basin offers valuable insights into the impact of land use change on carbon stocks in a specific region. For example, widespread research shows that deforestation and cropland expansion are significant sources of carbon release globally. In contrast, other regions, such as Europe and North America, primarily face carbon stock declines due to land degradation and urban expansion[37,38]. Therefore, while land use change generally has a negative impact on carbon storage, the specific context and

ecological background of different regions determine the form and extent of its effects. The Li River Basin study provides valuable experience for similar research, particularly in assessing the carbon stock losses associated with various types of land use change, offering strong representativeness in this area.

Impact of different development scenarios on carbon storage

Based on the land change trends from 2000 to 2020, the PLUS model was used to predict the land use patterns in the Li River Basin under different scenarios in 2040. The research results indicate that under different development scenarios, the trends and patterns of carbon storage vary significantly. Under the natural evolution scenario, total carbon storage decreases, and various land use types shift according to past land use patterns. This results in an overlapping and scattered distribution of carbon storage increase and decrease zones in the Li River Basin, with carbon storage decrease zones gradually expanding, particularly in the central region. Compared to other karst regions, the Li River Basin demonstrates some unique characteristics in terms of the impact of land use change on carbon storage. The karst landform's distinctive topographical and ecological features may affect carbon storage changes differently, especially the effect of forest and grassland protection measures on carbon storage increment. Relevant studies have shown that in watersheds with similar karst landforms, the impact of land use change on carbon storage is more complex and needs to be analyzed comprehensively, considering factors such as topography, climate, and land use history[39,40].

Under the farmland protection scenario, although the carbon storage of cropland increases, it cannot compensate for the decrease in carbon storage in other areas. This result aligns with studies from other regions. For example, research in the Jialing River Basin found that although farmland protection measures increased carbon storage in local areas, they were unable to cover other high-carbon-storage regions, limiting the overall carbon storage increase[41].

In the nature conservation scenario, the carbon storage variation pattern changes, and carbon storage begins to increase after land use structure adjustments. Nature conservation measures strengthen the protection of forests and grasslands, promoting the conversion of other land types to forests, which ensures the carbon sequestration capacity of high-carbon-storage land types and significantly increases carbon storage. Compared to other regions, the application of nature conservation measures in the Li River Basin may have special significance for karst areas. Due to the uniqueness of karst landforms, forest protection and restoration may have a more significant impact on carbon storage than in other regions[42]. Therefore, compared to the natural evolution scenario, after adopting ecological conservation measures, the proportion of carbon storage increase zones expands. At the same time, by reasonably controlling construction land and adjusting land use change direction, the conversion of high-carbon-storage land types to low-carbon-storage land types is restricted, significantly reducing the proportion of carbon storage decrease zones, especially in the central region of the basin.

Under the urban development scenario, total carbon storage decreases, and land development, construction, and population growth during urbanization are the main reasons for the decrease in carbon storage. These activities lead to large-scale land conversion and construction, which destroy the original vegetation cover and reduce the ecosystem's carbon absorption capacity. Similar to other basins, the impact of land development on carbon storage during urbanization generally shows a negative effect. Particularly in areas with higher carbon storage, urbanization often leads to the loss of land functions and a reduction in carbon storage[43,44].

In summary, the impact of land use change on carbon storage in the Li River Basin has some unique characteristics, particularly in the context of the special geographic and ecological environment of karst regions. Although this study provides valuable data on the relationship between land use change and carbon storage under different scenarios, comparing and contrasting with other basins, especially those with similar geographic features, economic development levels, and land use patterns, remains an important direction for future research. Through cross-regional comparative analysis, we can gain a more comprehensive understanding of the universality and limitations of land use change on carbon storage and provide more scientifically grounded support for regional carbon storage management.

Policy implications and recommendations

Land policies play a crucial role in adjusting carbon storage. Through various land management measures, land use patterns, and ecosystem protection efforts can greatly influence carbon storage directly or indirectly[45]. The implementation of the "Assessment Method for Balance between Occupied and Newly Added Arable Land" and China's macroeconomic control policies, combined with annual land use planning methods, have effectively protected arable land resources but have also reduced the total carbon storage in the basin. The local government in the region has diligently carried out arable land protection work and implemented the regulations for the "balance between occupied and newly added arable land," effectively maintaining the dynamic balance of the total arable land area in the region. With the implementation of the annual land use planning and management methods and the strict implementation of the land use control system, arable land resources have been effectively protected, resulting in an increase in arable land area after 2007 and maintaining a stable trend[46].

Although several policies have already been implemented, long-term policy revisions and corresponding measures are still needed. The following are the multi-faceted policy recommendations derived: (1)

strengthening forest protection and restoration is critical to enhancing carbon stocks. Our research indicates that forests hold a significant proportion of the carbon stock in the Li River Basin ecosystem. Therefore, the government should intensify efforts to protect forests by establishing and expanding forest conservation areas, implementing reforestation programs, and promoting sustainable forest management. These measures will ensure the stability of forest resources and their long-term carbon sequestration capacity. Additionally, mechanisms such as carbon trading and ecological compensation should be introduced to incentivize local governments and society to participate in forest conservation efforts. (2) promoting land use planning that prioritizes ecological protection can effectively mitigate the negative impacts of land use changes on carbon stocks. The Li River Basin should implement an ecological red line policy, which would designate key ecological areas for protection and prevent unnecessary land development and urban sprawl. At the same time, land use planning should prioritize ecological agriculture and green infrastructure, reduce the expansion of agricultural land, and protect vital ecosystems such as forests and grasslands. Furthermore, green urban development and low-carbon construction are equally important. By promoting green buildings, increasing urban greening, and optimizing urban planning, cities can enhance their carbon absorption capacity while alleviating the pressure that land development places on ecosystems. (3) enhancing agricultural land use and carbon management is a crucial strategy for addressing the decline in carbon stocks. The promotion of low-carbon agricultural technologies, optimizing the distribution of cultivated land, and improving soil carbon management will effectively prevent the detrimental impacts of land reclamation on carbon stocks and increase soil organic carbon storage. (4) cross-regional cooperation and policy coordination are essential for ecological protection in the watershed. As the Li River Basin spans multiple administrative regions, local governments must strengthen communication and collaboration to develop regional ecological protection and land use plans, ensuring consistency and effectiveness in policy implementation.

