RESEARCH ARTICLE

Driving model of land use change on the evolution of carbon stock: a case study of Chongqing, China

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Abstract

Terrestrial ecosystems are significant carbon sinks and are crucial for understanding the regional and global carbon cycles, energy flow, and climate change. As land use change is a significant process affecting ecosystem carbon stocks and striving for land degradation neutrality (LDN), studying it is essential for comprehending the evolution of regional carbon sink functions and achieving sustainable development goals. The drastically diverse land use patterns in each of the study area's regions resulted in significant differences in carbon stock. This study explores the evolution traits of carbon stocks based on land use data and their driving mechanisms in Chongqing during the past 30 years by using spatial analysis, the InVEST model, and geographic probes. The results demonstrate that from 1990 to 2020, land degradation in Chongqing was made worse by the demand for land for construction land, but the strategy of converting cropland back to forests raised the carbon stock of forest land. The overall result is a decrease in total carbon stocks of 5.1078 Tg or 1.5%. The main pathway for carbon loss pathway in the evolution of carbon stock is the conversion of cropland to construction land, and the primary carbon compensation pathway is the conversion of grassland and cropland to forest land, with a spatial distribution characterized by "higher in the whole area and obvious local differences." The land use intensity index has the most significant influence on the evolution of carbon stock. Moreover, the interaction of pairwise factors played a more important role in affecting the evolution of carbon stocks than did each factor individually. The case study in this paper shows that land use change is a significant driving mechanism for the evolution of carbon stock, and the development of a driving model theory is appropriate for deciphering the trajectory of carbon stock evolution and offering research suggestions for other regions.

Keywords Land use · Carbon stock dynamics · Driving model · Interaction

Introduction

While economic globalization and the rapid development of science and technology have promoted human progress, they have also brought many negative impacts on the natural environment on which human beings depend, among which a series of climatic and environmental problems represented by the greenhouse effect have caused scholars from various countries to think about the issue of sustainable development. The carbon store of terrestrial ecosystems is to have a significant impact on climate and is strongly linked to the global carbon cycle (Ito et al. 2016). Increasing carbon stocks in terrestrial ecosystems can effectively reduce the amount of CO_2 in the atmosphere and mitigate and respond to global climate problems (Tian et al. 2011). The global carbon stock of terrestrial ecosystems is about 2030–2538 Pg (Qiao et al. 2021a), which is much higher than that of marine and atmospheric ecosystems and is the largest global carbon reservoir (Piao et al. 2009). A growing number of academics have studied carbon stocks in terrestrial ecosystems to investigate the role of terrestrial ecosystems in global climate change in order to better understand the position of elemental carbon in the Earth's cyclic system (Bian et al. 2013).

Carbon stock in terrestrial ecosystems is the stock of elemental carbon in plants and soils through the uptake and accumulation of atmospheric greenhouse gases by

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surface vegetation and below soils (Molotoks et al. 2018; Dybala et al. 2019) and is influenced by land use change (Liu et al. 2018). Land use/cover change is the most direct manifestation of human activities affecting climate change (Su et al. 2011; He et al. 2022), With increasing atmospheric CO_2 concentration and global warming, its effects on the terrestrial carbon cycle have become central to the field of climate change study (Ma and Wang 2015). Small changes in surface cover carbon stocks may have a major impact on changes in atmospheric CO_2 and other greenhouse gases, where land use change and its resulting CO_2 emissions are equivalent to one-third of the total human-induced emissions (Lal et al. 2018; Austin et al. 2015; Houghton 2016). To reach "carbon neutrality," it is crucial to monitor surface cover dynamics, and "source reduction and sink enhancement" have emerged as crucial strategies for mitigating future climate change brought on by greenhouse gas enrichment (Kumar et al. 2017). Terrestrial ecosystems contain a variety of land uses, and forest ecosystems are the main source of carbon stock and can directly impact ecosystem carbon stock due to changes in their abundance (John et al. 2004); reduced carbon stock in the forest ecosystem can be caused by commercial harvesting, non-commercial goods, and the conversion of forest land to agriculture (He et al. 2011). Cropland soils are enormous carbon stores as well and that even minor alterations to them can have a significant impact on atmospheric CO_2 concentrations (Li et al. 2022). Grassland carbon stock accounts for about one-fourth of the total carbon stock in terrestrial vegetation (Connor et al. 2018) and should be one of the important ways to sequester carbon in global terrestrial vegetation. A significant portion of the original green land in terrestrial ecosystems has been converted into land for construction as a result of economic growth and population concentration (Liu et al. 2012), which directly causes a dramatic decrease in land carbon stocks (De Carvalho and Szlafsztein 2019). However, some studies have also highlighted the increase in carbon stocks from vegetation restoration due to proper forest management (Tong et al. 2020), as well as the potential role of rural agricultural abandonment (Piao et al. 2015). Thus, in the century of gradual sustainable development, analyzing the intricate effects of changing land use on carbon stocks is a new way to begin comprehending the difficulties faced by terrestrial ecosystems.

Forests and urban areas have received a lot of attention in previous studies. Van et al (2009) analyzed the effects of land use change on carbon cycling in terrestrial ecosystems during global history. In the UK, land use change resulted in a reduction of 95% of soil carbon stocks (Ostle et al. 2009). Different land use/land cover patterns result in major variations in the distribution of soil organic carbon, with forest (Pellis et al. 2019), urban (Zhuang et al. 2022), and water ecosystems serving as the main repositories of terrestrial carbon stocks (He

et al. 2022). Urban land use growth is an inevitable product of economic development, and the contribution of urban land use change to carbon stocks varies significantly under various urban expansion scenarios (Jiang et al. 2017; Yang et al. 2020). These studies may have looked at it from the proposed standpoint, but many other studies also consider the ecology.

Modeling methods are indispensable tools in research. After 1990s, with the development of GIS and remote sensing technology, carbon stock research tends to apply remote sensing information and techniques as well as complex mechanistic models. Current research methods focus on remote sensing observations and remote sensing models, statistical estimation, ecosystem models, and the coupling of land use prediction with ecosystem models (Pongratz et al. 2014; Quesada et al. 2018). In particular, the InVEST model is widely used due to its high data accessibility and spatial explicitness (Zhou et al. 2018), which allows a spatially explicit analysis of the carbon stock response to land use activities (He et al. 2016; Adelisardou et al. 2021). Liang et al. combined the CA–Markov model with the InVEST model to assess the impact of land use change on global key ecological carbon stocks (Liang et al. 2021), and Deng et al. used a combination of FLUS and InVEST models to investigate the relationship between future land use and carbon stocks (Deng et al. 2020). All of which reveal the accuracy of the InVEST model in establishing the link between changes in land use and carbon exchange.

These studies have shown a possible connection between land use change and carbon stock, but the majority of them only consider single-site ecosystems, whereas terrestrial ecosystems contain a variety of land use types. Ignoring the other land use types could lead to an inaccurate reflection of the current carbon stock and an inability to resolve the intricate relationships between the two. Furthermore, there are several factors influencing land use (Agency 2000), which adds to the complexity of the carbon stock influence process. There is an urgent need to fully understand the combined impact of climate, socioeconomic, and other factors on carbon stocks. In this way, it will be easier to establish workable policies to solve global concerns and achieve sustainable development.

Global land use has drastically changed as a result of socioeconomic growth (Song et al. 2016). The International Community has incorporated land degradation neutrality (LDN) into the Sustainable Development Goals (SDGs) to create no-net-loss policies and achieve sustainable land management (United Nations 2016).The mountainous areas of southwest China have seen rapid economic growth, urbanization, reconstruction of rural structures, and the impact of China's ecological civilization strategy (Jiang et al. 2021), which has altered agroecosystems and drastically altered land use patterns (Li et al. 2021). Since the "double-carbon" target was established, ecosystem carbon stocks, afforestation, and income have become the primary variables influencing each

country's ability to meet the aim (Van Soest et al. 2021). The study of ecosystem carbon sinks should therefore include a thorough discussion of the evolutionary traits of carbon stores induced by land use change. There is no quantitative information on the time-series changes of land use and ecosystem carbon stocks in the region and urgent need to construct a theory of carbon stock evolution model under land use change. This paper builds a complete analysis theoretical framework and uses Chongqing City as an example in order to close the aforementioned research gap, revealing the contribution of land use change to carbon stocks, the influence pathways, and their driving mechanisms in Chongqing from an overall-regional perspective provide a reference for timely and effective assessment of regional carbon stocks affected by land use change and also help to provide a reference for related studies in similar regions internationally.

Theoretical frame

Hypothesis of how land use change has influenced the evolution of terrestrial carbon stock

The most visible manifestation of human activities that alter terrestrial ecosystems is land use. Human activities alter land use patterns directly or indirectly and are also influenced by natural conditions; these changes can be seen in three different areas: time, space, and function. Six land types—forest land, grassland, cropland, construction land, unused land, and water area—are chosen in this paper based on the data support available to quantify the spatial and temporal characteristics of land use changes in the research field while taking into account the land use characteristics of the study area's region.

