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The Use of an Optimized Grey Multi-Objective Programming-PLUS Model for Multi-Scenario Simulation of Land Use in the Weigan–Kuche River Oasis, China

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Abstract: The oasis serves as the primary supply of cultivable land, along with the hub for human production and habitation in Xinjiang. Accordingly, predicting the land use of these areas based on various goals is an effective instrument for encouraging the sensible distribution of resource space. The study investigated the creation of a land use-allocation optimization model based on the various objectives of ecological protection, food security, and urban growth using the Weigan–Kuche River oasis as an example. The GMOP-PLUS model's restriction conversion area was adjusted to include the findings of the land suitability evaluation. Additionally, it optimized and simulated the spatial arrangement and quantitative structure of land usage in the Weigan–Kuche River oasis in 2035. The results indicate the following: (1) the model's overall accuracy is 89.36%, and its Kappa coefficient is 0.872, more than 0.8. Thus, the model can be considered for adoption in the future when predicting changes in land use in the districts and counties of the Weigan–Kuche River oasis; (2) based on the results of the land suitability evaluation, the percentage of areas that are most suited for agricultural development, urban development, and ecological protection is 39.32%, 24.21%, and 14.06%, respectively; and (3) the three scenarios satisfy the various demands for growth within the oasis, and the land use structure of the oasis varies considerably in response to the various development objectives, with the construction and cultivated land undergoing the most substantial modifications. The multi-scenario simulation of land usage in the oasis can provide essential support and a range of perspectives for future land spatial planning and socioeconomic development decision-making in the Weigan–Kuche River oasis. This is essential for both the efficient use of land resources and sustainable development.

Keywords: oasis; land suitability evaluation; multi-scenario simulation; GMOP-PLUS modeling

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1. Introduction

Land is a spatial entity that integrates several functions, such as the provision of resources, economic expansion, food security, and environmental preservation. It acts as the cornerstone of long-term human social and economic progress, which is critical to the development of human society [1,2]. Rapid population increase and economic development, unplanned land expansion for construction, and the frequent invasion of cultivated land, forest land, and other production and ecological land are all contributing factors to the growing conflict between ecology, agriculture, and urban space in land use [3]. The national land space strategy has made it a priority to address the following issues: how to achieve the synergistic optimization of urban–agricultural–ecological space; how to promote livable and moderate urban space and intensive and efficient agricultural space; and how to efficiently and scientifically optimize the spatial allocation of land use [4].

The optimization of land-use spatial patterns, which provides the overall framework for the development of territorial spatial development and ecological security patterns, is a crucial first step in promoting the harmonious coexistence of humans and nature [5]. Along with the continual advancement of related research, there has been a major advancement in the theory and methodology of land-use spatial configuration [6–8]. The first approach is the multi-objective optimization method tailored to sustainable land use planning, which overcomes the one-dimensionality of the linear planning model's objective function and builds the optimization of the land use pattern from the optimization objective, important influencing factors, and micro decision-making actors [9]. It also has the system dynamics model's positive and negative feedback features. Second, scenario analysis and model simulation are carried out to simulate and evaluate the land use pattern from the viewpoints of land quantity structure and geographical distribution [10]. The present state of research development informs the design of the appropriate driving factor system. When the amount of land structure has been optimized, the spatial distribution of land usage under various situations may be projected very accurately [11]. Due to the increasing complexity and diversity of land use-pattern changes brought about by urbanization, a recent trend in land use-pattern optimization research is the linked simulation model that takes into account both approaches [12]. However, several elements, including geographic location, time dimension, policy context, and other considerations, combine to affect the condition of land use change. When determining the restricted conversion area, the current land use-optimization model is frequently is unable to quantitatively optimize the land use structure since it mostly depends on the internally established principles of land use conversion [13]. In this instance, certain inappropriate conversions take place, converting previously well-developed areas to other land types. To fully assess a region's land use potential and suitability, the land suitability evaluation method can also take into account a wide range of factors, including the region's natural endowment of land resources, geographic location, socioeconomic conditions, and the quantity and spatial-distribution ratio of land resources. A scientific foundation and requirement for optimizing regional zoning and creating land use patterns is provided by this evaluation, which identifies the precise position and size of the region appropriate for town construction, agricultural output, and ecological conservation [14,15]. Therefore, adding such quantitative land suitability evaluation results in constraints on the land use-pattern optimization and the allocation model can provide novel insights and inspiration for further research and promote more scientific and rational land resource management and planning.

Quantitative simulation models are mostly used in research methodologies, with an emphasis on analyzing the area demand of various land types. Examples of these models are the linear programming approach [16], the Markov model [17,18], and others. Typical models for simulating spatial distributions are the Cellular Automata model (henceforth referred to as the CA model) [19,20], the Conversion of Land Use and its Effects model (henceforth referred to as the CLUE series model) [21], the Future Land-Use Simulation model (henceforth referred to as the FLUS model), etc. [22]. A single model is unable to solve the multi-scale land use-optimization problem due to the comprehensiveness and complexity of the land system, as well as the close relationship between the quantity structure and spatial distribution of land use. As a result, coupled simulation models that consider structure and layout have emerged as a popular area of study for land use-pattern optimization. Several models, such as the MOP-FLUS (Multiple Objective Planning, MOP) [14], MOP-CLUE [23], CA-Markov [24,25] and MCR-FLUS-Markov(Minimum Cumulative Resistance, MCR) [26], offer methodological assistance for the investigation of land use-pattern optimization in science. The Patch-generating Land Use-Simulation model (henceforth referred to as the PLUS model) strengthens the connection between influencing variables and land use change, while the Grey Multi-Objective Programming model (henceforth referred to as the GMOP model) can completely take into account top-down policy considerations and restrictions to find the best land quantity and structure [27,28]. We enhanced the performance of the land use patch-change simulation by using an ap-

proach to examine the relationship between the changing land use and the influencing factors. With the goal of optimize the future land use structure in the research region, the GMOP and PLUS models will be combined in this study. Thus, this research offers a new framework that incorporates the land suitability evaluation findings into the GMOP-PLUS model's restricted transformation zone setting. By responding to the continually changing conditions in the study region based on knowledge of its socioeconomic and ecological variables, this framework can be used to forecast and optimize land use in the future under various scenarios.

