Scenario-based Optimization of Low-carbon Land Use Patterns in Watersheds: A Case Study of the Fen River Basin (Postprint)

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Abstract

Land use optimization allocation aims to promote the scientific utilization of regional land resources and achieve carbon emission reduction targets. This study takes the Fen River Basin as the research area, and based on land use and resistance factor data from 2015 and 2020, employs the FLUS-MCR model and carbon budget coefficient method. After verifying model accuracy, five simulation scenarios for 2030 are established: low-carbon development priority, economic development priority, cultivated land protection priority, ecological protection priority, and natural development. The layout characteristics of land use types under different future scenarios are compared, and optimized layout schemes are proposed. The results show that: (1) In 2020, the areas of the four land use functional zones in the Fen River Basin—prohibited development zone, restricted development zone, key development zone, and optimized development zone—were 2,491.76 km^2, 6,445.99 km^2, 16,325 km^2, and 14,477 km^2, respectively. The net carbon emission of the basin was 2002.46×10^{4} t. The prohibited development zone served as the carbon sink area of the basin with a total carbon absorption of 0.76×10^{4} t, while the other three zones were carbon source areas with a total carbon emission of 2003.22×10^{4} t. (2) The land use carbon budget situations under various scenarios in 2030, in descending order, are: low-carbon development priority, ecological protection priority, cultivated land protection priority, natural development, and economic development priority. (3) In 2030, under different scenarios, except for the relatively rational land use structure in the prohibited development zone, the restricted development zone still needs to appropriately reduce the proportion of cultivated land and construction land in that zone. The key and optimized development zones should consider appropriately developing grassland suitable for cultivation, promoting the coordinated development of production, living, and ecological functions of land use in the basin, and achieving the goal of low-carbon land use.

Optimization of Low-Carbon Land Use Patterns Based on Scenario Simulation: A Case Study of the Fenhe River Basin

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Abstract: Optimizing land use allocation aims to promote the scientific utilization of regional land resources and achieve carbon emission reduction targets. This study takes the Fenhe River Basin as the research area. Based on land use and resistance factor data from 2015 and 2020, the FLUS-MCR model and carbon budget coefficient method are employed to validate model accuracy. Five simulation scenarios for 2030 are established: low-carbon development priority, economic development priority, cultivated land protection priority, ecological protection priority, and natural development. The layout characteristics of land use types under different future scenarios are compared, and optimized layout schemes are proposed. The results show that: (1) In 2020, the areas of the four land use functional zones in the Fenhe River Basin—prohibited, restricted, key, and optimized development zones—were 2491.76 km^2, 6445.99 km^2, 16325 km^2, and 14477 km^2, respectively. The basin' s net carbon emission was 2002.46$×10^{4}$ t. The prohibited development zone serves as the basin' s carbon sink area with total carbon absorption of 0.76$×10^{4}$ t, while the remaining three zones are carbon source areas with total carbon emissions of 2003.22$×10^{4}$ t. (2) In 2030, the land use carbon balance across scenarios ranks from high to low as: low-carbon development priority, ecological protection priority, cultivated land protection priority, natural development, and economic development priority. (3) In 2030, under different scenarios, except for the relatively reasonable land use structure in the prohibited development zone, the restricted development zone still needs to appropriately reduce the proportion of cultivated land and construction land. The key and optimized development zones should consider appropriately developing arable grassland to promote coordinated development of production, living, and ecological functions in the basin, thereby achieving low-carbon land use objectives.

Keywords: low-carbon land use; optimize configuration; FLUS-MCR model; carbon budget coefficient; Fenhe River Basin; Shanxi

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Global climate change represents a major crisis facing human society today. To effectively address the threats posed by climate change, countries worldwide have called for achieving carbon emission reduction targets and action plans to advance global climate governance through Nationally Determined Contributions (NDCs). As one of the world's largest carbon emitters, China has proposed the goal of "striving to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060," and has incorporated carbon peaking and carbon neutrality into China' s 14th Five-Year Plan and long-range objectives for 2035 to respond to global climate change governance. How to achieve these carbon peaking and carbon neutrality goals has become a primary research focus. Land use optimization layout adjusts land use type structures and spatial arrangements to maintain efficient regional land resource utilization, reduce carbon emissions, and effectively promote the achievement of dual-carbon targets.