A significant amount of carbon exchange typically occurs along with changes in land use, which has an impact on the carbon stock of terrestrial ecosystems. For example, forests can serve as a source of carbon stocks for aboveground vegetation through photosynthesis, and when plants wither and die, the carbon in their bodies returns to the soil. The grassland's below-ground root biogenic carbon stock and above-ground carbon stock converge, and the carbon stock is primarily distributed in the soil layer wellmanaged ones. Grassland growth is also a massive carbon sink process. The transfer of grassland will result in huge changes in soil carbon stocks, the transfer of forest land frequently leads to loss of carbon, and the development of construction land frequently has long-lasting, irreversible consequences on carbon stocks. As a result, there is a nonlinear relationship between changes in land use and the carbon stores of terrestrial ecosystems. The challenge is quantifying the spatial variations and inextricable connections between the pair.

Loss and compensation of carbon stocks are important indicators of the impact of global warming (Leonardo et al. 2016). Assessment of ecosystem carbon stocks ultimately serves the purpose of sustainable development. Sustainable ecological and economic development also contributes to the terrestrial ecosystem carbon cycle through the regulation of natural conditions and the development of policies applied to land use management. In contrast, the evolution of carbon stocks due to land use change has not had a unidirectional impact on sustainable development. To proceed toward the twin objective of low-carbon development and sustainable livelihoods, the synergistic link between the three is sorted out (Fig.1).

Research framework for land use change-related changes in carbon stock

For estimating carbon stocks in terrestrial ecosystems resulting from vegetation changes made by human activity, the combination of land use change and carbon stock modules is increasingly frequently utilized. This research analyzes the spatial and temporal evolution of terrestrial carbon stocks caused by land use change, reveals the intrinsic relationship between them, and simultaneously investigates the driving mechanism of terrestrial carbon stock evolution using four modules of aboveground carbon density, belowground carbon density, soil organic carbon density, and dead organic carbon density of different land use types (Fig.2).

Study area

In the southwest of China, in the middle and lower sections of the Yangtze River, between the longitudes 105°11′-110°11′E and the latitudes 28°10′-32°13′N is where the city of Chongqing may be found. There will be 32,124,300 inhabitants there in 2020, occupying a territory of 8.24×10^6 ha. The geomorphic type is complex, with mountains and hills dotting the landscape (98% of which are hills and mountains). The city will have a forest coverage rate of 54.5% in 2021 and a subtropical humid monsoon climate with dense river distribution, average annual temperatures of 16–18 °C, and annual rainfall of 1000–1350 mm (Fig.3).

Data and methods

Data

Carbon density data

This article uses uniform standards to categorize land use into cropland, forest land, grassland, construction land, water area,
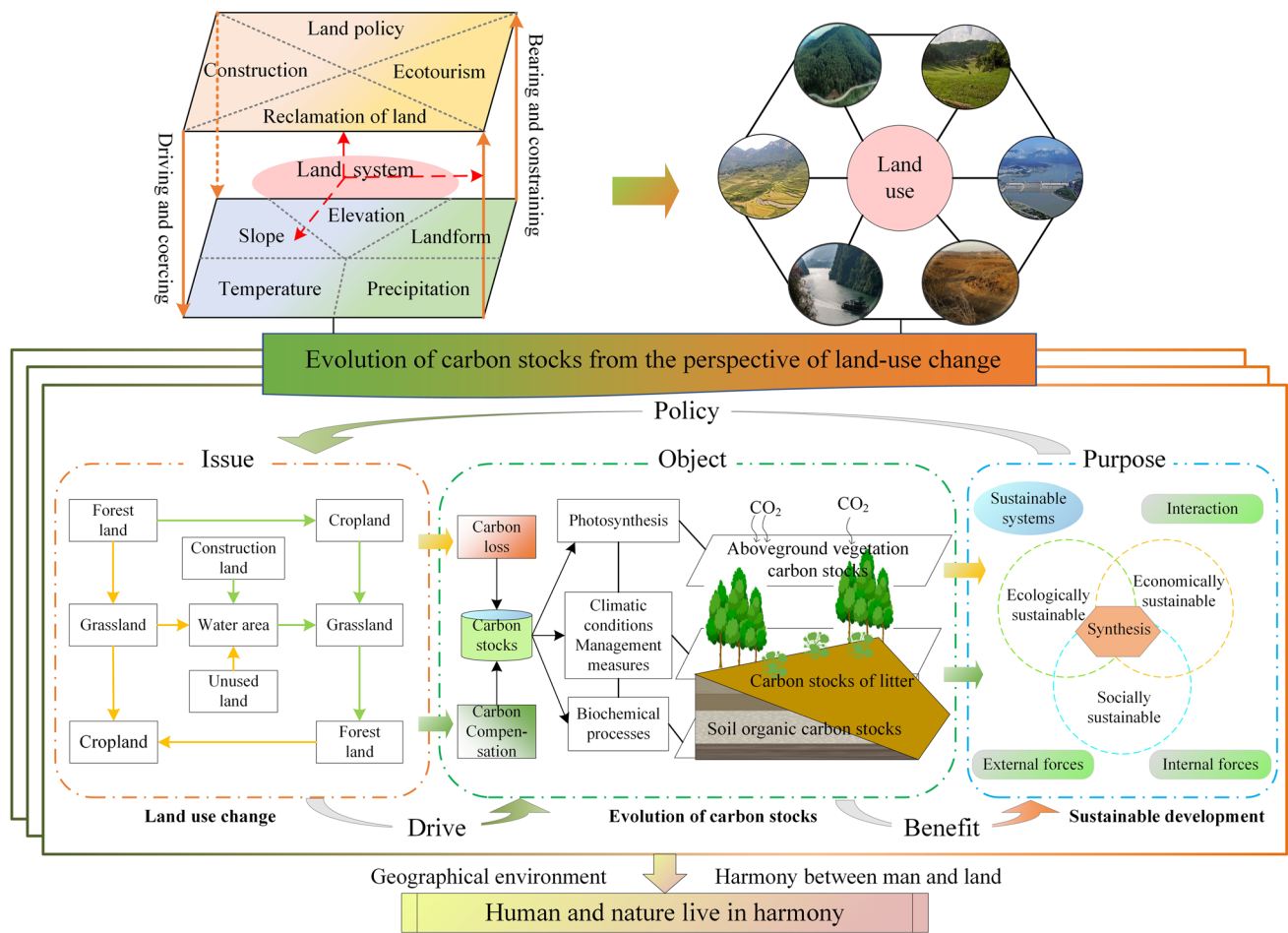
Fig. 1 Drivingmodel of land use change on carbon stock evolution

and unused land. Their carbon density measurements are taken from the findings of previous researchers (Xiang et al. 2022b). These data are based on measurements taken in Chongqing and the surrounding areas, and the carbon density data in nearby locations has been adjusted using a model that corrects for precipitation. It is essential to choose data from the same author as often as possible to prevent too many significant differences in the data to ensure the accuracy and scientific validity of the data.
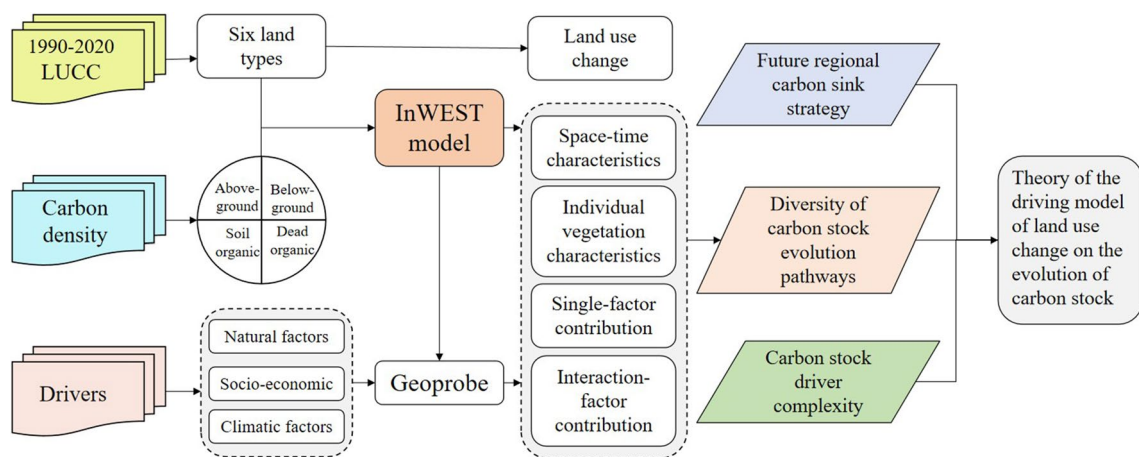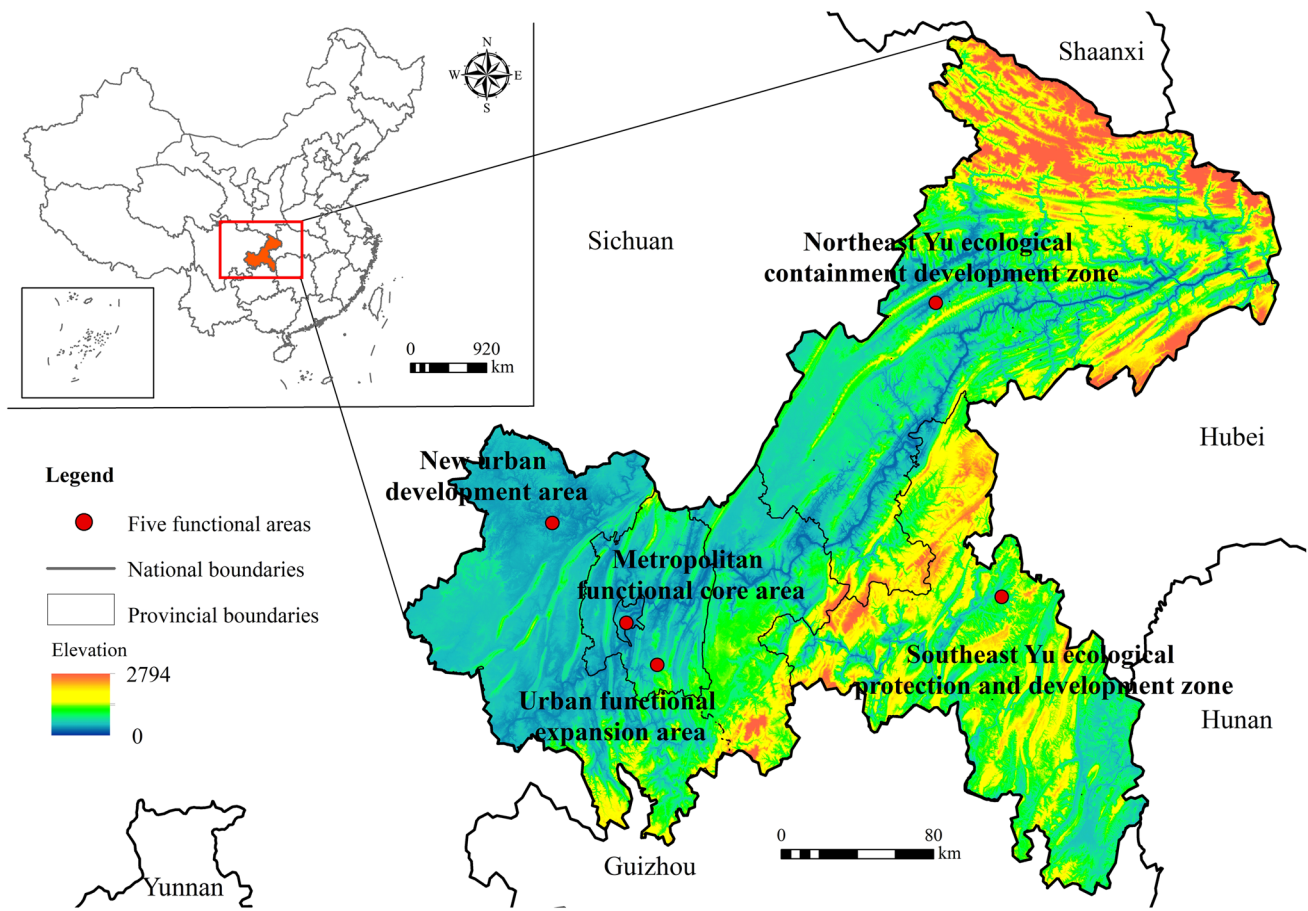

Fig. 2 Research frame

Fig. 3 Study area

The precise procedure is as follows: the carbon density data for cropland and grassland are taken from the measured data of Chongqing in the years 1980 to 1990, and the carbon density for cropland and grassland in Chongqing in the years 2000 to 2020 is then calculated using the precipitation model (Chuai et al. 2013; Alam et al. 2013). Forest land's density of carbon using the area-weighted technique and the precipitation correction model, the carbon density of forest land during the past 30 years was determined based on the primary forest types sampled at the Three Gorges Reservoir in Chongqing in 2005. The carbon densities of construction land and unused land were determined by referencing the prior sampling data of Hubei from 2000 to 2010 (Tang et al. 2020); subsequently, the carbon densities of construction land and unused land of Chongqing in the most recent years were computed using the aforementioned correction factor formula. Because earlier researchers discovered that water area carbon density is negligible in the carbon stock calculation module of the InVEST model (Zhang et al. 2016), and the tiny size

of the water body in this study area, the carbon density of water is set to zero in this study (Table1).

Spatial basic data

The data sources and their descriptions are shown in Table3, and the grids used in this paper are all 3 km × 3 km.

Table 1 Carbondensity of each land cover type (Mg/ha^2)

Land use type	Carbon density (Mg/ha^2)				
	Aboveground	Belowground	Soil	Dead	Total
Cropland	21.83	13.64	68.24	2.73	106.44
Grassland	18.37	21.43	76.56	3.06	119.42
Forest land	46.51	12.09	89.58	5.3	153.48
Construction land	0.71	1.34	33.99	0	36.04
Unused land	9.13	1.82	34.08	0.85	45.88
Water area	0	0	0	0	0

Methods

InVEST carbon stock model

This module mainly combines land use data to calculate the carbon stock of the ecosystem (Liu et al. 2020). It divides the ecosystem carbon stock into four basic carbon pools: aboveground carbon pool mainly refers to the carbon of living vegetation on the surface of the land, while the underground carbon pool mainly refers to the carbon in the root system of underground plants. Soil carbon pool mainly includes organic carbon in the soil. Dead organic carbon mainly refers to the organic carbon contained in dead vegetation and litter. Because the death organic carbon data are difficult to obtain, and the impact on the overall carbon stock is very small, this current study does not consider the impact of this part on the carbon stock (Zhu et al. 2019). The formula is:

$$C_i = C_{i,above} + C_{i,below} + C_{i,soil} + C_{i,dead}$$

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

where i is the land type; C_i is the carbon density of the i-land use type; $C_{i,above}$ is the aboveground biomass carbon density; $CC_{i,below}$ is the belowground biomass carbon; $C_{i,soil}$ is the soil organic matter carbon density; $C_{i,dead}$ is the dead organic matter carbon density; $C_{i,total}$ is the total carbon stock; S_i is the total area; n is the number of land types.

Land use intensity index

This mainly reflects the interaction between human activities and the natural environment. The formula is:

$$L = 100 \times \sum_{i=1}^{n} \left(D_i \times P_i \right)$$

where D_i denotes the graded index of land use level i; p_i denotes the percentage of the area of land use level i(%); n denotes the number of graded levels.

Geographic probes

The model is a new statistical method to detect spatial heterogeneity of data and reveal its driving factors. This method has no linearity assumption and can detect not only numerical and qualitative data, but also has the unique advantage of detecting the interaction of two factors on the dependent variable. This approach requires the independent variable X to be a type quantity (Wang and Xu 2017). To standardize the resolution, the driving factors in the table are sampled to the 3 km × 3 km grid scale in each category after being categorized into five groups using the ArcGIS natural breakpoint method.

1. Factor detector q: measures the degree of influence of a single environmental factor on the spatial partitioning of carbon stocks, the larger the value of q, the greater the degree of influence, and vice versa, the smaller. When $q = 0$ or $q = 1$, it means that the factor does not influence or completely control the spatial distribution characteristics of a research subject. The formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_{h^2}}{N_{\sigma^2}}$$

where h is the category of the impact factor; N_h is the number of samples in the h subregion; N denotes the total number of spatial units in the whole study area; σ_h and h denote the total variance and variance of the samples in the h subregion respectively.

2. Interaction detector: identify the extent to which the interaction between any two factors has an effect on vegetation cover, expressed as an increase or decrease in the explanatory power of vegetation cover change, mainly divided into the following results (Table 2).