Limitations and future prospects

The Li River Basin has typical karst landforms in some areas (karst peak cluster depression and karst peak forest plain), and the soil physical and chemical properties in karst areas differ significantly from non-karst areas, resulting in differences in soil organic carbon density between the two regions[47]. Due to the lack of measured data on carbon density in karst regions, this study did not differentiate between the soil carbon density of the two regions, which had some impact on the estimation of carbon storage.

The sources of error in the InVEST model primarily include data quality, parameter uncertainty, and issues related to the matching of spatial and temporal scales. The model relies heavily on high-quality spatial data, and any missing or low-resolution data can lead to biased output results. Moreover, some parameters in the model, such as carbon density and changes in soil types, are often based on assumptions or expert judgment, which introduces considerable uncertainty. The model's applicability is also limited by geographical boundaries and the complexity of ecosystems, as the unique characteristics of certain regions or ecological types may not be accurately captured by the InVEST model. Additionally, carbon density is a critical parameter in estimating carbon storage, but the data used for this parameter typically comes from local or regional studies, which may fail to reflect the spatial heterogeneity across different land types and ecosystems. As a result, the model's application across different regions or ecosystems may introduce substantial errors. Furthermore, in the PLUS model, the rules for land-use type conversion and parameter settings may carry a degree of subjectivity. The conversion rules for land-use types are usually based on historical data and assumptions, which are influenced by the researcher's subjective perspective. Moreover, the parameters related to the driving factors of land-use change, such as population growth and economic development, are also highly subjective, which could lead to bias in the model's results.

Future research can be further advanced in the following areas: (1) a more detailed analysis of the spatiotemporal dynamics of carbon storage changes is needed, particularly by utilizing long-term monitoring data to verify the cumulative effects of land use change.(2) it is important to explore the impacts of multi-factor interactions under different scenarios, especially the potential compound effects of land use change in the context of external factors such as climate change.(3) interdisciplinary collaboration should be strengthened, combining theories and methods from ecology, geographic information science, and socio-economics, to comprehensively assess the long-term impacts of land use change on carbon storage and the feasibility of ecological restoration strategies. These research efforts will enhance our understanding of the complex relationship between land use and carbon storage, providing more scientifically grounded support for the sustainable management of watershed ecosystems.For model errors, future research can employ higher-resolution remote sensing data and localized field survey data to provide more accurate inputs for the model. Additionally, incorporating sensitivity analysis can help assess the impact of different parameters on the model results, thereby identifying key influencing factors and optimizing them. Finally, through the integration of multiple models, researchers can gain a more comprehensive understanding of the uncertainty in the model results, helping to avoid biases that may arise from relying on a single model.

Conclusion

The implementation of arable land protection policies and macroeconomic control measures by the Chinese government has led to significant changes in arable land area in the Li River Basin. From 2000 to 2020, the arable land area increased by 132.73 km^2. At the same time, forest land decreased by 148.13

km^2, and grassland decreased by 19.38 km^2, indicating considerable damage and reduction in the basin's ecosystem.

The distribution pattern of land use in the Li River Basin is mainly influenced by factors such as economy, population density, topography, and roads. Population growth and economic development require more arable land, forest land, and construction land to meet the demand.

Land use change has had a significant impact on ecosystem carbon storage in the Li River Basin. From 2000 to 2020, ecosystem carbon storage in the Li River Basin decreased from 1.19×10^8 t to 1.16×10^8 t, a decrease of 3.69×10^6 t. At the same time, there have been significant changes in the land use pattern of the basin, with the carbon storage of forest land as a percentage of the total ecosystem carbon storage decreasing from 92.12% in 2000 to 90.76% in 2020.

Under the natural evolution scenario, the predicted carbon storage in 2040 is expected to decrease by 3.13×10^6 t compared to 2020. Under the farmland protection scenario, although the arable land area increases, it still cannot compensate for the decrease in carbon storage in other regions. Under the natural conservation scenario, the Li River Basin can achieve its carbon sequestration goals, with an increase of 2.26×10^5 t in forest carbon storage and an increase of 6.92×10^3 t in grassland carbon storage. Overall, the land ecosystem carbon pool increases by 2.75×10^5 t. Under the urban development scenario, apart from an increase in carbon storage in construction land, the carbon storage of other land use types fluctuates, resulting in an overall decrease of 3.17×10^6 t in the land ecosystem carbon pool of the Li River Basin.

Data availability

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Author contributions

Bai Yu wrote the main manuscript text, Tang Xiangling and Long Du Jiang and Li Jianhongwere responsible for the polishing of the article Yaoguo Tang were analyzed the data. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Data accessibility

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Additional information

Correspondence and requests for materials should be addressed to X.T.

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