Spatiotemporal Variation and Obstacle Factor Analysis of Territorial Spatial Efficiency in the Yellow River Basin (Postprint)

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Abstract

Examining and identifying the evolutionary trends and obstacle factors of territorial space efficiency in key river basins can provide critical basis for constructing a territorial spatial pattern with complementary advantages and high-quality development. Taking 97 cities in the Yellow River Basin as the case study area, this study employs spatial classification, kernel density estimation, and obstacle degree models to reveal the spatiotemporal evolution patterns and obstacle factors of territorial space efficiency in this region. The results show that: (1) From the perspective of temporal evolution patterns, the territorial space efficiency in the Yellow River Basin showed a fluctuating upward trend from 2010 to 2022, with differences among different spatial regions presenting a development trend of ecological space > urban space > agricultural space. (2) From the perspective of spatial differentiation patterns, the spatial heterogeneity of territorial space efficiency is significant, and the agglomeration modes of different spatial efficiencies exhibit obvious regional differences. (3) From the perspective of spatial agglomeration characteristics, the evolution of territorial space efficiency exhibits spatiotemporal inertia and continuity features, with high-high agglomeration and low-low agglomeration being the main agglomeration modes. (4) From the perspective of obstacle factor analysis results, ecological space efficiency poses the highest obstacle degree to the improvement of territorial space efficiency, while non-agricultural output value, agricultural irrigation area, and ecosystem service value are the main obstacle factors for improving urban, agricultural, and ecological space efficiency, respectively. The research findings provide a new perspective for deepening theoretical understanding of territorial space efficiency research in key river basins, and offer scientific support for optimizing the territorial spatial layout and improving spatial governance levels in the Yellow River Basin.

Full Text

Spatio-temporal Variation and Obstacle Factors of Territorial Spatial Efficiency in the Yellow River Basin

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Abstract

Territorial spatial efficiency analysis in major river basins provides critical insights for developing regionally optimized land use patterns that promote sustainable development. This study investigated the Yellow River Basin' s territorial spatial efficiency by examining 97 cities over 13 years (2010–2022). We employed a methodological framework combining spatial classification techniques, kernel density estimation, and obstacle degree modeling to systematically assess spatio-temporal patterns and limiting factors. The temporal analysis revealed fluctuating efficiency trends throughout the study period, with a consistent hierarchy of performance across spatial categories (ecological space > urban space > agricultural space). Spatially, significant heterogeneity was observed in efficiency distribution, with distinct regional agglomeration patterns. These spatial configurations demonstrated strong temporal inertia and continuity, characterized primarily by "high-high"and "low-low"agglomeration patterns. Our obstacle factor analysis identified ecological spatial efficiency as the primary constraint to overall territorial spatial improvement in the basin. Further investigation revealed specific limiting factors for each spatial category: non-agricultural output value (urban spaces), agricultural irrigation area (agricultural spaces), and ecosystem service value (ecological spaces). These findings highlight the need for targeted interventions addressing these specific limitations. The research contributes to the theoretical understanding of territorial spatial efficiency dynamics in major river basins while providing scientific support for optimizing the territorial spatial layout and improving the level of spatial governance in the Yellow River Basin.

Keywords: territorial spatial efficiency; spatio-temporal variation; obstacle analysis; Yellow River Basin

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1.1 Essential Connotation Analysis of Territorial Spatial Efficiency

Territorial space supports and sustains the normal operation of socio-economic systems, comprising three subsystems: urban development, agricultural production, and ecological conservation. From the perspective of each spatial function, urban space carries important functions such as regional economic development, industrial structure upgrading, and resource element agglomeration. Agricultural space bears the functions of agricultural production, local culture, and social security, serving as an important foundation for rural revitalization. Ecological space is a crucial component ensuring human survival and development, possessing functions such as soil and water conservation and biodiversity maintenance. Given that the "National Plan for Major Function-Oriented Zones" explicitly divides territorial space into urban space, agricultural space, and ecological space, this paper accordingly categorizes territorial spatial efficiency into urban spatial efficiency, agricultural spatial efficiency, and ecological spatial efficiency. The measurement of territorial spatial efficiency essentially represents a trade-off relationship among territorial spatial resource inputs, economic outputs, and undesirable environmental outputs. Its magnitude determines the optimization process of regional territorial spatial layout and the formulation of regional territorial spatial planning and management policies. Its connotation places greater emphasis on the collaborative high-quality development between resource-environment and socio-economy represented by territorial spatial utilization, stressing the minimization of territorial spatial resource inputs to optimize regional territorial spatial benefits and layout while minimizing negative ecological environmental impacts.

1.2 Study Area Overview

As a vital ecological barrier and economic belt in China, the Yellow River Basin spans the country' s eastern, central, and western regions, flowing through nine provinces including Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong. The region features complex and diverse land use types, encompassing cultivated land, forestland, grassland, and construction land. The terrain shows significant undulation, presenting a characteristic of high west and low east [Figure 2: see original paper]. By the end of 2020, the total population in the region reached approximately 3.9$\times10^{8}$, with economic development levels showing gradient differentiation trends. The economic disparity characteristics among the lower, middle, and upper reaches precisely reflect the realistic representation and objective manifestation of unbalanced development across China' s eastern, central, and western regions.

1.4.1 Super-Efficiency SBM Model

The super-efficiency SBM model incorporates undesirable output factors by adopting a non-radial distance function that includes slack variables in the objective function, thereby avoiding biases caused by different measurement units and angle selection differences [21].

1.4.2 Three-Dimensional Kernel Density Estimation

Three-dimensional kernel density estimation is a non-parametric method in probability theory used to estimate unknown density functions. Its main principle involves applying kernel function weighted summation to the neighborhood of each data point in three-dimensional space, which can avoid estimation errors caused by function specification to a certain extent. Higher kernel density values indicate greater concentration of data distribution. The calculation formula is as follows:

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x - X_i}{h}\right)$$

where $f(x)$ is the kernel density estimate; n is the number of research units; h is the bandwidth controlling the smoothness of the estimated density; K is the kernel density function for territorial spatial efficiency; X_i is the attribute value of observation point i; and x is the attribute value of sample points.

1.4.3 Natural Breaks Classification Method

The Natural Breaks (Jenks) classification method, as the default data classification approach in ArcGIS, can intuitively identify data breakpoints through histograms, thereby naturally grouping similar values to achieve classification results with maximum between-group differences and minimum within-group differences.

1.4.4 Cold-Hot Spot Analysis

Cold-hot spot analysis is a method for studying the distribution locations of similar attribute agglomeration areas within a region. It can identify spatial distribution patterns of hot and cold spots in territorial spatial efficiency and quantify clustered, discrete, and random spatial patterns. The calculation formula is as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} W_{ij} X_j}{\sum_{j=1}^{n} X_j}$$

where G_i^* is the Getis-Ord G_i^* index; W_{ij} represents the spatial proximity relationship between regions i and j; X_j is the attribute value of region j; $\bar{X}$ is the overall mean value; and S is the standard deviation.

1.4.5 Obstacle Degree Model

The obstacle degree model is commonly used for pathological diagnosis of intensive and economical territorial spatial utilization levels. By identifying influencing factors of intensive territorial spatial utilization, it effectively identifies key obstacle factors hindering territorial spatial efficiency improvement. However, traditional obstacle degree models cannot effectively distinguish between obstacle and non-obstacle factors. Therefore, this paper introduces an index deviation obstacle model based on optimal suitability values to modify and improve the traditional index deviation obstacle degree model. The calculation formulas are as follows:

$$U_j = R_j \times W_j$$

$$V_j = 1 - X_j$$

$$M_j = \frac{U_j \times V_j}{\sum_{j=1}^{n}(U_j \times V_j)} \times 100\%$$

$$B_j = \sum M_j$$

where U_j represents factor contribution; R_j is the weight of indicator j; W_j is the weight of the secondary indicator to which indicator j belongs; V_j is the deviation degree of indicator j; O_j is the optimal suitability value of indicator j; X_j is the standardized value of the indicator; M_j is the obstacle degree of indicator j; and B_j is the obstacle degree of secondary indicators.

1.5 Data Sources and Processing

Socio-economic data were primarily obtained from the *China City Statistical Yearbook* (2010–2022) and *China Statistical Yearbook* (2010–2022). Ecological land area was specifically categorized into four primary land types: forestland, grassland, wetland, and other unused land, indirectly derived from the China National Land Use Database established by Liu Jiyuan et al. [28]. Ecosystem service value indicators were calculated using the equivalent factor method based on the revised Chinese ecosystem service equivalent value per unit area table by Xie Gaodi et al. [29]. The ecological environmental quality index was directly obtained from existing datasets on urban ecological environmental quality evaluation in China [30]. Vectorized data were sourced from the Standard Map Service System (http://bzdt.ch.mnr.gov.cn/).

2. Results and Analysis

2.1 Overall Evolutionary Patterns of Territorial Spatial Efficiency Based on Coefficient of Variation

Based on the mean values and variation coefficients of urban spatial efficiency, agricultural spatial efficiency, and ecological spatial efficiency in Yellow River Basin cities from 2010 to 2022 [Figure 3: see original paper], territorial spatial efficiency exhibited a fluctuating upward trend, benefiting from the deepening implementation of the "Yellow River National Strategy" and its supporting role in facilitating cross-regional factor mobility and spatial governance. Urban spatial efficiency increased from 0.312 to 0.458, reflecting the positive development trend of urban space transitioning from excessive development to intensive and efficient utilization during the new urbanization process. Agricultural spatial efficiency continuously increased from 0.285 to 0.376, demonstrating the beneficial effects of agricultural industrial structure upgrading and scaled development in the region. Ecological spatial efficiency rose from 0.267 to 0.325, but its relatively low value indicates considerable potential for ecological spatial layout optimization. Regarding variation coefficient trends, regional imbalance in ecological spatial efficiency was more pronounced, likely due to the large span of the Yellow River Basin and significant differences in habitat quality among different regions. The variation coefficient of agricultural spatial efficiency fluctuated and increased from 0.245 to 0.312, while that of urban spatial efficiency decreased from 0.298 to 0.221, reflecting that while focusing on improving agricultural spatial efficiency, attention should be paid to regional imbalances in agricultural development. Overall, internal differences in territorial spatial efficiency gradually narrowed, with variation coefficients stabilizing between 0.230 and 0.330, laying a solid foundation for promoting territorial spatial layout optimization and regional high-quality development in the Yellow River Basin.

2.2 Temporal Evolution Trajectory of Territorial Spatial Efficiency Based on Kernel Density Estimation

Further employing Matlab software' s multi-period kernel density module to plot the kernel density curves of territorial spatial efficiency from 2010 to 2022 [Figure 4: see original paper], we conducted analysis from three aspects: peak morphology and quantity, distribution location, and distribution extension. Regarding peak morphology and quantity, the distribution curve of urban spatial efficiency exhibited a bimodal pattern characterized by "one primary and one secondary peak, with the left lower than the right," while the distribution curves of agricultural, ecological, and comprehensive spatial efficiency all showed unimodal evolution patterns, indicating significant polarization in the Yellow River Basin and strong spatial convergence. This also suggests that the number of high-efficiency clubs and their internal members is relatively small, with low-efficiency areas showing concentrated distribution across research units. In terms of distribution location, the primary and secondary peaks of urban spatial efficiency were respectively located near 0.45 and 0.30, with density curves evolving from short and fat to tall and thin types, indicating gradual improvement in urban spatial efficiency. The central positions of agricultural and ecological spatial efficiency curves remained relatively stable, while the central position of comprehensive spatial efficiency first shifted right then left, demonstrating a fluctuating upward trend in overall efficiency values. Regarding distribution extension, except for the urban spatial efficiency curve, other curves exhibited significant right-tail phenomena, indicating increased likelihood of extreme values in regional spatial efficiency and persistent unbalanced development within the region.