Regarding land use optimization layout, most studies have focused on the allocation of land quantity and quality, with less attention paid to optimization from a low-carbon land use perspective. Additionally, static optimization based on current land conditions is insufficient to effectively reflect the complexity, spatiotemporal heterogeneity, and uncertainty of land use change. In contrast, multi-scenario land use change simulation and spatial optimization allocation offer better flexibility for future land use changes and different socio-economic development needs. Research methods mostly employ linear programming models, system dynamics models, multi-objective particle swarm algorithms, and CLUE-S models. Research scales include administrative regions (provinces, cities, urban agglomerations), ecological vulnerable areas, and watersheds at different levels. Overall, existing research has mostly focused on optimizing current land resource conditions, with few studies reporting on optimization allocation from a low-carbon land use perspective.

The Fenhe River Basin is an important traditional energy production and consumption base in Shanxi Province and an ecologically fragile zone on the Loess Plateau. It possesses composite environmental backgrounds including watershed, mining area, and ecological sensitivity. Long-term human disturbances from coal and iron mining, farming, and urban economic construction have caused particularity and complexity in land use structure and layout changes in the study area, leading to more complex ecological environment and land carbon budget issues. Against the backdrop of China' s "dual-carbon" goals, the contradiction between the diversity of future socio-economic development within the basin and the dual-carbon targets may intensify. Achieving land use optimization allocation under the dual-carbon background is an urgent need to solve the above problems. Therefore, this study integrates the FLUS-MCR model and adopts the carbon budget coefficient method. Based on land use data from 2015 and 2020, and after validating model accuracy, five simulation scenarios for 2030 are established: economic development priority, cultivated land protection priority, ecological protection priority, low-carbon target priority, and natural development. The layout characteristics of land use under different future development scenarios are compared, and targeted optimization layout schemes are proposed. This provides references for effectively improving regional land carbon sink capacity, resolving carbon budget contradictions, achieving “dual-carbon” goals, promoting low-carbon-oriented territorial spatial planning, and formulating scientific emission reduction pathways.

1.1 Study Area Overview

The Fenhe River Basin is located in central Shanxi Province, on the eastern wing of the Loess Plateau (35°13 4 -39°4 4 N, 110°26 42 -113°26 56 E). It spans 9 prefecture-level cities and 51 counties, including Taiyuan, Jinzhong, and Lüliang, with a total area of approximately 3.95$\times10^{4}$ km^2. The region has a temperate continental monsoon climate with an average annual temperature of 9.7°C and average annual precipitation of 392.8 mm. The terrain slopes overall from north to south, with main landforms consisting of rocky mountains, loess hills, and valley basins. The main land use types are cultivated land, grassland, and forest land. Population, economy, and towns are relatively concentrated within the basin, with an urbanization rate of 60.3% and average annual grain output accounting for 42.6% of the province’ s total. Coal production accounts for 26.2% of the province’ s output, and carbon emissions account for 35.74% of Shanxi’ s total emissions, making it one of the province’ s major carbon source areas. In 2020, the basin’ s net carbon emission was 2002.46$\times10^{4}$ t.

[Figure 1: see original paper]

1.2 Data Sources and Processing

The 2015 and 2020 land use data were obtained through band synthesis, geometric correction, and image enhancement, followed by manual interactive interpretation with an accuracy of 91.1%. Data were reclassified into six categories according to China’ s land use classification system: cultivated land, forest land, grassland, water area, construction land, and unused land. Resistance factor data underwent corresponding geographic processing, clipping, correction, and coordinate transformation, with a sampling grid of 1 km$\times$1 km.

