Spatiotemporal Differentiation, Gravity Center Evolution and Driving Factors Analysis of National Wetland Parks in the Yellow River Basin (Postprint)

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Abstract

Wetland parks constitute an important component of China' s nature conservation system, and strengthening the construction and management of national wetland parks is of great significance for effectively protecting wetland resources and fulfilling wetland ecological functions. Taking national wetland parks in the Yellow River Basin as the research object and using 2010, 2015, and 2022 as time points, this study employs kernel density estimation, hotspot analysis, standard deviation ellipse, and geographic detector models to investigate their spatiotemporal differentiation, centroid evolution, and driving factors. The results indicate: (1) In 2010, national wetland parks in the Yellow River Basin exhibited a "dual-core, multi-point" density characteristic, whereas in 2015 and 2022 they demonstrated a "multi-core, contiguous" distribution trend, with substantial increases in both park numbers and areas, and their roles in economic development and ecological protection continuously strengthening. (2) From 2010 to 2022, the centroid coordinates of wetland parks shifted northeastward by 247.31 km overall, displaying a significant "northeast-southwest" distribution characteristic. From a sub-basin perspective, the centroid shift distance was largest in the middle-reach provinces and smallest in the lower-reach provinces. (3) The natural environment dimension has limited influence on wetland park distribution, while the socioeconomic dimension plays a decisive role in wetland protection, restoration, and park construction. The per capita GDP and Digital Elevation Model (DEM) factors have the greatest effects in the socioeconomic and natural dimensions, respectively.

Full Text

Spatiotemporal Differentiation, Center of Gravity Evolution and Driving Factors of National Wetland Parks in the Yellow River Basin

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Abstract

Wetland parks constitute a vital component of China's natural protection system. Strengthening the construction and management of national wetland parks is essential for effectively protecting wetland resources and harnessing their ecological functions. This study examines national wetland parks in the Yellow River Basin, analyzing their spatiotemporal differentiation, center of gravity evolution, and driving factors for the years 2010, 2015, and 2022 using kernel density estimation, hotspot analysis, standard deviation ellipse, and geographical detector models. The results indicate: (1) In 2010, national wetland parks in the Yellow River Basin exhibited a "dual-core and multi-point" density pattern, which evolved into a "multi-core and continuous patch" distribution trend by 2015 and 2022, with substantial increases in both park numbers and areas, thereby enhancing their roles in economic development and ecological protection. (2) From 2010 to 2022, the spatial center of gravity of national wetland parks shifted 247.31 km northeastward, showing a significant "northeast-southwest" distribution characteristic. By sub-basin, the middle reaches provinces exhibited the largest center-of-gravity movement distance, while the downstream provinces showed the smallest. (3) The natural environment dimension has limited influence on wetland park distribution, whereas the socioeconomic dimension plays a decisive role in wetland protection, restoration, and park construction. Per capita regional GDP and the digital elevation model (DEM) exert the greatest effects within the socioeconomic and natural dimensions, respectively.

Keywords: national wetland park; spatiotemporal differentiation; center of gravity evolution; driving factors; Yellow River Basin

Introduction

National wetland parks are designated areas approved by the National Forestry and Grassland Administration for the protection of wetland ecosystems, rational utilization of wetland resources, and the conduct of wetland education and scientific research. In recent years, China has prioritized wetland park construction as an effective approach to expanding wetland protection areas and promoting regional ecological improvement. At the 14th Conference of the Parties to the Ramsar Convention in November 2022, President Xi Jinping announced that China would establish a new batch of national parks, incorporating approximately 1100$×10^{4}$ hm^2 of wetlands into the national park system and implementing major wetland protection projects, thereby providing clear direction for wetland park development, construction, and management. Against the backdrop of ecological civilization construction and national high-quality development, research on the spatiotemporal differentiation, center of gravity evolution, and driving factors of wetland parks holds both theoretical value and practical significance.