Result

Spatial and temporal characteristics of land use change

During 1990–2020, Chongqing's land types are mainly cropland and forest land (Fig. 4). Cropland and grassland areas are decreased, by 119.1603×10^3 ha and 413.235×10^3 ha, respectively. Unused land is shrinking by 0.7068×10^3 ha, while forest land is growing by 330.7894×10^3 ha. Construction land is growing by 171.67×10^3 ha, and water area is growing by 29.5917×10^3 ha, respectively. The largest changes across all regions are in the area of forest land,

Table 2 Basis for determining the interaction

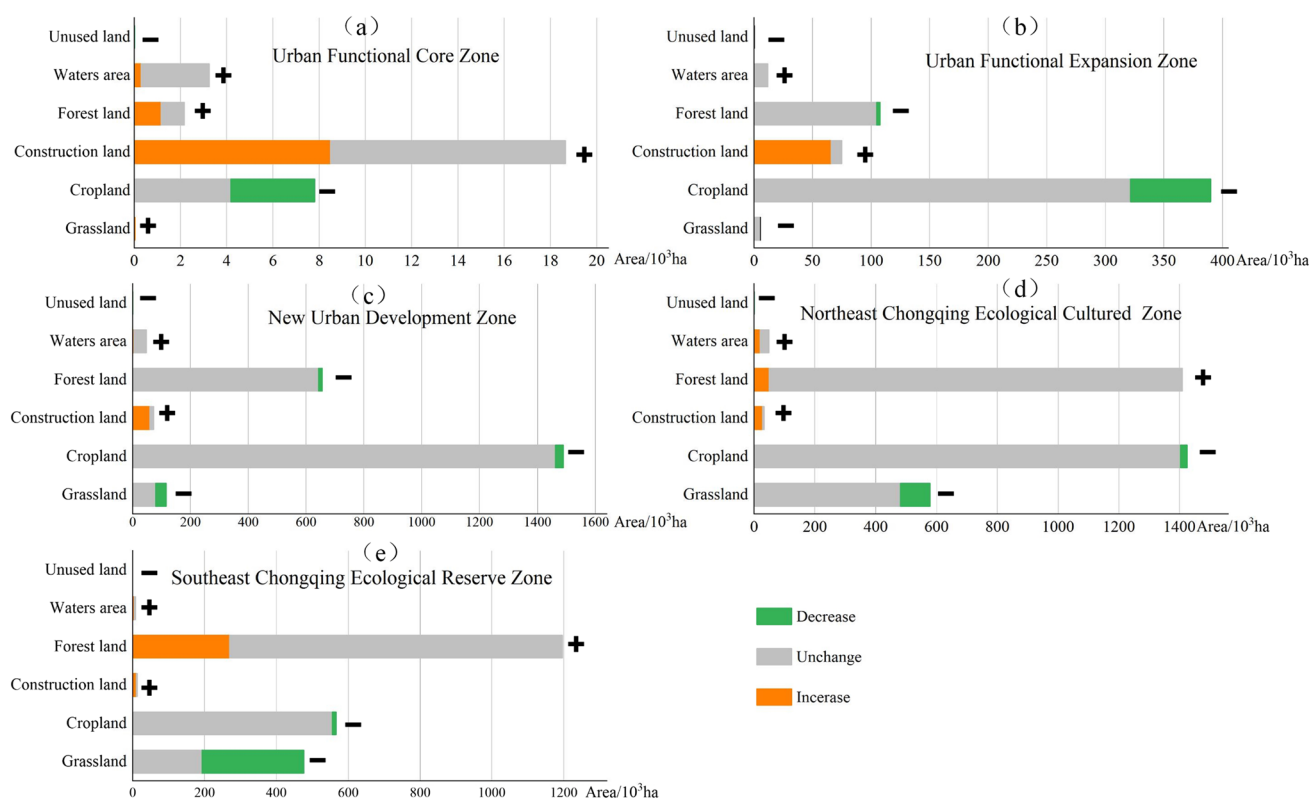| Basis for judgment	Interaction	Basis for judgment	Interaction
$q(\times 1 \cap \times 2) < Min(q(\times 1), q(\times 2))$	Nonlinearity decreases	$q(\times 1 \cap \times 2) = q(\times 1) + q(\times 2)$	Independent
$Min(q(\times 1), q(\times 2 < q(\times 1 \cap \times 2) < Min(q(\times 1), q(\times 2))$	One-way nonlinearity decreases	$q(\times 1 \cap \times 2) > (\times 1) + q(\times 2)$	Nonlinear enhancement

Fig. 4 Changes in land use area in major districts of Chongqing from 1990 to 2020

grassland, cropland, and construction land. The changes in the area of unused land and water area are less, and each region's construction land indicates a trend toward growth.

Land use changes that were spatially substantial were seen (Fig.11). In the study area, cropland is primarily distributed in the west and center, decreasing areas concentrated in the northeast and west; grassland decreases in the southeast and northeast; forest land greatly increases in the northeast and southeast, corresponding to areas with less grassland and cropland; construction land changes significantly, mainly in the west, with the core area as the center of rapid outward expansion, and in the rest of the area is mostly scattered patches of distribution. The other land categories have less variation in the area and a less clear spatial pattern. As a whole, Chongqing's land use pattern can be summarized as "east forest and west cropland."

Overall carbon stock evolution characteristics of Chongqing

Temporal characteristics

In Fig.5a, during 1990–2020, Chongqing's total terrestrial carbon inventories were 1023.6543Tg, 1060.9556Tg, 1022.4232Tg, 1022.9771Tg, 1022.0143Tg, 1019.3818Tg,

and 1018.5465Tg, with a generally downward trend. Overall carbon supply decreased by 5.1078Tg, or 1.5%. Environmental carbon stock activity declined at rates of 1.2%, 0.3%, and 3.4% each decade. In terms of regional differences, the core area (b) has the lowest ecosystem carbon stock at 145.4188Tg, with a generally fluctuating downward trend; the extension area (c) and the new development area (d) both have the lowest value in 2020, with an accelerated downward trend; northeast Chongqing (e) has the largest carbon stock at 424.2286Tg, accounting for roughly 41.91% of Chongqing's carbon stock; only in southeast Chongqing (f) is there a carbon stock that is becoming increasingly significant and steady. Each zone's combined carbon stock percentages are as follows: northeast Chongqing (41.92%) > southeast Chongqing (26.32%) > the new development zone (26.31%) > the extension zone (5.3%) > and the core zone (0.14%).

1995 had the largest value of the total carbon stock, as shown in Fig.5a. A significant portion of grassland area was turned into forest land in 1995, and the land use type that predominated was high carbon density forest land, according to the land use transfer analysis. The combined area of farmland and forested land reached its highest point in 1995, which was mostly responsible for the peak in total carbon stocks. However, land use
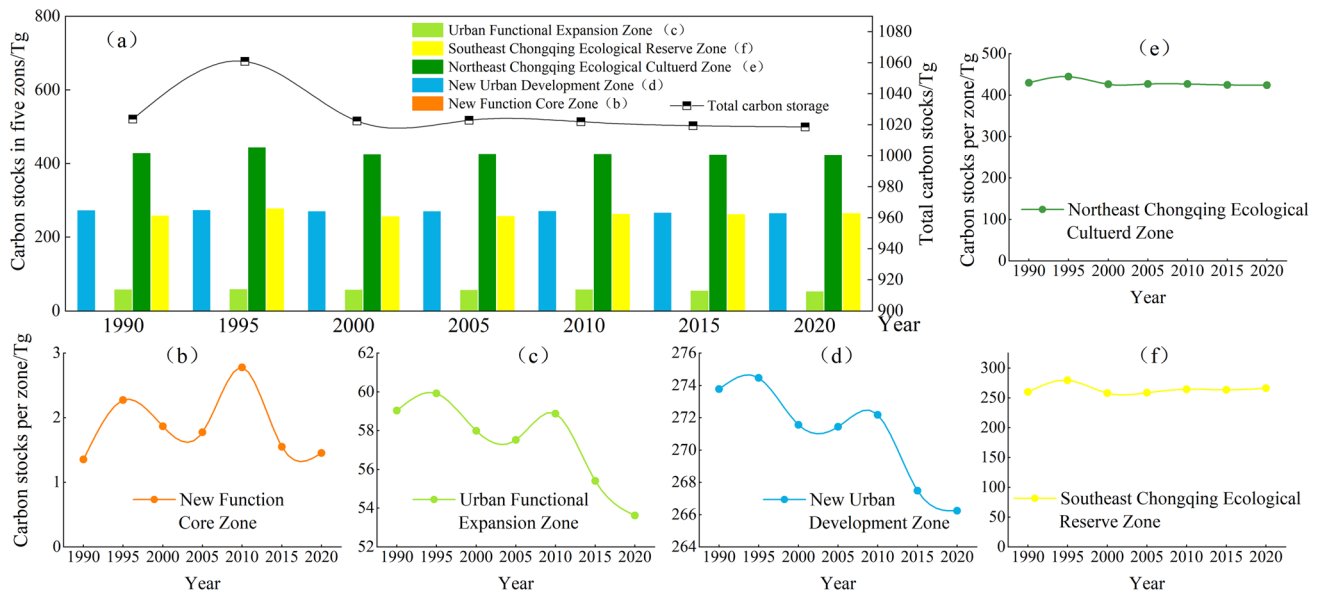
Fig. 5 Temporal changes of carbon stocks in Chongqing from 1990 to 2020

changes in the northeastern part of the northeast Chongqing changed dramatically from 1996 to 2000, which was a critical period for the launch of the Three Gorges Project, including the construction of the dam, resettlement of immigrants, and cutoff of water stock, resulting in a large amount of grassland area encroached upon by programmed construction land (Zhang et al. 2009), coupled with the sharp increase in development land in the Core Zone, exacerbated land degradation, and was a significant factor in the reduction of overall carbon stocks.

