Land Use Study in the Ganlingao Area of the Middle Reaches of the Heihe River Basin Based on the PLUS-SD Coupling Model: A Postprint

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Abstract

Land Use/Cover Change (LUCC) constitutes a significant component of global environmental change. Quantity-spatial coupling models have become a primary approach in land use research in recent years due to their effectiveness in simulating the quantity of land use patches and their rapid spatial changes. This study first compares the Patch-Generating Land Use Simulation Model (PLUS), Future Land Use Simulation Model (FLUS), and Conversion of Land Use and Its Effects at Small Regional Extent (CLUE-S) in simulating the land use structure of the Gan-Lin-Gao region (Ganzhou District, Linze County, and Gaotai County of Zhangye City) in the middle reaches of the Heihe River Basin in 2015, to identify the most suitable spatial simulation model for the study area; then couples it with the System Dynamics (SD) model to form a quantity-spatial coupling model; finally employs the coupled model to predict the land use structure of the study area in 2030 under Economic Development (ED), Ecological Protection (EP), and Harmonious Development (HD) scenarios, and conducts a comparative evaluation. The results indicate that: (1) At the same pixel scale, the Figure of Merit (FoM) of the PLUS model is higher than that of the FLUS and CLUE-S models, and the quantity Kappa coefficient (Kno) and location Kappa coefficient (Klocation) of the three models, from highest to lowest, are: PLUS, CLUE-S, and FLUS models, demonstrating that the PLUS model achieves the optimal spatial fitting effect in this study area; (2) The different scenarios predicted by the PLUS-SD coupled model show that in the ED scenario, construction land and cultivated land expand rapidly but forest coverage remains low; in the EP scenario, forest coverage increases significantly but the level of economic development is relatively low; and in the HD scenario, urbanization level improves while the ecological environment develops favorably. This study validates the significant advantages of the PLUS-SD coupled model, highlighting the effective land use spatial simulation capability of the PLUS model and the powerful data processing functionality of the SD model. These results can provide references for the formulation of land planning policies.

Full Text

Land Use Research in the Gan-Lin-Gao Region of the Middle Reaches of the Heihe River Basin Based on a PLUS-SD Coupling Model

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Abstract

Land Use and Cover Change (LUCC) constitutes a vital component of global environmental change. Quantity-space coupling models have emerged as the primary approach in land use research in recent years due to their ability to effectively simulate both the number of land-use patches and their rapid spatial changes. This study first compared the simulated land-use structure of the Patch-Generating Land Use Simulation Model (PLUS), Future Land Use Simulation Model (FLUS), and Conversion of Land Use and Its Effects at Small Regional Extent (CLUE-S) for the Gan-Lin-Gao region (Ganzhou District, Linze County, and Gaotai County of Zhangye City) in the middle reaches of the Heihe River Basin in 2015, screening out the most suitable spatial simulation model for the study area. This model was then coupled with the System Dynamics (SD) model to form a quantitative-spatial coupling model. Finally, the coupled model was employed to predict the land-use structure in 2030 under three scenarios: Economic Development (ED), Ecological Protection (EP), and Harmonious Development (HD). The results demonstrate that: (1) At the same pixel scale, the Figure of Merit of the PLUS model was higher than that of the FLUS and CLUE-S models, while the ranking of the three models in terms of Kno and Klocation coefficients from high to low was PLUS, CLUE-S, and FLUS, indicating that the PLUS model achieved the optimal spatial fitting effect in this study area. (2) The different scenarios predicted by the PLUS-SD coupling model revealed that construction land and arable land expanded rapidly in the ED scenario, but forest coverage remained low. In the EP scenario, forest coverage increased significantly, yet the level of economic development was relatively low. In the HD scenario, urbanization improved while the ecological environment exhibited benign development. This research validates the significant advantages of the PLUS-SD coupling model and highlights the powerful data processing capabilities of the SD model and the effective land-use spatial simulation capabilities of the PLUS model. These results can provide references for the formulation of land planning policies.

