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Scenario-based Simulation of Land Use/Cover Change and Carbon Storage Evaluation in Zhangye City Using the PLUS-InVEST Model

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Abstract: Carbon storage (CS) and its cycling processes in terrestrial ecosystems constitute a fundamental component of the global carbon cycle. Ecologically fragile regions, characterized by low ecosystem stability and high sensitivity to external disturbances, play a critical role in understanding regional and global carbon dynamics. Land Use/Land Cover Change (LUCC), as a major manifestation of human activities, is widely recognized as a key driver influencing CS and its spatiotemporal variations. However, for a typical ecologically fragile area such as Zhangye City in Gansu Province, there remains a lack of multi-scenario quantitative assessments regarding the impacts of LUCC on CS. In this study, the InVEST model and the PLUS model were integrated to analyze the evolution of land use patterns and CS in Zhangye City from 1990 to 2020. Furthermore, land use configurations and corresponding CS distributions under four ecological protection scenarios for 2030 were simulated. The results indicate that: (1) from 1990 to 2020, grassland and unused land decreased by 0.69% and 1.35%, respectively, while cultivated land expanded by 1.82% (approximately 698.86 km^2), reflecting a notable shift in land use structure; (2) LUCC contributed to a net increase of 0.49×10^7 t in total CS, exhibiting a spatial pattern of gradual increase from north to south; (3) by 2030, compared with the natural development scenario, CS under low-, medium-, and high-level ecological protection scenarios increased to 38.05×10^7 t, 38.06×10^7 t (38.05546×10^7 t), and 38.06×10^7 t (38.05544×10^7 t), respectively, with the medium-level ecological protection scenario yielding the most optimal land use configuration. By coupling the InVEST and PLUS models, this study effectively characterizes the impacts of land use change on CS, and provides methodological support for land use optimization and CS assessment in ecologically fragile regions. Based on these findings, it is recommended to strengthen the protection of ecological land, appropriately regulate the expansion of built-up areas, and promote a coordinated balance between economic development and ecological conservation, thereby contributing to the achievement of carbon peaking and carbon neutrality goals.

Keywords: Carbon Storage (CS); Land Use Change; Ecological Protection; InVEST Model; PLUS Model.

1. Introduction

Against the backdrop of global warming, both natural ecosystems and human societies are experiencing intensifying pressures. An increasing frequency of extreme climate events, together with the deterioration of ecosystem functions and a reduction in the carrying capacity of socio-economic systems, has emerged as a defining feature of contemporary global environmental change[1, 2, 3]. A broad consensus indicates that the sustained rise in greenhouse gas emissions represents a dominant driver of climate warming[4], prompting governments worldwide to reinforce climate governance and advance corresponding policy frameworks and technological strategies[5]. In this context, carbon neutrality has progressively been recognized as a central pathway for mitigating climate change and advancing sustainable development[6].

CS within terrestrial ecosystems represents a critical component of the global carbon cycle and underpins climate regulation processes. Carbon is primarily retained in forests, grasslands, wetlands, and soils[7], where vegetation assimilates atmospheric CO_2 via photosynthesis and sequesters it in biomass and soil organic matter over extended periods, thereby functioning as a major carbon sink[8]. At the global scale, terrestrial ecosystems account for approximately 25% of annual CO_2 uptake, underscoring their pivotal role in climate change mitigation[9]. The conservation and enhancement of ecosystem carbon stocks can effectively reduce atmospheric CO_2 concentrations and consequently decelerate the pace of global warming[10].

Land use change is a key factor influencing regional CS. It directly affects the dynamic changes of CS by altering the spatial distribution structure and function of different ecosystems[11]. The change in land use not only alters the CS capacity but may also lead to the conversion of carbon sources and carbon sinks, thereby affecting the balance of the global carbon cycle. Optimizing the quantity and spatial structure pattern of land use can not only increase the CS of the region, but also accelerate the realization of the carbon peaking and carbon neutrality goals and mitigate the negative impacts of global climate change[12]. Therefore, how to scientifically and reasonably plan land use, especially how to enhance the carbon sequestration capacity of ecosystems by optimizing the land use structure and promote the healthy development of the carbon cycle, remains one of the key issues that need to be urgently addressed in the global response to climate change[13]. In particular, there is still a lack of systematic research frameworks and implementation paths in the relevant fields on how to rationally plan territorial space, increase CS and accelerate the realization of carbon neutrality goals in combination with the specific characteristics of different regions[14, 15].

A variety of models have been used to analyze and optimize land use spatial patterns, including CLUE-S[16], CA-

Markov[17], FLUS[18], and PLUS[19]. Among these approaches, the PLUS model has attracted increasing attention in land use optimization studies because it is developed based on the cellular automata (CA) framework. By simulating the spatial transition processes among different landscape types, the model is capable of representing the nonlinear dynamics of land use change and producing reliable simulation results. In addition, the model shows strong robustness and adaptability under different simulation conditions[20].Through the establishment of multiple development scenarios, the PLUS model can be used to explore possible future trajectories of land use change. Consequently, it has been widely adopted in studies focusing on land use optimization, particularly in research related to carbon-neutral development strategies. With the advancement of territorial spatial planning, increasing attention has been paid to the relationship between land use change and the terrestrial carbon cycle, as well as to strategies for low-carbon land use management. Several models have been applied to estimate ecosystem CS, including the Bookkeeping method[21], the IPCC inventory approach[22], CASA[23], GLO-PEM[24], and InVEST. These models incorporate both climatic influences and human activities when assessing terrestrial ecosystem processes and can be used to quantify CS and evaluate its spatial distribution in regions characterized by complex land use patterns. Among them, the InVEST model has been widely employed in ecosystem CS studies because of its relatively simple data requirements, stable simulation performance, and broad applicability[25].