Spatial characteristics

The spatial distribution of terrestrial carbon stocks in Chongqing varies significantly, with an overall distribution characterized by "greater throughout the region and apparent local variances" (Fig.6). The core region is the most concentrated, the land use type is mainly construction land, and the low-value area has a clear trend of expansion in the past 30 years, gradually expanding to the perimeter. The lowest value is primarily dispersed in the West. The entire high-value region is dispersed, and the predominant land uses in the high-value and medium-value areas of northeast Chongqing are cropland and forest land. Regional differences include the following: the carbon stock in the core area decreases throughout the entire area, and the extended area's decreasing area of carbon stock extends from the central part to the northeast; the decreasing area in the new development area is dispersed; the decreasing area in northeast Chongqing only appears in the central and western part, and the

overall trend is increasing; the increase in the central and eastern part of southeast Chongqing is the most pronounced, which gradually expands to the whole region with a better ecological environment.

These spatial changes in carbon stock are caused by variations in land use change, due to its high level of urbanization; Western Chongqing has seen a major decrease in carbon stocks. Conversely, afforestation will enhance carbon stocks, for example, the ecological environment has benefited drastically in recent years as a result of ecological projects like the protection of forests in the middle and upper reaches of the Yangtze River, which have been successively identified in China (Peng et al. 2021), and the improvement of the ecological environment in southeast Chongqing corresponds with this trend.

Analysis of carbon stock differences among different land types

Contribution of different land types to carbon stock

The terrestrial carbon stock in Chongqing is influenced differentially by various land use types (Fig.12). 2020 contributions from forest land total more than 50.97%, grassland and cropland have contribution rates of 8.96% and 39.31%, respectively, whereas construction land has a contribution rate of only 0.75%, the lowest contribution of unused land. The contribution rate of grassland, cropland, and unused land has been declining over the past 30 years. From 1990 and 2000, it saw a quick decrease and recovery process
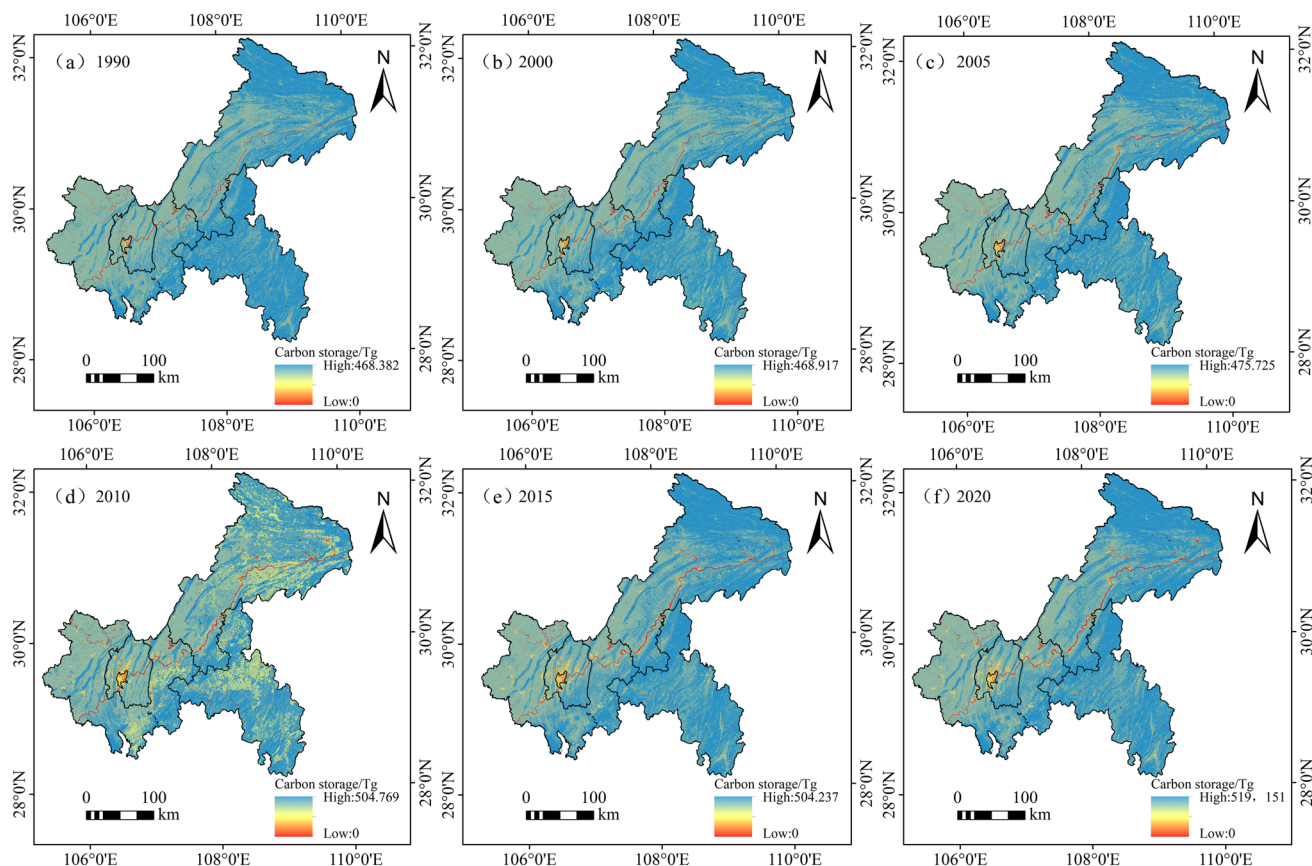
Fig. 6 Spatial distribution of carbon stocks in Chongqing from 1990 to 2020

before gradually declining after that year; but forest land's contribution rate reversed throughout the same time frame, demonstrating the existence of some sort of transfer relationship between these different land types; the contribution rate of construction land increased in a manner that was positively connected with time.

Carbon stock evolution due to land use transfer

In Chongqing, land use changes during the past 30 years have increased carbon stocks by 22.1624Tg, decreased them by 4.1561Tg, and resulted in a net increase of 18.0063Tg. The evolution of these carbon stocks can be divided into two pathways: carbon loss and carbon compensation (Fig.7).

Carbon loss pathways refer to the direction of land use transfer from high to low carbon intensity loss in Fig.7(a). The transfer of cropland to construction land and the transfer of forest land to cropland are the main carbon loss pathways in the study area. The area transferred by the two pathways is nearly equal, but the difference in carbon loss is 3.6778×10^3Mg, which is caused by more carbon loss per unit area growth of construction land; this finding shows that

increasing construction land at a single level is not beneficial for boosting the ecosystem's capacity to a carbon sink. Contrarily, the transition of grassland to cropland is also the main land use transfer direction, but not at the forefront of carbon loss; the remaining transfer carbon loss pathways only account for a small percentage, but it is still important to be aware of the potential risks involved with these conversions.

Carbon flow direction in the carbon compensation pathway is opposite to the loss pathway in Fig.7(a). Grassland and cropland conversion to forest land is the primary pathway for compensation, with a transfer area of 360.1049×10^3ha and 179.9592×10^3ha and compensating 12.2652Tg and 8.4653Tg of carbon stock for the ecosystem. As can be seen, there is a significant difference in the quantity of carbon compensation when an equal area is converted into various land types with varying carbon densities; even if the area remains the same, the conversion of grassland to forest land is a significant carbon sink process. The transition from cropland to grassland contributed 0.6465Tg of carbon; other transfer pathways also partially make up for the ecosystem's carbon loss.
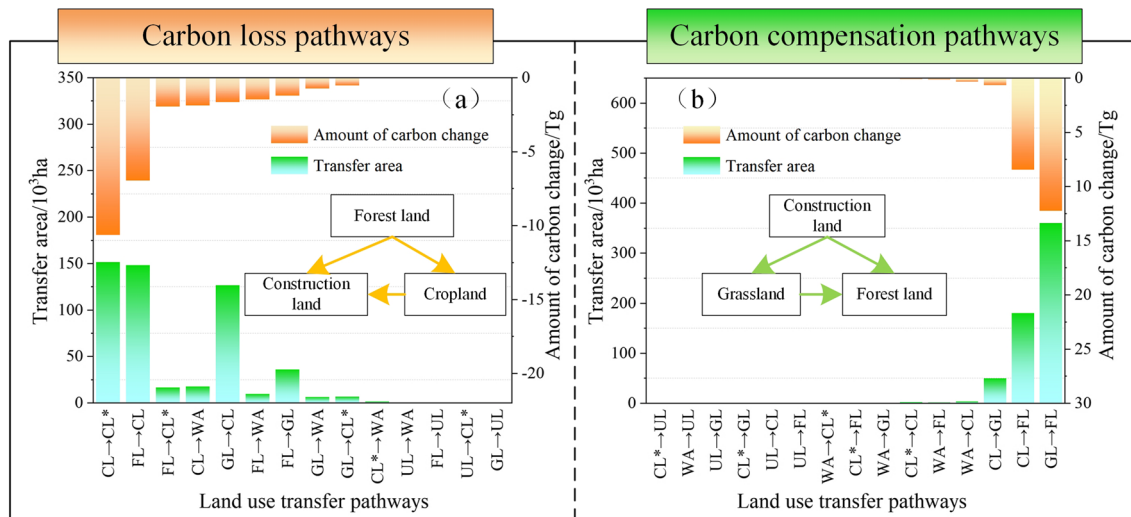
Fig. 7 Carbon stock evolution pathways. FL, forest land; GL, grassland; CL, cropland; CL*, construction land; WA, water Area; UL, unused land