Keywords: middle reaches of the Heihe River Basin; coupling model; land use/cover change; scenario prediction

1 Introduction

Land Use and Cover Change (LUCC) has been a focal point of global environmental change research since the 1990s and has now become a hotspot in the field. LUCC research serves as an important means to study the dynamic changes in land use, and various models can be categorized into quantity simulation models, spatial simulation models, and coupling models based on their advantages. Quantity simulation models, including System Dynamics (SD), Markov Chain, and Gray Forecast models, can effectively simulate and predict the quantitative structure of land-use types but struggle to achieve spatial structure simulation. Spatial simulation models such as Cellular Automaton (CA), Agent-Based Model (ABM), and Patch-Generating Land Use Simulation Model (PLUS) can simulate the spatial layout of land types but have shortcomings in quantity simulation. Coupling models aim to integrate the advantages of multiple models, thereby improving the simulation accuracy of single models and providing strong support for land use research.

Currently, several land-cover change simulation models are used for land use research, including CLUE-S, FLUS, and PLUS. These models can all simulate the spatial layout of land types but have deficiencies in quantity simulation. Coupling models primarily obtain the quantitative structure of each land type through quantity models and then use spatial models to derive the spatial allocation under different future scenarios. For instance, some studies have coupled SD and CLUE-S models to explore future urban growth under different scenarios, successfully conducting numerical simulations of various land types at the macro level and spatial allocation at the micro level. Other research has combined SD with InVEST models to simulate and predict the impact of land-use changes on carbon storage at both pixel and regional scales. Additionally, some scholars have established coupling models based on SD and InVEST to effectively simulate changes in human settlement environmental quality under different scenarios in Dongying City.

Performance varies among different spatial simulation models in different regions. For example, research on the Wuhan urban agglomeration found that the FLUS model outperformed the CLUE-S model in simulating wetland changes. Studies in the upper reaches of the Minjiang River demonstrated that the CLUE-S model was more suitable for simulating construction land, while the PLUS model showed overfitting in garden plots. Research on Jinan City revealed that the CLUE-S model' s simulation performance was superior to the FLUS model in that region. These findings indicate that different spatial simulation models produce varying results across different regions.

The Ganzhou District, Linze County, and Gaotai County of Zhangye City (hereinafter referred to as Gan-Lin-Gao) are located in the middle reaches of the Heihe River in the Hexi Corridor, connecting the Tibetan Plateau and the Mongolian Plateau. This region exhibits typical regional representativeness, and its ecological environment and socio-economic development are sensitive to land-use changes. Therefore, studying land-use changes in this area holds significant importance. To deeply investigate the applicability of spatial simulation models in this region and better predict land-use changes, this study selected the Gan-Lin-Gao region as the research area. By comparing the simulation results of the PLUS, FLUS, and CLUE-S models, the most suitable spatial simulation model for this region was identified. This model was then coupled with a quantitative simulation model to predict the land-use pattern of the study area in 2030 under different scenarios, providing references for regional sustainable socio-economic development.

1.1 Study Area Overview

The Heihe River is China' s second largest inland river. The middle reaches of the Heihe River Basin, comprising Ganzhou District, Linze County, and Gaotai County of Zhangye City, serve as the study area. The geographical location is 38°39 -39°59 N, 98°57 -100°52 E. The region has a temperate continental climate with an average annual precipitation of approximately 100–150 mm and an average annual evaporation of up to 2047.9 mm. The annual average temperature fluctuates between 8-9°C. The terrain is high in the north and south and low in the middle, with main land cover types including arable land, grassland, and desert. Located in an arid region with a fragile ecological environment, the shrinkage of grasslands and unreasonable expansion of arable land have intensified desertification.

1.2 Data Sources and Processing

The study utilized land-use data, natural environment data, and socio-economic data. All data were sourced from the Chinese Academy of Sciences' Resource and Environment Data Sharing Center (http://www.resdc.cn). Except for temperature, precipitation, population, and GDP data with a spatial resolution of 1 km, all other data had a spatial resolution of 30 m. This research resampled all data to a spatial resolution of 100 m. Distance data between pixels and roads, rivers, and residential points were calculated based on corresponding vector data using Euclidean distance in ArcGIS 10.2 software.

1.3 Methods

1.3.1 Land-Use Spatial Pattern Simulation and Validation The PLUS model includes two major modules: a land expansion analysis strategy-based conversion rule mining framework and a multi-type random patch seed mechanism. The CLUE-S model comprises two main components: a non-spatial land demand module and a spatial allocation module. This study employed linear interpolation to calculate the demand area of different land types between 2000 and 2015. The relationship between different land types and driving factors was determined using Logistic regression. The study used the Relative Operating Characteristics (ROC) method to test the regression results. When ROC > 0.7, the regression equation can adequately explain the land-type structure. The spatial allocation module was then used for spatial structure simulation.

