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Ecological Change Assessment and Protection Strategy in the Yellow River Basin

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Abstract: The ecological environment of the Yellow River basin is sensitive and fragile. Affected by climate change and large-scale, high-intensity human development, the overall and systemic ecological degradation of the basin is prominent, and the ecological security situation is unoptimistic. To effectively promote ecological protection, high-quality development of the Yellow River basin, and to build a strong ecological security barrier, we systematically evaluated the current status and changes in the Yellow River basin ecosystem regarding structure and quality in the past two decades. We summarized the main problems and deficiencies in the upper, middle, and lower reaches of the Yellow River, including the ecological fragility of the basin, prominent systemic degradation, and the constraints of the current work regarding institutional mechanism, investment, and implementing effect. Thus, we propose future ecological protection and restoration strategies. Our research shows that the Yellow River basin ecosystem has maintained a stable structure in the past two decades. However, ecosystem types have changed significantly, cities and towns have expanded considerably, forests, grasslands, and wetlands have increased, and desertified areas have been reduced considerably. The overall quality of the ecosystem, particularly in the middle reaches, has improved; however, degradation still occurs, particularly in the lower reaches. Therefore, we propose that ecological protection and restoration of the Yellow River basin should be strengthened through three aspects: (1) systematically evaluating the implementation of ecological projects, (2) promoting ecological protection and restoration according to local conditions, and (3) innovating the value realization mechanism of ecological products to ensure the ecological security of the region.
Keywords: Yellow River basin; ecosystem; assessment; conservation and restoration

1 Introduction

As an important ecological shelter in northern China, the Yellow River basin is the main ecological corridor connecting the Qinghai-Tibet Plateau, Loess Plateau, and North China Plain. The ecological status of the basin is critical. However, because most of the middle and upper reaches of the basin are located in arid and semi-arid areas, its ecosystem is featured as sensitive and fragile. Large-scale and long-term high-intensity human activities systematically degrade the ecosystem. Examples include the declining function of natural grasslands and wetlands in the upper reaches, severe soil and water loss in the middle reaches, many historical issues in the riparian zone at the lower reaches, and severe shrinking wetlands in the estuary delta [1]. This is arduous for ecological protection, restoration, and governance in the Yellow River basin.

A large number of studies on ecological protection and restoration have been carried out specific to the Yellow River basin in China, mainly focusing on areas with essential ecological functions, such as the source of the Yellow

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River [2], the Three-River Source area [3,4], Qilian Mountain [5], Gannan Yellow River [6], Ruoergai grassland wetland [7,8], Loess Plateau [9–11], and Yellow River Estuary delta wetland [12], which have played a guiding role in the ecological protection and restoration of river basins and local areas. However, little research has been conducted on integrated protection and restoration strategies for the entire basin. Existing research outcomes include the overall framework of water ecological protection and restoration of the whole basin [13], watershed ecological zoning, and ecological target identification [14]. Unfortunately, these cannot meet the requirements of the new era for integrated and systematic ecological protection and restoration in the Yellow River basin, since such research was conducted in prior years and only focused on water ecosystem protection.

Ecological protection and high-quality development in the Yellow River basin have become a national strategy. Therefore, it is necessary to study and put forward an overall strategy to strengthen environmental protection and restoration in the future. This should be developed from the perspective of the integrity and systematicness of ecosystems in the whole basin, which is of great strategic significance to ensure long-term stability and promote high-quality development of the Yellow River. Therefore, this paper thoroughly evaluates the present situations and changes in the ecosystem in the whole basin and identifies the prominent ecological problems and deficiencies. Then, according to the concept of a living community of mountains–rivers–forests–farmlands–lakes–grasslands, the overall strategy is put forward to vigorously protect and restore the ecology in the Yellow River basin. The three aspects of the strategy include systematically evaluating the effectiveness of ecological engineering, promoting the ecological protection and restoration according to the local conditions, and exploring and establishing the value realization mechanism for ecological products to provide the decision-making references to promote the ecological protection and high-quality development in the Yellow River basin.

2 Current status and ecosystem changes in the Yellow River basin

2.1 Ecosystem structure and changes in the Yellow River basin

From 2000–2020, the ecosystem structure remained generally stable in the Yellow River basin (Table 1), mainly composed of grasslands, farmland, and forest [15]. In 2020, the grassland, farmland, and forest areas were 3.85×10^5 km^2, 1.99×10^5 km^2, and 1.07×10^5 km^2, accounting for 48.4%, 25.1%, and 13.5% of the total basin area, respectively. The proportions of other ecosystem areas were relatively small. In terms of spatial distribution, grasslands are widely distributed in the upper and middle reaches of the Yellow River basin; farmlands are mainly distributed in the Ningmeng Irrigation Area around the north of the Yellow River loop, as well as Shaanxi, Shanxi, Henan, and Shandong in the south of the middle and lower reaches; forests are mainly distributed in the central south and west of the Yellow River basin; cities and towns are scattered in clusters and spots, mainly centered on the major cities of all provinces, while deserts are mainly distributed in the Inner Mongolia Autonomous Region and Ningxia Hui Autonomous Region in the middle and north of the Yellow River basin, and less so in Qinghai.

Table 1 Areas and changes of various ecosystems in the Yellow River basin in 2000 and 2020.

Type	Area (km^2)		Percentage (%)		Overall change		Change rate (%)		
	2000	2020	2000	2020	Change (km^2)	Change rate (%)	Upstream	Midstream	Downstream
Forest	103 495	107 255	13.0	13.5	3760	3.6	3.9	3.8	−3.2
Grassland	379 867	384 600	47.8	48.4	4733	1.2	1.9	0.7	−24.5
Wetland	20 983	22 961	2.6	2.9	1978	9.4	11.3	0.2	24.0
Farmland	211 714	199 108	26.7	25.1	−12 606	−6.0	−3.8	−6.9	−4.4
Town	17 123	28 164	2.2	3.5	11 041	64.5	59.9	76.2	34.2
Desert	47 732	39 384	6.0	5.0	−8348	−17.5	−35.9	−3.2	−80.3
Bare land	13 496	12 938	1.7	1.6	−558	−4.1	−7.6	22.6	81.7

Note: In the downstream area, the base numbers of desert and bare land areas are relatively small, so their changes are more intense.

From 2000–2020, some ecosystem types changed significantly in the Yellow River basin (Table 1). Specifically, the urban area has expanded substantially in the Yellow River basin, with an increase of 11 041 km^2 and a change rate of 64.5%, mainly from the net occupation of farmland (57.5%) and grassland (28.7%). The areas of forest, grassland, and wetland increased by 3760 km^2, 4733 km^2 and 1978 km^2 with change rates of 3.6%, 1.2% and 9.4% respectively, while the increased wetland mainly came from the net transfer of grassland. The areas of farmland, desert, and bare land decreased by 12 606 km^2, 8348 km^2, and 558 km^2 with change rates of −6.0%, −17.5%, and

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−4.1%, respectively, while the decreased desert area mainly resulted from the net transfer to grassland and bare land. The above results indicate that urban expansion in the Yellow River basin has occupied a specific agricultural and ecological space over the past 20 years. Meanwhile, certain ecological engineering projects have been implemented, such as natural forest protection, the Three-North Forest Shelterbelt Program, and the Grain for Green Project, which promoted the restoration of ecosystems, such as forests, grasslands, and wetlands in some areas and slowed down desertification.

From the spatial range of the Yellow River, the ecosystem types changed from 2000–2020 as follows: the urban expansion was the most significant in the middle reaches, with a change rate of 76.2%; the forest area increased significantly in the upper and middle reaches, and the wetland area increased substantially in the upper and lower reaches, with a change rate of 24.0%, especially in the lower reaches; and the desert area decreased substantially in the upstream and downstream areas with change rates of −35.9% and −80.3%, respectively.

2.2 Current status and changes in ecological quality in the Yellow River basin

According to the data on vegetation coverage of the Yellow River basin [16], the analysis (Table 2) showed that the ecological quality presented a positive trend in the basin from 2000–2019, and the vegetation coverage increased significantly. The proportions of low, relatively low, and medium vegetation coverage decreased by 5.7%, 13.5% and 2.8% respectively, while the proportion of relatively high and high vegetation coverage increased by 0.7% and 21.3% respectively. Over the past 20 years, the improved vegetation area accounted for 89.5% of the total area of the Yellow River basin, whereas the area with significant improvement (>20%) accounted for approximately 24.6% (Table 3). The areas of significant improvement are mainly located in the hilly and gully areas of the Loess Plateau. However, vegetation degradation still occurred in some areas, accounting for 10.5% of the total area of the basin. The degraded areas are mainly located in the west, north, and southeast of the basin, especially in areas with high urbanization in the middle and lower reaches.

Table 2. Classification characteristics of vegetation coverage in the Yellow River basin in 2000 and 2019.

Classification of vegetation coverage	2000		2019	
	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)
Low (0–20%)	73 730	9.3	28 603	3.6
Relatively low (20%–40%)	227 367	28.7	120 179	15.2
Medium (40%–60%)	201 050	25.4	178 860	22.6
Relatively high (60%–80%)	274 930	34.8	280 575	35.5
High (80%–100%)	14 002	1.8	182 862	23.1

Table 3. Characteristics of vegetation coverage change in the Yellow River basin in 2000 and 2019.

Change of vegetation coverage	Whole basin		Upstream		Midstream		Downstream	
	Change area (km^2)	Percentage (%)	Change area (km^2)	Percentage (%)	Change area (km^2)	Percentage (%)	Change area (km^2)	Percentage (%)
<−20%	4198	0.5	1137	0.3	2286	0.6	743	3.3
−20% –−10%	11 835	1.5	4344	1.2	5941	1.5	1436	6.5
−10%–0	67 104	8.5	36 708	10.2	25 725	6.3	4219	19.0
0–20%	513 206	64.9	255 096	70.7	24 1864	59.5	15 278	68.7
20%–40%	188 512	23.8	60 566	16.8	127 411	31.4	552	2.5
>40%	6218	0.8	3048	0.8	3151	0.8	15	0.1

Further analysis of ecosystem quality changes in the whole Yellow River basin indicated that the area with significantly improved vegetation is relatively large in the middle reaches, accounting for about 32.1% of the middle reaches, followed by the upstream area, accounting for approximately 17.6%. The extent of vegetation degradation was relatively large in the downstream area, and the total area of noticeable degradation and significant degradation accounted for approximately 9.8%.

3 Main ecological issues in the Yellow River basin

The Chinese government has always attached great importance to the ecological protection of the Yellow River basin. In recent years, ecological functions have been significantly improved in the Yellow River basin regarding soil-water conservation, wind prevention, and sand fixation. This has been achieved through the implementation of a series of major engineering projects, such as soil and water conservation, ecological protection of the Three-River Source area, Three-North Forest Shelterbelts, protection of natural forest, returning farmland to forest/grassland, returning grazing land to grassland, and Beijing–Tianjin sandstorm source control. However, ecological issues are still prominent in the Yellow River basin because of the sensitive and fragile ecological background and the continuous interference of human activities.

3.1 Fragile watershed ecology presents entire systematic degradation

Approximately 65.6% of areas in the Yellow River basin belong to arid and semi-arid areas. Over 3/4 of the areas belong to moderately vulnerable areas, which is higher than the national average. Compared with the Yangtze and Pearl Rivers, the water and sediment fluxes of the Yellow River are more sensitive and vulnerable to climate change and human activities [17]. Meanwhile, ecological issues are quite different among the upper, middle, and lower reaches of the Yellow River basin.

3.1.1 Grassland and wetland ecosystem is being degraded and water conservation service is being lowered in the upstream area

The headwaters of the Yellow River are fundamental for maintaining the ecological health of the basin [18], and an extremely important function in water conservation. However, affected by human activities, natural grasslands and wetlands are severely degraded in the upper reaches of the Yellow River, especially in headwaters. In 2017, the average overload and degradation rates of natural grassland were over 10% and 60%–90%, respectively, in Qinghai Province, Gansu Province, Sichuan Province, Ningxia Hui Autonomous Region, and Inner Mongolia Autonomous Region in the upper reaches of the Yellow River [1]. Moreover, certain ecological degradation phenomena have also occurred in the headwaters of the Yellow River. For example, the precipitation is relatively limited, the glaciers, some lakes, and wetlands are shrinking, the river runoff decreases, and even cuts off [18]; overgrazing has caused grassland degradation and desertification, resulting in a significant reduction in the area of high-cover alpine grassland, high-cover alpine meadow, and medium-cover alpine grassland in the source area of the Yellow River [19]. In addition, approximately 64.5% of the degraded grassland has not been restored in the Three-River Source area; therefore, the situation has not been fundamentally reversed [3,4]. In the important water-supply ecological function area of the Gannan Yellow River, 80% of natural grasslands have been degraded owing to serious rodent damage, increasing the black soil beach and sandy area, aggravating soil and water loss, and seriously shrinking lakes and swamps [6]. Affected by artificial dredging and reconstruction, as well as overgrazing, the wetland area of Ruoergai grassland has been sharply reduced owing to intensified degradation and desertification [7,8].

The Ordos Plateau and its surrounding areas are the sources of intensive sandstorms in China. In recent years, specific results have been achieved in the control of the Kubuqi Desert and Maowusu Sandy Land [20,21], but the trend of desertification has not been fundamentally curbed in some areas. The untreated areas still account for a large proportion [22], and repeated desertification can easily occur in areas with large population density. The sandy area in Ulan Buh presents an expanding trend [23], and such trends exist in the eastern Tengger Desert and the western foot of Helan Mountain through which the Yellow River flows [24]. The ecological issues are prominent in the Hetao plain area, such as land salinization, lake swamping, and water quality deterioration [25].

3.1.2 Fragile ecosystems and severe soil erosion in the middle reaches

Soil and water conservation is extremely important in the middle reaches, especially in the Loess Plateau. This is directly related to flood control and ecological security in the middle and lower reaches. In China, a series of water and soil conservation engineering projects have been implemented successively in the Loess Plateau. These include the construction of terraces and check dams, comprehensive management of small watersheds, Three-North Forest Shelterbelts, Grain for Green Project, slope farmland regulation project, and ditch and land reclamation projects. The scope and degree of water and soil loss have been gradually reduced, while the amount of mud and sand in the Yellow River has decreased significantly [26], thus achieving remarkable ecological benefits [9,10]. However, due to the sensitive and fragile ecological background and the impact of human activities, regional water and soil losses are still severe in this region. The soil erosion modulus is higher than 1000 t/(km^2·a) in most areas of the Loess Plateau, where soil erosion is intense in hilly and gully areas with a soil erosion modulus of over 5000 t/(km^2·a) [9]. In 2020, although the area of soil and water loss decreased by 11.4% in the Loess Plateau in comparison with that in 2011, there was still an area of 2.08×10^5 km^2 to be treated urgently. Approximately 40.2% of that area were areas with moderate or above water and soil loss and most of them were coarse sand areas. In the critical sandy area for the prevention and control of soil and water loss in the Yellow River basin, the area of soil and water loss reaches up

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to 1.08×10^5 km^2, of which approximately 46.4% are areas with moderate or above water and soil loss. It is extremely difficult to treat [27] (Table 4).

Currently, the operation and maintenance of water and soil conservation projects are still insufficient, such as some terraces and check dams. The management of economic forests is generally inefficient and extensive, and some artificial forests are characterized by low ecological stability and service function due to their single stand structure [9]. Currently, artificial vegetation restoration is close to the upper limit of the regional water-carrying capacity on the Loess Plateau [28]. Overall, soil and water loss was still severe in the middle reaches. In comparison with the objectives of the new era, namely the national ecological civilization construction and rural revitalization strategy, there is a relatively large gap in the single-goal orientation focusing on reducing soil and water loss and increasing cultivated land area [9,26].

Table 4. Changes of key sandy areas to prevent and control soil and water loss on the Loess Plateau and the Yellow River basin in 2011 and 2020

Region	Year	Water-soil loss area (km^2)			
		Light	Moderate	Strong and above	Total
The Loess Plateau	2020	12 4700	52 059	31 666	208 425
	2011	115 755.76	46 953.73	72 499.22	235 208.71
	Change rate (%)	7.7	10.9	−56.3	−11.4
Key prevention and control sandy areas in the Yellow River basin	2020	57 924	30 933	19 123	107 980
	2011	54 715	20 553	46 363	121 631
	Change rate (%)	5.9	50.5	−58.8	−11.2

3.1.3 Downstream beach area is facing complicated challenge, and the wetland is shrinking in the estuary delta

The beach area of the lower reaches is crucial for not only flood discharge, detention, and sediment deposition but also for local use. Subject to special natural and geographical conditions and safety construction progress, the local economy has been relatively backward for a long time. The contradiction is increasingly prominent between flood control, ecological governance, and the production/living of residents [29].

The ecological status of the Yellow River Delta is extremely important, as it is the core aquatic habitat for the transit, reproduction, and overwintering of birds from the inland regions of Northeast Asia and the Western Pacific. However, due to human disturbance and the reduction of water and sediment from upstream, the delta, especially the estuarine wetland, has been shrinking and degrading [12,30], and biodiversity is declining. Additionally, the habitat of rare and endangered birds has been seriously threatened, and land salinization is also severe [12]. Since 2002, measures have been taken, such as water and sediment regulation, ecological water replenishment, and reed swamp wetlands restoration in the Yellow River Delta Nature Reserve [30,31]. However, the reverse succession trend of regional ecology has not been fundamentally turned back. The area of natural wetlands is still far from the level in the 1990s.

3.2 Bottlenecks still exist in ecological protection and restoration

3.2.1 Lack of integrity and systematicness during the ecological protection and restoration

Restricted by the governance system and mechanism, the upper and lower reaches and the left and right banks of the Yellow River basin are under the jurisdiction of different administrative regions. In the past, ecological protection and restoration were under the jurisdiction of different administrative sectors for important ecological functional areas (e.g., key ecological functional areas, nature reserves, forest parks, and wetland parks) and important ecosystems (e.g., forests, grasslands, wetlands, rivers, and lakes in the basin), which are scattered and fragmented [32]. For example, many major ecological projects have been implemented in the Yellow River basin, but most are aimed at single ecological elements, such as forests, grasslands, wetlands, or deserts, which are planned and implemented by the competent authorities of forestry, grassland, water conservancy, or agriculture. Most focus on improving the functions of water and soil conservation, wind prevention, and sand fixation in the basin instead of improving the quality and function of the basin ecosystem as a whole. