# Impact of land use change on carbon storage in the middle reaches of the Yellow River, China (Postprint)

**Authors:** SHI Xiaoliang

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## Abstract

The implementation of long-term shelterbelt programs in the middle reaches of the Yellow River (MRYR), China not only has improved the overall ecological environment, but also has led to the changes of land use pattern, causing carbon storage exchanges. However, the relationship between carbon storage and land use change in the MRYR is not concerned, which results in the uncertainty in the simulation of carbon storage in this area. Land use changes directly affect the carbon storage capacity of ecosystems, and as an indicator reflecting the overall state of land use, land use degree has an important relationship with carbon storage. In this study, land use data and the integrated valuation of ecosystem services and trade-offs (InVEST) model were used to assess the trends in land use degree and carbon storage in the MRYR during 1980–2020. The potential impact index and the standard deviation ellipse (SDE) algorithm were applied to quantify and analyze the characteristics of the impact of land use changes on carbon storage. Subsequently, land use transitions that led to carbon storage variations and their spatial variations were determined. The results showed that: (1) the most significant periods of carbon storage changes and land use transitions were observed during 1990–1995 and 1995–2020, with the most changed areas locating in the east of Fenhe River and in northwestern Henan Province; (2) the positive impact of land use degree on carbon storage may be related to the environmental protection measures implemented along the Yellow River, while the negative impact may be associated with the expansion of construction land in plain areas; and (3) the conversion of other land use types to grassland was the primary factor affecting carbon storage changes during 1980–2020. In future land use planning, attention should be given to the direction of grassland conversion, and focus on reasonably limiting the development of construction land. To enhance carbon storage, it will be crucial to increase the area of high-carbon-density land types, such as forest land and grassland under the condition that the area of permanent farmland does not decrease.

# Full Text

## Preamble

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### Impact of Land Use Change on Carbon Storage in the Middle Reaches of the Yellow River, China

SHI Xiaoliang[1], ZHANG Jie[1]*, LIU Simin[2], DING Hao[1], CHEN Xi[1], WANG Li[1], ZHANG Dan[1]

[1]China National Forestry-Grassland Development Research Center, Beijing 100714, China

## Abstract

The implementation of long-term shelterbelt programs in the middle reaches of the Yellow River (MRYR), China has not only improved the overall ecological environment but has also led to changes in land use patterns, causing carbon storage exchanges. However, the relationship between carbon storage and land use change in the MRYR has not been adequately addressed, resulting in uncertainty in carbon storage simulation for this area. Land use changes directly affect ecosystem carbon storage capacity, and land use degree—an indicator reflecting the overall state of land utilization—has an important relationship with carbon storage. In this study, land use data and the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model were used to assess trends in land use degree and carbon storage in the MRYR during 1980-2020. The Potential Impact index and Standard Deviation Ellipse (SDE) algorithm were applied to quantify and analyze the characteristics of land use change impacts on carbon storage. Subsequently, land use transitions that led to carbon storage variations and their spatial patterns were identified. The results showed that: (1) the most significant periods of carbon storage changes and land use transitions occurred during 1990-1995 and 1995-2020, with the most changed areas located east of the Fenhe River and in northwestern Henan Province; (2) the positive impact of land use degree on carbon storage may be related to environmental protection measures implemented along the Yellow River, while the negative impact may be associated with construction land expansion in plain areas; and (3) the conversion of other land use types to grassland was the primary factor affecting carbon storage changes during 1980-2020. Future land use planning should pay attention to the direction of grassland conversion and focus on reasonably limiting construction land development. To enhance carbon storage, it will be crucial to increase the area of high-carbon-density land types such as forest land and grassland while ensuring that permanent farmland area does not decrease.