Table 1 Data type and source

Data Type	Source	Resolution
Land use	Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn)	Landsat 8 30 m
DEM	Geospatial Data Cloud (www.gscloud.cn)	SRTM 30 m

Data Type	Source	Resolution
Vegetation coverage	Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn)	MOD13Q1 250 m
Average annual precipitation	WorldClim version 2.0 (http://www.worldclim.org/)	-
Distance to roads	National Basic Geographic Information Center (www.ngcc.cn/ngcc/)	China Basic Geographic Information Data
Distance to water bodies	Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn)	-
Soil data	National Earth System Science Data Center–Soil Branch (http://soil.geodata.cn)	China High-resolution National Soil Information Grid Basic Attribute Dataset

1.3 Research Methods

1.3.1 Land Use Simulation Method The FLUS model is used to simulate future land use patterns. This model is an integrated model based on the traditional Cellular Automata (CA) model, improved by incorporating an Artificial Neural Network (ANN) algorithm to calculate the suitability probability of various land use conversions from initial land use data and driving factors. Combined with an integrated adaptive inertia competition mechanism, it calculates the comprehensive probability of land use change for the simulation year. Finally, a roulette wheel mechanism obtains the simulation results. The model validation uses the 2015 land use data to simulate the 2020 actual land use situation, achieving an overall accuracy of 91.1% and a Kappa coefficient of 0.89, confirming the model' s applicability for simulating land use changes in this study area.

[Figure 2: see original paper]

1.3.2 Land Use Optimization Zoning Method (1) Selection of "Sources"

Ecological sources refer to areas with high ecological environmental quality, stability, and expandability. Considering multi-year land use change characteristics in the basin, forest land areas within ecological protection red lines consistently larger than 50 km^2 and water areas consistently larger than 2 km^2 are selected as ecological sources. Urban sources refer to core areas of urban concentrated construction zones, extracting urban land and rural residential land as urban sources.

(2) Construction of Resistance Surfaces

Six resistance factors reflecting the current status and representativeness of the study area are selected and weighted. Except for land use type factor as a neutral factor, the attributes of other resistance factors have opposite effects on the two types of sources. Starting from ecological and urban sources, the resistance to outward expansion is analyzed and divided into five levels: high resistance, relatively high resistance, medium resistance, relatively low resistance, and low resistance zones.

(3) Minimum Cumulative Resistance Model

The Minimum Cumulative Resistance (MCR) model measures the sum of resistance overcome from a "source" to a destination through different resistances. According to this principle, land use functional zones are established using the following formula:

$$MCR = min\sum_{j} D_{ij} \times R_i$$

where MCR represents the minimum resistance (lowest cost) from any point in space to other points; D_{ij} represents the actual distance from starting point i to j within a certain range; and R_i represents the resistance coefficient of i to the destination.

$$MCR_d = MCR_e - MCR_c$$

where MCR_e represents the minimum cumulative resistance value for ecological expansion; MCR_c represents the minimum cumulative resistance value for urban expansion; and MCR_d represents their difference.

(4) Minimum Cumulative Resistance Surface Calculation

Based on the positive or negative difference values, the basin land use can be divided into two categories: areas less than 0 are ecologically suitable zones, and areas greater than 0 are construction suitable zones. To align with actual basin land use conditions, the zones are further refined. According to the mutation point of the difference value and area curve, zones suitable for economic construction are divided into key and optimized development zones, while zones suitable for ecological protection are divided into prohibited and restricted development zones.

[Figure 3: see original paper]
[Figure 4: see original paper]
[Figure 5: see original paper]

1.3.3 Carbon Budget Coefficient and Carbon Budget Calculation

To calculate carbon emissions (absorption) of different land use types, carbon budget coefficients are classified and determined by comparing similar regions and combining data from the *China Energy Statistical Yearbook*, China Carbon Accounting Database (https://www.ceads.net.cn/data/), and provincial/municipal statistical yearbooks. Since unused land accounts for a small proportion of the basin area with minimal multi-year changes and low carbon budget contribution, it is not included in the statistics (Table 4). The carbon budget calculation formula is:

$$C = \sum_i S_i \times E_i$$

where C is the total carbon emission (absorption); S_i is the area of land use type i; and E_i is the carbon emission (absorption) coefficient of land use type i. Positive values indicate carbon emissions, while negative values indicate carbon absorption.