Although numerous studies have explored future land use patterns from both economic and ecological perspectives, research focusing on land use optimization in ecologically fragile regions remains limited. Zhangye City represents a typical fragile ecological region where forest and grassland resources are relatively scarce. In recent decades, agricultural development has led to a continuous expansion of cultivated land, accompanied by a gradual decline in grassland and forest areas. Consequently, despite a gradual increase in ecosystem CS, the spatial extent of ecological land such as forests and grasslands has continued to shrink. Under these circumstances, developing rational land use strategies for Zhangye City from an ecological conservation perspective has become increasingly important. Scientific land use planning and structural optimization can not only enhance regional carbon sequestration and support ecological restoration, but also facilitate the achievement of carbon peaking and carbon neutrality targets, thereby promoting the development of an ecologically sustainable Zhangye.

This study quantitatively evaluated the impact of land use/land cover changes on CS based on the InVEST model, revealing the spatio-temporal dynamic changes and potential of ecosystem CS in Zhangye City. Meanwhile, the PLUS model was combined to simulate the future land use changes, and the potential changes in CS under different land use/land cover scenarios were evaluated. By exploring the optimal land use pattern, this study has proposed practical and feasible land use management strategies, providing new ideas and theoretical basis for further optimizing land use planning in ecologically fragile areas, enhancing regional carbon sequestration potential, promoting environmentally sustainable development, and supporting the attainment of regional carbon neutrality targets.

2. Research Area

Zhangye City (97°20' -102° 12’E, 37°28 '-39° 57’N) is situated in Gansu Province in northwestern China. The administrative region includes one district and five counties: Ganzhou District, Linze County, Gaotai County, Shandan County, Minle County, and Sunan Yugur Autonomous County. The city administers 65 towns (sub-districts) and covers an area of about 3.85×10^4 km^2[26]. Topographically, the study area shows a clear west–east gradient, with higher elevations in the west and relatively lower terrain toward the east. The region extends in a long and narrow pattern and contains diverse landforms, including snow-covered mountains and glaciers, forest and grassland ecosystems, as well as deserts and sand dune landscapes. Climatically, Zhangye belongs to the temperate arid continental zone and is characterized by limited precipitation, strong evaporation, sparse vegetation cover, and widespread desertification. These environmental characteristics make the region ecologically sensitive and vulnerable. In recent years, accelerated economic development and intensified human activities have imposed increasing pressure on the local ecological environment. As a result, the balance between ecological protection and economic growth has become increasingly strained. Achieving coordinated development between environmental conservation and regional economic expansion has therefore become an important issue for sustainable development in the study area (Fig 1).

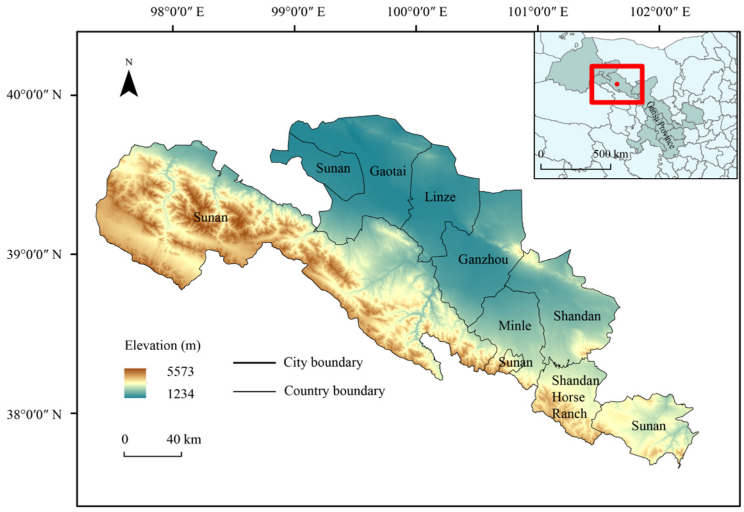


Fig 1. Geographic map of the research area

3. Data Sources and Research Methods

3.1. Data Sources

Detailed descriptions of the datasets used in this study are listed in (Table 1). All datasets were pre-processed in ArcGIS. During the preprocessing stage, the spatial resolution of all raster data was unified to 30 m through resampling, and missing values were removed to improve data reliability. In addition, the spatial extent of each raster layer was standardized and aligned to ensure consistent spatial positioning among all datasets, thereby providing a reliable basis for subsequent analysis[27].

Table 1. Research data

Dataset Type	Dataset Name	Format Spatial Resolution	Sources
LUC data	LUC data	Grid 1000 (m)	Resources and Environmental Sciences and Data Center, Chinese Academy of Sciences (hppts://www.resdc.cn)
Natural environmental factors	DEM	Grid 30 (m)	Geospatial Data Cloud (hppts://www.gscloud.cn)
	Slope	Grid 30 (m)	
	Annual average Precipitation	Grid 1000 (m)	Resources and Environmental Sciences and Data Center, Chinese Academy of Sciences (hppts://www.resdc.cn)
	Annual average Temperature	Grid 1000 (m)	
	Soil type	Grid 1000 (m)	
	Soil erosion	Grid 1000 (m)	
Socio-economic factors	Railway	Vector	OpenStreetMap (hppts://www.openhistoricalmap.org)
	National Highway	Vector	
	Provincial road	Vector	
	GDP	Grid 1000 (m)	Resources and Environmental Sciences and Data Center, Chinese Academy of Sciences (hppts://www.resdc.cn)
	Population	Grid 1000 (m)	

3.2. Research Methods

3.2.1. The InVEST Model Calculates CS

This study employed the CS module of the InVEST model to estimate the CS in Zhangye City. The InVEST model is commonly used for ecosystem service assessment at regional and landscape scales. By integrating land use/land cover spatial data with carbon pool parameters, the model calculates the CS of each spatial unit and produces a spatial distribution map of CS. The model quantifies CS based on different carbon pools associated with land use types, which enables spatially explicit estimation of CS under heterogeneous land use conditions. The calculation is expressed as follows[28]:

$$C_i = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (1)$$

$$C_{total} = \sum_{i=1}^{n} A_i \times C_i \quad (2)$$

where C_i denotes the total carbon density (t/hm^2); C_{above}, C_{below}, C_{soil}, and C_{dead} represent the carbon densities of aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter, respectively. C_{total} is the total CS (t), and A_i is the area of the i-th land use type (hm^2).