**Keywords:** carbon storage; land use degree; integrated valuation of ecosystem services and trade-offs (InVEST) model; potential impact; standard deviation ellipse (SDE)

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## 1 Introduction

Global warming is a major environmental challenge facing humanity, primarily driven by large-scale greenhouse gas emissions, particularly carbon dioxide [?, ?]. In response to this challenge, reducing greenhouse gas emissions and increasing carbon storage have become key objectives in global climate governance [?, ?]. Long-term implementation of shelterbelt programs in China has significantly contributed to carbon storage through large-scale afforestation and ecological restoration, playing a crucial role in mitigating climate change [?, ?]. However, while these shelterbelt programs have provided ecological benefits, they have also inevitably altered surface properties, subsequently influencing carbon storage, as these changes are primarily driven by land use changes [?, ?]. Therefore, studying the impact of land use changes on carbon storage has become particularly important.

Research on how different land use patterns affect carbon storage primarily encompasses influences on individual ecosystems and limited land use types [?, ?, ?]. Methods commonly used for assessing carbon storage in individual ecosystems and small study areas include average biomass, biomass regression equations, volume-derived approaches, and continuous methods utilizing conversion factors [?, ?]. For large study areas, ecological models are often used to evaluate comprehensive carbon storage. Due to its simple operation and ability to directly visualize spatial carbon storage, the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model has been extensively utilized in recent years for carbon storage studies [?, ?, ?].

Research findings indicate that factors causing carbon storage change as a result of land use change include increased impervious surfaces [?, ?], growth of construction land [?, ?], and reciprocal conversion among cultivated land, grassland, and forest land [?, ?]. Forest land transition typically results in carbon loss, whereas conversion of grassland and cultivated land may yield uncertain outcomes [?, ?]. Land use degree can serve as an indicator of overall land utilization status at the regional level [?, ?] and effectively represents the complexity of land use change. Therefore, the relationship between land use degree and carbon storage has been assessed in many previous studies. Methods for analyzing this relationship commonly include Moran’ s I index and the Potential Impact (PI) index. Previous results show that Moran’ s I index has identified a significant negative correlation between land use degree and carbon storage [?, ?]. Other studies demonstrated that carbon storage exhibited a downward trend as land use degree increased, indicating a negative relationship [?, ?]. Nevertheless, recent studies on land use, carbon storage, and PI showed that carbon storage increased as land use decreased, while PI remained negative [?, ?]. Although the relationship between land use and carbon storage has been explored, the quantitative effects on specific spatial scales and the spatial characteristics of these influences have not been thoroughly explained.

As one of China' s ecologically fragile areas, the middle reaches of the Yellow River (MRYR) has implemented a series of shelterbelt programs. Although these programs have improved the ecological environment, they have also promoted changes in land use patterns, leading to carbon exchange. Therefore, studying the impact of land use degree on carbon storage is crucial for regional land use planning and enhancing carbon storage. In this study, we analyzed trends in land use change and carbon storage, evaluated the impact of land use degree on carbon storage using the PI index, analyzed the distribution range and transfer direction of positive and negative PI using the Standard Deviation Ellipse (SDE) algorithm, and identified dominant factors of land use change in areas with significant PI changes using the Mixed Geographically Weighted Regression (MGWR) model. Subsequently, land use conversion that led to changes in carbon storage was clarified. This study aims to: (1) investigate changes in land use types and carbon storage; (2) calculate the PI of land use degree on carbon storage and clarify the directional characteristics of PI; and (3) identify the reasons leading to carbon storage changes in areas with significant PI changes.

## 2.1 Study Area

The MRYR is the section of the Yellow River Basin between Hekou Town in Inner Mongolia Autonomous Region and the Taohuayuan region in Henan Province (33°39 -40°35 N, 103°53 -113°41 E; Fig. 1 [Figure 1: see original paper]), with a total area of 3.44$×10^{5}$ km$^2$. The climate of the study area is arid, semi-arid, and semi-humid [?, ?]. Annual precipitation in the basin ranges from 300 to 800 mm, with uneven spatial and temporal distribution [?, ?]. The soil in the MRYR is loose, primarily characterized by loess landforms with strong precipitation infiltration [?, ?]. The main vegetation types include coniferous forest, cultivated vegetation, and broad-leaved forest. Geomorphic types include plains, tablelands, hills, and mountains. Land use types primarily consist of grassland, forest land, and cultivated land. Most cultivated land is distributed in plains and tablelands, grassland is mainly distributed in hills, and forest land is primarily located in mountainous areas. Due to the fragile ecological environment, various shelterbelt programs have been implemented within the basin, causing notable changes in land use patterns.

