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Study on Land Use Simulation based on PLUS Model

-- Taking the Yellow River Basin (Henan Section) as an Example

Xiaowei Yan

Henan Polytechnic University, Jiaozuo, Henan 454000, China

Abstract

Land use change, as an important issue in ecological environment and socio-economic development, has long attracted the attention of academia and policy makers. The Yellow River Basin, as an important water system and agricultural production area in China, has land use changes that are not only related to regional ecological security, but also involve multiple aspects such as water resources management, agricultural production, and urbanization. As an important part of the Yellow River Basin, the Henan section is facing the joint influence of multiple factors such as population growth, economic development, and climate change. The land use pattern may undergo profound changes in the next few decades. Therefore, studying the future land use changes in the Yellow River Basin (Henan section) is of great significance for formulating scientific land use planning and regional development strategies. This paper first analyzes the current status of land use in the Yellow River Basin (Henan section) in the past 30 years and its main change trends. Then, based on the PLUS model, a variety of driving factors are selected, and four scenarios of natural development, farmland protection, ecological protection, and economic development are set to simulate and predict the future land use changes in the Yellow River Basin (Henan section).

Keywords

Land Use; Yellow River Basin (Henan Section); Multi-Scenario Simulation; PLUS Model.

1. Introduction

Land use change is one of the important manifestations of global environmental change and social and economic development. Land use not only directly affects the ecological environment, resource management, and sustainable social and economic development, but also has a profound impact on climate change, ecosystem services, and biodiversity [1]. As the mother river of China, the Yellow River Basin covers rich water resources, agricultural resources and ecosystems, and is one of my country's important ecological security barriers [2]. However, with the rapid growth of regional population, sustained economic development, and accelerated urbanization, the land use pattern of the Yellow River Basin has undergone significant changes. In particular, the Henan section, as the core area of the Yellow River Basin, is facing land resource pressure and ecological environmental challenges[3]. How to scientifically predict and manage land use changes in the Yellow River Basin (Henan Section) is of great significance to regional ecological protection, resource utilization and socio-economic development.

Common prediction models generally include cellular automata (CA) model, CLUE model, FLUS model, and PLUS model. The cellular automata (CA) model is a land use change simulation model based on cellular automata theory [4]. Luo Ping et al. used the CA model of urban land use evolution based on urban life mechanisms and geographical characteristics to conduct spatiotemporal simulation and prediction of land use evolution in Shenzhen Special Economic Zone [5]. Wei Wei et

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al. used the CLUE-S model to solve the weight coefficient of the driving force factor of land use change, simulated the demand analysis of various types of land within a period of time and the dynamic allocation process of land use change, and simulated the land use evolution in the marginal area [6]. The FLUS land use simulation model is an integrated prediction model developed based on the extension of GeoSOS software. The core of the model is the improved cellular automation, including the suitability probability calculation based on artificial neural network and the adaptive inertial competition mechanism. Wu Xinxin et al. proposed a multi-scenario UGBs delineation model (FLUS-UGB) based on the future land use simulation (FLUS) model and the expansion and erosion algorithm to predict the urban expansion in the Pearl River Delta region under different scenarios in 2050[7]. The PLUS model is a patch-level land dynamic simulation model based on raster data, which mainly consists of two parts: the rule mining strategy for land expansion analysis (LEAS) and the CA model of multi-type random seed strategy (CARS), so as to predict the future land use pattern[8].

Although many studies have simulated and analyzed land use changes in the Yellow River Basin, there are relatively few systematic studies on future land use changes in the Henan section, especially the application research based on the PLUS model has not been carried out in depth. Therefore, this paper will fill this research gap and use the PLUS model to simulate and analyze future land use changes in the Yellow River Basin (Henan section). This paper aims to answer the following key questions: How has land use in the Yellow River Basin (Henan section) changed in the past 30 years? What are the characteristics of changes under future multi-period scenarios? The innovation of this study lies in: First, the prediction of future land use changes in the Yellow River Basin (Henan section) based on the PLUS model provides a new method and perspective for land use simulation in the region. Secondly, this paper uses a variety of scenario assumptions for simulation, predicts land use changes from different perspectives of socio-economic development and ecological protection, and has strong practical application value.

