Scenario-Based Forecasting Analysis of Ecosystem Carbon Storage in the Tarim River Basin: Postprint

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Abstract

Land use patterns are important factors causing changes in terrestrial ecosystem carbon storage and play a key role in maintaining stable carbon storage levels. By utilizing the coupled PLUS-InVEST model to evaluate and predict land use and carbon storage changes in the Tarim River Basin from 1980 to 2020, four scenarios were established: natural development, ecological protection, cultivated land protection, and urban development. Land use and carbon storage change trends in the study area for 2030 were predicted under each scenario, and based on this, the impact of land use change on carbon storage was explored. The results show that: (1) Over the 40-year period, the area of cultivated land, construction land, and unused land in the Tarim River Basin increased significantly, while the area of forest land, grassland, and water bodies decreased. (2) During the 40-year period from 1980 to 2020, carbon storage showed an overall upward trend, with a total increase of 22.66\$$\times 10^{6} t.Areasofincreasedcarbonstorageweremainlydistributedalongthemainstreamandtributariesofth$
t under the four scenarios, respectively. (4) Transitions from cultivated land to forest land, from grassland to forest land, from water bodies to grassland and unused land, and from unused land to cultivated land and grassland are all beneficial to carbon storage. Therefore, in future planning, cultivated land protection should be combined with ecological protection, local economic growth should be ensured while controlling the outward expansion of construction land, carbon storage levels should be improved, and efforts should be made to achieve the "dual carbon" goals.

Full Text

Scenario Projection Analysis of Ecosystem Carbon Stocks in the Tarim River Basin

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Abstract: Land use patterns are critical factors influencing carbon stock changes in terrestrial ecosystems and play a key role in maintaining carbon stock stability. This study employs a coupled PLUS-InVEST model to assess and predict land use and carbon stock changes in the Tarim River Basin from 1980 to 2020. Four scenarios were established: natural development, ecological protection, arable land protection, and urban development. The trends of land use and carbon stocks in the study area for 2030 were predicted under these scenarios, and the impacts of land use changes on carbon stocks were investigated. The results show that: (1) From 1980 to 2020, the areas of cultivated land, construction land, and unutilized land in the Tarim River Basin increased significantly, while forest land, grassland, and water areas decreased. (2) Carbon stocks exhibited an overall upward trend during the 40-year period, with a total increase of 22.66$×10^{6}$ t. The increased carbon stock area was mainly distributed along the main stream of the Tarim River and its tributaries. Unutilized land and grassland are the primary carbon reservoirs in the Tarim River Basin, accounting for 24.77% and 19.37% of the total carbon stock, respectively. (3) Scenario predictions indicate that carbon stock loss after 2020 will be substantial and the rate of loss will gradually accelerate. The carbon stock reduction area is mainly distributed in the central-southwestern part of the study area. Future transfers from grassland to unutilized land and from forest land to grassland are the main causes of carbon stock loss. Under the four scenarios, carbon stock losses are projected to be 0.0475$×10^{8}$ t, 0.0051$×10^{8}$ t, 0.0285$×10^{8}$ t, and 0.0473$×10^{8}$ t, respectively. (4) Transfers from cropland to forest land, grassland to forest land, water to grassland and unutilized land, and from unutilized land to cropland and grassland are all conducive to carbon storage. Therefore, future planning should integrate arable land protection with ecological conservation, controlling the outward expansion of construction land while ensuring local economic growth, improving carbon stock levels, and building capacity to achieve the “dual carbon” goals.

Keywords: Tarim River Basin; land use; carbon stock; PLUS model; InVEST model; Xinjiang

1 Study Area Overview

The Tarim River Basin (75°06 –92°50 E, 36°30 –42°10 N) is located in southern Xinjiang, with a total length of 2,179 km and an area of approximately 10.5$×10^{4}$ km^{2}. It is the world's largest inland river basin, formed by the confluence of the Tarim River main stream and its tributaries, with glacier meltwater as the primary water source. The basin is characterized by alternating mountains and plains, with deserts in its central region covering 37.04$×10^{4}$ km^{2}. Situated in the hinterland of the Eurasian continent, far from the ocean and surrounded by mountains, the region experiences large diurnal temperature variations, with summer temperatures averaging 20–30°C and winter temperatures ranging from -10 to -20°C. Precipitation is scarce and evaporation is intense, representing a typical arid continental climate within a warm temperate zone. Land use types in the study area are dominated by unutilized land and grassland [Figure 1: see original paper].

2 Data and Methods

2.1 Data Sources and Processing

Data used for future land use simulation included natural conditions, socioeconomic factors, and transportation location (Table 1). Land use data were obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn). Carbon density data are presented in Table 2. Considering model applicability and accuracy, land use changes were analyzed using 14 driving factors from natural conditions, socioeconomic factors, and transportation location, with the random forest method employed to address spatial autocorrelation and multicollinearity among driving factors. Carbon pool data from relevant literature were compared with data for the study area, outliers were screened and analyzed, and final carbon pool data were obtained.