Fig. 1 Land use type (a), geomorphic type (b), and implemented shelterbelt program (c) in the middle reaches of the Yellow River (MRYR), China. The images (land use type, geomorphic type, shelterbelt program, and other basic geographic features) are sourced from the Data Center for Resources and Environmental Sciences of Chinese Academy of Sciences (http://www.resdc.cn). The map of the MRYR is sourced from the National Earth System Science Data Center (http://www.geodata.cn) and the boundary has not been modified.

## 2.2 Materials

The data include land use, precipitation, temperature, gross domestic product (GDP), land use and cover change of China, and digital elevation model (DEM) (Table 1 ).

**Table 1** Detailed information of data

| Data | Year | Resolution | Resource |
|---|---|---|---|
| Land use | 1980, 1990, 1995, 2000, 2005, 2010, 2015, and 2020 | 1 km, yearly | Resource 1 |
| Precipitation | 1990, 1995, and 2000 | 1 km, monthly | Resource 3 |
| Temperature | 1990, 1995, and 2000 | 1 km, monthly | Resource 3 |
| GDP | 1990, 1995, and 2000 | - | Resource 2 |
| Land use and cover change dataset of China | 1990, 1995, and 2000 | 1 km, yearly | Resource 1 |
| Shelterbelt program | - | Shape file | Resource 1 |
| Geomorphic type | - | Shape file | Resource 1 |
| DEM | - | - | Resource 4 |

*Note: GDP, gross domestic product; DEM, digital elevation model; Resource 1, Data Center for Resources and Environmental Sciences of Chinese Academy of Sciences (http://www.resdc.cn); Resource 2, National Bureau of Statistics; Resource 3, National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/); Resource 4, National Oceanic and Atmospheric Administration (https://www.nesdc.org.cn). "-" means no value.*

### 2.3.1 Land Use Degree (LUD)

LUD is used to measure the integrated extent of regional land utilization, and the equation is as follows:

$$LUD = 100 \times \sum_{i=1}^{n}(A_i \times P_i)$$

where $A_i$ is the $i$th classification index, in which forest land, water body, and grassland are level 2, cultivated land is level 3, construction land and unused land are level 4; $P_i$ is the percentage of total area occupied by the $i$th land use type (%); and $n$ is the total number of land use types. LUD usually ranges from 100–400. The fishnet tool was employed to grid land use data and determine land use degree in every unit. An increase in land use degree indicates that land use is being improved and developed, while a decrease indicates that land use is in the adjustment stage [**?**, **?**].

### 2.3.2 Carbon Storage Estimation Method

Calculation of carbon storage ($C_i$) in terrestrial ecosystems considers four components in the InVEST model, and the equation is as follows:

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

where $C_{above}$ is the above-ground biomass (t/hm$^2$); $C_{below}$ is the below-ground biomass (t/hm$^2$); $C_{soil}$ is the soil organic matter (t/hm$^2$); and $C_{dead}$ is the dead organic matter (t/hm$^2$). Due to the minimal contribution from dead organic matter and the challenges in obtaining it, this component was not considered in calculating carbon storage.

Carbon density data for each land use type were obtained from previous studies conducted in similar or adjacent areas [**?**, **?**, **?**, **?**]. Since carbon density is influenced by regional climate conditions, it is necessary to adjust the data using a correction formula based on the actual precipitation and temperature conditions of the MRYR [**?**, **?**]. The equations are as follows:

$$C_{BP} = 0.0054 \times MAP^{6.798}$$

$$e^{3.3968 \times MAP} = 299.61$$

where $C_{BP}$ is the biomass carbon density (t/hm$^2$); MAP is the annual mean precipitation (mm); $e$ is the natural logarithm; MAT is the mean annual temperature (℃); $C_{BT}$ is the biomass carbon density (t/hm$^2$) corrected by MAT; $C_{SP}$ is the soil carbon density (t/hm$^2$) obtained using MAP; $K_{BP}$ is the correction coefficient obtained based on MAP; BPC are the biomass carbon density corrected by MAP of the MRYR (t/hm$^2$) and China (t/hm$^2$), respectively; $K_{BT}$ is the correction coefficient obtained based on MAT; BTC are the biomass carbon density corrected by MAT of the MRYR (t/hm$^2$) and China (t/hm$^2$), respectively; $K_B$ is the correction coefficient for biomass carbon density; $K_S$ is the correction coefficient for soil carbon density; and $SPC$ and $STC$ are the soil carbon density corrected by MAT of the MRYR (t/hm$^2$) and China (t/hm$^2$), respectively (Table 2 ).

**Table 2** Corrected carbon density of the middle reaches of the Yellow River (MRYR)

| Land use type | $C_{above}$ (t/hm$^2$) | $C_{below}$ (t/hm$^2$) | $C_{soil}$ (t/hm$^2$) |
|---|---|---|---|
| Cultivated land | 15.89 | 4.77 | 82.30 |
| Forest land | 41.54 | 12.46 | 140.47 |
| Grassland | 8.49 | 2.55 | 98.54 |
| Water body | 0 | 0 | 0 |
| Construction land | 0 | 0 | 0 |
| Unused land | 0.36 | 0.11 | 23.21 |

*Note: $C_{above}$, $C_{below}$, and $C_{soil}$ are the above-ground biomass, below-ground biomass, and soil organic matter, respectively.*

### 2.3.3 PI Index

The PI index can be used to characterize the relationship between carbon storage and land use degree. The equation is as follows [?, ?]:

$$PI = \frac{L_x - L_y}{L_x} \times \frac{C_y - C_x}{C_x}$$

where $L_x$ is the land use degree in the initial stage; $C_y$ is the carbon storage in the final stage (t/hm$^2$); $C_x$ is the carbon storage in the initial stage (t/hm$^2$); and $L_y$ is the land use degree in the initial stage. Positive PI indicates that the effect of land use degree on carbon storage is positive, and higher values indicate more pronounced effects.

The Standard Deviation Ellipse (SDE) algorithm is a method to summarize the directional characteristics of point-like geographical elements, and the calculation is as follows:

$$\tan(2\theta) = \frac{2 \times \mathrm{cov}(x, y)}{\mathrm{var}(x) - \mathrm{var}(y)}$$

where $C$ is the covariance matrix used to calculate SDE; $(x)$ and $(y)$ are the coordinates; $(x_i, y_i)$ are the coordinates of the $i$th feature; $(\bar{x}, \bar{y})$ is the mean center of the $i$th feature; $\lambda$ is the eigenvalue; $I$ is the identity matrix; $r_1$ is the semi-major axis of the ellipse; $r_2$ is the semi-minor axis of the ellipse; $\lambda_1$ and $\lambda_2$ are eigenvalues calculated using Equation 12; and $\theta$ is the rotation angle of the ellipse.

SDE was used to analyze the directional characteristics of PI in this study. The distribution range of SDE represents the main impact areas, and the centroid represents the relative position of PI in space. The major axis of SDE represents the principal direction of data distribution, while the minor axis indicates the spread.

### 2.3.4 MGWR Model

The MGWR model can better capture local spatial effects in data, allowing explanatory variables to vary spatially [**?**, **?**]. MGWR was used to analyze the drivers of land use degree in areas where PI changed significantly, and it was calculated as follows:

$$w_i = \beta_{0i} + \sum_{j=1}^{p} \beta_{ij} x_{ij} + \varepsilon_i$$

where $w_i$ is the response variable; $\beta_{0i}$ is the intercept; $p$ is the number of independent variables; $\beta_{ij}$ is the coefficient of the explanatory variable $x_{ij}$; and $\varepsilon_i$ is the error term.