Previous studies indicate that vegetation carbon density and soil organic carbon density are positively correlated with precipitation and negatively correlated with temperature. This relationship has been widely observed in arid regions[29]. Therefore, the initial carbon density values were adjusted using temperature and precipitation data to obtain carbon density parameters that better reflect local environmental conditions. The detailed calculation procedure is described as follows.

(1) Consider the regression model of precipitation (MAT≤10℃):

$$C_{SP} = 0.07 \times \text{MAP} + 79.1 \quad (3)$$

$$C_{BP} = 0.03 \times \text{MAP} + 14.4 \quad (4)$$

(2) Consider the regression model of temperature (MAP≤400 mm):

$$C_{ST} = -5.8 \times \text{MAT} + 100.5 \quad (5)$$

$$C_{BT} = -1.3 \times \text{MAT} + 16.7 \quad (6)$$

(3) Consider the regression model of temperature (MAP>400 mm):

$$C_{ST} = -3.4 \times \text{MAP} + 157.7 \quad (7)$$

$$C_{BT} = -0.4 \times \text{MAP} + 43.0 \quad (8)$$

In the formula, C_{BP} and C_{BT} are the organic carbon densities (t/hm^2) of the vegetation considering precipitation and temperature respectively; C_{BT} and C_{ST} are the soil organic carbon densities (t/hm^2) considering precipitation and temperature respectively; MAT and MAP represent the multi-year average temperature (℃) and the multi-year average rainfall (mm), respectively. The multi-year average temperatures in Zhangye City and across the country are 6.00℃ and 9.96℃ respectively. The multi-year average rainfall in Zhangye City and across the country is 216.40 mm and 643.25 mm respectively.

Substituting the multi-year average temperature and multi-year average rainfall at the scale of Zhangye City into the above formula respectively, we obtain C'_{SP} , C'_{ST} , C'_{BP} , C'_{BT} ; Substituting the multi-year average temperature and multi-year average rainfall on a national scale into the above formula respectively, we obtain C''_{SP}, C''_{ST}, C''_{BP}, C''_{BT}, The ratio of the two is the correction factor.

$$K_{SP} = \frac{C'_{SP}}{C''_{SP}} \quad (9)$$

$$K_{ST} = \frac{C'_{ST}}{C''_{ST}} \quad (10)$$

$$K_{BP} = \frac{C'_{BP}}{C''_{BP}} \quad (11)$$

$$K_{BT} = \frac{C'_{BT}}{C''_{BT}} \quad (12)$$

In the formula, K_{BP} and K_{BT} are the vegetation carbon density correction coefficients considering precipitation and temperature respectively; K_{SP} and K_{ST} are respectively the correction coefficients of soil organic carbon density considering precipitation and temperature.

$$K_S\text{=Average}(K_{SP},K_{ST}) \tag{13}$$

$$K_B\text{=Average}(K_{BP},K_{BT}) \tag{14}$$

In the formula, K_S is the correction coefficient of soil organic carbon density, and K_B is the correction coefficient of vegetation organic carbon density, multiply the national vegetation and soil organic carbon density by K_B and K_S respectively, then the biomass carbon density and soil organic carbon density of different land use types in Zhangye City were obtained. After calculation, K_S and K_B the sums are 0.6449 and 0.4240 respectively.

The revised carbon density data was integrated to obtain the carbon densities of various land use types in Zhangye City as shown in Table 2.

Table 2. Carbon density values (t/hm^2)

LUC type	C_{above}	C_{below}	C_{soil}	C_{dead}	C_{Total}
Cu	2.42	42.07	79.50	9.08	133.07
Fo	51.80	62.51	158.80	9.49	282.61
Gr	1.44	45.40	64.42	1.41	112.67
Wa	0.64	0.45	52.30	0.00	53.39
Co	0.83	1.45	57.80	0.00	60.08
Unuse	0.30	0.87	21.60	0.00	22.77

3.2.2. The PLUS Model Optimizes the Spatial Layout of Land Use

To achieve high-precision simulation of land use change processes, the PLUS model was employed to construct the simulation framework. This model integrates the Land Expansion Analysis Strategy (LEAS) with a Cellular Automata (CA) model driven by multiple random seeds (CARS), enabling the characterization of land use change from both the perspectives of driving mechanism identification and spatial dynamic evolution. Specifically, the LEAS module is used to extract the dominant driving factors and their effects on the expansion of different land use types, while the CARS module simulates the spatial allocation and dynamic evolution of land use patterns based on these identified mechanisms[19].

(1) Driving factor identification and development potential assessment:

Based on land use data from two periods and corresponding natural and socio-economic driving factors, the LEAS module employs a random forest algorithm to establish nonlinear relationships between driving factors and land use expansion. This process quantitatively evaluates the contribution of each factor to the expansion of different land use types, thereby generating spatial distributions of development potential, which serve as constraints for subsequent simulations.

(2) Simulation of spatial dynamics and model validation：

Building upon the identified driving mechanisms, the CARS module introduces a multi-random seed mechanism to simulate the spatial competition among different land use types. The model integrates key parameters, including land use transition rules (Table 3.), neighborhood effects, and development probabilities, to allocate land use patterns under different future scenarios. Furthermore, using land use data from 1990 to 2020, a backcasting simulation of the 2020 land use pattern was conducted and compared with observed data. The results demonstrate a high level of agreement between simulated and actual land use patterns, with a Kappa coefficient of 0.94, a Figure of Merit (FoM) of 0.14, and an overall accuracy of 0.96, indicating that the model is capable of effectively capturing land use change dynamics in the study area[30].

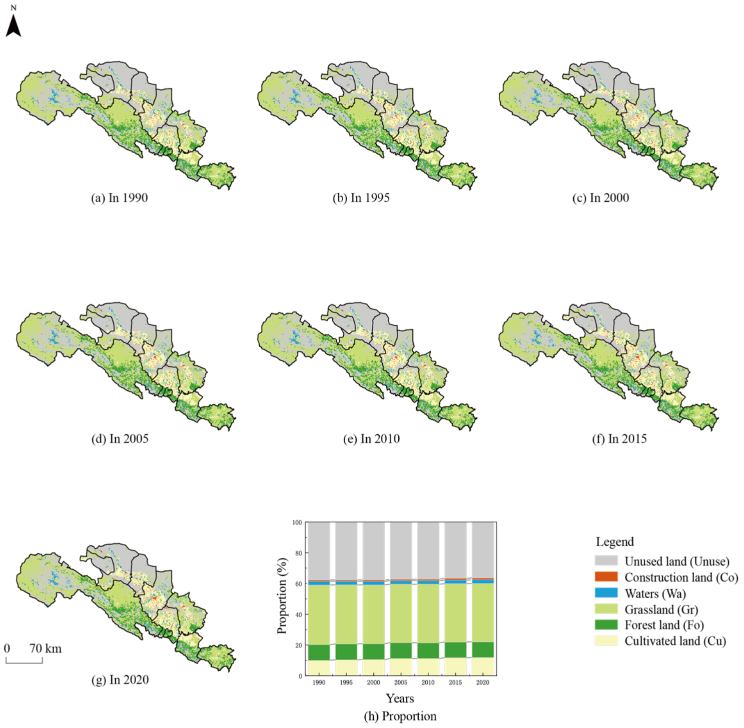
Table 3. Land use/land cover transition matrix

NDS						
LUC type	Cu	Fo	Gr	Wa	Co	Unuse
Cu	YES	YES	YES	YES	YES	YES
Fo	YES	YES	YES	YES	YES	YES
Gr	YES	YES	YES	YES	YES	YES
Wa	YES	NO	YES	YES	NO	YES
Co	NO	NO	NO	NO	YES	NO
Unuse	YES	YES	YES	YES	YES	YES
LEPS						
LUC type	Cu	Fo	Gr	Wa	Co	Unuse
Cu	YES	YES	YES	YES	YES	YES
Fo	YES	YES	YES	YES	YES	YES
Gr	YES	YES	YES	YES	YES	YES
Wa	YES	NO	YES	YES	NO	YES
Co	NO	NO	NO	NO	YES	NO
Unuse	YES	YES	YES	YES	YES	YES
MEPS						
LUC type	Cu	Fo	Gr	Wa	Co	Unuse
Cu	YES	YES	YES	YES	YES	YES
Fo	YES	YES	YES	YES	YES	YES
Gr	YES	YES	YES	YES	YES	YES
Wa	YES	NO	YES	YES	NO	YES
Co	NO	NO	NO	NO	YES	NO
Unuse	YES	YES	YES	YES	YES	YES
HEPS						
LUC type	Cu	Fo	Gr	Wa	Co	Unuse
Cu	YES	YES	YES	YES	YES	YES
Fo	YES	YES	YES	YES	YES	YES
Gr	YES	YES	YES	YES	YES	YES
Wa	NO	NO	NO	YES	NO	NO
Co	NO	NO	NO	NO	YES	NO
Unuse	YES	YES	YES	YES	YES	YES

Note: The value 0 denotes that conversion between land use types rarely occurs, while 1 represents a high probability of such conversion. NDS (natural development scenario) reflects the continuation of previous land-use transition patterns, while LEPS (low ecological protection scenario), MEPS (medium ecological protection scenario), and HEPS (high ecological protection scenario) represent ecological protection at low, medium, and high intensity levels, respectively.