2.2.1 InVEST Model

The InVEST model spatializes and visualizes ecosystem service functions and economic values under different land cover scenarios. This study adopted the carbon storage module from terrestrial ecosystems. The module's regional total carbon stock is calculated by summing the products of four carbon pools (aboveground, belowground, soil, and dead organic matter) and their respective land use areas:

$$C_{it} = \sum_{i} (C_{i_{\text{above}}} + C_{i_{\text{below}}} + C_{i_{\text{soil}}} + C_{i_{\text{dead}}}) \times S_i$$

where C_i represents the carbon density of land use type i; $C_{i_{\text{above}}}$, $C_{i_{\text{below}}}$, $C_{i_{\text{soil}}}$, and $C_{i_{\text{dead}}}$ are the aboveground, belowground, soil, and dead organic matter carbon densities, respectively; and S_i is the area of land use type i.

Carbon density data from previous studies were used and compared, outliers were removed, and final carbon density values for each land use type in the Tarim River Basin were obtained (Table 2). Correction formulas for aboveground and soil carbon stocks are:

$$BP = 6.798 \times e^{0.005 \times MA} + 3.9961$$

$$SP = 3.3968 \times MA + 398$$

$$BT = 28 \times e^{0.0006 \times MT}$$

where MA and MT are mean annual precipitation and mean annual temperature, respectively; BP, SP, and BT are aboveground carbon stock, soil carbon stock, and biological carbon stock corrected by mean temperature, respectively; and C_1 and C_2 are coefficients calculated from national and regional precipitation and temperature data.

2.2.2 PLUS Model

The PLUS model is a patch-level land use change simulation model based on raster data. It extracts samples of mutual conversions among land use categories and simulates land use based on transition probabilities. The random forest algorithm calculates the expansion potential of each land category and the contribution of driving factors. Using 2020 land use data as the baseline, 14 driving factors were employed to simulate the PLUS model. By modifying transition probability matrices, four scenarios were established: natural development, arable land protection, ecological protection, and urban development. Future land use changes under different scenarios for 2030 were predicted.

The transition cost matrix defines whether conversions between land types can occur under different scenarios, where convertible relationships are marked as 1 and non-convertible as 0. The integrated Markov chain predicts future land type changes based on historical transition cost matrices:

$$S_{t+1} = P_{ix} \times S_t$$

where S_t is the land type at time t; P_{ix} is the land type transition probability; and S_{t+1} is the land type at time $t+1$.

Model validation showed an overall accuracy of 94.531% and Kappa coefficient of 0.89 when comparing simulated 2020 land use with actual data, indicating high reliability for predicting future land use changes in the Tarim River Basin.

3 Results

3.1 Land Use Change Analysis

Land use distribution in the Tarim River Basin from 1980 to 2020 is shown in [Figure 2: see original paper]. Unutilized land is widely distributed in the central Taklamakan Desert of the Tarim Basin. Grassland is distributed around the desert edges. Water areas and cultivated land are located in the southwestern part of the basin and along the Aksu, Yarkant, and Kashgar Rivers, as well as the lower reaches of the Hotan and Konqi Rivers. Forest land and construction land are distributed in the middle and upper reaches of the Tarim River, with construction land concentrated on cultivated land.

From 1980 to 2020, land use in the Tarim River Basin was dominated by grassland and unutilized land, followed by water and forest land (Table 4). All land categories showed significant changes, with grassland and water areas exhibiting negative growth in dynamic degree (Table 5, [Figure 3: see original paper]). Conversely, cultivated land and construction land showed positive dynamic degree with obvious expansion. Unutilized land and forest land experienced slight increases and decreases, respectively. Construction land changed most significantly, followed by cultivated land, water, grassland, and forest land. Cultivated and construction land areas increased substantially, with dynamic degrees of 3.4574% and 14.2387%, respectively, driven by urbanization and national food security policies.

To clarify land use conversion flows, a Sankey diagram was created using Origin software to visualize transfers between land use types from 1980 to 2020 ([Figure 4: see original paper]). Cultivated land expanded by 17,876.97 km^2, primarily from grassland (13,063.14 km^2) and unutilized land (4,164.75 km^2). Water area decreased by 14,382.09 km^2, mainly converting to grassland, unutilized land, and forest land. Mutual conversions occurred between grassland and unutilized land, grassland and cultivated land, and grassland and forest land. Forest land and grassland decreased by 182.87 km^2 and 26,631.9 km^2, respectively, while unutilized land increased by 22,147.11 km^2. The significant mutual conversion between grassland and unutilized land resulted from overgrazing, unsustainable human activities, and severe land desertification. However, ecological restoration policies implemented since 2005, including returning farmland to forest and grassland, have gradually increased grassland coverage. Water area loss was primarily caused by cultivated land expansion increasing irrigation water demand, leading to imbalanced water resource allocation. Implementation of ecological water transfer and water-saving irrigation projects has gradually increased water area.

3.2 Simulated Land Use Predictions for 2030

Using the PLUS model with different scenario transition matrices, land use changes in the Tarim River Basin for 2030 were predicted based on 2020 baseline data [Figure 5: see original paper].

Natural Development Scenario: Cultivated land, water area, and construction land increased by 5,196.96 km^2, 276.39 km^2, and 468.99 km^2, respectively. The expansion of cultivated and construction land was consistent with 1980–2020 trends, primarily due to grassland conversion to cultivated land, and forest land and unutilized land conversion to water and construction land. Forest land, grassland, and unutilized land decreased by 193.14 km^2, 5,476.68 km^2, and 272.52 km^2, respectively.

Arable Land Protection Scenario: This scenario protected cultivated land area by preventing its conversion to other land types, controlled construction land expansion into cultivated land, and restricted conversions of forest land and water areas. Cultivated land, water area, and construction land expanded by 5,660.01 km^2, 276.39 km^2, and 6.03 km^2, respectively, while forest land, grassland, and unutilized land decreased by 193.14 km^2, 5,476.77 km^2, and 272.52 km^2, respectively.

Ecological Protection Scenario: This scenario protected forest land quantity while restricting transfers from forest land, grassland, and water to construction land and unutilized land. Cultivated land and unutilized land decreased by 1,728.90 km^2 and 272.52 km^2, respectively, with cultivated land showing the largest reduction. Forest land and grassland increased by 638.82 km^2 and 389.61 km^2, respectively, due to water protection and returning farmland to forest/grassland policies. However, construction land was not effectively controlled, increasing by 696.60 km^2 due to low intensive use levels and infrastructure development along railway lines for Xinjiang's economic growth.

Urban Development Scenario: All land categories except water could transfer to construction land, while conversions from cultivated land to forest land, grassland, and water were restricted. Forest land, grassland, and unutilized land decreased by 193.14 km^2, 5,476.68 km^2, and 272.52 km^2, respectively, while construction land, cultivated land, and water increased by 467.19 km^2, 5,198.76 km^2, and 276.39 km^2, respectively.

3.3 Ecosystem Carbon Stock Evolution and Prediction

The InVEST model was used to assess and analyze carbon stock changes in the Tarim River Basin from 1980 to 2020 and predict carbon stocks under four 2030 scenarios. Carbon stocks showed an overall increasing trend from 1980 to 2020, with a total increase of 22.66$×10^{6}$ t, averaging 0.04% annually. Compared with 1980, carbon stocks in 1990, 2000, 2010, and 2020 increased by 34.76$×10^{6}$ t, 45.34$×10^{6}$ t, 2.13$×10^{6}$ t, and 20.01$×10^{6}$ t, respectively. In 2030, carbon stocks under natural development, arable land protection, ecological protection, and urban development scenarios are predicted to be 53.3717$×10^{6}$ t, 53.3483$×10^{6}$ t, 53.3293$×10^{6}$ t, and 53.3295$×10^{6}$ t, respectively, representing changes of -0.0475$×10^{6}$ t, -0.0051$×10^{6}$ t, -0.0285$×10^{6}$ t, and -0.0473$×10^{6}$ t from 2020 levels.

Unutilized land and grassland remain the primary carbon reservoirs in the Tarim River Basin, despite decreasing grassland area and carbon stock trends. Compared with 2020, carbon stocks under natural development and urban development scenarios show the greatest losses, primarily in the central-western region. Under arable land protection and ecological protection scenarios, carbon stock distribution changes are less pronounced. Grassland carbon stock shows the largest reduction (0.4981$×10^{6}$ t), while unutilized land and cultivated land carbon stocks increase by 0.0123$×10^{6}$ t and 0.0017$×10^{6}$ t, respectively. Forest land, water area, and construction land show minimal changes. High carbon stock areas are concentrated along the Tarim River and its tributaries, dominated by grassland, cultivated land, and forest land. Low carbon stock areas are concentrated in the desert belt, dominated by unutilized land. This demonstrates high consistency between land use types and carbon stock changes in the Tarim River Basin [Figure 6: see original paper].

3.4 Response of Carbon Stocks to Land Use Change

The InVEST model assessed carbon stock changes caused by land use changes in the Tarim River Basin from 1980 to 2020 . Over time, land use changes resulted in carbon stock losses of 22.6713$×10^{6}$ t, with aboveground biomass decreasing by 4.2956$×10^{6}$ t and belowground biomass increasing by 4.7832$×10^{6}$ t. Soil carbon stock increased by 357.3192$×10^{6}$ t, while dead organic matter carbon decreased by 43.8733$×10^{6}$ t.

By land use type, grassland to unutilized land transfer caused the largest carbon stock loss (12.0563$×10^{6}$ t), primarily from soil carbon reduction. Forest land to grassland transfer caused a loss of 0.1643$×10^{6}$ t, mainly from aboveground biomass reduction. Cropland to construction land transfer also caused carbon stock loss. Excessive land resource development without ecological protection has led to severe land desertification and salinization, with continuous grassland transfer to unutilized land causing carbon stock loss.

Conversely, transfers from cropland to forest land, grassland to forest land, water to grassland and unutilized land, and from unutilized land to cropland and grassland are beneficial for carbon storage. Among these, conversions from cropland to forest land, grassland to forest land, water to grassland and unutilized land, and unutilized land to cropland and grassland cause relatively large carbon stock increases. Other land use conversions are detrimental to regional carbon storage. Both forest land and grassland conversion to unutilized land cause substantial soil carbon stock reduction, with grassland to unutilized land being the primary cause of carbon stock loss. Transfers between water and construction land cause minimal carbon stock changes.

4 Discussion and Conclusions

4.1 Discussion

Land use change is a complex process influenced by socioeconomic and natural environmental factors. This study used 14 driving factors from socioeconomic, natural condition, and transportation location categories to simulate land use patterns. However, land use development is also affected by policies and future planning. To improve model accuracy, subsequent studies should incorporate policy and planning factors. Additionally, carbon stocks change over time and with environmental conditions, and parameters derived from literature may have inconsistencies that affect model estimation accuracy. Future research should incorporate field survey data for carbon stock estimation.

The coupled PLUS-InVEST model demonstrates advantages in predicting future land use quantity and spatial patterns and carbon stocks, providing guidance for environmental protection. Under arable land protection scenario, construction land expansion is controlled while protecting cultivated land area. Under ecological protection scenario, cultivated land decreases significantly while forest land and grassland with high carbon content increase. Under urban development scenario, construction land expansion is not effectively controlled.

Scenario simulations reveal that arable land protection measures protect cultivated land area and limit construction land expansion but reduce ecological benefits. Ecological protection measures allow natural development of forest land and grassland and protect carbon stocks but fail to protect cultivated land area. Therefore, future planning should continue focusing on biodiversity restoration, enriching wetland vegetation, and improving soil structure to enhance regional carbon storage capacity. Forest land and grassland have strong carbon storage capacity but currently occupy small proportions. Future efforts should cultivate suitable vegetation types in sparse areas and strengthen forest and grassland protection and restoration to increase regional carbon stocks. Compared with unutilized land, paddy fields have stronger carbon storage capacity, so developing aquatic crops in suitable areas while maintaining cultivated land red lines, including rice-dryland crop rotation, should be considered. The government can formulate ecological protection development plans with tailored measures to improve the Tarim River Basin's direction, preserve current carbon stocks, and enhance land carbon sequestration capacity to provide a foundation for achieving "dual carbon" goals.

4.2 Conclusions

This study coupled the PLUS and InVEST models to analyze land use and carbon stock changes in the Tarim River Basin from 1980 to 2020 and predict changes in land use and ecosystem carbon stocks, reaching the following conclusions:

1) During the study period, cultivated land, construction land, and unuti-

lized land areas in the Tarim River Basin increased, while forest land, grassland, and water areas decreased. Water area decreased by 14,382.09 km^2 and unutilized land increased by 22,147.11 km^2, primarily due to the dry climate and human activities causing stream cutoff and exacerbating land desertification.

2) From 1980 to 2020, carbon stocks in the study area showed an overall upward trend, increasing by 22.66$\times10^{6}$ t. Under different 2030 scenarios, carbon stocks generally continued the 2020 growth trend. Under arable land protection and ecological protection scenarios, carbon stocks in unutilized land and cultivated land increased by 0.0123$\times10^{6}$ t and 0.0017$\times10^{6}$ t, respectively, while carbon stocks in forest land, grassland, and water area decreased by 0.0332$\times10^{6}$ t, 0.4981$\times10^{6}$ t, and 0.0026$\times10^{6}$ t, respectively.

3) Under natural development scenario in 2030, cultivated land expands significantly while grassland decreases substantially, with varying degrees of expansion and reduction in forest land, water area, construction land, and unutilized land. Under arable land protection scenario, construction land expansion is effectively controlled, increasing by only 6.03 km^2. Under ecological protection scenario, cultivated land decreases substantially while forest land and grassland with high carbon content increase. Under urban development scenario, construction land is not effectively controlled, increasing by 696.60 km^2.

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