International research on wetland parks has focused on biological communities, functional roles, planning and construction, and park management. Biological communities represent a key conservation target, with scholars extensively examining their living environments and structural characteristics. Wetland parks host diverse organisms including plants, animals, and microorganisms that survive in interactive soil-water environments. Functional studies have demonstrated that wetland parks can purify water by degrading pollutants, provide nutrients to promote crop growth, regulate local climate to influence community life, and leverage natural scenery to boost wetland tourism. Park planning should integrate local culture and folk customs to achieve comprehensive utilization of cultural and landscape resources. Management research has proposed diversified measures including strengthening legal frameworks, transforming government management models, encouraging governmental ecological conservation initiatives, and developing low-carbon tourism.

Domestic research has emphasized ecosystem structure, value assessment, and spatiotemporal patterns. Wetland park ecosystem structure comprises both abiotic elements (soil, water, climate) and biotic components (plants, animals, microorganisms). Value assessment studies have identified ecological values such as water conservation, soil retention, and carbon sequestration, as well as aesthetic and economic values derived from natural scenery and species communities. Spatiotemporal pattern analyses have primarily employed descriptive statistics and analytic hierarchy process at national and provincial scales (e.g., Guizhou, Henan). While existing research covers multiple domains, explorations of spatial differentiation evolution patterns and driving mechanisms remain limited, particularly at the river basin scale. This study addresses this gap by examining national wetland parks in the Yellow River Basin for 2010, 2015, and 2022, employing spatial analysis tools to investigate spatiotemporal differentiation and center of gravity evolution, and utilizing geographical detector analysis to identify driving factors, thereby providing reference for ecological protection and sustainable development of wetland parks in the Yellow River Basin.

1.1 Study Area Overview

The Yellow River flows through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong provinces. As a massive ecological corridor connecting “ecological highlands”such as the Three-River Source, Qilian Mountains, Fenwei Plain, and North China Plain, the Yellow River Basin holds significant importance in China’ s ecological construction. The basin contains 113 national wetland parks, accounting for 32.297% of the national total, which play crucial roles in maintaining biodiversity, promoting efficient ecological governance, and regulating local climate.

Regarding regional delineation, following Zuo Qiting et al.’ s classification, this study adopts the “full administrative region of the Yellow River Basin”approach, encompassing all administrative districts in the nine provinces traversed by the Yellow River, covering approximately 356.867$×10^{4}$ km^{2}. This approach is suitable for research objects with cross-provincial distribution, regional management requirements, and diverse influencing factors, enabling comprehensive analysis of spatial differentiation characteristics and providing basis for spatial coordination, cross-regional protection, and scientific management.

1.2 Data Sources and Processing

The list of national wetland parks was obtained from the Wetland Management Department of the National Forestry and Grassland Administration. Geographic coordinates were acquired using the Baidu coordinate picker and corrected using ArcGIS software. Spatial driving factor analysis involved natural indicators including wetland area, annual precipitation, digital elevation model (DEM), normalized difference vegetation index (NDVI), and accumulated temperature $ $10°C, sourced from the Geographic Remote Sensing Ecology Network and the Resource and Environmental Science Data Center of the Chinese Academy of Sciences. Socioeconomic indicators included year-end population, per capita regional GDP, highway mileage, per capita disposable income, and number of AAAA-level and above tourist attractions, derived from the China Statistical Yearbook, China Urban Statistical Yearbook, and China Culture and Tourism Statistical Yearbook.

1.3 Methods

1.3.1 Kernel Density Estimation Kernel density estimation analyzes the distribution characteristics of sample points within spatial units, accurately identifying aggregation patterns. This study abstracted national wetland parks in the Yellow River Basin as point elements to analyze density characteristics. The formula is:

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

where K is the kernel density function, h ($h > 0$) is the bandwidth, n is the number of wetland parks in the study area, x is the estimated point, x_i is the sample point, and d is the data dimension.