2.3 Spatio-Temporal Differentiation Patterns of Territorial Spatial Efficiency Based on Classification Method

The Natural Breaks classification method can better group and classify territorial spatial efficiency naturally. Therefore, this method was adopted to visually extract the spatial differentiation patterns of territorial spatial efficiency in the Yellow River Basin from 2010 to 2022 [Figure 5: see original paper], dividing it into five categories from high to low: high-efficiency zone, relatively high-efficiency zone, medium-efficiency zone, relatively low-efficiency zone, and low-efficiency zone. From a spatio-temporal differentiation perspective, the differentiation characteristics of territorial spatial efficiency in the Yellow River Basin are significant, with high-value agglomeration and low-value continuous distribution coexisting. Specifically, high-efficiency and relatively high-efficiency zones in urban space increased noticeably and gradually covered the middle and upper reaches, reflecting the objective reality of steadily improving urbanization quality in the region. Low-efficiency zones were only distributed in border areas of Inner Mongolia, mainly limited by the region' s vast territory and sparse population density. The low-value dominant state in agricultural space was broken after 2015, with high-efficiency and relatively high-efficiency zones beginning to cluster in Henan, Shandong, and Inner Mongolia, likely benefiting from the region' s agricultural development foundation and orderly industrial restructuring. High-efficiency and relatively high-efficiency zones in ecological space gradually shifted eastward, with agglomeration patterns gradually dispersing, indicating that ecological space carrying capacity faces considerable pressure during regional development. High-value areas of territorial spatial efficiency were scattered in provincial capitals and core cities, with an overall rising trend in the southern belt. Overall, territorial spatial efficiency in the Yellow River Basin still has substantial improvement potential, and the spatial spillover effects of leading cities and core growth poles need further enhancement.

2.4 Spatio-Temporal Agglomeration Characteristics of Territorial Spatial Efficiency Based on Cold-Hot Spot Analysis

Given that cold-hot spot analysis can directly determine the presence of high-value or low-value agglomeration features through local spatial clustering attributes, this study employed ArcGIS to conduct cluster analysis on various spatial efficiencies in the Yellow River Basin from 2010 to 2022, classifying results from high to low as hot spot zones, sub-hot spot zones, non-significant zones, sub-cold spot zones, and cold spot zones [Figure 6: see original paper]. From a spatio-temporal agglomeration perspective, the cold-hot spot distribution of territorial spatial efficiency in the Yellow River Basin exhibits temporal inertia and continuity characteristics, with significant high-value and low-value agglomeration features spatially and obvious local imbalances. Specifically, hot spots in urban spatial efficiency evolved from dispersed distribution to concentrated and continuous distribution, finally forming clustered coverage across the middle and upper reaches. The number of cold spots gradually decreased, with agglomeration scope shrinking to northern Inner Mongolia, fully demonstrating the positive effects of intensive and economical spatial utilization promoted by new urbanization. Hot spots in agricultural spatial efficiency were distributed in patches within Sichuan and Henan, reflecting the objective reality of abundant agricultural economic output in these "land of abundance" and major grain-producing provinces. Cold spots were concentrated along the "spine" of the Yellow River Basin, where these marginal areas lagged in agricultural production development due to the lack of effective synergistic effects. The number of hot spots in ecological spatial efficiency first increased then decreased, with cold spot agglomeration gradually dispersing over the years, indicating significant spatially unbalanced development, which aligns with the aforementioned conclusion of large regional differences in ecological spatial efficiency. High-value areas of comprehensive spatial efficiency migrated from west to east, while cold spots showed a migration pattern from east to west, mainly caused by uneven distribution of different spatial efficiencies and reflecting the difficulty and urgency of territorial spatial layout optimization tasks in the Yellow River Basin.

2.5 Obstacle Factor Analysis

Integrating the spatio-temporal evolution process of territorial spatial efficiency, we employed the obstacle degree model to effectively identify obstacle and non-obstacle factors for efficiency improvement. On one hand, we calculated the obstacle degree of each original indicator to urban, agricultural, and ecological spatial efficiency; on the other hand, we deeply analyzed the obstacle degree of urban, agricultural, and ecological spatial efficiency to overall territorial spatial efficiency improvement [Figure 7: see original paper].

At the urban spatial level, urban construction land area, non-agricultural employment population, fixed capital stock, and non-agricultural output value constituted obstacle factors. Among these, the obstacle degree of non-agricultural output value fluctuated upward, with an annual average obstacle degree reaching 0.312, making it the primary obstacle factor. The obstacle degrees of non-agricultural employment population and urban construction land area alternated as secondary and tertiary obstacle factors, reflecting the significant roles of land and labor elements in promoting urban spatial utilization efficiency improvement, which aligns with objective laws of urban transformation development. Fixed capital stock ranked as the fourth obstacle factor with an annual average obstacle degree of only 0.087, but its obstacle degree steadily increased from 0.052 to 0.128, indicating that capital element input' s influence on urban spatial efficiency has significantly strengthened.

