Theory of the 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 factor affecting ecosystem carbon stocks, studying it is essential to 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 functional areas resulted in significant differences in carbon stocks between them. 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 the significant change in land use change in the study area, which led to a 5.1078Tg decrease in total carbon stock, a decline of 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 degree of land use contributes most to the evolution of carbon stocks. 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.

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 thought 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 CO₂ in the atmosphere and mitigate and respond to global climate problems (Tiao et al., 2011). The global carbon stock of terrestrial ecosystems is about 2030–2538 Pg (Qiao et al., 2021), 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 surface vegetation and 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 1/3 of the total human-induced emissions (Lal et al., 2018; 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, can directly impact ecosystem carbon stock due to changes in their distribution (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). Croplands sequester CO$_2$ in agricultural soils to reduce atmospheric greenhouse gas concentrations and mitigate global warming. Grassland carbon stock accounts for about 1/4 of the total carbon stock in terrestrial vegetation (Connor, 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). Therefore, studies from the perspective of land use change are necessary and pertinent.

Van et al. analyzed the effects of land use change on carbon cycling in terrestrial ecosystems during global history (Van et al., 2009). 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 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 studies could lead to an inaccurate reflection of the current carbon stock and an inability to resolve the intricate relationships between the two. Furthermore, the driving effect of land use cannot be considered in isolation, a more thorough comparison and inclusion of drivers would make it easier to establish workable policies to solve global concerns and achieve sustainable development.

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. 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 relationship between land use change and terrestrial ecosystem carbon exchange relationship.

Global land use has drastically changed as a result of socioeconomic growth, agriculturalization, and industrialization (Song et al., 2016), driving the alteration of regional land use. 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 provides a reference for timely and effective assessment of regional carbon stocks affected by land use change and also helps 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 five functional areas.
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 above-ground 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. Grassland growth is also a massive carbon sink process. The transfer of grassland will result in huge changes in soil carbon sinks, 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. 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 $8.24 \times 10^6$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 1000–1350mm. (Fig. 3).

**Data and Methods**
Data

The data sources and their descriptions are shown in Table A, and the grids used in this paper are all 3km×3km.
<table>
<thead>
<tr>
<th><strong>Data</strong></th>
<th><strong>Sources and handling</strong></th>
<th><strong>Type and unit</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use data</td>
<td>Globe land use data for 30 from 1990 to 2018 (<a href="https://www.resdc.cn">https://www.resdc.cn</a>)</td>
<td>Vector</td>
</tr>
<tr>
<td>Carbon density dataset</td>
<td>Aboveground, ground, soil, dead organic carbon density</td>
<td>Form /kg/ha</td>
</tr>
<tr>
<td>Climatic factors</td>
<td><strong>X₁</strong> Annual precipitation</td>
<td>Raster /mm</td>
</tr>
<tr>
<td></td>
<td><strong>X₂</strong> Annual temperature</td>
<td>Raster /°C</td>
</tr>
<tr>
<td></td>
<td><strong>X₃</strong> Annual sunshine</td>
<td>Raster /h</td>
</tr>
<tr>
<td>Natural factors</td>
<td><strong>X₄</strong> Elevation</td>
<td>Raster /m</td>
</tr>
<tr>
<td></td>
<td><strong>X₅</strong> Slope</td>
<td>Raster /°</td>
</tr>
<tr>
<td></td>
<td><strong>X₆</strong> Landform</td>
<td>Vector</td>
</tr>
<tr>
<td></td>
<td><strong>X₇</strong> Lithology</td>
<td>Vector</td>
</tr>
<tr>
<td></td>
<td><strong>X₈</strong> Soil type</td>
<td>Vector</td>
</tr>
<tr>
<td></td>
<td><strong>X₉</strong> Vegetation type</td>
<td>Vector</td>
</tr>
<tr>
<td></td>
<td><strong>X₁₀</strong> Vegetation cover</td>
<td>Raster</td>
</tr>
<tr>
<td>Socio-economic factors</td>
<td><strong>X₁₁</strong> Land use index</td>
<td>Land Use Index</td>
</tr>
<tr>
<td></td>
<td><strong>X₁₂</strong> Economic density</td>
<td>3km × 3km grid</td>
</tr>
<tr>
<td></td>
<td><strong>X₁₃</strong> Agricultural population</td>
<td></td>
</tr>
</tbody>
</table>
Methods