2. Study Area and Materials

Study area: The part of the Yellow River basin that flows through Henan Province is located in the middle and lower reaches of the Yellow River, spanning a vast area from 33°13′ to 33°31′ north latitude and 110°21′ to 116°6′ east longitude. The Yellow River in Henan is 711 kilometers long. It originates from Tongguan, Shaanxi Province, meanders through Lingbao City, and then flows through eight municipal administrative regions, including Sanmenxia, Luoyang, Jiyuan, Zhengzhou, Jiaozuo, Xinxiang, Kaifeng, and Puyang, and finally exits the country in Puyang. This section of the basin covers an inflow area of about 36,200 square kilometers and affects a vast area of about 57,412.33 square kilometers. In terms of topography, the area gradually decreases from west to east, with an altitude ranging from a minimum of 31 meters to a maximum of 2,411 meters. Among them, Laoyachanao Peak in the Xiaoqinling Mountains in the west is the highest peak, while the east is a broad alluvial plain[9].

Materials: (1) Land use dataset: This dataset is derived from the CLCD national land cover dataset released by Wuhan University, with a resolution of 30 meters. According to research needs, the dataset is reclassified into six categories: cultivated land, forest land, grassland, water area, construction land, and unused land. (2) Driving factor dataset: This dataset is further divided into natural driving factors and socioeconomic driving factors. Natural driving factors include precipitation, temperature, night light, and soil erosion. These data are from the National Tibetan Plateau Data Center (https://www.tpdc.ac.cn/). The DEM data is from the European Space Agency (https://panda.copernicus.eu/), and the slope and aspect data are obtained based on this data. The socioeconomic driving factors include the distance to roads at all levels, county seats, and rivers. These data are all from OSM (https://www.openstreetmap.org/) and are obtained using the Euclidean distance method. In addition, population and GDP data are from the Resources and Environmental Science and Data Center (https://www.resdc.cn/). Finally, all data are cropped to unify the coordinate system and the number of rows and columns.

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3. Methods

3.1 Land Use Transfer Matrix

The land use transfer matrix is a matrix that studies the mutual transformation and quantitative relationship between different land use types within a certain period of time[10].

$$S_{ij} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \tag{1}$$

In the formula: S_i is the area of land use type i at the beginning of the study, S_j is the area of land use type j at the end of the study, S_{ij} is the area converted from the i-th land use type to the j-th land use type during a specific time period, and n is the number of land types 1-6.

3.2 Land Use Dynamics

Land use dynamics refers to the quantitative change of a certain land type in the study area within a certain time range. It is generally used to reflect the change rate of a certain land use type within a certain period of time. The larger the K value, the more intense the change of the land type during the study period[11].

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \tag{2}$$

In the formula: K is the dynamic degree of a certain land use type. U_b is the area of a certain land use type at the end of the study period, U_a is the area of a certain land use type at the beginning of the study period, and T is the time interval between the initial year and the end year.

3.3 PLUS Model

The land use simulation PLUS model is a grid data-driven land use change simulation tool that integrates high precision, high speed, ease of use and openness. It can simulate the generation and evolution of multiple types of arbitrary land use type patches[12]. The model couples the land expansion analysis strategy (LEAS) and the cellular automaton (CA) model (CARS) based on multi-type random patch seeds. LEAS can identify and extract the expansion area between various land cover types based on land use data at two time points. Subsequently, by applying the random forest algorithm, it deeply analyzes the complex relationship between various land cover expansions and their driving factors, thereby revealing the development possibilities between various types of land and the relative importance of the impact of various driving factors on different land types[13]. The CARS module is based on the cellular automaton (CA) theory and combines multiple types of random patch seeds. By analyzing factors such as land use status, development probability, and driving factors, it simulates the future land use pattern[14].

Multiple scenarios: Based on previous experience, four scenarios were set to predict the spatiotemporal change pattern of land use in 2030: natural development, farmland protection, ecological protection, and rapid development[15]. (1) Natural development scenario (ND): This scenario continues to follow the historical development trend; (2) Farmland protection scenario (CD): This scenario will implement the strictest farmland protection system, restrict the conversion of farmland to other land types to ensure the area of farmland, and reduce the probability of farmland conversion to construction land and forest land by 60% and 30% respectively; (3) Economic control scenario (ED): This scenario takes economic development as the primary goal, restricts the conversion of construction land to some land types, and allows all types of land to be converted to construction land except water areas, and prohibits all types of land from being converted to land types other than construction land and its own land types; (4) Ecological priority scenario (EP): This scenario pursues the maximum ecological benefit, allows the conversion of forest land and grassland, allows forest land and grassland to be converted to water areas, and prohibits the conversion of farmland, forest land, grassland, and water areas to construction land.