1.3.2 Hotspot Analysis Hotspot analysis explores the clustering degree and aggregation patterns of geographic sample points, where hotspots and coldspots represent statistically significant high-value and low-value spatial clusters, respectively. This method identifies spatial clustering locations of wetland parks in the Yellow River Basin. The formula is:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_j - \bar{X} \sum_{j=1}^{n} w_{ij}}{S \sqrt{\frac{n \sum_{j=1}^{n} w_{ij}^2 - (\sum_{j=1}^{n} w_{ij})^2}{n-1}}}$$

where w_{ij} is the spatial weight between provinces i and j, n is the total number of provinces, x_j is the number of wetland parks in province j, $\bar{X}$ is the mean number across provinces, and S is the standard deviation. The G_i^* statistic represents a z-score, where larger values indicate hotspots and smaller values indicate coldspots.

1.3.3 Standard Deviation Ellipse The standard deviation ellipse calculates the distribution center of gravity and standard deviations of X and Y coordinates to generate a directional ellipse containing a certain proportion of sample points. This method analyzes center of gravity evolution characteristics. The formulas are:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}, \quad \bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$$

$$\theta = \arctan \left(\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2 - \sum_{i=1}^{n} (y_i - \bar{y})^2 + \sqrt{(\sum_{i=1}^{n} (x_i - \bar{x})^2 - \sum_{i=1}^{n} (y_i - \bar{y})^2)^2 + 4(\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y}))}}{2 \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})} \right.$$

$$SD_x = \sqrt{\frac{\sum_{j=1}^{n} ((x_j - \bar{x}) \cos\theta - (y_j - \bar{y}) \sin\theta)^2}{n}}$$

$$SD_y = \sqrt{\frac{\sum_{j=1}^{n} ((x_j - \bar{x}) \sin\theta + (y_j - \bar{y}) \cos\theta)^2}{n}}$$

where SD_x and SD_y are standard deviations along the x and y axes, (x_i, y_i) are coordinates of wetland parks and their deviations from the mean center, θ is the ellipse rotation angle, and n is the number of wetland parks in province i.

1.3.4 Geographical Detector Geographical detector is a statistical method that reveals driving factors behind spatial differentiation without requiring extensive assumptions, offering advantages in handling mixed data types. It includes four modules: factor detection, interaction detection, risk detection, and ecological detection. This study employs factor and interaction detection to analyze driving factors. The formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where L is the classification of driving or driven factors ($h = 1, 2, \dots, L$), N is the total sample size, N_h is the sample size of layer h, σ^2 is the total sample variance, and σ_h^2 is the variance of layer h. The q value ranges [0,1]. The interaction detection module examines the explanatory power of factor pairs, revealing relationships including nonlinear weakening, single-factor nonlinear weakening, independence, dual-factor enhancement, and nonlinear enhancement.

Results

2.1 Spatial Differentiation Characteristics

2.1.1 Spatial Density Differentiation Kernel density estimation reveals that in 2010, wetland parks in the Yellow River Basin displayed a "dual-core and multi-point"density pattern, forming two major core areas in the Guanzhong Plain and Ningxia Plain. The Guanzhong Plain contains national wetland parks such as Chanba, Qingyu River, Zhaoshi River, and Tongguan Yellow River, which provide multiple functions including industrial pollution degradation, water source conservation, and urban environment improvement. The Ningxia Plain features parks like Xinghai Lake, Tian Lake, and Yinchuan, primarily riverine and lacustrine wetlands with strong flood storage and water regulation capacities. Additional point areas are located in central Shandong, north-central Henan, northeast Sichuan, and eastern Qinghai, providing valuable experience for neighboring provinces despite their smaller numbers.

By 2015 and 2022, the distribution evolved into a "multi-core and continuous patch" pattern [Figure 1: see original paper]. The central Shandong core area expanded significantly due to continuous institutional improvements and leapfrog tourism development, with substantial increases in approved national wetland parks. The central Shaanxi core area also expanded through the enlargement of parks such as Qixing River, Qianwei Zhihui, Longyuan, and Tianyu River. Furthermore, areas in eastern Sichuan, central-southern Shanxi, most of Henan, and northeastern Inner Mongolia transformed from scattered points in 2010 to continuous patches in 2022, demonstrating remarkable achievements in wetland protection and management under the guidance of Xi Jinping' s ecological civilization thought, with substantial increases in park numbers and areas enhancing economic development and ecological protection.

2.1.2 Hotspot-Coldspot Differentiation Hotspot analysis reveals spatial clustering patterns [Figure 2: see original paper]. From 2010 to 2022, provinces with rising hotspot levels include Shandong, Inner Mongolia, and Henan. Shandong upgraded from a hotspot in 2010 to a significant hotspot, ranking second nationally with 27 national wetland parks by 2022, benefiting from enhanced socioeconomic development, strengthened ecological protection, and proactive park application efforts. Inner Mongolia, as China’ s largest and most comprehensive ecological function zone in the north, upgraded from sub-cold/sub-hot to a significant hotspot, achieving remarkable wetland protection and construction results by prioritizing “ecology-first, green development.” Henan upgraded from sub-coldspot to sub-hotspot, increasing park numbers from 4 to 20.

Provinces with declining hotspot levels include Shaanxi (hotspot to sub-hotspot) and Ningxia (sub-hotspot to coldspot), due to their early advantage in park numbers before 2015 followed by slower growth relative to neighboring provinces. Provinces with unchanged levels include Gansu (coldspot) and Sichuan (sub-coldspot), with 5 and 12 parks respectively by 2022. Qinghai and Shanxi fluctuated, with Qinghai upgrading from coldspot to sub-coldspot then reverting, and Shanxi following a similar pattern, reflecting concentrated park development during 2010-2015.

Overall, national wetland parks exhibit a spatial pattern of more coldspot provinces in the upper reaches and more hotspot provinces in the middle and lower reaches of the Yellow River Basin.

2.2 Center of Gravity Evolution

2.2.1 Overall Center of Gravity Evolution National wetland parks in the Yellow River Basin demonstrate a “northeast-southwest” distribution pattern [Figure 3: see original paper]. The standard deviation ellipse flattening rate decreased from 76.14° to 57.10°, indicating increasing spatial differentiation along the northeast-southwest axis. The center of gravity moved from Ling County, Yan’ an, Shaanxi (109.868°E, 35.789°N) in 2010 to Pingyao County, Jinzhong, Shanxi (111.786°E, 36.881°N) in 2022, shifting 247.31 km northeastward. This shift reflects rapid park growth in eastern Shandong, Henan, and northern Inner Mongolia, where ecological conditions have continuously improved. The standard deviation ellipse area expanded from 911,403 km^2 to 1,789,454 km^2, nearly doubling and indicating strong spatial expansion trends.

2.2.2 Sub-Basin Center of Gravity Evolution The Yellow River Basin spans China’ s eastern, central, and western regions with substantial ecological and socioeconomic variations. Analyzing by sub-basin (upper: Sichuan, Qinghai, Gansu, Ningxia; middle: Inner Mongolia, Shanxi, Shaanxi; lower: Henan, Shandong) reveals that the middle reaches exhibited the largest center-of-gravity movement (630.95 km), shifting from Huanglong County, Yan’ an to Pingcheng District, Datong, consistent with the overall northeastward trend. The upper reaches showed the second-largest movement (40.66 km), shifting from Huining County, Baiyin to Lintan County, Gannan Tibetan Autonomous Prefecture. The lower reaches showed the smallest movement (7.78 km).

The ellipse rotation angle for the upper reaches changed from 58.30°-61.82° to 41.03°-43.44°, shifting from a northeast-southwest to a northwest-southeast orientation. The middle and lower reaches maintained northeast-southwest orientations (49.49°-76.14° and 41.03°-43.44° respectively), indicating distinct directional distribution patterns.

2.3 Driving Factor Analysis

2.3.1 Factor Detection of Spatial Driving Factors Drawing on research by Yang Li et al. and Ba Qi et al., this study examines two dimensions: natural environment and socioeconomic factors. Factor detection results show that the socioeconomic dimension has a mean q-value of 0.417, while the natural environment dimension has only 0.132 . This indicates that while topography, precipitation, and temperature are prerequisites for wetland formation, natural factors have limited influence on park distribution patterns. In contrast, socioeconomic factors decisively shape wetland protection, restoration, and park construction.