InVEST carbon stock model

The carbon stock module of InVEST model is based on different land use types and carbon density per unit area to estimate the net carbon stock of a land type over some time. The total carbon stock is obtained by calculating the average carbon density of each land type represented by the four modules of aboveground, belowground, soil, and dead organic matter, and then multiplying it with the area of each land type and summing it up. The formula is:

\[ C_i = C_{i, \text{above}} + C_{i, \text{below}} + C_{i, \text{soil}} + C_{i, \text{dead}} \]

\[ C_{i, \text{total}} = \sum_{i=1}^{n} C_i \times S_i \]

Where: \( i \) is the land type; \( C_i \) is the carbon density of the \( i \) land use type; \( C_{i, \text{above}} \) is the aboveground biomass carbon density; \( C_{i, \text{below}} \) is the belowground biomass carbon; \( C_{i, \text{soil}} \) is the soil organic matter carbon density; \( C_{i, \text{dead}} \) is the dead organic matter carbon density; \( C_{i, \text{total}} \) is the total carbon stock; \( S_i \) is the total area; \( n \) is the number of land types.

Specific land class carbon density data were used for the measured carbon density data in the study area, and these data were corrected by the model to obtain the land class carbon density data in the study area (Xiang et al., 2022), and it has been shown that the carbon density of waters is negligible (Zhang et al., 2016), and the area of waters in the study area of this paper accounts for a small percentage (Table 2).

<table>
<thead>
<tr>
<th>Land type</th>
<th>Carbon density Mg/ha²</th>
<th>Land type</th>
<th>Carbon density Mg/ha²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland</td>
<td>106.44</td>
<td>Construction land</td>
<td>36.04</td>
</tr>
<tr>
<td>Forest land</td>
<td>153.48</td>
<td>Water area</td>
<td>0</td>
</tr>
<tr>
<td>Grassland</td>
<td>119.42</td>
<td>Unused land</td>
<td>45.88</td>
</tr>
</tbody>
</table>

Land use index

This mainly reflects the interaction between human activities and the natural environment. The formula is:
\[ L = 100 \times \sum_{i=1}^{n} (D_i \times P_i) \]

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.

**Geo-detector**

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.

(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; \( \sigma_h \) and \( \sigma \) 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 3).

<table>
<thead>
<tr>
<th>Basis for Judgment</th>
<th>Interaction</th>
<th>Basis for Judgment</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q(x1 \cap x2) ) ( \min(q(x1), q(x2)) )</td>
<td>Nonlinearity decreases</td>
<td>( q(x1 \cap x2) = q(x1) + q(x2) )</td>
<td>Independent</td>
</tr>
<tr>
<td>( \min(q(x1), q(x2), q(x1 \cap x2)) )</td>
<td>One-way nonlinearity decreases</td>
<td>( q(x1 \cap x2) (x1) + q(x2) )</td>
<td>Nonlinear enhancement</td>
</tr>
</tbody>
</table>

**Result**

**Spatial and temporal characteristics of land use change**

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

During 1990-2020, Chongqing's total terrestrial carbon inventories were $1023.6543\text{Tg}$, $1060.9556\text{Tg}$, $1022.4232\text{Tg}$, $1022.9771\text{Tg}$, $1022.0143\text{Tg}$, $1019.3818\text{Tg}$, and $1018.5465\text{Tg}$, with a generally downward trend. Overall carbon supply decreased by 5.1078Tg, or 1.5%, in a downward trend. Environmental carbon sink activity declined at rates of 1.2%, 0.3%, and 3.4% each decade. In terms of regional differences, the core area has the lowest ecosystem carbon stock at 145.4188Tg, with a generally fluctuating downward trend; the extension area and the new development area both have the lowest value in 2020, with an accelerated downward trend; northeast Chongqing has the largest carbon stock at 424.2286Tg, accounting for roughly 41.91% of Chongqing’s carbon stock; only in southeast Chongqing is there a carbon sink that is becoming increasingly significant and steady. The five primary zones' 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%) (Fig. 5).