Table 2 Situation types and conversion principles

Scenario Type	Conversion Principle
Low-carbon development priority	Targeting the lowest growth rate, prioritize conversion to carbon sink land types: forest land, water area, grassland, etc.
Ecological protection priority	Incorporating ecological protection red line areas as restricted conversion zones, convert land use types according to ecological benefit ranking: forest land, water area, grassland, others
Cultivated land protection priority	Adding permanent basic farmland protection zones as restricted conversion zones, controlling conversion of cultivated land to construction land, and increasing conversion of other land types to cultivated land

Scenario Type	Conversion Principle
Natural development	Using 2015-2020 land use change rates and baseline year driving factors as sources, without policy planning restrictions, to predict future scales of various land types
Economic development priority	Based on the *Shanxi Provincial National Economic and Social Development 14th Five-Year Plan and 2035 Vision Outline* and historical construction land change trends, targeting maximum growth rate, arrange construction land conversion according to single-direction conversion principle from low to high grade: construction land, cultivated land, forest land, grassland, water area, etc.

Table 3 Classification and weight of ecological/urban source resistance factors

Resistance Factor	Classification (Ecological/Urban Source)	Weight
Land use type	Forest land, water area	30/100
Vegetation coverage	45-60/13-30	13/12
Average annual precipitation	515-548/447-483	15/14
Distance to roads	88-138/182-284	14/15
Distance to water bodies	54-114/0-447	12/13

Table 4 Carbon budget coefficient table of land use types

Land Use Type	Carbon Budget Coefficient (t/hm^2)
Cultivated land	0.42
Forest land	-0.52
Grassland	-0.21
Water area	-0.25
Construction land	5.50

2.1 Current Land Use and Functional Zoning in Fenhe River Basin

In 2020, the main land use types in the Fenhe River Basin were cultivated land, forest land, grassland, and construction land, accounting for 40.44%, 26.64%, 24.03%, and 8.08% of the basin area, respectively. Forest land and grassland are concentrated in the mountainous and hilly areas at the basin’ s edge, while construction land and cultivated land are concentrated in the core basin area. According to land use functional orientation, the basin is divided into prohibited, restricted, key, and optimized development zones. The ecologically-function-dominant prohibited and restricted development zones have areas of 2491.76 km^2 and 6445.99 km^2, respectively, accounting for 6.27% and 16.22% of the basin area, mainly located in forest and grassland conservation areas at the basin’ s source and edge mountains. The production and living function-dominant key and optimized development zones have areas of 16325 km^2 and 14477 km^2, respectively, accounting for 41.08% and 36.43% of the basin area. The key development zone is concentrated in the core basin areas of Taiyuan and Jinzhong, while the optimized development zone is distributed on its periphery.

[Figure 6: see original paper]

2.2 Current Carbon Budget Status of Fenhe River Basin

In 2020, the basin’ s net carbon emission was 2002.46$\times10^{4}$ t, accounting for 35.74% of Shanxi Province’ s total emissions, making it one of the province’ s major carbon source areas. The carbon budget is relatively poor, consistent with Zhu Xiangmei et al.’ s conclusion that the Fenhe River Basin in the Yellow River Basin shows a carbon-water deficit and weak carbon ecological sustainable development capacity. Therefore, land use optimization needs to be strengthened to further improve the land use carbon budget status. By functional zone, the prohibited development zone has an annual carbon absorption of 0.76$\times10^{4}$ t, serving as an important carbon sink area for the basin, with forest and grassland area accounting for 84.07% of this zone, enhancing its carbon absorption capacity. The other three zones are all carbon source areas, with carbon emissions ranking as: key development zone (1022.69$\times10^{4}$ t), optimized development zone (915.24$\times10^{4}$ t), and restricted development zone (65.29$\times10^{4}$ t). Overall, each functional zone’ s carbon budget capacity differs due to variations in dominant land use types influenced by terrain, slope, transportation accessibility, and other factors, which affect the proportion of carbon sources and sinks.

[Figure 7: see original paper]

2.3 Multi-Scenario Land Use Pattern Optimization and Carbon Budget in Fenhe River Basin

Based on 2015 land use data, the 2020 actual land use situation was simulated for validation, achieving an overall accuracy of 91.1% and a Kappa coefficient of 0.89, confirming the model’ s applicability. In 2030, except for the relatively reasonable land use structure in the prohibited development zone, other zones have varying degrees of land use structural issues.