Table 1. Land use transfer matrix for each scenario

ND	cultivated	forest	grass	water	construction	unused	CD	cultivated	forest	grass	water	construction	unused
cultivated	1	1	1	1	1	1	cultivated	1	0	0	1	1	0
forest	1	1	1	0	1	0	forest	1	1	0	1	1	0
grass	1	1	1	1	1	1	grass	1	1	1	1	1	0
water	1	1	1	1	1	1	water	0	0	0	1	0	0
construction	0	0	0	0	1	0	construction	0	0	0	0	1	1
unused	1	0	1	1	1	1	unused	1	0	0	1	1	1
ED	cultivated	forest	grass	water	construction	unused	EP	cultivated	forest	grass	water	construction	unused
cultivated	1	0	0	0	1	0	cultivated	1	1	1	1	0	0
forest	0	1	0	0	1	0	forest	0	1	1	1	0	0
grass	0	1	1	0	1	0	grass	0	1	1	1	0	0
water	0	0	0	1	0	0	water	0	0	0	1	0	0
construction	0	0	0	0	1	0	construction	0	0	0	0	1	0
unused	1	0	0	0	1	1	unused	1	0	1	1	0	1

4. Results

4.1 Analysis of Spatiotemporal Characteristics of Land Use

From the spatial distribution map of land use types (Figure 1), it can be seen that the spatial distribution of the Yellow River Basin (Henan Section) has changed significantly in the past 30 years. Cultivated land is mainly distributed in the alluvial plains of the central and eastern regions, covering Xinxiang, Jiaozuo, Zhengzhou, Kaifeng and Puyang City. Woodland is mainly distributed in most areas of the west and the northern edge, showing a spatial distribution pattern dominated by the west; Grassland is mainly distributed around the woodland, showing a spatial distribution pattern with staggered edges; water starts from the northwest edge, traverses the central area from west to east, and ends at the southeast edge, showing a thin strip distribution pattern; construction land is mainly distributed in the central area , the scope of coverage is mainly concentrated at the junction of the middle and lower reaches, showing an obvious discrete distribution; due to its extremely small proportion, unused land is the least characteristic land type in the study area.

From the analysis of Table 2, it can be seen that cultivated land, forest land and construction land are the main land types in the Yellow River Basin (Henan section). The proportion of each land type from large to small is: cultivated land, forest land, construction land, grassland, water area, unused land. The average area of cultivated land accounts for 61.31%, the average area of forest land accounts for 23.25%, the average area of construction land accounts for 11.41%, and the average area of grassland and water area accounts for a small proportion, which are 3.05% and 0.99% respectively. The cultivated land area showed a clear and continuous decreasing trend from 1990 to 2020, with a decrease of 8.81% in the past 30 years; the forest land area showed a clear and continuous increasing trend from 1990 to 2020, an increase of 1.91%, reflecting the positive results of ecological protection and forestry development; the grassland area will show a continuous decreasing trend from 1990 to 2020, a decrease of 1.69%; the construction land showed a sharp expansion trend from 1990 to 2020, an increase of 8.47%.

Table 2. 1990-2020 Statistical Table of Land Type Area and Proportion in Yellow River Basin (Henan Section)

Land Type		cultivated	forest	grass	water	construction	unused
1990year	area/km²	37648.93	12887.13	2075.23	554.16	4188.22	0.56
	Proportion/%	65.64	22.47	3.62	0.97	7.3	0
2000year	area/km²	36200.87	12940.79	1949.39	454.58	5808.45	0.17
	Proportion/%	63.12	22.56	3.4	0.79	10.13	0
2010year	area/km²	34200.92	13518.23	1856.12	634.7	7142.75	1.51
	Proportion/%	59.63	23.57	3.24	1.11	12.45	0
2020year	area/km²	32593	13984.93	1107.1	624.4	9043.14	1.68
	Proportion/%	56.83	24.38	1.93	1.09	15.77	0