## 3.1 Temporal Variation of Carbon Storage and Land Use Types

Annual total carbon storage in the MRYR was 7408.60$×10^{5}$ Mg, with an average of 2155.52 Mg/km$^2$ in 1980. Both total and mean carbon storage showed an increasing trend during 1980-1990, decreased during 1990-1995, reached maximum carbon storage in 2000, and then continued decreasing during 2000-2020 (Fig. 2a [Figure 2: see original paper]).

Forest land, grassland, and cultivated land were the main land use types in the MRYR during 1980-2020. Land use changes were primarily characterized by a decrease in cultivated land area and an increase in construction land area during this period (Fig. 2b). During 1990-2005, cultivated land transfer was relatively active. For example, the areas of cultivated land transferred into other land use types and other land use types transferred into cultivated land were 9055 and 10,460 km$^2$, respectively. During 1995-2000, the area of cultivated land transferred in continued to increase by 10,128 km$^2$, while the area transferred out decreased significantly to 8545 km$^2$. During 2000-2005, the area of cultivated land transferred out exceeded that transferred in, and the total area of cultivated land continuously decreased from 2000 onward.

Forest land area fluctuated during 1990-2000. During 1990-1995, the area of forest land transferred in was less than that transferred out, while during 1995-2000, the area transferred in was greater than that transferred out. Overall, the total area of forest land slightly increased during 1980-2000. Grassland area increased significantly by 8910 $km^2$ during 1990-1995, followed by a decrease of 8302 $km^2$ during 1995-2000. This change showed an opposite trend compared with forest land area. Overall, grassland area also slightly increased during 1980-2000. Water body area showed little change and remained relatively stable. Construction land area continued to increase, with the largest growth occurring in 2005.

## 3.2 Spatial Variation of Land Use Degree and Carbon Storage

Spatial variation in land use degree and carbon storage in the MRYR is shown in Figure 3 [Figure 3: see original paper]. Significant changes in land use degree and carbon storage occurred during 1990-1995 and 1995-2000. During 1990-1995, land use degree in most parts of Inner Mongolia Autonomous Region exhibited a declining trend, while carbon storage mainly displayed an upward pattern. In Shaanxi Province, Gansu Province, and Ningxia Hui Autonomous Region, land use degree and carbon storage exhibited significant spatial heterogeneity. The areas with the most dramatic changes in land use degree were primarily located in the hilly regions at the border of Ningxia Hui Autonomous Region and Gansu Province, the hilly regions at the border of Shaanxi Province and Inner Mongolia Autonomous Region, the tableland areas in northern Shaanxi Province, and the plains along the Weihe River. The hilly regions at the border of Shaanxi Province and Inner Mongolia Autonomous Region and the plains along the Weihe River mainly exhibited an upward trend in carbon storage, while other areas primarily underwent decreasing carbon storage. In Shanxi Province, land use degree east of the Fenhe River showed a significant increasing trend, whereas south of the Yellow River in Henan Province, land use degree showed a significant decreasing trend, with carbon storage mainly decreasing in these areas.

During 1995-2000, areas with significant changes in land use degree were primarily concentrated south of the Weihe River and east of the Yellow River. In most of these areas, the trends in land use degree and carbon storage were opposite to those observed during 1990-1995. There were also notable changes in the spatial distribution of land use during 2010-2015. In this interval, carbon storage in the MRYR predominantly demonstrated a decreasing trend, characterized by a dispersed distribution pattern without large-scale aggregated changes. During 1980-2020, the main change areas of land use degree gradually shifted from eastern to western parts of the MRYR.

To better understand the significant changes in carbon storage during 1990-1995 and 1995-2000, we examined land use transfer patterns in the basin where these carbon storage changes occurred (Fig. 4 [Figure 4: see original paper]). Grassland transfer during 1990-1995 occurred mainly east of the Fenhe River and in northern Shaanxi Province, which increased carbon storage in the MRYR by 9.43$\times10^{6}$ t and decreased it by 11.99$\times10^{6}$ t, respectively. Cultivated land and forest land transfer mainly occurred in northwestern Henan Province. Forest land transfer increased carbon storage by 7.29$\times10^{6}$ t, while cultivated land transfer increased carbon storage by 1.84$\times10^{6}$ t and decreased it by 4.87$\times10^{6}$ t. Construction land transfer mainly occurred along the Weihe River, reducing carbon storage in the MRYR by 7.40$\times10^{3}$ t.