4. Results and Analysis

4.1. Land Use/Cover Dynamics in Zhangye City during 1990-2020

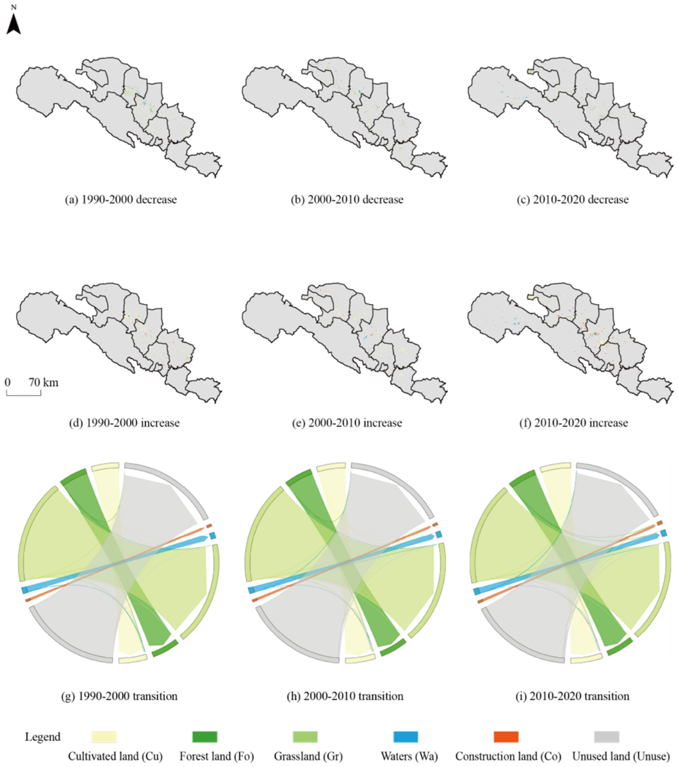


(a) In 1990 (b) In 1995 (c) In 2000

(d) In 2005 (e) In 2010 (f) In 2015

(g) In 2020 (h) Proportion

Fig 2. Land use/cover spatial pattern



(a) 1990-2000 decrease (b) 2000-2010 decrease (c) 2010-2020 decrease

(d) 1990-2000 increase (e) 2000-2010 increase (f) 2010-2020 increase

(g) 1990-2000 transition (h) 2000-2010 transition (i) 2010-2020 transition

Fig 3. Land use/cover variation during 1990-2020

The evolution of land use patterns in Zhangye City from 1990 to 2020 is shown in Fig 2. Overall, Gr and Unuse dominated the study area throughout the study period, jointly accounting for approximately 80% of the total area. The remaining land use types, including Cu, Fo, Wa, and Co, occupied relatively smaller proportions. In terms of spatial distribution, all land use types exhibited a distinct southeast-northwest banded pattern. Specifically, Cu, Wa, and Co were mainly distributed in the central region, Fo and Gr were primarily located in the southern region, while Unuse was concentrated in the northern region, where sandy surfaces are widely developed.

From a temporal perspective, the land use structure of the study area underwent notable adjustments over the past three decades. The areas of Cu and Co increased by 1.82% (698.86 km^2) and 0.33% (127.14 km^2), respectively, indicating a continuous expansion trend. In contrast, Gr and Unuse showed a decreasing trend, declining from 38.66% to 37.97% and from 37.74% to 36.39%, respectively. By comparison, Fo and Wa remained relatively stable, with only minor changes during the study period.

The land use transition process is illustrated in Fig 3.

During 1990-2000, the conversion from Gr to Cu was the most significant, with a net transition area of 193.88 km^2. In the subsequent periods (2000-2010 and 2010-2020), the overall trend of land use change became more stable; however, the conversion from Gr to Cu continued, resulting in net increases of Cu by 116.14 km^2 and 59.78 km^2, respectively. Meanwhile, Unuse was gradually converted into other land use types, further promoting the expansion of Cu and Co. By 2020, the net increase in Co reached 60.15 km^2.

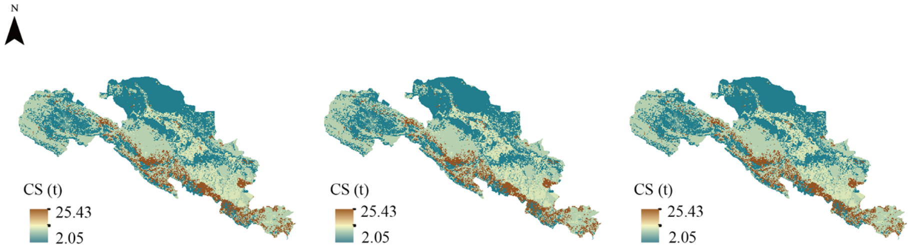
From the perspective of spatial evolution, land use/cover change was mainly concentrated after 2000. With rapid regional economic development, Cu and Co increased significantly in Gaotai County, Linze County, and Ganzhou District, where urban expansion was particularly evident.

4.2. Spatiotemporal Variations in CS in Zhangye City (1990-2020)

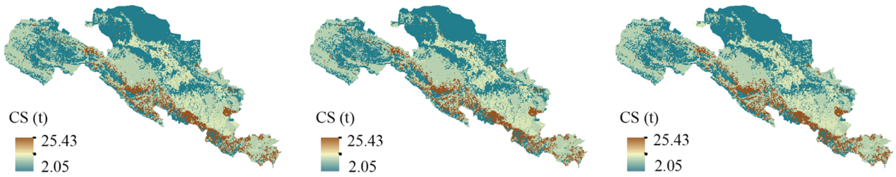
CS in Zhangye City was estimated using the InVEST model, and its spatiotemporal dynamics from 1990 to 2020 were further analyzed (Table 4). Quantitative results show that during 1990-2020, CS associated with Cu and Co increased by 0.93×10^7 t and 0.08×10^7 t, respectively. In contrast, Fo, Gr, Wa and Unuse all experienced declines. Among these categories, the largest decrease occurred in Gr, with a reduction of 0.30×10^7 t. Overall, total CS in Zhangye City rose from 37.09×10^7 t in 1990 to 37.58×10^7 t in 2020, representing a net increase of 0.49×10^7 t. The most notable growth occurred during 2000-2005, when CS increased by 0.19×10^7 t, whereas changes in other periods remained relatively stable. Spatially, CS displays a band-like gradient decreasing from south to north (Fig 4). The southern region, characterized by mountainous terrain and Fo distribution, is constrained by higher elevations and steep slopes, which limit urban expansion and human activities. In contrast, natural constraints in the central and northern regions are weaker, and land-use conversion occurs more intensively. Consequently, CS forms a band-like spatial pattern that gradually decreases from south to north.

Table 4. CS variation during 1990-2020 (10^7 t)

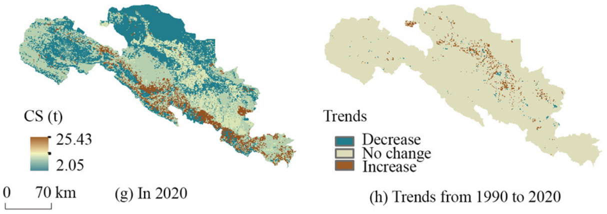
LUC type	1990	1995	2000	2005	2010	2015	2020	1990-2020
Cu	5.11	5.31	5.39	5.74	5.73	5.99	6.04	0.93
Fo	11.23	11.20	11.18	11.14	11.14	11.14	11.14	-0.09
Gr	16.75	16.64	16.57	16.48	16.50	16.43	16.45	-0.30
Wa	0.50	0.49	0.48	0.48	0.48	0.48	0.49	0.00
Co	0.20	0.21	0.21	0.22	0.22	0.26	0.28	0.08
Unuse	3.30	3.30	3.30	3.26	3.25	3.21	3.19	-0.12
Total	37.09	37.14	37.13	37.32	37.33	37.51	37.58	0.49