Carbon stock evolution drivers

Effect of single factors on carbon stocks

To determine the relative impact of each factor on the terrestrial carbon stock in Chongqing, the q-values were calculated using a single-factor detector in Fig.8a. All factors passed the significance test ($P < 0.050$), and the contributions were ranked as $X_{11} > X_6 > X_{12} > X_{13} > X_9 > X_3 > X_1 > X_7 > X_{10} > X_8 > X_2 > X_4 > X_5$. In this paper, the more significant elements were chosen to further examine the carbon impetus behind the evolution of the carbon stock.

Natural conditions are the primary determinants of how land is used, and the variety of landforms to some extent limits the growth and dispersion of plants. In Chongqing, the Zhongshan landform, which makes up 52% of the total area, and is composed primarily of limestone and quartz sandstone, has strong water retention, is rich in calcium elements, suitable height typically maintains suitable climatic conditions, and forest land typically grows more successfully. Contrarily, human activity severely impairs the growth of vegetation in low mountain and plain areas. For instance, sloping land is gradually abandoned because it is unsuitable for farming, flat areas with good livability are invaded by construction land, and high-altitude areas frequently become marginalized by forest and grassland (Xia et al. 2023). With forests serving as the primary carbon sink, carbon density at each level of tree > shrub > herb, together with a large range of forest land species and lengthy growth cycles, the carbon sink potential can remain stable for a very long period. Because crops are harvested so quickly, the carbon sink impact of crop biomass in cropland is not readily apparent. The carbon stock channel for crop biomass is primarily

soil carbon accumulation, though the carbon stock varies depending on the type of soil (Li et al. 2022).

The highest contribution of land use index is the renewed evidence of the major effects on carbon stocks of anthropogenic land use change. The rapid reduction of cropland and the rapid rise in the scale of construction land are distinguishing characteristics of land use type change during the processes of economic growth, industrialization, and urbanization. In the last 20 years, Chongqing's economy developed quickly from "one wing and two circles" to "functional zoning," and the percentage of land used for construction land has increased. This has resulted in a decline in the region's carbon stocks, which is consistent with the findings of other researchers (Xiang et al. 2022a). Rapid economic growth results in an increase in GDP per capita, which indirectly influences land use change. Rural labor exodus and conversion to non-agriculture, however, will result in a decline in the population of farmers and an increase in abandoned land, which is precisely the path to lowering ecosystem carbon stocks through a switch to low-carbon density land types.

Our case study of Chongqing shows that climate variables have little effect on terrestrial carbon stocks. This might occur as a result of Chongqing's location in southwest China, which has a subtropical monsoon climate zone and is rich in hydrothermal resources, and the climatic variables were steadier (Tong et al. 2016). Some studies have demonstrated that climate factors affect carbon stocks by influencing vegetation growth. However, in areas with favorable hydrothermal conditions, vegetation growth is no longer mainly influenced by climate; hence, the impact on terrestrial carbon stocks decreases (Qiao et al. 2021b; Zheng et al. 2023).
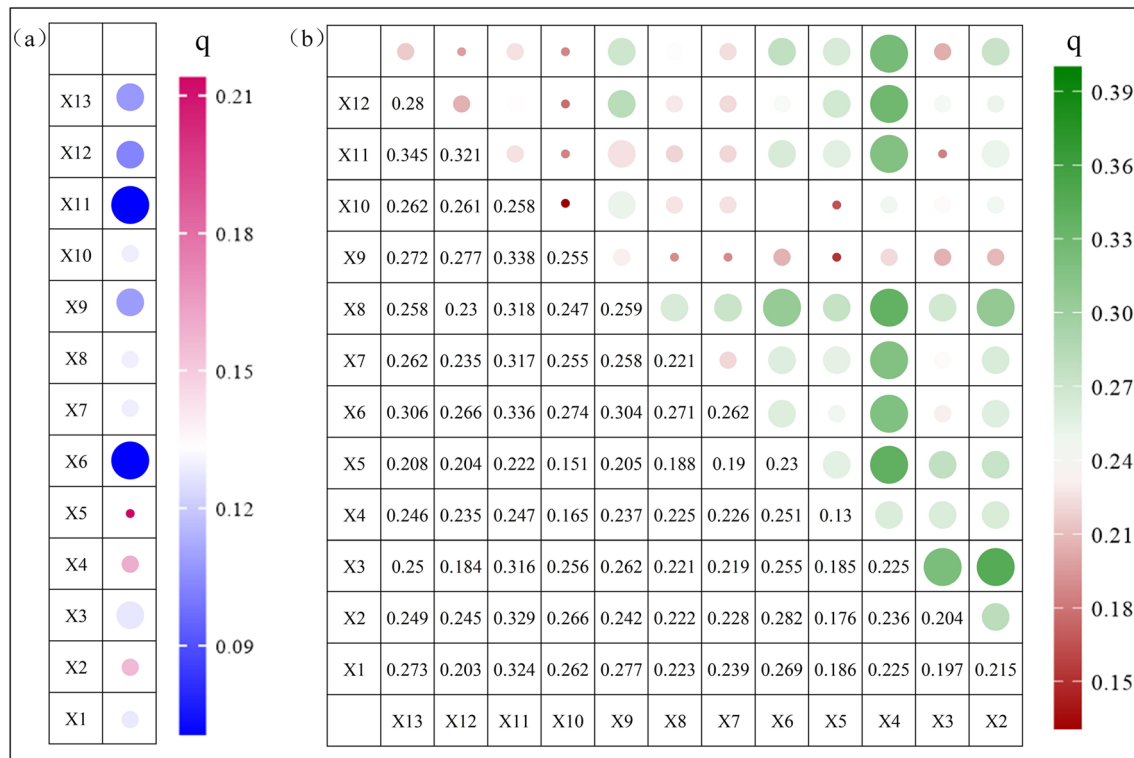
Fig. 8 Heatmap of the contribution diffience between single and double factors to terrestrial carbon stock

Effects of dual factors interaction on carbon stock

The results indicate that the interactions between land use intensity and other significant influencing factors are all greater than 0.3 in Fig.8b. The interactions between land use degree and agricultural population density are the highest at 0.3448, followed by the interactions between landform type and other factors, which are all greater than 0.25. Furthermore, there were major relationships between economic density, farming population density, and vegetation type with other variables, highlighting the significance of the primary single factors on terrestrial carbon stocks once more.

Climate variables like temperature and precipitation, which play a relatively small role as single factors, when combined with socioeconomic, geomorphological, and vegetational factors, have a considerably larger explanatory power. The impact of human actions on carbon stocks is also exacerbated by lithology, soil type, and vegetation cover. All two-factor interactions had q-values that were higher than those of the single factors, indicating that two-factor interactions have a larger impact on carbon stock influencing than the single factors do. Moreover, the outcomes of every two-factor interaction also demonstrate that there is a nonlinear enhancement process that occurs as opposed to merely being superimposed easily.

Discussion

Complexity of the drivers of carbon stock evolution

Land systems are driven by a variety of factors; those factors both directly and indirectly affect carbon stocks by changing land use patterns. Within the driving system (Fig.1), natural factors mainly play the role of driving and coercing, while the socio-economic system carries and restricts the natural environment, and they exist separately and interact closely. The findings of Chongqing provide more precise quantification of the complicated impact of several potential causes on carbon reserves (Fig.8), for example, complex landforms have a pronounced independent influence, and economic conditions have a greater impact after interacting with landforms and altitudes. But there are regional differences in the mechanisms driving carbon stocks. In North Asia, warming is accelerating the accumulation of vegetative carbon; similar large areas appear to be more sensitive to climate (Liu et al. 2022; Yang et al. 2021). In dryland, appropriate grazing management may be a critical control to maximize the provision and control of ecosystem carbon services (Onatibia et al. 2015), and soil organic carbon is negatively affected by land use change in semi-arid environments in northern Iran (Kooch et al. 2022). In addition, socio-economic factors

such as the level of household residential affluence (Feng et al. 2021) and the application of solar power generation (Kim et al. 2022) exert their potential influence. It is clear that there is no single driver for the evolution of carbon stocks, but they are all dependent on how human activities on the land surface, of the carbon stock, are significantly impacted by this process.