Land use patterns in the MRYR underwent significant changes again during 1995-2000. Large areas of other land use types were converted to forest land and cultivated land east of the Fenhe River, and converted to grassland in northwestern Henan Province. The continued expansion of construction land led to a reduction in carbon storage by 11.10$\times10^{3}$ t. Overall, during 1980-2020, changes in carbon storage were mainly driven by grassland transfer and construction land expansion. Grassland transferred in mainly occurred in western MRYR, while construction land expansion primarily took place along urban edges.

### 3.3.1 Spatiotemporal Variation of PI

Statistical results of PI for the basin during 1980-2020 are shown in Figure 5 [Figure 5: see original paper]. During 1980-1995, PI exhibited a decreasing tendency. During 1995-2010, PI continued to increase. However, during 2010-2020, PI was negative, indicating a shift from positive to negative impact of land use degree on carbon storage, with the negative impact continually strengthening.

Spatial heterogeneity of PI is shown in Figure 6 [Figure 6: see original paper]. In 1990, only a few areas had PI less than -0.1, primarily clustered in the southern part of the MRYR. In 1995, the spatial distribution of PI exhibited clustering characteristics, with numerous areas of negative PI across the basin. Areas with PI less than -0.1 were mainly distributed in the hilly regions in the northwest and mountains in the southeast of the MRYR, the hilly regions, plains, and tablelands in central Shaanxi Province, and the hilly areas in northeastern Gansu Province. Areas with PI greater than 0.1 were primarily situated in the mountains east of the Yellow River. In 2000, areas with PI less than -0.1 decreased, and the overall spatial distribution was similar to that in 1995. In 2005, areas with PI less than -0.1 were primarily distributed in the hilly regions in eastern Gansu Province, southern Inner Mongolia Autonomous Region, and northern Shaanxi Province. During 2005-2010, land use degree changed little, and the spatial distribution of PI was not particularly pronounced. In 2015, areas with PI less than -0.1 appeared around some urban areas. In 2020, areas with PI less than -0.1 increased, primarily situated in the hilly regions of Gansu

Province and Inner Mongolia Autonomous Region, the plains of Shaanxi and Shanxi provinces, and the mountainous areas of Henan Province.

### 3.3.2 Directional Characteristics of PI

A noteworthy shift occurred in the distribution range of land use degree impacts on carbon storage during 1990–2020 (Fig. 7 [Figure 7: see original paper]). During 1980–2000, the distribution range of positive PI was smaller than negative PI, while during 2005–2020, the range of positive PI was larger than that of negative PI. Directional characteristics of positive PI were quite evident in 1990, 1995, 2000, and 2015, while those of negative PI were relatively noticeable in 1990, 2005, 2015, and 2020. The gravity center for negative PI was primarily located near the confluence of the Weihe River, Yellow River, and Fenhe River, while positive PI was mainly situated in the region between the Yellow River and Fenhe River.

Regions of both positive and negative PI were located near the junction of the Fenhe River and Yellow River in 1990, with the difference that positive PI extended further west. In 1995, regions with positive PI were mostly situated in northern Shaanxi and western Shanxi provinces, with a "north-south" distribution pattern that aligned with the orientation of the Yellow River. In these regions with positive PI, the primary land use types were forest land, grassland, and cultivated land. Conversely, regions with negative PI aligned with the distribution of plains, primarily following a "northeast-southwest" direction.