Oases serve as "islands of life" amid the otherwise arid and semi-arid region of Xinjiang, offering vital spaces for survival and procreation. They are essential to preserving the natural balance of the area. Oases are the vital hubs for the production of cash crops and food, but they also sustain nearby animal husbandry and other businesses. Since the area of the oasis is limited, it has become imperative to figure out how to make the most of the limited land resources to achieve the oasis' sustainable development. A strong scientific foundation for regional planning and decision-making may be established through scientific land-suitability evaluation, which also guarantees the coordinated development of oasis areas in terms of social, economic, and ecological factors [29,30]. A typical desert oasis in Xinjiang, the Weigan–Kuche River Oasis (henceforth referred to as the Weiku Oasis) serves as a model for research on the ecological environment and sustainable growth of oases in the region. The Weiku Oasis's land distribution among urban, agricultural, and ecological areas has progressively become more disorganized as a result of the rapid socioeconomic development. Thus, from the standpoint of development requirements, this study incorporates the land-suitability evaluation results into the GMOP-PLUS model, investigates the creation of an optimization model considering quantitative regulation and spatial patterns based on the multiple goals of food security, urban development, and ecological protection, and suggests a way to optimize and regulate the Weiku Oasis's land area overall. In addition to offering theoretical support for the development of regional food security, ecological security, and other numerous purposes, this study can be used to reduce the conflict between urban space, agricultural space, and ecological space in the Weiku Oasis. Based on the study's findings, an optimization strategy for the Weiku Oasis' land use pattern in 2035 can be developed, with the goal of offering scholarly references for the best possible distribution of the area's land resources.

2. Study Area and Data Sources

2.1. Study Area

The Weigan–Kuche River oasis is located in the arid region of Northwest China, between the southern part of the middle Tianshan Mountains and the northern edge of the Taklamakan Desert. Its geographic range is 82°8′20° E~83°39′50° E, 40°59′13° N~41°54′35° N (Figure 1), making it a relatively complete oasis of the pre-mountain alluvial fan plains in the range of the arid zones of China [31]. As one of the main hubs for economic growth along the southern border of Xinjiang, it is spread throughout the regions of Kuche City, Xinhe County, and Shaya County in the Aksu region. The Weiku Oasis's gross domestic product (GDP) was CNY 43.566 billion in 2020, and statistics from the seventh population census revealed that the rate of urbanization had increased to 41%, a 43.39% increase from the data from the sixth population census. The Weiku Oasis has experienced a surge in population and economic development, leading to increased expectations for the wise distribution of land resources. But, starting in 2016, the towns and cities in Weiku Oasis have been growing faster and faster, gradually encroaching on other land use types. The land allocation has also been gradually becoming more and more disorganized, and the way the area has been developing has put a great deal of pressure on energy, resources, and the ecological environment. As a result, there is an urgent need to find development paths that will work together to achieve the multifaceted goals of society, agriculture, and ecology, as well as to integrate the layout of urban, agricultural, and ecological spaces [32,33].

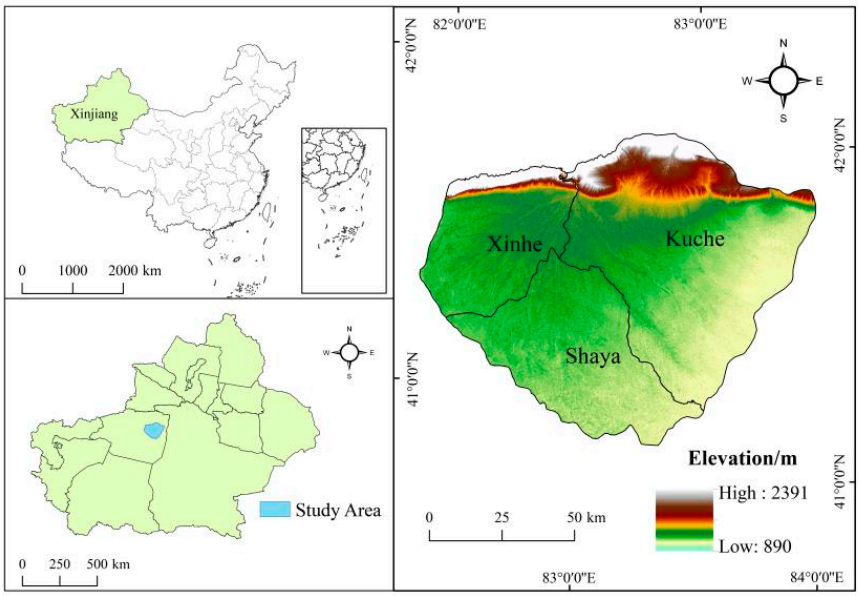


Figure 1. Location of the study area.

2.2. Data Sources

The two primary categories of data utilized in this paper are the following: (1) spatial data, mostly consisting of information on the climate, land use, topography, cultivated land quality, traffic, and roads, among other topics. To ease the processing of data and meet the requirements for PLUS model input data, land use data as a baseline, a uniform resolution of 30 m × 30 m, and 4991 × 4480 rows and columns are needed; (2) statistical and textual data, including a statistical yearbook and a series of special plans and other textual data including text data such as the Xinjiang Statistical Yearbook and a series of special plans. The data sources and related information are shown in Table 1.

Table 1. Data content and sources.

Data Types	Data Content	Data Sources
Land use data	Land use data in 2005 and 2020, divided into six categories: cultivated land, forest land, grassland, wetland, construction land and unutilized land.	Data Platform of Resource and Environmental Science and Data Center, Chinese Academy of Sciences (CAS) (http://www.resdc.cn/, accessed on 20 November 2023)
Meteorological data	Annual 10 °C cumulative temperature and annual rainfall in the study area.	
NDVI data	Normalized difference vegetation index (NDVI) in 2020.	
Population density	2020 Population Density	
Topographic data	Elevation, slope, direction of slope.	Geospatial data cloud platform (http://www.gscloud.cn/, accessed on 22 November 2023)
Transportation data	Transportation arterials and transportation spurs.	OpenStreetmap platform (www.openstreetmap.org, accessed on 20 November 2023)
POI data	Mining areas, nature reserves, rural settlements.	
Soil quality data	Soil texture, soil organic carbon, soil effective water content, soil carbonate content, soil exchangeable-salt base content, soil gravel volume, soil pH.	World Soil Database (https://www.fao.org/soils-portal/en/, accessed on 30 November 2023)
Red line for ecological protection	Ecological-protection red line.	County and municipal natural resources bureaus
Socioeconomic data	Xinjiang Statistical Yearbook 2005–2020 Kuche City Master Plan (2006–2020) Shaya County City Master Plan (2011–2030) Xinhe County City Master Plan (2012–2030)	People's Government of Xinjiang Uygur Autonomous Region (https://www.xinjiang.gov.cn/, accessed on 20 November 2023) People's governments of counties and cities