In addition, the InVEST model assumes that the carbon densities of vegetation, soil, and dead organic matter are fixed in a given period, and the results are detailed and plausible only for different land use types. Due to land use types differing in branch biomass of vegetation and biomass of soil organic matter with time, long-termresearch should also give more attention to how carbon density is affected by factors like photosynthetic rate and soil microbial changes.

Diversity of carbon stock evolution pathways in terrestrial

The theoretical model developed in this paper classifies the carbon changes brought on by land transfer into two pathways, and there is diversity within the pathways (Fig.9).

The path to carbon loss brought on by land use is complex. Among the conclusions reached by global researchers, carbon loss is substantial when forest cover continues to disappear (Hansen et al. 2013; Stephanie et al. 2018). Remote sensing monitoring indicates that timber deforestation results in the reduced carbon sequestration capacity of terrestrial vegetation due to timber deforestation in Indonesia. The construction land expansion has always been predominant, and land urbanization exhibits a negative linear connection with carbon stock, impacting soil carbon and carbon sequestration (Peng et al. 2017). In China, terrestrial ecosystems are currently absorbing less carbon as a result of the widespread conversion of natural green space to artificial land and modifications to regional meteorological conditions that impact plant photosynthesis (Huang et al. 2011). Cropland-based agricultural activities are more susceptible

to seasonal and environmental influences; a prolonged abandonment of cropland will increase the area of unused land and reduce the potential for carbon stocks (Su et al. 2020). Carbon compensation pathways facilitate the carbon sink potential of ecosystems. By providing vegetation cover on vulnerable cropland, ecological conservation policies in the USA reduce soil erosion and encourage soil organic carbon enrichment (Breuer et al. 2006). In the mountainous regions of northern Iran, the conversion of forests and pastures to agricultural land significantly increased soil organic carbon stock (Wu et al. 2022). Agricultural vegetation absorbs substantial amounts of CO_2 through photosynthesis and stores it in crops, and straw return also boosts soil carbon stocks; growing grasslands and forests in eastern China is the primary method of making up for the carbon emissions caused by partial urbanization (Guo et al. 2022; Li et al. 2023).

Chongqing's shift to forest land brings the most carbon compensations, still demonstrating the importance of land-use conversion to ecosystem carbon stock. Comparisons in the above paths are systemically analyzed in the theoretical model developed in this paper. The variety of carbon stock evolution pathways is clarified to promote the achievement of sustainable development goals and regulate the issue through policy feedback to construct a sustainable development model in harmony with people and land.

Land use optimization strategies for future carbon stock enhancement

Over the last three decades, forest and grassland, cropland, and construction land have dominated land use changes in Chongqing; there have been clear geographical variations in Chongqing's carbon stock evolution (Fig.10), and it is important to underline that ecosystem carbon stores are at risk of declining. As a result, we support the following land use policies.

Land use policies should be more uniform and efficient future, with proactive policy changes having a mitigating or
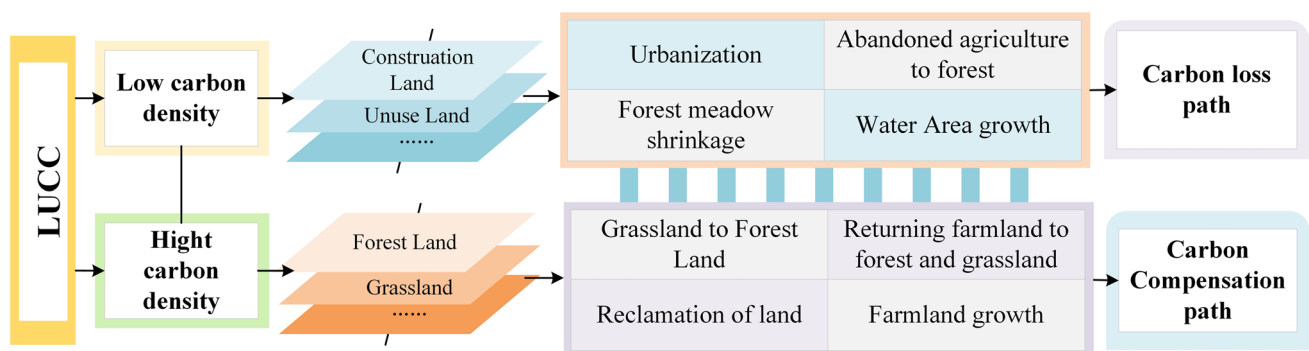

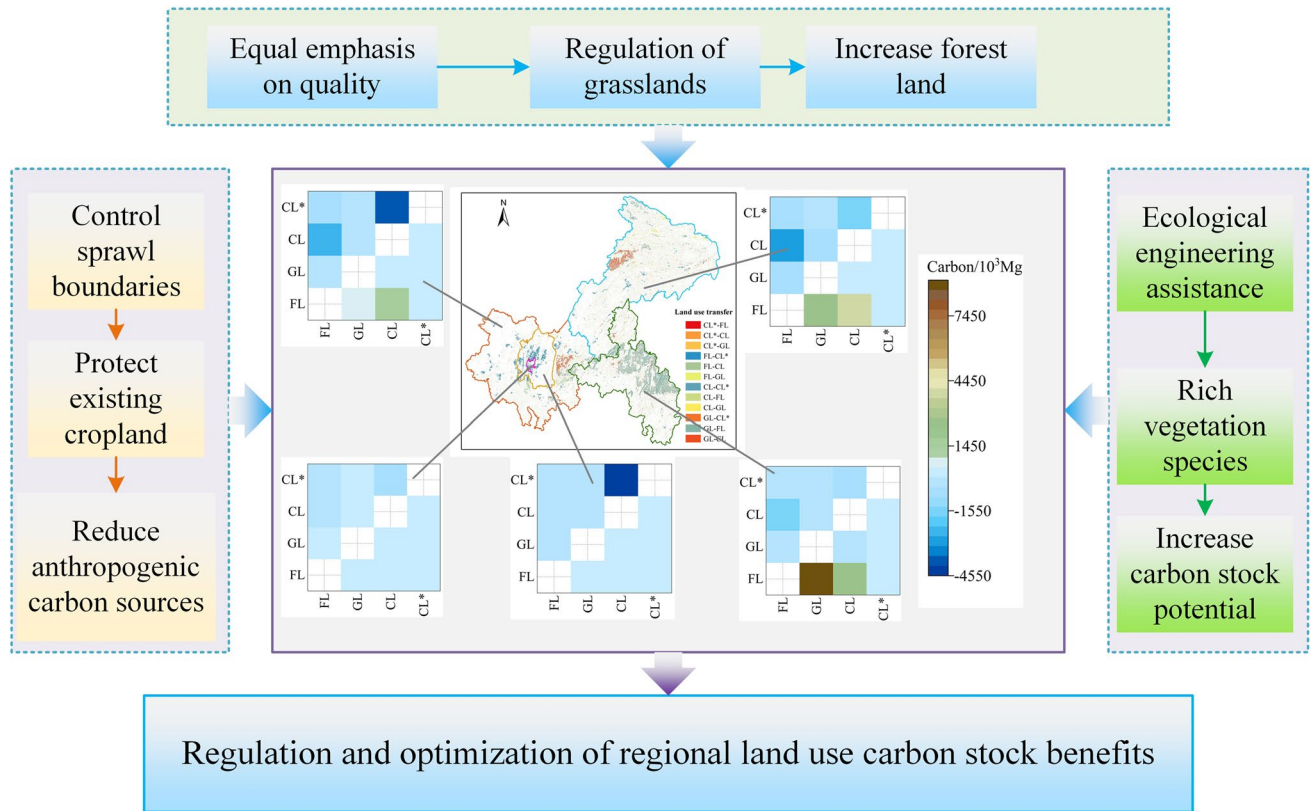**Fig. 9** Carbon stock evolution pathways

Fig. 10 Strategies to increase carbon stocks in Chongqing

even preventive impact on carbon losses (Wang et al. 2018). For instance, substantial carbon emissions caused by urban development in western Chongqing, in the future, the permanent basic agricultural land surrounding the cities should be used to decide the spreading boundary of construction land and implement total control; this can contribute significantly to the sustainability and security of arable land. Agricultural operations on arable land are seasonal, which has an impact on the soil's organic carbon stock, maximizing the roles of the food supply and carbon sinks by choosing to grow crop varieties with high yields per unit area on the limited amount of arable land available. Additionally, more thorough ecological management strategies for biodiversity in high-value land categories and high-potential carbon sinks are needed. Grassland in Northeast Chongqing should be maintained since they are large and at risk of being destroyed, allowing them to develop into forests with larger carbon stores. Finally, deepen the study of the unused land category and develop the multiple functions of the land. Thearea shows abandonment of sloping cropland and fallow land (Huang et al. 2022), the last remaining assurance of human food security is cropland, and the stability of the real cropland should be maintained to improve food and resource security, except for the area that must be used for the national unified deployment.