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
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. 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 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. 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 $3.6778 \times 10^3$ Mg, 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 in the carbon compensation pathway is opposite to the loss pathway. Grassland and cropland conversion to forest land is the primary pathway for compensation, with a transfer area of 360.1049×10^3 ha and 179.9592×10^3 ha, 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.

**Carbon stock evolution drivers**

**Effects of several variables Alone on Carbon Stock**

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 (Fig. 8). 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 the 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 a 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 sink 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 intensity among the socioeconomic factor's contribution demonstrates once more the strong relationship between land use change and carbon stock. 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., 2022). 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.

Climate variables have little effect on terrestrial carbon stocks. The climate is no longer the primary factor affecting vegetation development at the regional scale in Chongqing, which is situated in the water- and heat-rich southwestern China, a subtropical monsoon climate area.

**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(Figure.8). 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, according to the built model theory, those factors both directly and indirectly affect carbon stocks by changing land use patterns (Fig. 2). The key determinants of the amount of carbon sequestration in above-ground plants are light and radiation since photosynthesis is required to fix carbon in the rhizomes. When the carbon in plants' bodies is returned to the soil as they wither and die, soil type and hydrological circumstances have an impact on how soil
biology is formed and decomposed. Within the driving system, 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, according to the Chongqing study, this process has distinct
effects on carbon stocks, with complex landforms having a pronounced independent influence and
economic conditions having a greater impact after interacting with landforms and altitudes. The findings
provide a more precise quantification of the complicated impact of several potential causes on carbon
reserves.

In addition, large areas appear to be more sensitive to climate (Yang et al., 2021), and in North Asia,
warming is accelerating the accumulation of vegetative carbon (Liu et al., 2022). Appropriate grazing
management may be a critical control in dryland rangelands to maximize the provision and control of
ecosystem carbon services (Onatibia et al., 2015); the level of household residential affluence is also an
important driver of household carbon footprint (Feng et al., 2021); artificial treatment of dryland straw is
an effective channel for increasing soil organic carbon (Li et al., 2016); and soil organic carbon is
negatively affected by land use change in semi-arid environments in northern Iran (Kooch et al., 2022);
land occupation by solar power plants has also become one of the most popular ways to achieve global
carbon neutrality targets in Korea (Kim et al., 2022); and in Bangladesh, the development of rice-vegetable
land farming practices has led to an increase in soil carbon stocks with soil depth (Munny et al., 2021). It
is clear that there is no single driver for the evolution of carbon stocks, but they are all dependent on the
diversity of surface land use practices, which directly or indirectly exert their potential influence on carbon
stocks.

**Diversity of Carbon stock evolution pathways in terrestrial**

Land use change is global in nature, and the carbon intensity of the various land use types varies. This
will result in a significant quantity of carbon exchange when the transfer occurs. The results of
international researchers in various locations also demonstrate the relationship between the two.
According to a study in Chongqing, the growth of construction land results in the greatest loss of carbon,
with forest land contributing more than 50% of the carbon stock. The theoretical model developed in this
paper classifies the carbon changes brought on by land transfer into two pathways, carbon loss, and
carbon compensation pathways, and there is diversity within the pathways (Fig. 9).

The path to carbon loss brought on by land use is complex. Forests store more carbon than other surface
covers, and their encroachment will result in significant carbon losses (Panlasigui et al., 2018). In
Southeast Asia, forest loss has been ongoing for the past 20 years, and carbon emissions are also rising
(Hansen et al., 2013). In Indonesia, the reduced carbon sequestration capacity of terrestrial vegetation is
due to timber deforestation (Ausstin et al., 2015). Significant changes in the sources of greenhouse gases
have resulted from rapid land use changes in Asia, the expansion of construction land in line with
regional economic development, and the enormous rise in energy consumption (Calle et al., 2016); with
notable changes in the geographic heterogeneity of carbon stocks on different classes of cities, land
urbanization exhibits a negative linear connection with carbon stock, impacting soil carbon and carbon
sequestration (Peng et al., 2017); due to the extensive conversion of original green space to artificial land
and changes in regional meteorological conditions that affect plant photosynthesis, China's terrestrial ecosystems are now absorbing less carbon (Huang et al., 2011). Changes in forest land and cropland have a significant negative impact on carbon stocks (Wang et al., 2021). Cropland-based agricultural activities are more susceptible to seasonal and environmental influences, either as a sink or a source of carbon (Su et al., 2020). A prolonged abandonment of cropland will increase the area of unused land and reduce the potential for carbon sinks.