At the agricultural spatial level, the annual average obstacle degrees of agricultural irrigation area, rural electricity consumption, year-end livestock numbers, and plastic film usage were 0.298, 0.187, 0.165, and 0.142 respectively, forming a factor ladder that showed an initial increase followed by a decrease. Agricultural irrigation area consistently ranked as the primary obstacle factor. Considering the actual agricultural development conditions in the Yellow River Basin, issues such as soil erosion, desertification, and water resource shortages in some areas severely constrain high-quality agricultural development. Limited water resources and overloaded agricultural populations lead to insufficient agricultural irrigation area, urgently requiring agricultural industrial structure adjustment to promote sustainable regional agricultural development.

At the ecological spatial level, ecosystem service value, ecological spatial land area, water conservancy/environmental and public facilities management employment, and water conservancy/environmental and public facilities management fixed-asset investment constituted obstacle factors, indicating that sufficient land, labor, and capital elements are important factors driving intensive ecological spatial utilization. The continuously rising ecological environmental standards and higher land use costs in the Yellow River Basin place greater pressure on ecological spatial optimization and efficiency improvement.

Building upon this, we conducted in-depth analysis of the evolution process and formation mechanisms of obstacle factors at various levels to reveal universal problems and general patterns in territorial spatial efficiency improvement across different regions [Figure 8: see original paper]. It can be observed that in the obstacle diagnosis system for territorial spatial efficiency improvement in the Yellow River Basin from 2010 to 2022, ecological spatial efficiency constituted the main obstacle factor, while the influence of urban and agricultural spatial efficiency showed an inverse relationship. From the actual development of the Yellow River Basin, urban space, agricultural space, and ecological space form a complex open system where the three spaces interact and constrain each other. In the early research period, with urban spatial expansion and scaled industrial agglomeration, resource and environmental carrying capacity gradually intensified, causing the obstacle degree of ecological spatial efficiency to overall territorial spatial efficiency to continuously increase. With the implementation of Xi Jinping' s ecological civilization thought and the deployment of the "Yellow River Basin Ecological Protection and High-Quality Development" strategy, the regional ecological environment in the Yellow River Basin has effectively improved, leading to fluctuating decreases in ecological spatial efficiency' s obstacle degree, while agricultural spatial efficiency' s obstacle degree gradually increased, becoming the second major obstacle factor constraining territorial spatial efficiency improvement. In summary, during this critical transition period for territorial spatial layout optimization in the Yellow River Basin, it is urgent to recognize the driving force of urban space and the industrial cultivation of agricultural space, effectively maintain the coordinated relationship between ecological restoration protection and high-quality socio-economic development, gradually construct an interactive development framework for the "three spaces" of urban, agricultural, and ecological areas, and truly achieve positive driving improvement of urban spatial efficiency, agricultural spatial efficiency, and ecological spatial efficiency to overall territorial spatial efficiency.

3. Discussion

(1) The necessity of recognizing shortcomings in territorial spatial efficiency improvement and formulating coordinated development measures by zones. Obstacle factor analysis results indicate that current territorial spatial efficiency improvement in the Yellow River Basin still faces numerous obstacle factors with different contribution rates, among which ecological spatial efficiency constitutes the primary obstacle factor, and ecosystem service value has become the main obstacle element for ecological spatial efficiency improvement. Therefore, against the backdrop of ecological civilization construction and ecological protection strategy implementation, it is essential to fully recognize shortcomings in the territorial spatial efficiency improvement process, start from ecological space, and achieve orderly improvement of this indicator by combining the element composition and calculation process of ecosystem service value. This will consequently optimize regional urban spatial utilization efficiency, agricultural spatial production efficiency, and ecological spatial protection efficiency, improve the refined control and regional differentiated development management system of territorial space in the Yellow River Basin, and ultimately form a favorable interactive situation where multi-dimensional spatial efficiency integrates and advances together.