The FLUS model consists of two modules: the first uses neural network algorithms to obtain suitability probabilities based on initial-year land-use data and driving factor raster data, while the second studies the conversion of various land types under different driving factors based on a roulette-wheel adaptive inertia competition mechanism.

Three model accuracy verification methods were employed. The first is a pixel-by-pixel accuracy evaluation method using Kappa coefficient as the evaluation index. The second is a spatial pattern comparison method using landscape pattern similarity as the evaluation index. This study used Fragstats 4.2 software to calculate landscape indices of simulated and actual land-use structure maps to obtain landscape pattern similarity (Sim). The formula is as follows:

$$Sim = 1 - \frac{1}{n}\sum_{i=1}^{n}\left|\frac{l_i^s - l_i^o}{l_i^o}\right| \times 100\%$$

where n represents the total number of indices, l_i^s represents the landscape index of the simulated land-use structure map, and l_i^o represents the landscape index of the actual land-use structure map. The third method is the Kappa coefficient, which is primarily used to verify spatial simulation accuracy. This study used the Kappa standard developed by Pontius to quantify location error and quantity error.

1.3.2 Future Scenario Prediction Based on SD Model The SD model was established in 1958 and serves as a simulation laboratory for complex systems of ecological environment and economic development, with powerful data simulation capabilities. The SD model used in this study includes four subsystems: population, economy, productivity, and climate. Variable data for the Gan-Lin-Gao region were referenced from the Zhangye region, with numerical values for each system variable derived from literature such as the Gansu Development Yearbook, Zhangye Statistical Yearbook, and China City Statistical Yearbook. SPSS 23 was used for statistical analysis to obtain quantitative relationships between different variables. The simulation time range was 2000–2030, with a time step of one year. The relative error formula for historical simulation testing of the SD model is:

$$\text{Relative Error} = \frac{\text{Simulated Value} - \text{Actual Value}}{\text{Actual Value}} \times 100\%$$

To verify the model simulation effect, this study determined the historical test time period to be 2000-2015. The relative errors of all indicators were below 10%, indicating high simulation accuracy of the SD model and its ability to correctly predict the land system structure.

Three development scenarios were designed: Economic Development (ED), Ecological Protection (EP), and Harmonious Development (HD). The ED scenario emphasizes economic growth, the EP scenario prioritizes ecological protection, and the HD scenario seeks coordinated development between economy and ecology. Parameter settings for different scenarios were based on planning documents and statistical data. For example, population growth rates were set according to the two-child policy, urbanization rates were based on the Gansu Province Urban System Plan, and annual temperature and precipitation changes were set as positive values referencing IPCC reports and previous studies.

2 Results and Analysis

2.1 Simulation Results of PLUS Model and Other Models

To compare the simulation effects of different models, the study unified the pixel scale to 100 m through resampling. The simulation results showed that at the 100 m scale, the Kappa coefficients of the PLUS, FLUS, and CLUE-S models were 0.81, 0.79, and 0.80, respectively, while the Klocation coefficients were 0.78, 0.75, and 0.76, respectively. The landscape similarity indices (Sim) were 0.85, 0.82, and 0.83, respectively. These results indicate that the PLUS model achieved the best overall simulation effect.

The study also examined different grid scales (100 m, 200 m, 500 m, 750 m, and 1000 m). The results revealed that the correlation between land use and different influencing factors was highest at the 500 m scale. However, the PLUS model did not necessarily produce better results with increasing grid density, as it excels in simulating fine-scale cellular changes. The CLUE-S model, based on traditional binary logistic regression to determine correlations between land-type structure and influencing factors, is not suitable for overly dense research scales.

Visual comparison of the 2015 simulation results showed that in the flat terrain of Linze County and Gaotai County, the PLUS model' s simulated arable land range was slightly larger than the actual range but with high accuracy. In high-altitude areas of Gaotai County, the simulated grassland range was smaller than the actual range. In the flat central region, the simulated construction land range was slightly smaller than the actual range, while in high-altitude areas, the simulated forest land and construction land ranges were larger than actual. Overall, the PLUS model demonstrated higher simulation accuracy than the FLUS and CLUE-S models, particularly in landscape pattern simulation.

2.2 Different Scenario Prediction Results of PLUS-SD Coupling Model

The PLUS-SD coupling model predicted the 2030 land-use structure under three scenarios. The results showed that all three scenarios exhibited increased water area, likely due to urban heat island effects and global warming-induced precipitation increases. During 2020–2030, arable land area increased in all scenarios, primarily converted from grassland. In the ED scenario, arable land area increased significantly, with rapid expansion of construction land but low forest coverage. In the EP scenario, forest area increased due to returning farmland to forest, but economic development lagged. In the HD scenario, the rate of land-use type change was moderate, with less occupation of arable land by construction land, stable economic operation, and favorable conditions for sustainable social development.

The transition matrices revealed that in all scenarios, urban construction land area increased, mainly converted from unused land. Rural construction land showed varying degrees of decline across all scenarios, possibly due to large-scale rural-to-urban population shifts. Unused land primarily converted to arable land and urban construction land, with the smallest conversion area in the EP scenario and the largest in the ED scenario.

3 Discussion

3.1 Applicability Analysis of PLUS-SD Model in Gan-Lin-Gao Region

Analysis of the PLUS-SD model' s simulation results in the Gan-Lin-Gao region indicates that the PLUS model outperformed the FLUS and CLUE-S models in location prediction, quantity prediction, and landscape pattern similarity. Previous studies have reached similar conclusions. For instance, research on Chengdu showed that the CLUE-S model was superior for simulating historical land-use changes, while studies in Jinan found that the FLUS model' s Kappa coefficient was slightly lower than CLUE-S. The PLUS model demonstrates high simulation accuracy in flat terrain areas, while the CLUE-S model performs better at high altitudes. The PLUS model' s advantage lies in its ability to simulate fine-scale cellular changes, while the CLUE-S model is based on traditional logistic regression, making it unsuitable for overly dense scales.

The coupling of the PLUS and SD models combines the advantages of both: the SD model' s powerful data processing function and the PLUS model' s effective spatial simulation capability. This coupling model can better simulate the dynamic changes of landscape ecosystems and clearly reveal the coupling relationships among various factors in the economic-environment system.

3.2 Comparative Analysis of Different Scenario Simulation Results

The surface environment in the Gan-Lin-Gao region is harsh, with large areas of desert and Gobi. The ED and EP scenarios in this study emphasize either economic development or environmental protection, which is not conducive to coordinated ecological and economic development. The HD scenario combines the advantages of ecological friendliness and economic construction.

The HD scenario shows that with improved urbanization levels, the ecological environment develops benignly. The primary direction of urban expansion is unused land, and with technological development, the utilization rate and conversion rate of unused land have significantly improved. In recent years, oasis expansion in Gaotai and other areas has been evident, with oasis fluctuation zones mostly located at the junction of oases and deserts. The HD scenario shows that a small amount of grassland and rural construction land is converted to arable land, which mainly comes from unused land. Increased efforts in returning farmland to forest and development of unused land have led to increased forest area, which is beneficial for national territorial ecological functions.

Under the ED scenario, construction land area will reach 4948.90×10^4 hm^2 by 2030. The government needs to strictly control construction land to prevent excessive occupation of arable land, protect permanent basic farmland, and arrange construction land intensively and rationally to form a scientific and orderly territorial spatial development pattern.

4 Conclusion

This study found that the PLUS model' s accuracy in landscape pattern, location, and quantity simulation was superior to that of the FLUS and CLUE-S models. The CLUE-S model showed high simulation accuracy in low-lying flat areas of the study area, while the FLUS model performed better at high altitudes. The PLUS-SD coupling model simulated land-use conditions in the Gan-Lin-Gao region under three scenarios, revealing differences in the rate of land-use type changes. The ED scenario showed the fastest change rate with rapid economic development but severe environmental damage and large-scale forest reduction. The EP scenario exhibited a slower change rate with obvious returning farmland to forest but lagging economic development. The HD scenario showed moderate change rates, less occupation of arable land by construction land, stable economic operation, and favorable conditions for sustainable social development.

The PLUS-SD coupling model obtained land-use structures under different scenarios, which is beneficial for sustainable ecological and economic development. Many studies have predicted future land-use patterns under different scenarios, and coupling models can better simulate the dynamic changes of landscape ecosystems and reveal coupling relationships among various factors in economic-environment systems. This study verifies the significant advantages of the PLUS-SD coupling model and provides references for land planning policy formulation.

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Note: Figure translations are in progress. See original paper for figures.