2.3.1 Low-Carbon Development Priority

In 2030, the basin’ s carbon emission is 2093.62$\times10^{4}$ t, carbon absorption is 52.77$\times10^{4}$ t, and the carbon budget level is superior to other scenarios. Analyzing changes in land use types, forest land and grassland area increase by 100.09 km^2 and 29.92 km^2 respectively compared to the starting year, increasing carbon absorption by 1666.26 t. Cultivated land area decreases by 184.25 km^2, reducing carbon emissions by 6817.25 t. In each zone, the key and optimized development zones have the same ranking of main land use type proportions. In the key development zone, cultivated land and construction land area slightly exceed 50% of the zone’ s total area, so appropriately increasing production and living function-oriented land types in this zone can promote economic agglomeration and scale development. The prohibited and restricted development zones have high proportions of carbon sink forest and grassland, with the prohibited zone reaching 86.99% and the restricted zone totaling 78.73%, playing important roles in maintaining the basin’ s overall carbon budget balance.

2.3.2 Ecological Protection Priority

In 2030, carbon emission is 2171.35$\times10^{4}$ t, carbon absorption is 52.95$\times10^{4}$ t, with the carbon budget level slightly lower than the low-carbon development scenario. Compared to the starting year, ecological function land including forest land, grassland, and water area increases by 196.52 km^2 (2.70%), contributing to carbon absorption. Water area increases by 542.64 km^2, while grassland area decreases by 234.62 km^2 and construction land increases by 1085.28 t, causing carbon emissions to increase by 153.21$\times10^{4}$ t. Grassland becomes the main source of conversion to cultivated land and construction land, also increasing total carbon emissions. In the key development zone, cultivated land and construction land account for 57.67% of the zone’ s area, while grassland accounts for 27.90%. In the optimized development zone, cultivated land and construction land account for 64.20%. Comparatively, the key development zone’ s economic construction function orientation is relatively weak. Therefore, transferring arable grassland to supplement regional cultivated land production needs can promote regional food security. In the prohibited and restricted development zones, forest land has the highest area proportion. The restricted development zone has a relatively high proportion of cultivated land (21.95%), and should increase efforts in returning farmland to forest and grassland to balance regional ecological security.

2.3.3 Cultivated Land Protection Priority

At the global level, this scenario has carbon emissions of 2209.38$\times10^{4}$ t and carbon absorption of 25.61$\times10^{4}$ t in 2030. Cultivated land area increases by 291.34 km^2, a growth rate of 1.90%. Compared to the starting year, cultivated land area expands by 376.14 km^2, with some cultivated land being returned to forest and grassland, increasing carbon absorption by

116.27$×10^{4}$ t and reducing carbon emissions by 3167.07 t. In each zone, both key and optimized development zones have high proportions of forest and grassland, each accounting for about 44-46% of their respective zone areas, while construction land accounts for about 13-15%. Therefore, these zones still require rational planning of construction land to promote urbanization level improvement. In the prohibited and restricted development zones, forest and grassland account for about 99.39% and 78.73% of each zone' s area respectively, with relatively reasonable land use type structures.

2.3.4 Natural Development

Under this scenario, five land use types show two change characteristics. Compared to the starting year, cultivated land, forest land, and grassland all show decreasing trends, with area reductions of 169.51 km^2, 52.95 km^2, and 99.55 km^2 respectively. Construction land shows substantial growth, expanding by 327.61 km^2 (34.29% growth rate). Water area and unused land have minimal changes, basically maintaining previous levels. The carbon budget situation shows that carbon absorption decreases by 2.34$×10^{4}$ t while carbon emissions increase by 213.31$×10^{4}$ t, with annual net carbon emissions of 2216.07$×10^{4}$ t. In the key development zone, cultivated land and construction land account for 56.19% of the zone' s area, while forest and grassland account for 42.91%, which can better maintain regional ecological security levels. In the optimized development zone, the main land use types are cultivated land, grassland, forest land, and construction land, accounting for 44.68%, 29.47%, 13.43%, and 11.51% respectively. The zone is overall a carbon source, contributing 25.51% of the basin' s carbon emissions. The optimized development zone has relatively sufficient land reserve resources for production and living functions, allowing for increased development of arable areas. Except for the prohibited development zone with relatively reasonable land use structure, the restricted development zone still needs rational allocation of land use type structure.

2.3.5 Economic Development Priority

In 2030, the basin' s net carbon emissions reach 2666.66$×10^{4}$ t, the highest among all scenarios. Compared to the starting year, construction land area increases by 1049.54 km^2, a growth rate of 34.29%, higher than other scenarios. During the same period, cultivated land and grassland have the largest area reductions, decreasing by 619.48 km^2 and 227.19 km^2 respectively, with reduction rates of -4.04% and -2.20%. Carbon absorption decreases by 2.34$×10^{4}$ t. In the key development zone, the combined proportion of cultivated land and construction land accounts for 46.08% of the zone' s area, while forest and grassland account for 44.68%. The zone is a carbon source with emissions of 2686.68$×10^{4}$ t, accounting for 46.08% of the basin' s total. The optimized development zone has similar main land use types as the key development zone, with carbon emissions of 1194.65$×10^{4}$ t. Following the same functional zone optimization principles, this zone has relatively high proportions of ecologically functional land like grassland, especially in the key development zone where grassland ranks among the main land use types. Therefore, appropriate development of arable grassland should be considered to optimize its land use structure. The prohibited development zone has forest and grassland accounting for 99.39% of its area, with a relatively reasonable land use type structure. The restricted development zone has cultivated land and construction land accounting for 21.95% of its area; as an ecological buffer zone, it should increase efforts in returning farmland to forest and grassland to promote overall ecological function improvement across the basin.

In 2030, the basin’ s net carbon emissions under all five scenarios exceed the starting year, with excess amounts from high to low being: economic development priority (2666.66$×10^{4}$ t), natural development (2216.07$×10^{4}$ t), cultivated land protection priority (2209.38$×10^{4}$ t), ecological protection priority (2171.35$×10^{4}$ t), and low-carbon development priority (2093.62$×10^{4}$ t). The trend of land use evolution and net carbon emission changes under each scenario is consistent with the basin’ s socio-economic development trends. Comparing scenarios horizontally, the carbon budget level ranks from high to low as: low-carbon development priority, ecological protection priority, cultivated land protection priority, natural development, and economic development priority. According to 2030 socio-economic development needs, the target scale of construction land is between 3120.43–4109.92 km^2. When construction land area reaches 3120.43 km^2, forest and grassland areas are 10118.84 km^2 and 9518.73 km^2 respectively, and net carbon emissions are lowest. Compared with other scenarios, the low-carbon development priority scenario is more conducive to optimizing the carbon budget in the future study area. Based on land use functional zones and structure, future land use should leverage the carbon sink function of prohibited development zones, effectively increase the proportion of forest and grassland in restricted development zones to enhance their ecological buffer role, while rationally arranging the proportions of cultivated land and construction land in key and optimized development zones to coordinate the basin’ s overall carbon budget level and achieve future low-carbon emission land use layout.

3 Conclusions

1) The areas of the four land use functional zones in the Fenhe River Basin—prohibited, restricted, key, and optimized development zones—are 2491.76 km^2, 6445.99 km^2, 16325 km^2, and 14477 km^2 respectively. Except for the prohibited development zone, which is the basin’ s carbon sink area with carbon absorption of 0.76$×10^{4}$ t, the other three zones are carbon source areas with carbon emissions of 2003.22$×10^{4}$ t. The basin’ s net carbon emission is 2002.46$×10^{4}$ t.

2) In 2030, the land use carbon budget levels across scenarios rank from high to low as: low-carbon development priority (2093.62$×10^{4}$ t), ecological protection priority (2171.35$×10^{4}$ t), cultivated land protection

priority (2209.38$×10^{4}$ t), natural development (2216.07$×10^{4}$ t), and economic development priority (2666.66$×10^{4}$ t).

3) In 2030, except for the relatively reasonable land use structure in the prohibited development zone, the restricted development zone still needs to appropriately reduce the proportion of cultivated land and construction land. The key and optimized development zones should consider appropriately developing arable grassland to promote coordinated development of production, living, and ecological functions in the basin, achieving low-carbon land use objectives.

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