Landscape Ecological Risk Assessment and Coupling Coordination Degree in Qingyang City from the Production-Living-Ecological Space Perspective (Postprint)

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Date: 2025-04-08T16:51:16+00:00

Abstract

Qingyang City is located in the Longdong Loess Plateau region with abundant natural resources, serving as one of China' s important energy supply areas. It plays a pivotal role in promoting the Western Development Strategy, large-scale protection, high-quality development, and ecological environmental protection, making the exploration and analysis of landscape ecological risk patterns and coupling coordination of production-living-ecological space profoundly significant. This study takes Qingyang in the Longdong Loess Plateau region as the research object, employing methods such as land use transfer matrix, landscape ecological risk assessment model, and coupling coordination degree model to explore and analyze land use structural changes from 2000 to 2020, evaluate landscape ecological risk patterns based on production-living-ecological space, and assess the coupling coordination of production-living-ecological space. The results indicate: (1) From 2000 to 2020, the areas of ecological and living spaces in Qingyang City demonstrated a steady and continuous year-by-year upward trend, while the area of production space showed a year-by-year downward trend. (2) The overall landscape ecological condition of Qingyang City is in a low-risk state, with risk levels exhibiting an "east-low, west-high" distribution pattern. (3) The coupling coordination degree of production-living-ecological space shows an overall positive development trend with spatial concentration, displaying a "south-high, north-low" distribution characteristic. The area of coupling coordination regions demonstrates continuous year-by-year expansion, while the area of uncoordinated regions shows year-by-year reduction. (4) Analysis of the coupling coordination of production-living-ecological space using natural and socio-economic factors reveals that socio-economic factors exert a greater influence. Therefore, integrating driving factors with the demands and characteristics of

production-living-ecological space, optimizing the layout of production-living-ecological space to promote coordinated development of landscape ecological risk patterns, enhancing regional landscape ecological security, and advancing sustainable ecological-economic development in Qingyang City.

Full Text

Landscape Ecological Risk Assessment and Coupling Coordination Degree in Qingyang City from the Perspective of Production-Living-Ecological Space

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Abstract: Qingyang City is located in the loess plateau region of eastern Gansu Province, endowed with abundant natural resources and serving as one of the country' s important energy supply zones. It plays a pivotal role in promoting large-scale development, ecological protection, high-quality growth, and environmental conservation in western China, making the exploration and analysis of landscape ecological risk patterns and coupling coordination of production-living-ecological space profoundly significant. This study takes Qingyang in the loess plateau region of eastern Gansu as the research area, employing methods such as land use transfer matrix analysis, landscape ecological risk assessment models, and coupling coordination degree models to investigate land use structure changes from 2000 to 2020. This work also evaluates landscape ecological risk patterns based on production-living-ecological space and assesses the coupling coordination among the three spaces. Results show: (1) From 2000 to 2020, the ecological and living spaces in Qingyang City showed a steady and continuous upward trend, while the production space area exhibited a yearly decline. (2) The overall landscape ecological condition of Qingyang City is in a low-risk state, with risk levels displaying an "east low, west high" distribution pattern. (3) The coupling coordination degree of production-living-ecological space shows an overall improving trend and concentration, presenting a "south high, north low" distribution characteristic, with coordinated areas expanding continuously year by year while uncoordinated areas are shrinking. (4) Analysis of coupling coordination using natural and socioeconomic factors reveals that socioeconomic factors have a greater impact. Therefore, integrating driving factors with the needs and characteristics of production-living-ecological space to optimize spatial layout can promote coordinated development of landscape ecological risk patterns, enhance regional landscape ecological security, and advance sustainable ecological-economic development in Qingyang City.

Keywords: production-living-ecological space; landscape ecological risk; coupling coordination; driving factor; Qingyang City

Introduction

The concept of "production-living-ecological space" refers to the system and place where production, living, and ecological functions interact, serving as the carrier for human survival and development and reflecting humanity' s capacity to transform nature and its own development level. Production space is dominated by production functions, primarily providing economic output and obtaining products and services. Living space accommodates various daily life activities such as residence, consumption, leisure, and entertainment. Ecological space is national territory with ecological services or products as its main function, encompassing diverse natural ecosystems (e.g., forests, grasslands, rivers, lakes) that provide necessary environmental conditions for organisms to maintain their survival and reproduction. These three spaces are interrelated yet independent in territorial spatial planning, collectively forming the main framework of national space utilization.