Carbon compensation pathways facilitate the carbon sink potential of ecosystems. By providing vegetation cover on vulnerable cropland, ecological conservation policies in the United States 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), indicating that regional land use changes characterized by increased paddy and dryland may increase carbon stocks. Agricultural vegetation absorbs substantial amounts of CO₂ through photosynthesis and stores it in crops, straw return also boosts soil carbon stocks; In India, the largest source of carbon stocks is the conversion of cropland to agroforestry and grassland (Sahoo et al., 2021); 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), and growing forest land will significantly increase carbon sequestration (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.

The above results are methodically analyzed in the theoretical model developed in this paper (Fig. 2). The issue of land use change is the key to understanding the evolution of terrestrial carbon stocks, and the variety of carbon stock evolution pathways is clarified with the aim of promoting the achievement of sustainable development goals and regulating the issue through policy feedback to construct a sustainable development model in harmony with people and land.

**Land use optimization strategies for future Chongqing carbon sink**

Systematic analysis of the impacts of land use change is beneficial for the development of land use policies to improve carbon stock in terrestrial ecosystems and enhance their carbon sink capacity (Wang et al., 2018). Forest and grassland, cropland, and construction land have dominated land use changes in Chongqing over the past 30 years, and that there are clear regional variations in the carbon stock evolution pathways (Fig. 4). The western districts primarily accomplish urban expansion through the CL→CL* carbon loss pathway, in the future, the permanent basic agricultural land surrounding the cities should be used to decide the spreading boundary of construction land, implement total control, and implement the reasonable layout (Fig. 8). There is currently 3,382,400 ha of forest land, with the majority of the decline taking place in the new zone where the FL→CL carbon loss pathway is dominant. There are clear signs of cropland abandonment in Chongqing (Huang et al., 2022). Development of abandonment afforestation to revitalize the stock by local conditions is a viable pathway for future forest land
adjustment and increase. On the contrary, the grassland area in northeastern Chongqing uses the FL→GL carbon loss pathway as the primary increase pathway. Grassland is highly adjustable, and its growth into forest land is also an important carbon sink process, utilizing increment and implement protection. The last remaining assurance of human food security is cropland, the stability of the real cropland should be maintained, except for the area that must be used for the national unified deployment into ecological retreat. However, farming activities on arable land are seasonal, which impacts the organic carbon stock of cultivated soil. The food supply and carbon sink functions of cropland can be maximized by choosing crop varieties with high yields per unit area (Fig. 10).

**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 are 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 a carbon compensation, which compensation the ecosystem with 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.

Due to research methods and data constraints, land use types differ in branch biomass of vegetation and biomass of soil organic matter with time, and carbon density will vary the drivers chosen are not
exhaustive, and additional research is required to fully understand the potential factors affecting carbon stock.

Declarations

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Declaration of Competing Interest

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Author Contributions


Consent to Participate Not applicable.

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Figures

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Theory of driving model of land use change on carbon stock evolution
Figure 2

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Figure 4

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Figure 5
Temporal changes of carbon stocks in Chongqing from 1990-2020

Figure 6

Spatial distribution of carbon stocks in Chongqing from 1990-2020
Figure 7

Carbon stock evolution pathways

FL: Forest land; GL: Grassland; CL: Cropland; CL*: Construction land; WA: Water Area; UL: Unused land
Figure 8

Contribution of single and double factors to terrestrial carbon stock

Figure 9

Carbon stock evolution pathways
Figure 10

Carbon Sink Strategy in Chongqing

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