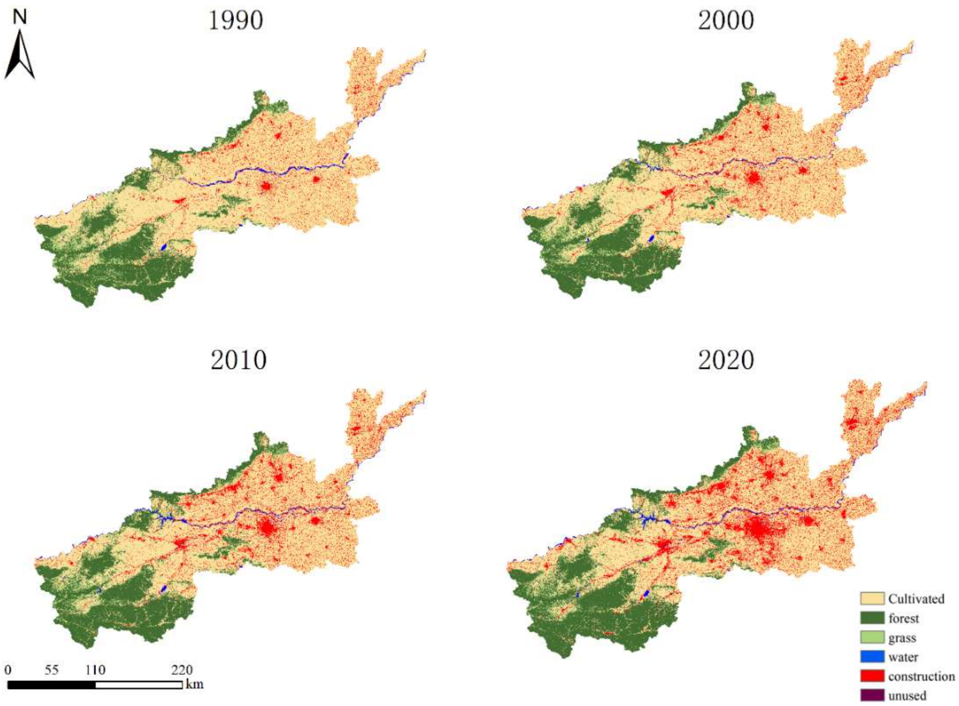

Fig. 1 Spatial Distribution Map of Land Use Types in the Yellow River Basin (Henan Section) from 1990 to 2020

4.2 Model Accuracy Verification

The Kappa coefficient is a key indicator for evaluating simulation accuracy. Its value range is limited to between 0 and 1. The closer the value is to the upper limit of 1, the higher the accuracy of the simulation. In terms of specific classification, if the Kappa coefficient is lower than 0.5, it usually means that the accuracy of the simulation results is low; if the coefficient value falls between 0.5 and 0.75, the accuracy of the simulation is evaluated as medium; and when the coefficient value reaches between 0.75 and 1, it indicates that the accuracy of the simulation is quite good. In order to verify the accuracy of the PLUS model, this paper uses two indicators, the Kappa coefficient and the overall accuracy. By comparing and analyzing the actual land use pattern with the simulation results, it was finally determined that the Kappa value was 0.845 and the overall accuracy was as high as 0.913. Since the Kappa coefficient exceeded the critical threshold of 0.75, the simulation process showed a high degree of reliability and consistency, and the simulation results were considered to be high-quality and accurate.

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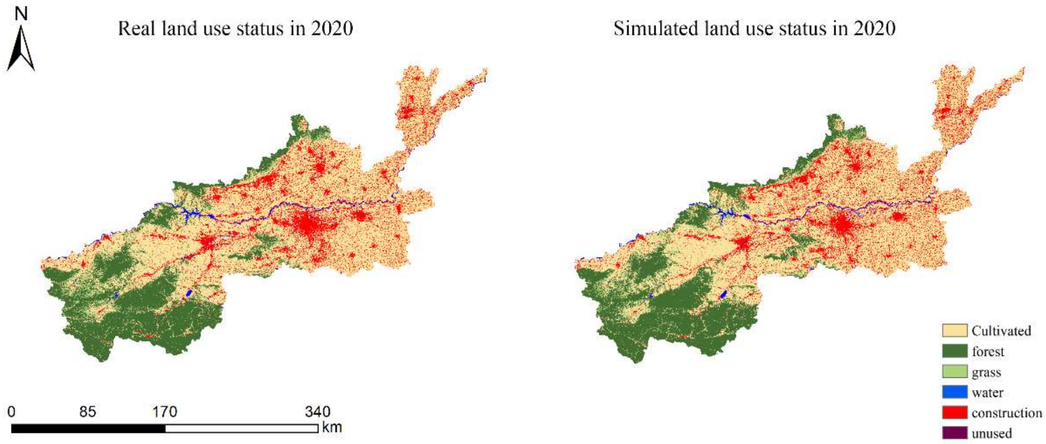