In the early 21st century, international organizations formally proposed the concept of "agricultural multifunctionality," which was subsequently applied to the study of land use multifunctionality and continuously expanded to ecological environment and socio-economic dimensions. De Groot [3] research indicated that ecological, socio-cultural, and economic values could be used to assess land multifunctionality, and that the relationship between land use and land function should be considered in comprehensive land use change assessments. The SENSOR project first proposed summarizing land use multifunctionality into three major functions: social, economic, and environmental [4]. As global urbanization develops, various complex urban problems have re-emerged. The urban growth boundary proposed to limit urban sprawl has become a relatively novel research topic [6]. Domestic scholars have constructed evaluation indicator systems for "production-living-ecological" functions from different perspectives and scales, employing coupling coordination degree models to explore the evolution characteristics, driving mechanisms, and relationships with regional sustainable development of production-living-ecological space.

Landscape ecological risk primarily evaluates the negative impacts of human activities on regional landscape patterns and ecosystems [10], focusing on proposing risk management pathways for ecological environment deterioration [11]. Research has assessed landscape ecological risk and optimized landscape patterns at regional scales, examined their spatiotemporal evolution, improved assessment methods using ecosystem services, and employed human-nature system approaches to explain theoretical foundations, serving scientific ecological management strategy formulation. In recent years, domestic scholars have extensively studied landscape ecological risk from the perspective of production-living-ecological space. Zhang et al. [19], Zou et al. [20], and Wang et al. [21] constructed landscape ecological risk assessment models based on landscape ecology theory and systematically analyzed spatiotemporal changes and coupling coordination characteristics of regional landscape ecological risk using coupling coordination models.

Against this background, analyzing the evolution characteristics of production-living-ecological functions and exploring regional coordinated development of these spaces has become a key issue for regional sustainable development. Optimizing the layout of production-living-ecological space structure and studying landscape ecological risk and coupling coordination characteristics are crucial for enhancing landscape ecological security. Qingyang City, located in western China, plays an important role in promoting large-scale development and protection in the western region. This study takes Qingyang City as the research area to analyze the distribution characteristics of production-living-ecological space, assess ecological risk, and analyze the coupling coordination degree among the three spaces, revealing the closeness and coordinated development level of their interrelationships, with the aim of providing a basis for ecological civilization construction, environmental protection, and regional sustainable development in Qingyang City.

1.1 Study Area Overview

Qingyang City is located in the easternmost part of Gansu Province, in the gully region of the Loess Plateau, at the intersection of Shaanxi, Gansu, and Ningxia provinces. The elevation ranges from 885 to 2082 m, with geographical coordinates of 35°15 ~37°10 N, 106°20 ~108°45 E. It borders Yan' an City of Shaanxi Province to the east, Pingliang City of Gansu Province to the west, Xianyang City of Shaanxi Province and Dingxi City of Gansu Province to the south, and Guyuan City and Wuzhong City of Ningxia to the north. Qingyang City governs seven counties and one district: Xifeng District, Qingcheng County, Huan County, Huachi County, Heshui County, Zhengning County, Ning County, and Zhenyuan County, with a total area of approximately 2.7$\times10^{4}$ km^2. The region has a warm temperate continental monsoon climate, cold and dry in winter, hot and rainy in summer, with uneven seasonal precipitation distribution –scarce in winter and spring, concentrated in summer.

1.2 Data Sources

Land use secondary classification data from 2000–2020 were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn) with a resolution of 30 m. Vegetation data were sourced from the National Ecological Science Data Center (http://www.nesdc.org.cn) with a spatial resolution of 1 km. Socioeconomic data such as GDP were derived from statistical yearbooks and other published data.

1.3 Methods

1.3.1 Production-Living-Ecological Space Classification Referring to existing research [18], based on land use data, 6 land use types were reclassified into 8 categories of production-living-ecological space: agricultural production space, industrial and mining production space, urban living space, rural living space, forest ecological space, grassland ecological space, water ecological space, and other ecological space. According to the dominant functions of land use, the classification system is shown in Table 1 .

1.3.2 Landscape Ecological Risk Index The Landscape Ecological Risk Index (ERI) quantifies the degree of ecological risk that landscapes experience under human or natural influences. It is a comprehensive indicator of multiple landscape ecological indices that can quantitatively describe landscape pattern distribution and composition, thereby effectively revealing the internal relationship between regional landscape structure and ecological risk [19]. Therefore, combining the actual situation of the study area, the ERI was calculated using Fragstats software with the area-wide method. The landscape ecological risk assessment model was constructed using landscape loss degree, separation degree, dominance degree, disturbance degree, vulnerability index, and landscape loss degree index.

The calculation formula is:

$$ERI_i = \sum_i \frac{A_{ki}}{A_k} \times R_i$$

where ERI_i is the ecological risk index of the ith risk unit; the smaller the value, the lower the landscape ecological risk degree, and the larger the value, the higher the risk degree; A_{ki} is the area of the ith landscape type in the kth risk unit; A_k is the area of the kth risk unit; and R_i is the landscape loss degree index of the ith landscape type.

The landscape loss degree index describes the ecological loss degree of natural attributes of various landscape types when disturbed by external interference. Its calculation typically involves landscape disturbance degree and landscape vulnerability degree.

The landscape disturbance degree index (E_i) indicates the impact degree of natural or human activities on the landscape ecological environment, reflecting the transformation from simple, regular-shaped, and closely connected landscapes to fragmented, irregular, discontinuous, and increasingly heterogeneous landscapes under external factors. It can be calculated through landscape fragmentation (N_i), separation degree (D_i), and dominance degree (C_i). Greater fragmentation and separation degree lead to higher disturbance degree index and higher landscape ecological risk degree. a, b, and c are the weights of fragmentation, separation degree, and dominance degree, respectively, assigned as $a = 0.5$, $b = 0.3$, $c = 0.2$ according to references [19,22].

$$E_i = aC_i + bN_i + cD_i$$

Landscape fragmentation index:

$$N_i = \frac{n_i}{A_i}$$

where n_i is the number of patches of landscape type i, and A_i is the total grid number (patch frequency) of landscape type i.

Landscape separation degree index:

$$D_i = \frac{Q_i}{M_i \times L_i}$$

where Q_i is the total number of grids (patch frequency) of landscape type i; M_i is the number of patches i (patch density); and L_i is the area of patch i / total landscape area (patch proportion).

Landscape dominance degree index:

$$C_i = \frac{Q_i + M_i + L_i}{3}$$

Landscape vulnerability degree index characterizes landscape vulnerability to external factors. The weaker the resistance to external interference, the higher the vulnerability and landscape risk degree. Different landscape types play different roles in ecosystems with varying vulnerabilities. The assignment method considers both natural attributes and the combined effects of human and natural factors. Referring to existing research [19,22,24], vulnerability values were assigned to 8 secondary land classes: urban living space (8), forest ecological space (7), water ecological space (6), grassland ecological space (5), industrial and mining production space (4), rural living space (3), agricultural production space (2), and other ecological space (1), then normalized to obtain more scientific and reasonable landscape vulnerability indices.

Referring to existing research [19], the study area was divided into grids based on patch sizes of different land use types. A 600 m × 600 m grid was determined as the evaluation unit, creating 7,500 grid units using ArcGIS fishnet division. Land use data from each period were imported into Fragstats software to calculate the landscape ecological risk index for each grid unit. Finally, the landscape ecological risk index was assigned to the center point of each evaluation unit through 'Kriging interpolation' to obtain the landscape ecological risk pattern distribution.

1.3.3 Coupling Coordination Degree Model Coupling degree refers to the degree of interaction between two or more systems; coordination degree is a quantitative indicator measuring the coordination state or level of various elements within a system [25]. This means the coupling coordination degree not only considers the interaction degree among system elements but also reflects their coordinated development level.

The calculation formulas are:

$$C = \frac{1}{2} \times \left[\frac{P_i \times R_i \times E_i}{(P_i + R_i + E_i)^3} \right]^{\frac{1}{2}}$$

$$T = \alpha P_i + \beta R_i + \gamma E_i$$

$$D = \sqrt{C \times T}$$

where C is the coupling degree of production-living-ecological space; the larger the C value, the stronger the coupling, and vice versa; P_i, R_i, and E_i represent production, living, and ecological landscape ecological risk indices, respectively; T represents the coordination index of production, living, and ecological landscapes; α, β, and γ are 待定 coefficients for production, living, and ecological functions, respectively; based on existing research results, the coefficients are assigned as $\alpha = \beta = \gamma = 1/3$; D is the coupling coordination degree of production, living, and ecological landscapes; higher D values indicate better coupling coordination, while lower values indicate poorer coordination.

According to existing literature [26], combined with study area characteristics, the coupling coordination degree is divided into: severe disconnection ($D \leq 0.010$), moderate disconnection ($0.010 < D \leq 0.034$), basic coordination ($0.034 < D \leq 0.060$), moderate coordination ($0.060 < D \leq 0.089$), and high coordination ($D > 0.089$) for corresponding area calculations.

1.3.4 Geographical Detector Geographical detector is a statistical method for exploring spatial differentiation and revealing its underlying driving forces. By calculating and comparing the q-values of individual factors, the q-value measures the explanatory power of driving factors on spatial differentiation, with stronger explanatory power as the q-value increases [27]. This study selected eight factors including elevation, slope, annual average temperature, annual average precipitation, NDVI, total population at year-end, population density, and urbanization rate to analyze driving force impacts.

Results

2.1 Spatiotemporal Evolution Characteristics of Production-Living-Ecological Space

2.1.1 Temporal Variation Characteristics Among the production-living-ecological space types in Qingyang City from 2000 to 2020 (Fig. 2 [Figure 2: see original paper]), ecological space accounts for the largest proportion, exceeding 70% annually. Qingyang City is dominated by agricultural production space, forest ecological space, and grassland ecological space (Fig. 3 [Figure 3: see original paper]), with their combined area accounting for over 85% of the total area. Grassland ecological space has the largest area, representing the main land use type, further confirming that ecological space occupies the largest proportion. Other ecological space has the smallest area, primarily consisting of sandy land, saline-alkali land, bare land, bare rock gravel land, and other unused land, indicating relatively sufficient land use in Qingyang City.

During this period, agricultural production space and water ecological space areas showed gradual decline, with total reductions of 891.82 km^2 and 2.40 km^2, respectively. These reduced areas mainly transformed into grassland and forest ecological spaces. Meanwhile, industrial and mining production space, urban and rural living spaces, forest and grassland ecological spaces, and other ecological space types all showed upward trends, with growth primarily converted from agricultural production space, largely benefiting from the "Grain for Green" policy.

2.1.2 Spatial Distribution Characteristics Agricultural production space is mainly distributed in the central region of Qingyang City (Fig. 4 [Figure 4: see original paper]), where conditions are suitable for agricultural production. As one of the country' s important energy supply zones, Qingyang has abundant reserves of petroleum, coal, and natural gas, concentrated in Ning County, Xifeng District, Huan County, and Heshui County. Vegetation cover is relatively sparse, mainly distributed in Huachi County, Heshui County, Ning County, and Zhengning County. Grassland ecological space is widely distributed in northwestern Huan County and surrounding Xifeng District, with some distribution in other counties. Water ecological space mainly consists of tributaries of the Wei River basin, including the Malian River (flowing through Huan County, Qingcheng County, Heshui County, Ning County), Pu River (flowing through Zhenyuan County, Xifeng District, Ning County), Hulu River (flowing through Huachi County, Heshui County), and Siling River (flowing through Zhengning County).

2.2 Landscape Ecological Risk Evolution Under Production-Living-Ecological Space

Based on actual conditions, the ecological risk index is divided into five levels: low-risk area (ERI $<$ 0.110), lower-risk area [0.110~0.121], medium-risk area [0.121~0.133], higher-risk area [0.133~0.191], and high-risk area [0.191<]. Kriging interpolation cross-validation accuracy evaluation (Table 2) shows that the mean error and standardized mean are close to 0, the average standard error is close to the root-mean-square, and the standardized root-mean-square is close to 1, confirming interpolation reliability.

From 2000 to 2020, Qingyang City' s landscape ecological risk status is dominated by lower-risk and medium-risk areas, together accounting for over 75%

of the total area, while higher-risk and high-risk areas occupy relatively small proportions, with their combined share not exceeding 8%. This benefits from environmental protection and ecological civilization construction policies implemented since 2000, with comprehensive development of the "Grain for Green" and "Ecological Civilization Construction" strategies steadily improving regional landscape pattern security. Over the past 20 years, medium-risk areas have the largest proportion, exceeding 35%; high-risk areas have the smallest proportion, below 3%. Among area changes of different levels, medium-risk and high-risk areas show small variation amplitudes and relative stability, with overall upward trends. Lower-risk, medium-risk, and higher-risk areas show larger variation amplitudes, with higher-risk areas decreasing by over 810.36 km^2. Overall, lower-risk areas show a gradual increasing trend, while medium-risk and higher-risk areas show yearly decreasing trends.

Qingyang City's landscape ecological risk pattern shows an "east low, west high" distribution (Fig. 6 [Figure 6: see original paper]). Low ecological risk areas are mainly concentrated in eastern Huachi County, Heshui County, Ning County, and Zhengning County, where land use is dominated by forest ecological space, followed by grassland ecological space, with good ecological environment and self-stability and minimal landscape fragmentation and separation. Lower-risk and medium-risk areas are widely distributed in northern Huan County, Huachi County, and Qingcheng County, dominated by grassland ecological space and agricultural production space. Higher-risk and high-risk areas are mainly distributed in urban living space, rural living space, industrial and mining production space, and intensively cultivated areas in Xifeng District and surrounding counties, primarily because Xifeng District is the administrative center of Qingyang City with high urbanization levels, frequent human activities and industrial construction, resulting in high land fragmentation and high landscape ecological risk after human interference.

2.3 Coupling Coordination Degree of Production-Living-Ecological Space

2.3.1 Temporal Variation Characteristics From 2000 to 2020, the coupling coordination of production-living-ecological space in Qingyang City was dominated by severe disconnection (Fig. 7 [Figure 7: see original paper]), accounting for over 50% of the regional area. High coordination areas were the smallest, accounting for less than 5% of the regional area. From the trend perspective, high coordination and moderate coordination areas both showed steady and continuous upward trends annually, with high coordination areas increasing from 201.96 km^2 to 814.32 km^2, an increase of 612.36 km^2. Severe disconnection areas showed a continuous yearly decreasing trend, with a total reduction of 873.12 km^2. Moderate disconnection and basic coordination areas showed a "first decrease then increase" pattern, with an overall upward trend, increasing by 217.08 km^2 and 593.28 km^2, respectively.

2.3.2 Spatial Distribution Characteristics From 2000 to 2020, the spatial distribution of coupling coordination of production-living-ecological space in Qingyang City was relatively concentrated, generally showing a "south high, north low" distribution characteristic with obvious regional differences (Fig. 8 [Figure 8: see original paper]). High coordination and moderate coordination areas of Qingyang' s "production-living-ecological" space are concentrated in Zhenyuan County, Xifeng District, Ning County, and Zhengning County, where urban and rural layouts are relatively concentrated, land use types are diverse, and land use efficiency is high, resulting in higher coupling coordination. Moderate disconnection and basic coordination areas are scattered, roughly distributed around frequently used rural living land and interactive zones of agricultural production land. Severe disconnection areas are widely distributed in northern Qingyang City, where water resources are scarce due to natural geographical environment, land use types are relatively simple, and the ecological environment is fragile.

2.4 Driving Forces of Production-Living-Ecological Space Coupling Coordination

From natural environment and socioeconomic factors, eight factors were selected: elevation, slope, annual average temperature, annual average precipitation, NDVI, total population at year-end, population density, and urbanization rate. Geographical detector was used for interaction detection and single factor detection analysis of driving forces for production-living-ecological space coupling coordination.

2.4.1 Factor Detection From the perspective of single influencing factors (Fig. 9 [Figure 9: see original paper]), the average explanatory power q-value of influencing factors on production-living-ecological space coupling coordination degree is sorted as: annual precipitation > GDP > NDVI > urbanization rate > total population at year-end. This shows that the single factor with the strongest explanatory power for coupling coordination in this region is annual precipitation, with an average q-value of 0.35. Natural influencing factors have profound impacts on water resource management, ecosystem health, urban planning, and land use, showing a positive correlation with coupling coordination within a certain appropriate range. Urbanization rate, NDVI, and total population at year-end have relatively high explanatory power, with average q-values exceeding 0.15, indicating significant impacts on coupling coordination. As important components of socioeconomic factors and indirect indicators of land use efficiency, higher values indicate better land use efficiency and better coupling among various land patches. Temperature, elevation, and population density have smaller explanatory q-values.

2.4.2 Interaction Detection First, we analyze whether the explanatory power of these factors is independent to quantitatively characterize the joint effects between factors pairwise. Specific changes are driven by particular factors, and various influencing factors interact to jointly promote changes. Interaction detection results can be categorized as double-factor enhancement, nonlinear enhancement, single-factor nonlinear weakening, and nonlinear weakening.

The interaction detection between influencing factors of production-living-ecological space coupling coordination degree in Qingyang City shows (Fig. 10 [Figure 10: see original paper]) that all interaction detection q-values exhibit double-factor enhancement, indicating that all interactive factors have significantly stronger impacts on spatial heterogeneity of coupling coordination than single factors. The interaction between annual precipitation, urbanization rate, NDVI, population, and other factors has greater influence on spatial heterogeneity of production-living-ecological space coupling coordination.

Discussion

"Production-living-ecological space" is a combination of three land use patterns under territorial spatial planning: production, living, and ecological. It is a complex place for human survival and production activities, reflecting the interaction and relationship between human activities and the natural environment. Changes in production-living-ecological space structure affect the stability of landscape ecological risk patterns [28], and the two interact and influence each other. Only through coordinated development of production-living-ecological space can landscape ecosystem stability and ecological environment security be achieved [29].

This study analyzed land use data to examine regional land use structure transfer characteristics. Overall, production space shows a declining trend, while living and ecological spaces show upward trends, similar to Chen et al.' s [30] research findings. The landscape ecological risk assessment model was constructed using landscape loss degree, disturbance degree, and vulnerability index, with weights assigned to reflect different index importance. The study area is dominated by medium-risk areas, similar to Zhang et al. [19] and Zou et al. [20], with landscape ecological security showing an expansion trend.

When analyzing coupling coordination of production-living-ecological space, the "production-living-ecological"landscape ecological risk index was introduced. Future research could independently construct production-living-ecological function indices for more precise evaluation of landscape ecological risk patterns and coupling coordination. This study found that coupling coordination is inversely proportional to landscape ecological risk degree, similar to Zou et al. [20]. River valley areas have dense population distribution, high land use patch fragmentation, efficient and intensive land use, frequent human activities, and high coupling coordination, yet landscape ecology is more vulnerable to external interference. Therefore, this study employed some socioeconomic and natural environmental factors to analyze driving mechanisms. Future research could incorporate national policy impacts with more detailed and comprehensive driving force analysis when data are available.