3. Research Methods

In this study, the Weiku Oasis's present state of land development in terms of urban growth, agricultural development, and ecological conservation was assessed using the land suitability evaluation. Next, the evaluation results were incorporated into the restricted conversion-zone setting of the GMOP-PLUS model. A multi-scenario simulation of land use in the study area in 2035 incorporated three scenarios of urban development, ecological conservation, and food security. The integrated framework diagram of this paper is shown in Figure 2.

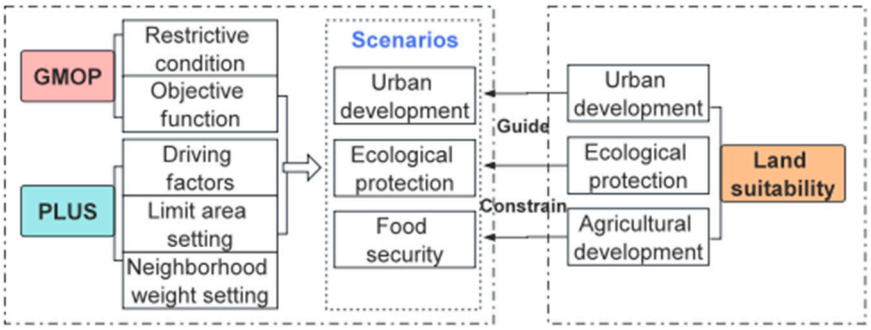


Figure 2. An integrated framework of this study.

3.1. Land Suitability Evaluation

There are many different ways to evaluate land suitability, ranging from straightforward empirical techniques to intricate modeling techniques. To thoroughly evaluate land suitability, this study combines geographic information systems (GISs) with multi-criteria decision-making techniques. It does this by building a multi-level evaluation structure, breaking down the complicated issue into several levels and factors, and then using expert scoring and weight calculation [34]. By calculating each indicator's information entropy, the weight calculation takes the entropy weight method—an objective assignment method—to evaluate the relative relevance of each indicator in the evaluation system. This approach is appropriate for handling the land suitability evaluation of numerous variables and can increase the objectivity and fairness of weight allocation [35].

3.1.1. Construction of the Evaluation Indicator System

By reviewing the relevant research results and planning texts of the Weiku Oasis and referring to the pertinent literature [4,36–39], this paper constructs the following: the evaluation index system of the urban development suitability in Weiku Oasis from the perspectives of limiting factors and location conditions; the evaluation index system of the agricultural development suitability in the oasis according to the location conditions, climatic conditions, policy control, and soil properties; and the evaluation index system of the ecological protection suitability according to the ecological sensitivity, ecological significance, and policy control (Table 2).

Table 2. Index system for three types of land suitability.

Objective	Category	Indexes	Weights
Urban development suitability	Limiting factors	Elevation	0.06001
		Slope	0.07050
		Ecological protection red line	0.10621
		Land use type	0.08459
		Distance to water source	0.11423
		Geological disaster area	0.08615

Table 2. *Cont.*

Objective	Category	Indexes	Weights
	Location conditions	Population density	0.06719
		Distance to town	0.09725
		Distance to construction land	0.08306
		Transportation arterials	0.13473
		Transportation spurs	0.09608
Agricultural development suitability	Location conditions	Distance to water source	0.09986
		Distance to main road	0.09325
		Distance to rural settlements	0.04116
		Distance to town	0.03904
	Geographic location	Slope	0.06824
		Slope direction	0.05828
		Elevation	0.06159
	Climatic conditions	Annual 10 °C cumulative temperature	0.11146
		Annual rainfall	0.07804
	Soil nutrient status and physical and chemical properties	Soil texture	0.04212
		Soil organic carbon	0.04183
		Effective soil-water content	0.06033
		Soil carbonate content	0.06289
		Soil exchangeable salts	0.06402
		Soil gravel volume	0.03855
		Soil pH	0.03932
Ecological protection suitability	Ecological sensitivity	Elevation	0.0478
		Slope	0.04874
		Slope direction	0.04926
		Soil texture	0.05931
		Land use type	0.07676
		Distance to water source	0.07543
		NDVI	0.07854
	Ecological importance	Carbon stock	0.0983
		Nature reserve	0.07835
		Net primary productivity of vegetation	0.12824
		Water conservation	0.09927
		Habitat quality index	0.16
	Policy controls	Ecological-protection red line	/

After standardizing the initial indicators to remove variations in scale, order of magnitude, and positive and negative trends among the evaluation indicators, the entropy weight method was used to determine the indicators' weights.

3.1.2. Calculation of the Suitability Index

An extensive picture of the degree to which changes in one or more indicators impact appropriateness is made possible by the integrated evaluation method's calculation of the suitability index [40]. The following is the formula:

$$S_i = \sum_{i=1}^{n} W_j Y_{ij} \quad (1)$$

where S_i is the suitability index of the ith class of land space type, the value range is 0~1, and the larger the value the more suitable it is; W_j is the weight of the jth evaluation index; and Y_{ij} is the value of the jth index of the ith class of land space type after processing.

Based on the evaluation results of the suitability of urban development, agricultural development, and ecological protection, they are classified into five grades based on ArcGIS10.8 using the natural fracture method: the most suitable, suitable, moderately suitable, unsuitable, and the most unsuitable. The most suitable class will be used for the setting of the restricted conversion zone in the GMOP-PLUS model below.

3.2. GMOP Model

3.2.1. Restrictive Condition

A series of binding indicators for socioeconomic development and the ecological environment are set in accordance with the Kuche City Master Plan (2006–2020), Xinjiang Shaya County City Master Plan (2011–2030), Xinhe County City Master Plan (2012–2030) and other plans and relevant policies (Table 3).

Table 3. Setting constraints for optimizing land use structure in the Weiku oasis.