In 2000, directional characteristics had weakened, and the intensity of both positive and negative PI was relatively lower than in 1995. In 2005, the distribution range of positive PI was mainly located in eastern Shaanxi and western Shanxi provinces, covering most mountainous and plain areas, although directional characteristics were not very distinct. The distribution range of negative PI was primarily concentrated in the southern part of the MRYR, with its gravity center near the confluence of the Weihe River, Yellow River, and Fenhe River. In 2010, directional characteristics of both positive and negative PI became less distinct, distributing primarily in the southeastern part of the MRYR. The gravity center was located in the plains of Shanxi Province, and the distribution range of positive PI was notably larger than that of negative PI. In 2015, the direction of positive PI was north-south, aligning with the course of the Yellow River. The gravity center of negative PI was located at the confluence of the Fenhe River and Yellow River. In 2020, the distribution range of positive PI covered most of the MRYR. The principal direction of negative PI was northeast-southwest, aligning with the course of the Fenhe River and the plain of Shanxi Province. By comparing directional characteristics of positive and negative PI, we found that the range of positive PI concentrated on forest land, grassland, and cultivated land, aligning with the direction of the Yellow River. This result suggests a strong association between the Yellow River and positive PI. However, the range of negative PI was related to plains.

## 3.4 Dominant Factors of Land Use Degree

Significant land use changes occurred during 1990-1995 and 1995-2000, resulting in notable fluctuations in carbon storage. To analyze the driving factors behind land use changes and carbon storage variations, we selected natural factors (slope, aspect, precipitation, and temperature), socioeconomic factors (GDP), and policy factor (change in forest land cover proportion) (Fig. 8 [Figure 8: see original paper]). During 1990-1995, slope-driven land use changes were primarily concentrated in the Weihe River area and southern Henan Province, involving conversions between forest land, grassland, and cultivated land. Precipitation and temperature facilitated conversions among cultivated land, forest land, and grassland in Henan and Shanxi provinces. GDP primarily drove the conversion of grassland to forest land in Henan Province and forest land to grassland in Shanxi Province. Policy impact was mainly observed along the Weihe River and in parts of Shanxi and Henan provinces, promoting the conversion of cultivated land to grassland and forest land.

During 1995-2000, slope-driven changes shifted to southwestern Shanxi Province, promoting the conversion of grassland to forest land. Meanwhile, the influence of precipitation strengthened, significantly contributing to forest land expansion. Although the impact of GDP weakened, it still drove localized conversions among land use types in Henan and Shanxi provinces, leading to mutual changes among cultivated land, forest land, and grassland. Policy impact was primarily concentrated in northeastern MRYR, as well as in Henan and Shanxi provinces, contributing to conversions among cultivated land, grassland, and forest land.

## 4 Discussion

During 1980-2020, significant changes in land use types were observed in the MRYR, primarily characterized by conversions among forest land, grassland, and cultivated land, as well as expansion of construction land [?, ?]. Intensive implementation of shelterbelt programs occurred in the MRYR during 1980-2000, and the primary changes during this period involved mutual conversions among forest land, grassland, and cultivated land, with grassland conversion being particularly active [?, ?]. Conversion into cultivated land primarily occurred east and south of the Yellow River, likely driven by implementation of the "Regulations on the Protection of Basic Farmland" [?, ?]. Conversion of forest land and grassland in eastern Fenhe River may be related to the Grain for Green Project [?, ?]. Implementation of policies encouraging cultivated land retirement in western MRYR also led to increased grassland area [?, ?]. In the hilly regions of Shaanxi Province, conversion of unused land and cultivated land into grassland may be attributed to ecological restoration [?, ?]. During 2000-2010, the intensity of shelterbelt programs decreased, and land use changes were less pronounced. Under policy influence, both forest land and grassland areas increased. However, due to urbanization development, construction land expanded by encroaching on cultivated land [?, ?]. Additionally, construction land development was facilitated by implementation of the "Western Development Strategy" [?, ?], with main development areas being urban fringes [?, ?]. Overall, both shelterbelt program implementation and urbanization have significantly impacted land use structure in the MRYR. While vegetation cover has substantially improved, construction land area has also expanded rapidly. In the future, greater efforts should be made to protect afforestation areas, pay attention to economic development impacts on land use structure, and reasonably limit construction land expansion.

Carbon storage in the MRYR exhibited a trend of initial increase followed by decrease. During the intensive shelterbelt program implementation phase, carbon storage notably increased [?, ?, ?]. The trend of land use changes in areas where shelterbelt programs were implemented aligns with carbon storage trends, indicating that program implementation can significantly increase carbon storage [?, ?]. However, carbon storage benefits gradually diminish during policy implementation [?, ?]. The gravity center of negative land use impact on carbon storage was primarily located at the junction of Shaanxi and Shanxi provinces, gradually shifting toward Shanxi Province. This shift may result from more significant land use changes in Shaanxi from 1980 to 2005, while from 2005 onward, land use changes in Shanxi Province became more pronounced [?, ?, ?]. As the land use type with the largest area in the MRYR, cultivated land plays a crucial role in regional carbon storage. To mitigate agricultural carbon emissions, farmers should promote green agriculture development, focusing on reducing fertilizer and pesticide use and enhancing soil carbon sequestration capacity [?, ?]. Forest land is the land use type with the highest carbon density. Therefore, to enhance carbon storage, future efforts should focus on strengthening vegetation restoration and ecological afforestation, particularly in areas with severe soil erosion. It is essential to select plant species well-suited to the local growing environment. Additionally, protecting vegetation in afforested areas is critical to prevent ecological degradation and ensure long-term stability of carbon sequestration capacity in these ecosystems. Construction land expansion is largely irreversible [?, ?]. To mitigate carbon storage reduction and other environmental issues caused by this expansion, policymakers should place greater emphasis on urban green space development [?, ?], which can help offset decreased carbon storage impacts in urban areas.

Carbon density is affected by multiple factors such as climate and soil properties, while the InVEST model simulates carbon storage based on static carbon density, which brings limitations to the results [?, ?]. In this study, carbon density data primarily come from measurements conducted by previous researchers in the same study area, and carbon density data for the MRYR were obtained by applying a correction formula to these measurements. However, there is large variation in carbon density across different ecosystems, and the lack of long-term monitoring data from sample plots means that the precision of these estimates still requires further improvement [?, ?]. In future ecological construction in the MRYR, it is essential to adhere to relevant shelterbelt programs and ecological restoration projects, converting cultivated land to grassland and forest land.

Additionally, it is important to manage construction land expansion sustainably. At the same time, maximizing the use of various resources to protect the MRYR ecological environment and prevent ecological degradation is crucial.

## 5 Conclusions

With shelterbelt program implementation during 1980–2000, carbon storage in the MRYR showed a fluctuating increase, but it began to decline steadily after 2000, with the decrease becoming more pronounced after 2010. The most significant changes in land use types and carbon storage were observed during 1990–1995 and 1995–2000. Large amounts of forest land and grassland were converted into cultivated land, leading to negative impacts in most areas during 1995–2000. During 1995–2000, due to policy interventions, forest land and cultivated land partially recovered, while grassland decreased, leading to reduced areas experiencing negative impacts. Overall, positive impacts were primarily associated with environmental protection measures implemented along the Yellow River, while negative impacts were mainly driven by construction land expansion in plains. The main land use changes in the MRYR are concentrated on mutual conversion between cultivated land, forest land, and grassland, while construction land primarily expanded by occupying existing cultivated land.

Construction land development should be reasonably limited in the future to increase carbon storage. Efforts should be made to increase forest land and grassland areas, and permanent basic farmland area should be maintained. Furthermore, ecological protection should be strengthened to prevent ecological degradation in the MRYR.

### Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Author Contributions

Conceptualization: SHI Xiaoliang, ZHANG Jie; Methodology: SHI Xiaoliang, ZHANG Jie, LIU Simin, WANG Li; Investigation: SHI Xiaoliang, DING Hao, ZHANG Dan; Formal analysis: ZHANG Jie, LIU Simin, CHEN Xi, WANG Li; Writing - original draft preparation: ZHANG Jie; Writing - review and editing: SHI Xiaoliang, LIU Simin, CHEN Xi; Funding acquisition: SHI Xiaoliang; Supervision: SHI Xiaoliang, ZHANG Jie. All authors approved the manuscript.

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