Conclusion

1) Among production-living-ecological space types in Qingyang City from 2000 to 2020, ecological space has the largest area proportion, exceeding 70%, dominated by forest and grassland ecological spaces. Production space ranks second, accounting for over 20% of the study area, dominated by agricultural production space. Living space has the smallest proportion, less than 5%. Land use structure changes mainly involve transformation from production space to ecological space types, with ecological space as the main component and appropriate production space proportion, indicating good agricultural cultivation conditions and abundant grassland and forest resources suitable for developing animal husbandry and crop farming.
2) The overall landscape ecological condition of Qingyang City is safe, dominated by medium security level. From the overall trend, low landscape ecological risk areas show a gradual increasing trend, while high-risk areas show a yearly decreasing trend. The landscape ecological risk pattern shows an "east low, west high" distribution pattern.
3) From 2000 to 2020, the coupling coordination of production-living-ecological space in Qingyang City was primarily uncoordinated. From the trend perspective, coordinated areas show a continuous yearly upward trend, while uncoordinated areas show a continuous downward trend. The overall coupling coordination degree shows improving development and concentration, with a "south high, north low" distribution characteristic.
4) Regarding influencing factors, the degree of influence is sorted as: annual precipitation > GDP > NDVI > urbanization rate > total population at year-end. Annual precipitation, urbanization rate, NDVI, and population are the most significant factors for production-living-ecological space coupling coordination. The interaction between these factors has greater impact on spatial heterogeneity of coupling coordination.

References

[1] Li Mingwei. Transformation of Land use Function and Response of Eco-environment Based on Production-Living-Ecology Space in Danjiangkou Reservoir Area[D]. Wuhan: Hubei University, 2021.

[2] Li Wengyu, Tao Lixia, Wen Chuanhao. Study on function evolution and coupling coordination degree of production-living-ecological space in the upper reaches of Yangtze River in China[J]. Environmental Science and Pollution Research International, 2024, 31(9): 13026-13045.

[3] De Groot R. Function analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes[J]. Landscape and Urban Planning, 2006, 75(3-4): 175-186.

[4] Verburg P H, Van De Steeg J, Veldkamp A, et al. From land cover change to land function dynamics: A major challenge to improve land characterization[J]. Journal of Environmental Management, 2009, 90(3): 1327-1335.

[5] Pérez Soba M, Petit S, Jones L, et al. Land use functions—a multi-functionality approach to assess the impact of land use changes on land use sustainability[J]. Sustainability Impact Assessment of Land use Changes, 2008: 375-404.

[6] Jun M. The effects of Portland's urban growth boundary on housing prices[J]. Journal of the American Planning Association, 2006, 72(2): 239-243.

[7] Liu Xiao. Landscape ecological risk assessment and landscape security pattern optimization in Shule River Basin[J]. Chinese Journal of Ecology, 2016, 35(3): 791-799.

[8] Dang Hui, Rong Lihua, Li Yitong, et al. Spatiotemporal evolution characteristics and influencing factors of production-living-ecological spaces in the farming-pastoral ecotone: Taking Hohhot of Inner Mongolia as an example[J]. Arid Zone Research, 2023, 40(10): 1698-1706.

[9] Yao Chengbin, Zhou Mingzhong, Zhang Di, et al. Spatiotemporal characteristics and evolution of rural production-living-ecological space function coupling coordination in Wumeng Mountain area[J]. Journal of Guizhou Normal University (Natural Sciences), 2024, 42(1): 45-54.

[10] Yang Long, Meng Huihong, Wang Jitao, et al. The vulnerability assessment and obstacle factor analysis of urban agglomeration along the Yellow River in China from the perspective of production-living-ecological space[J]. PloS One, 2024, 19(4): e0299729-e0299729.

[11] Peng Jian, Dang Weixiong, Liu Yanxu, et al. Review on landscape ecological risk assessment[J]. Acta Geographica Sinica, 2015, 70(4): 664-677.

[12] Faber J H, Van Wensem J. Elaborations on the use of the ecosystem services concept for application in ecological risk assessment for soils[J]. Science of the Total Environment, 2012, 415: 3-8.

[13] Peng Jian, Pan Yajing, Liu Yanxu, et al. Linking ecological degradation risk to identify ecological security patterns in a rapidly urbanizing landscape[J]. Habitat International, 2018, 71: 110-124.

[14] Wang Kaige, Zheng Huihui, Zhao Xiangyu, et al. Landscape ecological risk assessment of the Hailar River basin based on ecosystem services in China[J]. Ecological Indicators, 2023, 147: 109795.

[15] Li Shaokun, He Wenxi, Wang Lei, et al. Optimization of landscape pattern in China Luojiang Xiaoxi basin based on landscape ecological risk assessment[J]. Ecological Indicators, 2023, 146: 109887.

[16] Zhang Xuemao, Du Huaming, Wang Ying, et al. Watershed landscape ecological risk assessment and landscape pattern optimization: Take Fujiang River

basin as an example[J]. Human and Ecological Risk Assessment: An International Journal, 2021, 27(9-10): 2254-2276.

[17] Huang Yicheng, Zhang Jinbing, Zhang Pengyan, et al. Construction and optimization of ecological security pattern based on landscape ecological risk assessment in the affected area of the Lower Yellow River[J]. Frontiers in Ecology and Evolution, 2023, 11: 1176545.

[18] Guo Hongjiang, Cai Yanpeng, Li Bowen, et al. An integrated modeling approach for ecological risks assessment under multiple scenarios in Guangzhou, China[J]. Ecological Indicators, 2022, 142: 109252.

[19] Zhang Xiang, Zhang Shichao, Zhang Xuanyun, et al. Spatial and temporal evolution of landscape ecological security and its influencing factors in the Yangtze River Economic Belt from the perspective of production-living-ecological space in the past 40 years[J]. Chinese Journal of Eco-Agriculture, 2023, 31(10): 1539-1552.

[20] Zou Yongcai, Lan Anjun, Fan Zemeng, et al. Evaluation of landscape ecological security and its coupling characteristics analysis in Guizhou Province from the perspective of production-living-ecological space[J]. Research of Soil and Water Conservation, 2024, 31(3): 432-442.

[21] Wang Fei, Ye Changsheng, Hua Jiqing, et al. Coupling relationship between urban spatial expansion and landscape ecological risk in Nanchang City[J]. Acta Ecologica Sinica, 2019, 39(4): 1248-1262.

[22] Zhang Xuebin, Shi Peiji, Luo Jun, et al. The ecological risk assessment of Arid Inland River Basin at the landscape scale: A case study on Shiyang River Basin[J]. Journal of Natural Resources, 2014, 29(3): 410-419.

[23] Xu Lei. Research on the Optimization of Geographical Spatial Pattern of Urban Agglomeration in the Middle Reaches of the Yangtze River Based on the Production-Living-Ecological Function[D]. Wuhan: Huazhong Agricultural University, 2017.

[24] Pan Jinghu, Liu Yanxu, Liu Ying, et al. Landscape ecological risk evaluation and degree of coupling coordination in Qingyang City from the perspective of production-living-ecological space[J]. Arid Zone Research, 2025, 42(3): 556-567.

[25] Li Wengyu, Tao Lixia, Wen Chuanhao. Study on function evolution and coupling coordination degree of production-living-ecological space in the upper reaches of Yangtze River in China[J]. Environmental Science and Pollution Research International, 2024, 31(9): 13026-13045.

[26] Dang Hui, Rong Lihua, Li Yitong, et al. Spatiotemporal evolution characteristics and influencing factors of production-living-ecological spaces in the farming-pastoral ecotone: Taking Hohhot of Inner Mongolia as an example[J]. Arid Zone Research, 2023, 40(10): 1698-1706.

[27] Wang Cheng, Tang Ning. Spatiotemporal characteristics and evolution

of rural production-living-ecological space function coupling coordination in Chongqing municipality[J]. Geographical Research, 2018, 37(6): 1100-1114.

[28] Cheng Jiaqi, Lin Yilin, Zhao Junsan, et al. Spatiotemporal characteristics and influencing factors of functional coupling and coordination of production-living-ecological spaces in Kunming City[J]. Research of Soil and Water Conservation, 2024, 31(3): 299-310, 319.

[29] Chen Bin, Xu Shangzhao, Zhou Yangyang, et al. Evaluation and coupling coordination analysis of landscape ecological security of Yichang from the perspective of production-living-ecological space[J]. Research of Soil and Water Conservation, 2022, 29(4): 344-351.

[30] Holmes J. Impulses towards a multifunctional transition in rural Australia: Gaps in the research agenda[J]. Journal of Rural Studies, 2006, 22(2): 142-160.

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