Constraint Factors	Restrictive Condition (km^2)	Binding Basis
Total land area	X1 + X2 + X3 + X4 + X5 + X6 = 9456.51	The sum of all land use categories in 2035 equals the total area of the Weiku Oasis in 2020.
Cultivated land	X1 $\geq$ 4461.89	Combined with the policy of cultivated land protection and the status quo of the study area, the cultivated land area of the Weiku Oasis in 2035 should meet the demand of the population in the area in 2035 and be not less than the status quo in 2020.
Forest land	X2 $\geq$ 744.46	According to the planning text of counties and cities, it is necessary to pay attention to ecological restoration and increase the green space, and the area of forestland in 2035 should not be lower than the projected value obtained from the natural development forecast.
Grassland	1467.41 $\leq$ X3 $\leq$ 1606.42	The area of grassland in 2035 is higher than the current value but lower than the projected value obtained from the natural development projection.
Wetland	X4 $\geq$ 59.44	The area of water bodies in 2035 will not be lower than the current value.
Construction Land	223.03 $\leq$ X5 $\leq$ 267.64	The area of construction land in 2035 is higher than the status quo but not more than 120% of the status quo area.
Unutilized land	X6 $\leq$ 2562.94	The area of unutilized land in 2035 is not higher than the projected value obtained from the natural development projection.
Variable non-negative constraints	Xi $\geq$ 0 (i = 1, 2, 3, 4, 5, 6)	The area of each land use type shall be a non-negative value.

3.2.2. Objective Function Setting

(1) Urban development

This scenario is aimed at maximizing economic efficiency, and the evaluation of land use economic-efficiency value is mostly accounted for by the economic output value per unit of land use type [41,42], and the GMOP economic-efficiency objective function is

$$\max e(x) = \max \sum_{i=1}^{6} c_i x_i \quad (2)$$

Using the coefficients of land economics, the benefits in the target years were predicted using a gray prediction GM(1:1) model based on the output-per-unit area of six land-use

types in the Weiku Oasis from 2005 to 2020. Among these, the output of cultivated land is characterized by the output value of plantation in primary industry; the output value of forest land is characterized by the output value of forestry; the output value of livestock products is taken as the output benefit of grassland; the output value of wetland is expressed by the output value of fishery; the output value of secondary and tertiary industry is used to characterize construction land; and the unutilized land does not produce economic benefits in general, but in order to safeguard the needs of mathematical model calculation, the economic benefit of the land is set as 0.1 million CNY/km^2. So the objective function expression of the economic benefit of land utilization in the Weiku oasis is obtained as

$$\max F_1(X) = 1185.06\,X1 + 50.4\,X2 + 545.52\,X3 + 13.3\,X4 + 59311.41\,X5 + 0.1\,X6 \quad (3)$$

where $F_1(X)$ denotes the value of economic benefits, Xi is the area of i type of land use, and i = 1, 2, . . ., 6 are cultivated land, forest land, grassland, wetland, construction land and unutilized land, respectively.

(2) Ecological protection

This scenario aims at maximizing low-carbon benefits, i.e., minimizing carbon emissions [42,43], and sets the GMOP low-carbon scenario objective function:

$$\min e(x) = \min \sum_{i=1}^{6} c_i x_i \quad (4)$$

Carbon emissions from land use can be classified as either direct or indirect. Direct carbon emissions can be attributed to cultivated land, forest land, grassland, unutilized land, and wetland [44]. On the other hand, construction land has an indirect carbon-emission category, primarily resulting from human activities like energy consumption. The carbon emission coefficients for the various land categories used in this paper are derived from previous research on Northwest China [45–48]. The objective function for the scenario of maximizing the low-carbon benefits of land use in the Weiku oasis is expressed as follows:

$$\min F_2(X) = 497\,X1 - 577\,X2 - 39\,X3 - 245\,X4 + 40730\,X5 - 5\,X6 \quad (5)$$

where, $F_2(X)$ denotes the value of the low-carbon benefits, Xi is the area of i type of land use, and i = 1, 2, . . ., 6 are cultivated land, forest land, grassland, wetland, construction land and unutilized land, respectively.

(3) Food security

The goal of the scenario is to reduce the degradation of cultivated land while increasing food production. The standard grain yield is calculated by multiplying the seeded area by the yield-per-unit area. Therefore, the scenario has to minimize the degradation of the cultivated land and safeguard the cultivated land area. Under this scenario, cultivated land will be changed to other land uses less frequently. The natural development scenario predicts that the quantity of cultivated land converted to construction land, grassland, and wetland will decrease by 40%, 15% and 15%, respectively, and that the amount of cultivated land in the reduced area will increase [49].

3.2.3. Obtaining GMOP Model Results

After using Lingo 12.0 software to solve the goal function and constraints, the quantity structure of various land use kinds under the multi-scenario in 2035 was eventually achieved.

3.3. PLUS Model

The PLUS model is a rule mining framework based on the Land Expansion Analysis Strategy (LEAS) and a CA model with many types of random seeds (CARS). It is capable of

delving deeply into the factors that lead to changes in land use and dynamically simulating such changes over time and space.

3.3.1. Selection of Driving Factors

Taking data availability into account and consulting the existing literature [41,42,49,50], the selection of driving factors was mainly based on natural and socioeconomic aspects. Six socioeconomic factors were chosen, including population, GDP, distance from railroads, distance from main roads, distance from secondary roads, and distance from towns. Eight natural factors were chosen, including elevation, slope, slope direction, mean annual temperature, mean annual precipitation, soil texture, NDVI, and distance from water sources.

3.3.2. Cost Matrix and Limit-Area Setting

The cost matrix indicates whether the land types can be transformed into each other. With the development of social economy and science and technology, the possibility of transforming construction land into other land types is low; the transformation between other land types cannot be judged directly, and needs to be carried out according to different scenarios [43,51] (Figure 3).