(a) In 1990 (b) In 1995 (c) In 2000



(d) In 2005 (e) In 2010 (f) In 2015



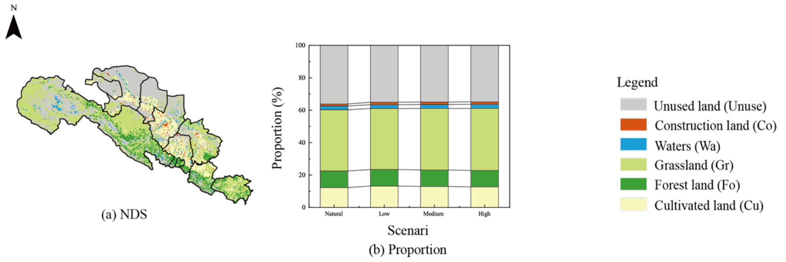
(g) In 2020 (h) Trends from 1990 to 2020

Fig 4. Spatiotemporal changes in CS from 1990 to 2020

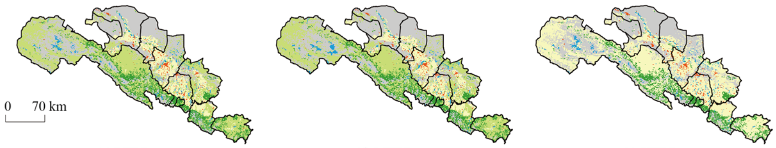
4.3. Predict Land Use and CS in 2030 under Different Scenarios

4.3.1. Land Use/Cover Changes under Different Scenarios in 2030

Between 2020 and 2030, land use patterns in Zhangye City are projected to vary considerably under different development scenarios (Fig 5). In the absence of policy intervention, Gr and Unuse are expected to decline by 0.21% and 0.25%, respectively, whereas Cu increases by 0.49%. Most of the newly expanded Cu is concentrated in Gaotai, Linze, Ganzhou, Shandan and Minle, accompanied by a marked reduction of Unuse in these areas. Under the LEPS, Unuse decreases by 1.35%, while Cu and Co expand by 1.46% and 1.35%, respectively. The growth of Cu is mainly observed in Gaotai County and Ganzhou District. Correspondingly, the most notable decreases in Unuse occur in Gaotai, Linze, Ganzhou, Shandan and Minle, largely resulting from the conversion of Unuse to Cu. In the MEPS, Unuse is reduced by 1.44%, whereas Cu increases by 1.15%. Overall, Unuse across Zhangye City shows a declining tendency, which contributes to the expansion of Cu, Wa and Co to different extents. Under the HEPS, Cu, Gr, Wa and Co all exhibit noticeable growth. Among them, Cu shows the largest increase, reaching 0.84%. The expansion of Cu and Co occurs across most parts of the municipal area. Gr growth is mainly observed in Sunan and Shandan, while Unuse declines across the region, with a total reduction of 1.54%. The comparison of the four scenarios suggests that Cu expansion is most pronounced under LEPS, whereas Fo continues to shrink. In contrast, HEPS the most effective conservation, resulting in the smallest decrease in Fo. Overall, as ecological protection measures are strengthened, the areas of Fo and Wa gradually increase, while Co and Unuse continue to decline.



(a) NDS (b) Proportion



(c) LEPS (d) MEPS (e) HEPS

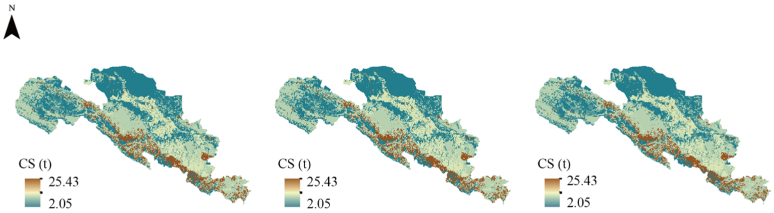
Fig 5. Land use/land cover changes under different scenarios

4.3.2. Spatial Distribution of CS under Different Land Use Scenarios in the Future

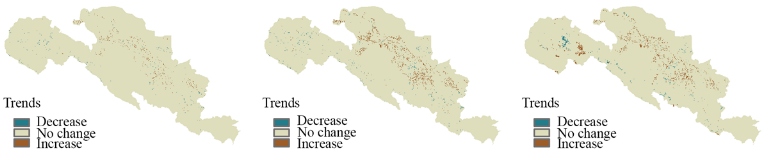
Based on the simulation results of land use in 2030, the corresponding CS was estimated (Table 5). The results show that under the NDS, the CS of Cu has increased significantly, with an increase of 0.25×10^7 t. After the implementation of ecological protection strategies, the CS of Cu under lower protection is the largest. With the intensification of ecological protection efforts, the CS gradually decreases, but it is still higher than that of Cu under natural conditions. They were respectively increased by 0.75×10^7 t, 0.59×10^7 t and 0.43×10^7 t. The changing trend of CS of Co is consistent with that of Cu. In the four scenarios, it increases by 0.01×10^7 t, 0.08×10^7 t, 0.07×10^7 t (0.073×10^7 t) and 0.07×10^7 t (0.070×10^7 t) respectively. Contrary to the growth trends of Cu and Co, the CS of Fo and Unuse in all four cases was lower than that in 2020. Under the policies of strengthening Fo protection and reducing Unuse, the shrinking area of Fo has been reduced, and the reduction rate of CS has correspondingly narrowed. The CS in the four situations decreased by 0.03×10^7 t, 0.07×10^7 t, 0.05×10^7 t and 0.03×10^7 t respectively. The Unuse carbon reserves decreased by 0.02×10^7 t, 0.12×10^7 t, 0.13×10^7 t (0.126×10^7 t) and 0.13×10^7 t (0.134×10^7 t) in sequence. Under the impetus of Gr and Wa restoration policies, the areas of the two types of land have continued to expand. Specifically, the area of Gr will be restored by 2030 under the HEPS, while the area of Wa has already been restored under the MEPS.