Conclusions

This paper established a systematic research framework: carbon stock evolution model caused by regional land use change. Taking the land use of Chongqing in the past 30 years as the research object, the response of carbon stock to its change, its evolution pathway, and its potential driving factors is analyzed from the time–space dimension and overall-region dimension. The specific findings are as follows:

(1) The overall carbon stock is decreased as a result of significant land use changes. The geographical distribution of carbon stock is "greater in the overall area, with evident local variances," the contribution rate of forest land is the largest, and the inter-regional distribution is new development zone > expansion zone > core zone: northeast > southeast.

(2) The evolution of the carbon stock occurs by carbon loss or carbon compensation. Transfers of cropland to construction land and forest land to cropland dominate the pathways for carbon loss, respectively. Transfers of cropland and grassland to forest land dominate the pathways for carbon compensation, where compensation of the ecosystem is 20.7305Tg of carbon. The overall carbon stock declines by 5.1078Tg, and

the ecosystem's capacity to store carbon continuously declines.

(3) The evolution of carbon stocks responds to all factors, and land use intensity dominates. Landform types are the fundamental prerequisites for the distribution of land use patterns; changes in economic density and agricultural population density directly cause changes in land use patterns, which in turn affect carbon stocks, and climate contribution is relatively weak. Compared to all one-factor interactions, the two-factor interactions were stronger.

(4) This study constructs a carbon stock evolution model caused by regional land use change that can be used to analyze the evolutionary pathways of carbon stocks in the region represented by Chongqing City. It also offers new perspectives and research ideas for revealing the universal evolutionary patterns of carbon stocks in other regions. Significant land use changes are present in the studied area. The theory reveals the diversity of carbon stock evolution routes in Chongqing, and the study's findings can be used as a guide for other places.

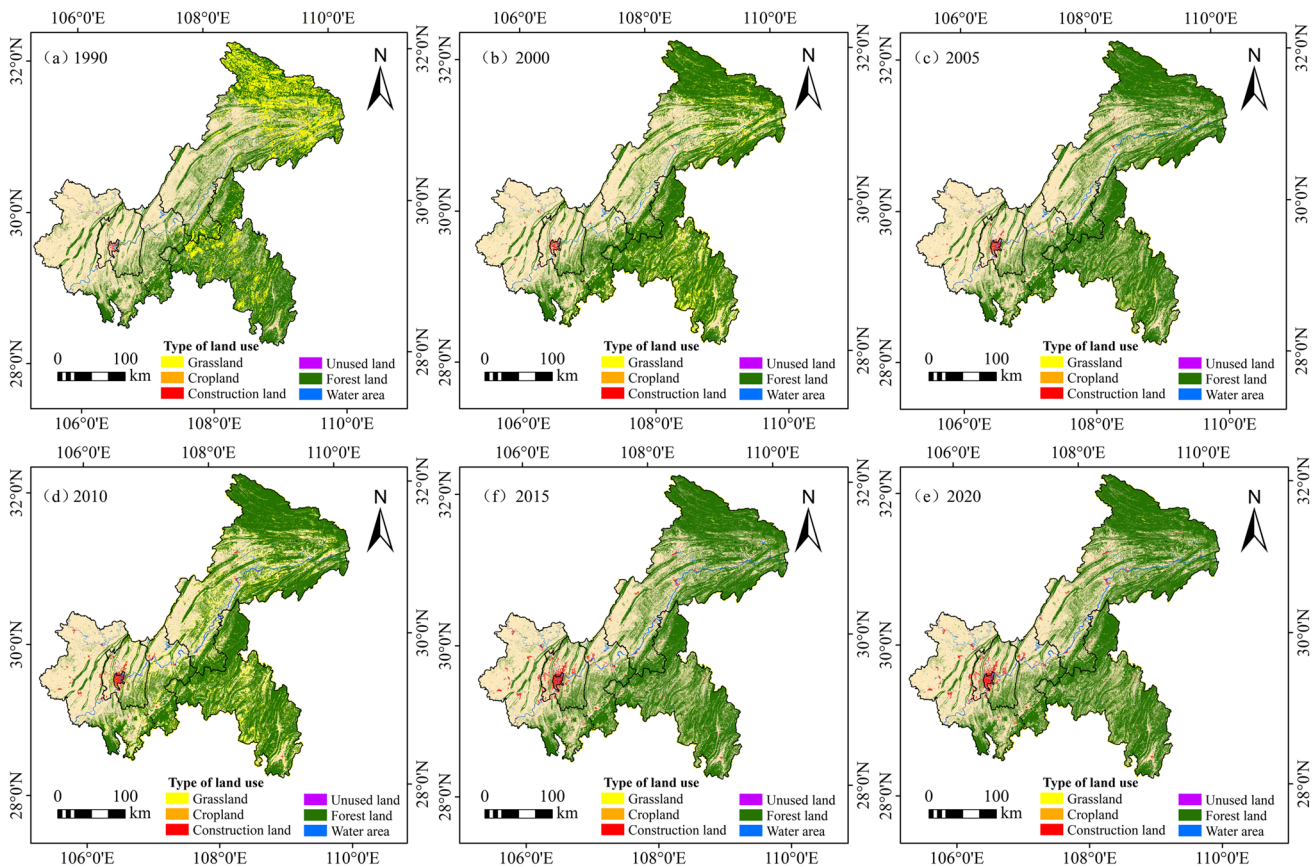## Appendix A. Spatial changes in land use in Chongqing

See Fig. 11

Fig. 11 Spatial changes in land use in major districts of Chongqing from 1990–2020

Appendix B. Contribution of different land types to carbon stock

See Fig. 312

(10^2Tg)	Grassland		Cropland		Construction land		Forest land		Unused land	
Year	Carbon	percentage	Carbon	percentage	Carbon	percentage	Carbon	percentage	Carbon	percentage
1990	140.6418	13.74	413.0491	40.35	1.5013	0.15	468.3819	45.76	0.0802	0.01
1995	3.2574	0.31	420.6003	39.64	1.4412	0.14	635.6564	59.91	0.0002	0
2000	140.317	13.72	410.9212	40.19	2.188	0.21	468.9167	45.86	0.0803	0.01
2005	136.8122	13.37	407.7532	39.86	2.6212	0.26	475.7247	46.5	0.0658	0.01
2010	106.6737	10.44	405.6106	39.69	4.9041	0.48	504.7686	49.39	0.0573	0.01
2015	106.5471	10.45	402.3649	39.47	6.0406	0.59	504.3722	49.48	0.0569	0.01
2020	91.2933	8.96	400.3656	39.31	7.6883	0.75	519.1515	50.97	0.0478	0

Fig. 12 Contribution of different land types to carbon stock

Appendix C. Carbon stock drivers

See Table

Table 3 Data sources and descriptions

Data		Sources and handling	Type and unit
Land use data		Globe land use data for 30 from 1990 to 2018 (https://www.resdc.cn)	Vector
Carbon density dataset		Aboveground, ground, soil, dead organic carbon density	Form/kg/ha
Climatic factors	X_1 Annual precipitation	China Land Climate Daily Value Dataset (V3.0) published by China Meteorological Science Data Sharing Network (http://cdc.nmic.cn/home.do), interpolated into 30m raster data	Raster/mm
	X_2 Annual temperature		Raster/°C
	X_3 Annual sunshine		Raster/h
Natural factors	X_4 Elevation	Geospatial Data Cloud (www.gscloud.cn/search)	Raster/m
	X_5 Slope		Raster/°
	X_6 Landform	Compiled the Geological and Geomorphological Map of Chongqing, published by the National Bureau of Surveying and Mapping	Vector
	X_7 Lithology		Vector
	X_8 Soil type	Resource Environment and Data Center, Chinese Academy of Sciences (https://www.resdc.cn)	Vector
	X_9 Vegetation type	Data from the 2002 Forest Resources Type II Survey	Vector
	X_{10} Vegetation cover	Using the cell dichotomous model, the threshold value is set to 0.5–0.95 and the data extraction is based on NDVI	Raster
Socio-economic factors	X_{11} Land use intensity index	Land use index	3 km×3 km grid
	X_{12} Economic density	Data from the statistical yearbook of each district and county in 2020, GDP density = GDP/area	
	X_{13} Agricultural population	Data from the statistical yearbook of each district and county in 2020, agricultural population density = agricultural population/area	

Data availability Not applicable.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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