Fig. 2 Comparison between real and simulated land use pattern of PLUS model in 2020

4.3 Analysis of Spatiotemporal Characteristics of Future Land Use

As can be seen from Table 3, land use under the four scenarios has changed to varying degrees. Specifically, under the natural development scenario, the areas of construction land and forest land increased by 1700.3km² and 262.39km² respectively, while the areas of cultivated land and grassland decreased by 1680.16km² and 285.7km² respectively; the areas with increased construction land were mainly concentrated in the central and eastern parts of the study area, northeastern Luoyang and northern Sanmenxia, while the areas with increased forest land were mainly concentrated in the northern part of Lushi County in Sanmenxia and the western edge of Luoyang; Under the cultivated land protection scenario, the areas of construction land and forest land increased by 720.1km² and 144.9km² respectively, and cultivated land and grassland decreased by 671.45km² and 201.46km² respectively. Affected by the cultivated land protection policy, the occupation of cultivated land by construction land was significantly reduced by more than half. In addition, the area of cultivated land was reduced by more than half. Luoning County, Luanchuan County and Song County increased significantly; Under the economic control scenario, the construction land area increased by 1714.1 km², while the cultivated land and grassland decreased by 1608 km² and 134.71 km² respectively; Under the ecological protection scenario, the forest land and water areas increased by 1825.31km² and 155.18km² respectively, while the areas of other land types decreased. The areas with increased forest land were mainly located in the southern part of Lingbao City and the northern part of Lu's County in Sanmenxia City, as well as Luoning County, Luanchuan County, Song County and Yiyang County in Luoyang City. The increase in water area was mainly located near the Yellow River Basin.

Table 3. Changes in land use area in the Yellow River Basin (Henan section) in each scenario in 2020 and 2030 (km²)

year	scenario	cultivated	forest	grass	water	construction	unused
2020		32593	13984.93	1107.1	624.4	9043.14	1.68
2030	ND	30912.84	14247.32	821.4	628.68	10743.41	0.59
	CD	31921.55	14129.83	905.64	632.25	9763.24	1.71
	ED	30985	14014.46	972.3915	624.8115	10757.24	0.3375
	EP	30984.87	15810.24	736	779.58	9043.14	0.42
2020-2030	ND	-1680.16	262.39	-285.7	4.28	1700.27	-1.09
	CD	-671.45	144.9	-201.46	7.85	720.1	0.03
	ED	-1608	29.5271	-134.709	0.4115	1714.099	-1.3425
	EP	-1608.13	1825.31	-371.1	155.18	0	-1.26

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5. Discussion

Based on the land use data of the Yellow River Basin (Henan section), this paper analyzes the spatiotemporal characteristics of land use in the past 30 years, and then uses the PLUS model to predict the land use pattern under multiple scenarios in the future, and then analyzes the land changes under multiple scenarios in the future. The main conclusions are as follows:

(1) The spatial distribution of land use types in the Yellow River Basin (Henan Section) has changed significantly in the past 30 years. According to the spatial distribution map of land use types, cultivated land is mainly concentrated in the alluvial plains in the central and eastern parts, forestland is mainly distributed in the western and northern edges, grassland is distributed around the forestland, water runs through the central part in a thin strip from northwest to southeast, and construction land is in the central region Especially the junctions between the middle and lower reaches are concentrated.

(2) Cultivated land, forest land and construction land are the main land types in the region, among which cultivated land accounts for the largest proportion, reaching 61.31%, followed by forest land, accounting for 23.25%, and construction land accounts for 11.41%. In terms of temporal changes, the cultivated land area has continued to decrease from 1990 to 2020, while the forest area has continued to increase, the grassland area has also shown a decreasing trend, and the construction land has expanded sharply. These changes together reveal the dynamic evolution of the land use pattern in the Yellow River Basin (Henan section).

(3) Land use will change to varying degrees in the four scenarios in 2030. Under different scenarios, construction land and forest land areas tend to increase, but the amount of change is different under different scenarios. Under the cultivated land protection scenario, the encroachment of construction land on cultivated land is significantly reduced by more than half; under the economic control scenario, the encroachment of construction land on cultivated land The encroachment is significant; under the ecological protection scenario, the areas of woodland and water areas tend to increase.

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