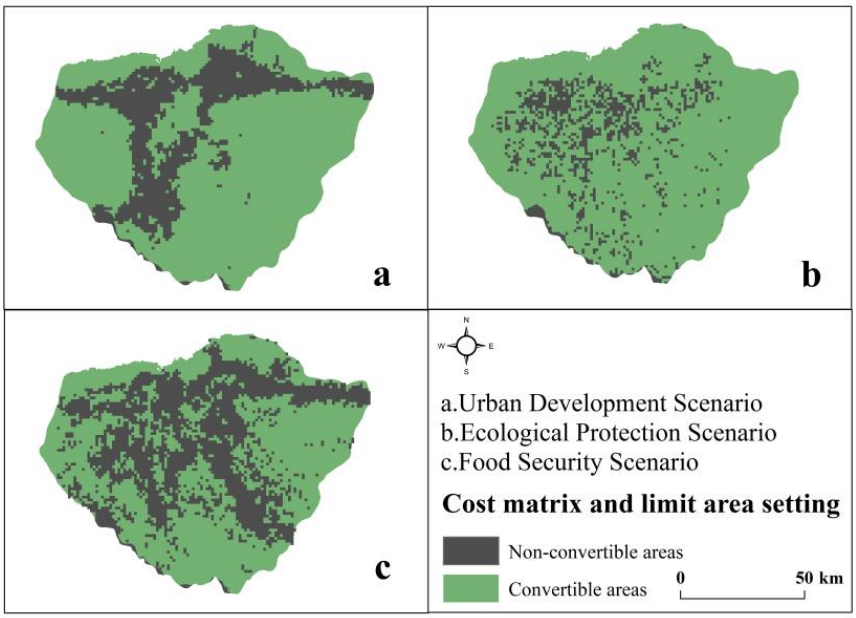


Figure 3. Cost matrix and limit-area setting.

(1) Natural Development Scenario

The natural development scenario is designed to sustain historical land-use change patterns, thereby maximizing the continuation of established development trends. When configuring the parameters for the GMOP-PLUS model, the focus was solely on the land use changes induced by human and natural processes, deliberately excluding the constraints imposed by land suitability-evaluation results. Consequently, this scenario primarily serves as a baseline for comparative analysis with other scenarios. The projected land use demand for 2035 under this scenario is derived from the Markov chain projections based on land use data spanning from 2005 to 2020.

(2) Urban development scenario

The urban development scenario primarily prioritizes economic growth and urban expansion, which is why it supports converting other land uses to construction sites and strictly prohibits converting the areas that are deemed most suitable for urban development in the study area and those that fall inside the ecological-protection red line to other land uses.

(3) Ecological protection scenario

Enhancing the ecosystem's capacity to absorb carbon dioxide and tightly regulating the amount of land used for building are essential components of the low-carbon ecological protection scenario. As a result, this scenario strictly prohibits the conversion of the study area's ecological-protection red line and the most suitable areas in the ecological protection-suitability evaluation to other land types. It also prohibits the conversion of forest land and watersheds to other land use types.

(4) Food security scenario

Cultivated land must be protected more in the food security scenario, which is why it strictly forbids its conversion to other land uses based on the natural development scenario. It also strictly forbids the conversion of the most suitable zones—those determined by evaluating the suitability of the study area's agricultural production—and areas within the ecological-protection red line to other land uses.

3.3.3. Neighborhood Weight Setting

In the PLUS model, the neighborhood weights have a range of 0~1. A bigger value denotes a stronger expansion capability or a larger neighborhood influence. To accomplish the corresponding goals of each scenario, the domain weights of the various scenarios are set independently by combining the expansion area share of each land use type in the Weiku Oasis and consulting the literature [43,52]. Table 4 displays the precise domain weights for each form of land use under the various scenarios:

Table 4. Neighborhood weights under several scenarios for every form of land use.

Scenario Setting	Neighborhood Weight					
	Cultivated Land	**Forest Land**	**Grassland**	**Wetland**	**Construction Land**	**Unutilized Land**
Natural development	0.3	0.3	0.3	0.4	0.85	0.25
Urban development	0.55	0.3	0.4	0.4	0.8	0.25
Ecological protection	0.2	0.8	0.5	0.75	0.75	0.25
Food security	0.8	0.3	0.3	0.4	0.5	0.25

3.3.4. Precision Testing

This research is based on land use data from 2005, and the PLUS model is utilized to obtain the 2020 simulation results. The accuracy of the simulation results is then evaluated in comparison to 2020's real land use. The simulation can be applied to the land use pattern in 2035, as evidenced by the high degree of accuracy of the results (89.36% for the Kappa coefficient and 0.872 for the total accuracy). The results show how precise the simulation results are at projecting the land use pattern in 2035.

4. Results

4.1. Land Suitability

The spatial distribution of the study area's appropriateness for ecological protection, agricultural development, and urban development was determined by thoroughly assessing the land's adaptability (Figure 4).

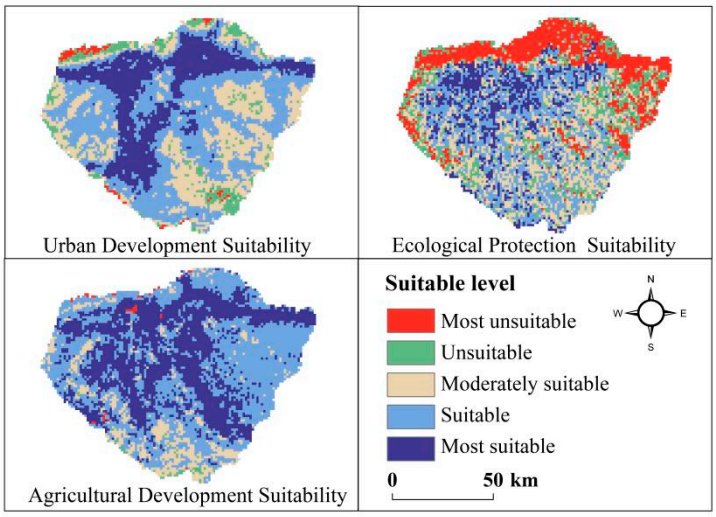


Figure 4. Spatial distribution of land suitability.

4.1.1. Urban Development Suitability

The area of the most-suitable type makes up 24.21% of the total area in terms of urban development suitability, while the area of the unsuitable type (including the most-unsuitable level and the unsuitable level) makes up 8.21%. The more-suitable class is primarily concentrated around the most-suitable class, but its geographic environment and location conditions are lower than those of the most-suitable class; the study area's periphery is where the least-appropriate and inappropriate classes are continually distributed, while the most-suitable class is primarily concentrated around the main roadways and has the maximum density in the center. It is clear that location factors—such as the separation from the transportation arterials—have a big influence on the suitability of urban growth.