Table 5. CS changes from 2020 to 2030 (10^7 t)

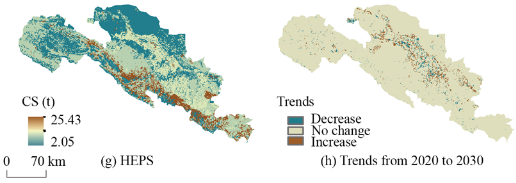
LUC type	NDS	2020 -2030	LEPS	2020 -2030	MEPS	2020-2030	HEPS	2020 -2030
Cu	6.29	0.25	6.78	0.75	6.63	0.59	6.47	0.43
Fo	11.11	-0.03	11.07	-0.07	11.09	-0.05	11.11	-0.03
Gr	16.36	-0.09	16.30	-0.15	16.43	-0.02	16.55	0.10
Wa	0.48	-0.01	0.49	0.00	0.51	0.01	0.53	0.04
Co	0.29	0.01	0.35	0.08	0.35	0.07	0.35	0.07
Unuse	3.16	-0.02	3.07	-0.12	3.06	-0.13	3.05	-0.13
Total	37.68	0.10	38.05	0.47	38.06	0.48	38.06	0.48



(a) NDS (b) LEPS (c) MEPS



(d) Trends from 2020 to 2030 (e) Trends from 2020 to 2030 (f) Trends from 2020 to 2030



(g) HEPS (h) Trends from 2020 to 2030

Fig 6. CS patterns under different development scenarios (2020-2030)

This led to a reduction of 0.09×10^7 t, 0.15×10^7 t, and 0.02×10^7 t in Gr CS in the first three scenarios respectively, and an increase of 0.10×10^7 t in the final situation. The CS in Wa decreases by 0.01×10^7 t and 0.00×10^7 t (0.005×10^7 t) under NDS and LEPS, and increases by 0.01×10^7 t and 0.04×10^7 t under MEPS and HEPS. Overall, the total CS is the highest under the MEPS, followed by the HEPS, LEPS and NDS, with total CS of 38.06×10^7 t (38.05546×10^7 t), 38.06×10^7 t (38.05544×10^7 t), 38.05×10^7 t and 37.68×10^7 t respectively. From the perspective of spatial distribution (Fig 6), the reduction in CS is mainly concentrated in Gaotai, Linze, Ganzhou, Shandan and Minle, which indicates that in future land use planning, ecological management and protection in these areas should be strengthened. Implementing appropriate ecological protection strategies can help enhance regional CS capacity and promote the stability and sustainable development of ecosystems.

5. Discussion

From 1990 to 2020, the CS in Zhangye City changed significantly and showed an overall upward trend. Research shows that the total CS rose from 37.09×10^7 t in 1990 to 37.58×10^7 t in 2020, with a cumulative increase of 0.49×10^7 t. This change is mainly driven by the rapid development of the city's agricultural economy, which has increased the input of agricultural production factors and the intensity of agricultural development, thereby promoting the expansion of Cu area and resulting in an increase in CS in Zhangye City[31]. The increase and decrease of CS in Zhangye City show significant spatial heterogeneity. The southern mountainous area, due to its high altitude, rugged terrain and mainly mild soil erosion, with less human interference, has maintained a relatively high and stable level of CS[32]. In contrast, although the western mountainous area also has a relatively high altitude and complex terrain, it is affected by moderate to mild soil erosion and there is some Unuse in the central area, resulting in a relatively low overall CS in this region[33]. The central region has a relatively low altitude, flat terrain, good accessibility and development conditions, and high land use intensity, especially in districts and counties such as Gaotai, Linze, Ganzhou and Minle. Driven by both the demand for economic growth and population growth, Cu has significantly expanded and occupied some Gr and Unuse. Given that Cu has a relatively high carbon density level among the land use types in Zhangye City, the above-mentioned land use transformation has significantly enhanced the CS in the central region[32]. The northern part is mainly distributed in the Unuse with the lowest carbon density, and thus it is the area with the lowest CS in the city.

From a time scale perspective, the growth of CS in Zhangye City exhibits different characteristics at different stages. CS declined from 1995 to 2000, while it increased in other periods. The decline during this period was mainly due to the fact that the scale of conversion from Cu to Gr with lower carbon density was larger than that of other land types converting to Cu and other types with higher CS, resulting in a decrease in total carbon density. Between 1990 and 2000, population growth led to an increase in food demand, but it was limited by the level of productivity. This was mainly achieved by expanding the area of Cu, manifested as the conversion of wasteland and Gr into Cu[34]. Entering the 21st century, with the continuous advancement of agricultural economic construction in Zhangye, the expansion of Cu has further accelerated, thereby promoting a continuous increase in CS. Overall, agricultural development and the land use changes driven by it are the key mechanisms for the increase in CS in Zhangye City.

Based on the future scenario simulations using the InVEST and PLUS models, CS in Zhangye under the NDS increased by only 0.11×10^7 t relative to 2020, representing the smallest growth among the four scenarios. In terms of model mechanisms, variations in ecosystem CS are primarily controlled by the conversion of land area among different land use categories. Under this scenario, only Cu and Co exhibit expansion, and the growth of Cu is smaller than that observed in the other scenarios. As a result, CS increases slightly, but the overall gain remains limited. Under the LEPS, the areas of Cu and Co expand more rapidly, while Fo and Gr decline markedly. The regional CS generally shows a significant upward trend, with an estimated increase of 0.11×10^7 t. In contrast, under the scenario of MEPS, the increase in CS slows down compared to the scenario of LEPS. It is expected to increase by 0.48×10^7 t. However, the reduction in the area of Fo with a higher carbon density has been effectively controlled, indicating the effectiveness of ecological protection measures. If ecological protection continues to be strengthened and urban expansion is restricted, the CS in Zhangye will slightly decline compared to the MEPS. This is because the area of the Fo with the highest carbon density has not shown a significant increase, while the area of Cu with a higher carbon density has decreased significantly, thereby weakening the growth potential of regional CS to a certain extent[35].

Over the past 30 years, the CS in Zhangye City has undergone a phased change from decline to continuous growth. With the adjustment of land use patterns, regional CS is expected to maintain a growth trend in future scenarios. The main reasons for this are the continuous expansion of Cu area and the relatively high CS per unit area of Cu. The growth of Cu area makes the most significant contribution to the increase in CS in land use changes and has become the dominant driving factor for the current growth of CS. Against this backdrop, although Cu has played a significant role in enhancing regional CS, its carbon sink function still has certain limitations in terms of ecosystem stability and comprehensive ecological services[36]. In contrast, basic ecological land such as Fo and Gr have more prominent advantages in terms of long-term CS capacity, the co-accumulation of biomass and soil carbon, and the stability of ecosystem structure. Therefore, in the future, Zhangye City should, on the basis of maintaining the carbon sink contribution of Cu, further enhance the regional CS level and ecological quality by moderately increasing the proportion of Fo and Gr and optimizing the land use structure[37].

6. Recommendations

The changes in CS in Zhangye City are mainly influenced by the development of agricultural economy, urbanization process and land development. To achieve sustainable management of regional CS and ecological protection, it is necessary to enhance the level of CS and ecosystem service functions by optimizing land use planning. Based on this, this study puts forward the following policy recommendations to alleviate the pressure brought about by the slow increase in CS and promote the realization of the carbon peaking and carbon neutrality goals in Zhangye City.

(1) Establishing a carbon sink conservation framework for key southern regions

The results indicate that the Qilian Mountains and Shandan Military Horse Farm in southern Zhangye serve as the primary carbon sink areas of the region. Their high CS is closely associated with complex topographic conditions and relatively low levels of human disturbance. For these areas, it is necessary to improve the ecological protection system from a holistic perspective by delineating key conservation zones and implementing hierarchical management to reduce external disturbances to ecosystems. At the same time, priority should be given to regions with high potential for CS enhancement, where the restoration and optimized allocation of ecosystems such as forests, wetlands, and grasslands should be systematically promoted. By integrating natural recovery processes with engineering measures, ecosystem stability and CS capacity can be strengthened. On this basis, it is important to encourage the development of industries relying on ecological resources, and to establish long-term support mechanisms through ecological compensation, thereby fostering a positive interaction between ecological protection and regional development.

(2) Reshaping land use patterns and development pathways in the central region

The central region exhibits relatively low CS levels, mainly influenced by ongoing urban expansion and land development activities. With the continuous concentration of population and economic activities, the spatial structure of the region is undergoing significant transformation. To mitigate the negative impacts of land use change on CS, it is necessary to promote a more intensive and ecologically oriented development model through spatial restructuring. In practice, this can be achieved by optimizing the layout of built-up land, enhancing the connectivity of urban green spaces, and establishing multi-level ecological corridor networks to improve the ecological carrying capacity of urban areas. Meanwhile, focusing on the Heihe River Basin, systematic restoration of wetlands, water bodies, and forest ecosystems should be advanced. Through ecological restoration processes, regional CS can be gradually enhanced, thereby achieving coordinated development between economic growth and ecological functions.

(3) Optimize the structure of agricultural land use

Studies show that the high-quality cultivated land resources in Zhangye City are limited, and the contradiction between population and land is prominent. Agricultural expansion has occupied Gr and caused problems such as the decline of land fertility and the increase of ecological environment pressure. To this end, it is suggested that while continuously developing oasis agriculture, a land use policy oriented towards sustainable agriculture be implemented, the red line for grassland protection be strictly enforced, and land reclamation and intensive agricultural development be promoted. Specific measures include improving the agricultural ecological compensation mechanism, guiding farmers to adopt environmentally friendly production methods such as organic and ecological agriculture, promoting intensive agricultural development through scientific planning, enhancing land use efficiency, and reducing the negative impact of disorderly reclamation and agricultural expansion on regional CS.

7. Conclusion

This study takes Zhangye City as an example to explore the impact of land use change on CS from 1990 to 2020. Under the guidance of ecological protection goals, future land use scenarios were constructed, and a quantitative assessment was conducted on different land use patterns and their CS contributions in Zhangye City in 2030. The research results show that:

(1) Between 1990 and 2020, the distribution of Gr and Unuse in Zhangye City changed markedly, with their proportions declining by 0.69% and 1.35%, respectively.

These changes largely contributed to the ongoing expansion of cultivated land in Gaotai County, Linze County and Ganzhou District. During this period, the total Cu area increased by 1.82%, reaching approximately 698.86 km^2.

(2) With the rapid advancement of urbanization and land development, the transformation of land use resulted in an increase of 0.49×10^7 t in the overall CS of Zhangye City from 1990 to 2020. The spatial distribution of CS displays a decreasing gradient from south to north. Owing to favorable natural conditions, the southern mountainous region maintains relatively high CS, whereas the central and northern areas exhibit lower CS levels due to human activities and local environmental conditions.

(3) Further analysis reveals a clear spatial association linking land use change to CS variation. By 2030, CS in Zhangye City presents noticeable differences under different land use scenarios. Relative to the natural development scenario, CS under the LEPS, MEPS and HEPS reaches 38.05×10^7 t, 38.06×10^7 t (38.05546×10^7 t) and 38.06×10^7 t (38.05544×10^7 t), respectively. Among these scenarios, the MEPS produces the highest CS level. While taking economic development into account, this scenario effectively mitigates the decline in forest area and can therefore be regarded as a relatively optimized land use pattern for Zhangye City. The results suggest that scientifically optimizing land use patterns plays a crucial role in improving regional CS capacity and facilitating sustainable regional development.

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