(2) The necessity of objectively recognizing the comprehensive nature of regional differences in territorial spatial efficiency in the Yellow River Basin. Efficiency temporal evolution patterns indicate that regional difference characteristics present an ecological space > urban space > agricultural space pattern, which is closely related to the Yellow River Basin' s own positioning characteristics (an important ecological function zone and ecological typical area in China). Coupled with the large span of the region, different spaces exhibit significant development pattern differences. Therefore, all sectors should fully respect regional natural geographical laws, objectively recognize regional differences in territorial spatial efficiency in the Yellow River Basin, and avoid blindly pursuing digital convergence of territorial spatial efficiency, thereby falling into the trap of excessive competition or intense involution.

4. Conclusions and Recommendations

4.1 Conclusions

(1) From the perspective of efficiency mean values, territorial spatial efficiency in the Yellow River Basin from 2010 to 2022 showed a fluctuating upward temporal evolution pattern; from a regional difference perspective, different spatial regions exhibited a development pattern of ecological space > urban space > agricultural space; based on kernel density curves, different spatial efficiencies showed significant differences in peak morphology and quantity.

(2) From 2010 to 2022, high-value areas of territorial spatial efficiency in the Yellow River Basin were concentrated in core nodes or provincial capitals, while low-value areas were widely distributed in a substrate pattern; the heterogeneous patterns of urban, agricultural, and ecological spatial efficiency were significant, with agglomeration patterns showing obvious regional differences.

(3) From 2010 to 2022, the spatial agglomeration evolution of territorial spatial efficiency in the Yellow River Basin exhibited temporal inertia and continuity characteristics, with significant positive agglomeration patterns dominating within the region. The agglomeration types were primarily characterized by significant high-high and low-low clusters, with high-value clusters and low-value continuous distribution coexisting.

(4) The main obstacle factor for territorial spatial efficiency in the Yellow River Basin was ecological spatial efficiency, whose obstacle degree first increased then decreased, while the obstacle degrees of urban and agricultural spatial efficiency showed an inverse relationship. Non-agricultural output value, agricultural irrigation area, and ecosystem service value were the primary obstacle factors for urban spatial efficiency, agricultural spatial efficiency, and ecological spatial efficiency, respectively.

4.2 Recommendations

Territorial space possesses both spatial and resource attributes, and the key to optimizing territorial spatial development patterns lies in achieving rational allocation among urban, agricultural, and ecological spaces. Therefore, combining spatio-temporal evolution patterns and obstacle factor identification results, we propose the following zonal regulation measures:

(1) **Synchronized development advanced zones of ecological space**: Cities such as Sanmenxia, Jiayuguan, and Shuozhou should continue promoting coordinated utilization of spatial resources, fully leveraging the economic leadership and dominant role of core growth poles, and orderly enhancing the economic value creation of regional agricultural and ecological products to steadily advance regional territorial spatial layout optimization.

(2) **Synchronized development lagging zones of ecological space**: Cities such as Xining, Ulanqab, Dingxi, and Lanzhou must rapidly establish an optimized territorial spatial layout system. Under the premise of strengthening ecological protection, they should reasonably tap the development potential of urban-ecological spaces, gradually guide the transformation of territorial spatial utilization structure toward high-end and high-efficiency patterns, and strengthen the factor agglomeration functions and inter-regional connections of various cities through multiple measures to achieve diversified urban development and high-quality transformation of territorial spatial utilization.

(3) **Non-synchronized development zones of ecological space**: The development potential and characteristics of each space should be fully exploited. Urban spatial low-efficiency zones (such as Ankang, Xinzhou, and Luohe) should give full play to regional agricultural or ecological advantages, orderly promote the gradient evolution of ecological and agricultural characteristics into economic benefits, and thereby enhance regional urban spatial efficiency. Agricultural spatial low-efficiency zones (such as Jiyuan, Linyi, and Lüliang) should gradually introduce high-tech agricultural development technologies and planting patterns, orderly undertake product transfers from high-efficiency agricultural zones, and thus achieve improved agricultural development potential. Ecological development low-efficiency zones (such as Zhengzhou, Zhongwei, and Taiyuan) should fully leverage the economic leadership and dominant role of core growth poles to orderly enhance the economic value creation of regional ecological products.

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