4.1.2. Agricultural Development Suitability

In terms of agricultural development suitability, the area of the most-suitable kind makes up 39.32% of the total area, while the area of the unsuitable type only makes up 1.29%. Regarding the arrangement of spaces, the best class is concentrated in the center of the study region, where the water, soil, and site quality are superior to those of the other classes. This is essentially identical to the distribution of cultivated land as it exists now. There is a greater distribution of unsuitable land in the oasis edge zone due to the poor soil environment, which hinders the development of agriculture.

4.1.3. Ecological Protection Suitability

The area of the most-unsuitable kind makes up 35% of the total area in terms of ecological protection suitability, while the area of the most-suitable type makes up 14.06%. The most-suitable class is distributed in the center of the study area, but its spatial distribution is more fragmented; the more-suitable class and the moderately-suitable class are distributed around the most-suitable class's periphery, with an unclear boundary and a more fragmented overall distribution. The class that was least appropriate was placed at the edge of the study area. This regional distribution is comparable to that of the vegetation's net primary productivity, water conservation, and habitat quality, suggesting that these indicators are significant variables influencing the ecology of the research region.

4.2. Multi-Scenario Simulation Results

Table 5 displays the amounts of each land use category in 2035 for each of the four scenarios, as determined by the GMOP and Markov models. The spatial distribution of land use patterns in the Weiku Oasis in 2035 for various scenarios was then obtained by entering the data into the respective scenarios in the PLUS model (Figure 5).

Table 5. Changes in the quantitative structure of land use under different scenarios.

Land Use Type	Current (2020) Unit: km^2	Scenarios (2035) Unit: km^2			
		Natural Development	Urban Development	Ecological Protection	Food Security
Cultivated land	4461.88	4681.63	4739.08	4462.03	4927.83
Forest land	744.87	707.46	745.11	965.27	760.38
Grassland	1467.41	1318.41	1541.24	1468.31	1501.11
Wetland	59.44	53.49	60.02	60.42	63.73
Construction land	223.03	256.10	267.64	224.59	232.82
Unutilized land	2499.88	2439.43	2103.42	2275.89	1970.65

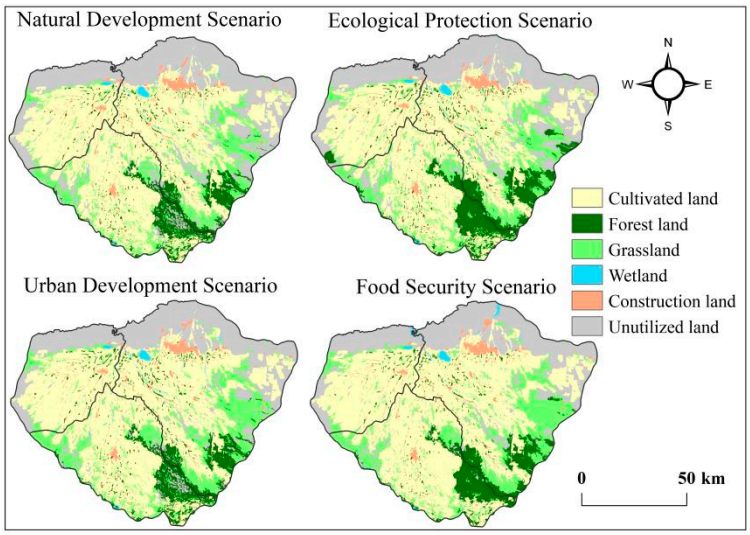


Figure 5. Land use results for different scenarios in 2035.

(1) Land use situation in 2020

To facilitate comparison with various scenarios discussed later, this paper first presents the land use situation of the Weiku Oasis in 2020 (Figure 6). The Weiku Oasis encompasses a total area of 9456.51 km^2, with the predominant land use being cultivated land, which constitutes 47.18% of the total area. It is primarily located in the central region of the study area. Ecological zones within the Weiku Oasis are relatively limited, with forest land, grassland, and wetland collectively accounting for 24.02% of the total area. Significant expanses of forest and grassland, forming the largest ecological regions within the oasis, are found along the border between Kuche City and Shaya County. Construction land, which makes up 2.36% of the area, is mainly situated around the cultivated land. Unutilized land is predominantly located in the northernmost part of the study area.

(2) Natural development Scenario

The natural development scenario only takes into account changes in land use that are brought about by human and natural processes, and it maximizes the continuation of the original development law. In this scenario, the area of cultivated land is 4681.63 km^2, up 4.92% from 2020; the area of forest land is down significantly, down 37.4%; the area of wetland and grassland is also down significantly from 2020, down roughly 10%; and the most notable trend is the expansion of construction land, up 33 km^2, or nearly 14.83%. The findings of the simulation show that, in the absence of legislative restrictions, the influence of human activity causes the area needed for construction to expand quickly to meet the demands of socioeconomic development. Regarding the spatial pattern of transformation, the expansion of construction land is primarily based on the expansion

of the original distribution status quo; the reduction in forest land is concentrated in the southern part of the study area and is converted to cultivated land and unutilized land, and the growth of cultivated land is primarily based on the original pattern, encroaching on the surrounding grassland. Xinhe County expands around the water source, and there is also a sporadic increase in the northeastern corner of the city of Kuche, which mainly occupies the unutilized land, wetland, and grasslands; cultivated land and other ecologically functional land types are also encroached upon, and if not restricted, the ecological environment of the study area will be destroyed and food security may be threatened. In general, unchecked development under natural development scenarios will lead to a fast expansion of the region's building land, making it impossible to sustain the synergistic development of the towns, agriculture, and ecology in the area, endangering the security of both food and the environment.

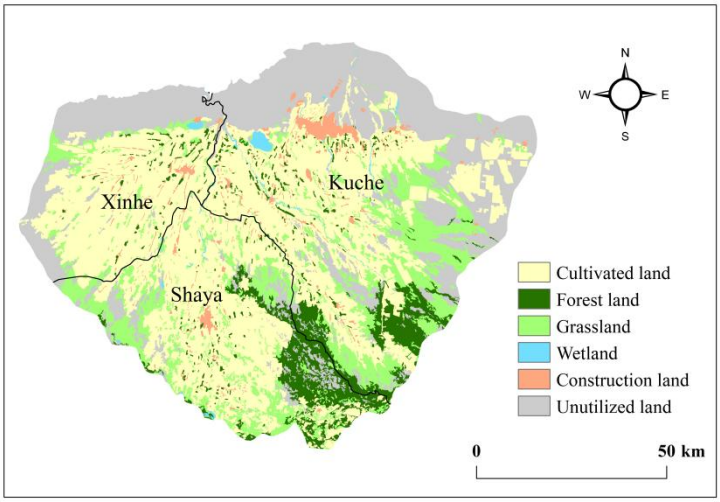


Figure 6. Land use situation in 2020.

(3) Urban development Scenario

The urban development scenario aims to maximize economic development within the given constraints. When compared to 2020, the area of cultivated land in the urban development scenario will increase by 6.2% by 2035; the area of water and forest land remains mostly unchanged from 2020; the area of grassland increases by 5.03%, or 73.83 km^2, and the trend of expanding construction land is noteworthy, increasing by nearly 20%. From the standpoint of the spatial pattern of transformation, cultivated land has slightly expanded throughout the entire range of the study area, and the area mostly affected by cultivated-land degradation is the scattered grassland that is distributed near the cultivated land. Forest land and waters, essentially, do not exhibit noticeable changes; the research area's wide grassland in the center and to the east displays an expanding trend, and the growth of construction land is primarily based on the original distribution pattern. The expansion of construction land is mainly based on the original distribution pattern, and is more pronounced in Kuche City than in Xinhe and Shaya counties.

(4) Ecological protection scenario

The ecological protection scenario aims to maximize low-carbon benefits, so the scenario should prevent disorderly expansion of construction land and expand the area of ecological land. The extent of regional forest land increases by 220.4 km^2, or 29.6%, in 2035 compared to 2020. The quantity of the remaining land use categories is almost unchanged from the base year. The southern portion of the border between Kuche City and Shaya County, as well as the southernmost portion of Kuche City, have seen the greatest growth in forested land in terms of the transformation's spatial aspect. In this scenario, additional orderly expansion based on the original pattern primarily occupies land that was previously unutilized.

(5) Food security scenario

To meet the population's need for food within the study region, the food security scenario tries to protect more cultivated land and restrict its transfer or conversion to other land categories. The region's cultivated land area increased by 10%, or 464.95 km^2, between 2020 and 2035. There is a minor increase of 4.4% in construction land; the trend of rising water is more important, increasing by 4.3 km^2; and there is a slight rise of 2% in forest land and grassland. The area of increased cultivated land was dispersed and mostly encroached upon the nearby fragmented grassland, according to the spatial pattern of transformation. The area of increased water area was primarily located in the northern part of the study area, with the wetland significantly widened, and the area of increased forest land and grassland was concentrated at the edge of the Weiku Oasis, expanding based on the original large forest and grassland.

4.3. Comparison between Multiple Optimization Strategies' Outcomes

It is possible to clarify the relationship between changes in land use structure, carbon emissions, economic benefits, and benefits related to food production by experimenting with different scenarios. The results of the Weiku Oasis simulation in 2035 indicate that the town development scenario has the most economic benefits, increasing by CNY 30,143,747,000, or 15.57%, compared with 2020, which maximizes the economic benefits. The construction of land has the greatest impact on these benefits. Furthermore, the amount of building land expanded in comparison to the natural development scenario, enhancing the property's economic benefits. The ecological protection scenario, on the other hand, is the least economically efficient due to its limitation of unchecked settlement expansion and emphasis on the preservation of ecological regions. While town and city growth is good for the economy, planning should consider the environment as well as the economy and maximize the benefits of high-quality regional development rather than sacrificing cultivated land area and ecological benefits for unplanned and irresponsible growth.

The ecological protection scenario enhances the advantages of low-carbon growth because of the extension of forest land. As a result, the ecological protection scenario lowers carbon emissions by 1,548,117.27 tons in comparison to the natural development scenario, while the urban development scenario increases carbon emissions by 468,166.5 tons. Thus, it demonstrates that the number of carbon emissions is directly correlated with the expansion of land used for construction and that industrial carbon emissions will also demand attention to the ecology and the control of carbon emissions. As a result, the greatest number of low-carbon benefits can be achieved by limiting the area of construction land and expanding the area of eco-land. Forest land has the highest ecological benefits, energy savings, and emission reduction efficiency when compared to other land use options. However, over time, ecological initiatives and efforts to protect agriculture must be carried out concurrently; ecological regions cannot be sacrificed for the development of cultivated land.

By contrast with the scenarios of urban development and ecological protection, the cultivated land area under the food protection scenario increased significantly, by 188.75 km^2 and 465.8 km^2, respectively. This indicates that the food protection scenario is capable of effectively protecting the cultivated land, maximizing the value of food production, and ensuring the food security of the Weiku oasis. However, the effects of agricultural growth, such as soil erosion, pollution of water resources, and loss of biodiversity, cannot be disregarded. Therefore, to achieve sustainability and guarantee stable food security for human society, ecological environment management must be given careful consideration during the agricultural development process.

5. Discussion

To achieve quantitative regulation and effective land use allocation in the Weiku Oasis, three optimization objectives are created in this study using the GMOP-PLUS model: food security, urban development, and ecological protection. The land suitability evaluation serves as the basis for these objectives. The optimization results can effectively protect the

existing well-developed areas and the ecological red line from being damaged, while also accurately reflecting the long-term planning goals and development requirements of the Weiku Oasis. This is made possible by the constraints of the land suitability results, the direction of the goals for decision-making, and the driving force of multiple key factors.

Traditional land use-optimization models often fail to consider the spatial suitability of different land use modes or the attributes of various elements (such as socioeconomic, locational, and ecological factors) under the unique regional conditions of the oasis region [53,54]. Therefore, incorporating suitability evaluation results can better address the contextual characteristics of the Weiku Oasis, ensuring that the prediction and optimization outcomes align more closely with the region's actual development trajectory. By comparing the natural development scenario with the urban development scenario, it becomes evident that in the natural development scenario, although construction land significantly expands, some of the originally optimal urban zones are converted to other land types, primarily arable land. Conversely, the urban development scenario safeguards these land types from destruction and facilitates a rational and orderly expansion along the pre-existing construction areas. Both the food security scenario and the natural development scenario focus on expanding around the original arable land, ensuring that areas suitable for agricultural development are not inappropriately converted. Moreover, the ecological protection scenario, compared to the natural development scenario, provides better protection for the original ecological areas, thereby enhancing ecological preservation. The results of the comprehensive land suitability evaluation indicate that the most suitable areas for development in the Viku Oasis are generally more concentrated, with significant overlap among the three types of spatial suitability. Consequently, the optimal locations can serve as hubs for outward radiation, promoting safe development in the surrounding regions. Simultaneously, it is crucial to consider the multiple indirect impacts of urban and agricultural activities on ecological spaces to foster synergistic optimization and integrated development across urban, agricultural, and ecological domains.

The Weiku Oasis's development requirements and the predetermined objective conditions can be satisfied by any of the three optimization scenarios. The three optimization scenarios that have been suggested can alter the current state of land use, but they differ in terms of development features and priorities. Cultivated land and natural areas can be protected from degradation by the urban development scenario, which can successfully encourage the growth of towns and cities. Weiku Oasis can efficiently ensure food and ecological security by allowing towns and cities to grow in an orderly manner without infringing on cultivated land or ecological land, hence promoting economic development. To achieve the low-carbon and green development of the Weiku Oasis and to ensure the ecological security of the area, the ecological protection scenario can effectively promote the increase in forested land area while guaranteeing the cultivated land and the area of towns and cities. The border zone between Kuche City and Shaya County has a sizable area of continuous forest land, and the area should preserve as much of the ecological land as possible. The food security scenario can effectively guarantee the amount of cultivated land, slow down the rate at which it is converted to cultivated land, and implement the policy of protecting cultivated land. It should be noted that, given the districts' and counties' rapid economic development, the expansion of construction land is still inevitable. Therefore, cultivated land should not be expanded too recklessly in this scenario to the point where it intrudes on nearby forests, grasslands, and other ecological areas [54–56]. However, diverse solutions should be adopted based on the unique characteristics of each region, rather than restricting regional planning to a single scenario. Alternately, creating a complete development scenario to maximize the coordinated growth of the region's towns, agriculture, and ecology and attain fully sustainable development [57,58].

The paper's conclusions are helpful not just for the Weiku Oasis's growth but also for other oasis areas dealing with related issues. These findings allow for the proposal of the following policy guidelines.

(1) Enhance the quality of the land suitable for farming by adhering to the red line. The Weiku Oasis should keep developing relevant rules to stop or lessen the appropriation of cultivated land by other land use types. When selecting cultivated-land protection zones, areas highly suitable for agricultural development can be comprehensively considered based on the results of land suitability evaluation [58,59].
(2) Limit the overall area used for building while raising the standard of intensive land use [60,61]. Weiku Oasis should evaluate the amount of land needed for the high-quality growth of the local economy, logically establish a complete land use plan based on the land's appropriateness and real development demands, and make sure that the land is used effectively and intensively.
(3) The first batch of the Carbon Peak Pilot Park was chosen to be the Kuche Economic and Technological Development Zone. Despite the city of Kuche's rapid urbanization, the region should prioritize environmental protection, encourage a comprehensive green transformation of the region's social and economic development, and responsibly handle the relationship between construction land and ecological land. [53].
(4) Adaptive planning to maximize the arrangement of land use. Regional conditions will shift over time, as planning is carried out within the constraints of the current socioeconomic environment [62]. Thus, land use planning needs to be flexible and dynamically monitored, and the arrangement of land uses needs to be promptly modified in response to shifts in the outside environment. Stronger limitations are placed on the development and usage of land resources [63].

Even though the study's findings more closely match the regional land use's spatial growth, certain shortcomings remain:

(1) Land use change is an intricate and dynamic process. The study examined in detail the legal, anthropogenic and natural barriers, but due to constraints such as the availability of data, factors such as the geological environment were neglected; future studies can consider more of this aspect when designing the land suitability-evaluation index system and combine it with the model.
(2) The neighborhood factor parameters, for example, are subject to subjectivity in light of prior research experience. These factors are primarily determined by the extent of human influence on different land types and are subject to ongoing debugging to maximize simulation accuracy.
(3) The current study is still unable to fully account for the limitations of the multi-objective planning model and the spatial simulation law of land use due to the complexity of the land-use-simulation model and the limitations of the core data. To increase the precision and timeliness of the land-use-pattern optimization model, future studies should concentrate on the implications of land-use management guidelines on land-use-pattern optimization [64].

6. Conclusions

Following an assessment of the Weiku Oasis' land suitability, the GMOP model was used to create three quantitative structural-optimization objectives: food security, low-carbon benefit maximization, and economic benefit maximization. Three scenarios for spatial development were established using the PLUS model: one for urban development, one for ecological protection, and one for food security. The Weiku Oasis's land use structure and spatial layout in 2035 were simulated and optimized with the application of macro-control and limitations based on the findings of the land suitability evaluation. The following results were reached by contrasting the variations in cultivated land area, economic gains, and carbon emissions under each simulation scenario:

(1) With its great regional applicability, the GMOP-PLUS model predicts better the Weiku Oasis's future spatial pattern of land use. The model's total accuracy after validation is 89.36%, and its Kappa coefficient is 0.872—a value more than 0.8—meaning it may be used to forecast future changes in land use in the Weiku Oasis districts and counties.

(2) The most suitable type of area for urban development is 24.21% of the study area's most intensive area; the most suitable type of area for ecological protection is 14.06% of the study area's most suitable type, scattered throughout the study area's central zone and continuously distributed throughout Kuche City's southern region and the Shaya County border zone; and the most suitable type of area for agricultural development is 39.32% of the study area's central zone, which is consistent with the distribution of currently cultivated land.

(3) The modifications to land use in each scenario differ significantly from the others. The cultivated land protection scenario increases the area of cultivated land by 10%; the urban development scenario significantly increases the area of land used for construction by 20% compared to 2020; and the ecological protection scenario notably increases the area of ecological areas by increasing the area of wetland, grassland, and forest land by 29.6%, 0.06%, and 1.66%, respectively. Overall, the scenarios satisfy the Weiku Oasis's various development criteria. From the standpoint of spatial patterns, the cultivated land, construction land, and unutilized land are the areas that have changed the most in each scenario, with the majority of the change regions concentrated around the boundaries of the research area.

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