Among specific factors, per capita regional GDP (q=0.612) and DEM (q=0.286) have the strongest effects in their respective dimensions. Per capita GDP, representing regional economic level and prosperity, provides financial and material support for ecological maintenance, tourism development, and landscape design. DEM significantly influences wetland ecosystem formation and distribution, as Yellow River Basin wetland parks are primarily riverine and coastal types concentrated below 500 m elevation, with only 12 parks above 4000 m. Year-end population and NDVI have weaker effects (q=0.142 and 0.086), suggesting they indirectly influence park development through impacts on regional economy and ecology.

2.3.2 Interaction Detection of Spatial Driving Factors Interaction detection reveals that combined factors exhibit stronger driving effects than single factors alone, showing two main relationship types: nonlinear enhancement and dual-factor enhancement . Six factor pairs demonstrate nonlinear enhancement ($q(X_1\ X_2) > q(X_1)+q(X_2)$), including per capita GDP highway mileage, per capita GDP AAT10, highway mileage AAT10, wetland area annual precipitation, wetland area NDVI, and annual precipitation NDVI. The remaining 15 factor pairs show dual-factor enhancement ($q(X_1\ X_2) > \max\{q(X_1), q(X_2)\}$), where the combined explanatory power exceeds individual factors but remains below their sum.

Discussion

This study employs GIS spatial analysis to examine the spatiotemporal differentiation and center of gravity evolution of national wetland parks in the Yellow

River Basin, aiming to provide methodological reference for spatial information presentation and dynamic management. Geographical detector analysis of driving factors seeks to identify development bottlenecks and pathways for optimization.

Compared with national-scale studies by Pan Jinghu et al., Zhou Ting et al., and Liu Hanhu et al., this research focuses specifically on the Yellow River Basin to address national strategic needs for ecological protection and high-quality development. The temporal focus on 2010, 2015, and 2022 better reveals evolution patterns. Findings align with previous research emphasizing the shaping role of economic scale and transportation conditions on wetland park spatial patterns.

Based on the results, we propose the following management strategies: (1) Adapt to regional wetland resource differences by developing differentiated construction pathways according to wetland types, spatial distribution, and environmental characteristics across basins and river sections. For example, prioritize high-altitude wetland ecosystems in the Yellow River source area (Ruoergai), emphasize flood storage and water quality improvement in upper-reach canyon and Hetao areas, and focus on pollution reduction and low-carbon tourism development in middle and lower reaches. (2) Leverage key construction factors to support ecological protection and high-quality development, emphasizing the financial and technical support roles of regional economies and promoting organic integration between cultural tourism development and wetland park construction. (3) Improve top-level institutional design to establish a three-dimensional management system, continuously refining laws, regulations, development plans, construction standards, and management norms, and integrating Yellow River Basin national wetland parks into China's national park system and the broader national strategy for ecological protection and high-quality development.

Conclusion

This study reveals that: (1) From 2010 to 2022, national wetland parks in the Yellow River Basin evolved from a "dual-core and multi-point" pattern centered on the Guanzhong and Ningxia Plains to a "multi-core and continuous patch" distribution, with substantial increases in number and area. The parks display a spatial pattern of more coldspot provinces in the upper reaches and more hotspot provinces in the middle and lower reaches, with hotspot levels rising in Shandong, Inner Mongolia, and Henan, and declining in Shaanxi and Ningxia. (2) The center of gravity moved 247.31 km northeastward with a distinct northeast-southwest orientation, while the standard deviation ellipse area nearly doubled, indicating strong spatial expansion. The middle reaches showed the largest center-of-gravity movement, while the lower reaches showed the smallest. (3) Natural environmental factors have limited influence on park distribution, while socioeconomic factors play a decisive role. The interaction of specific factors demonstrates stronger driving effects than single factors, exhibiting nonlinear and dual-factor enhancement relationships.

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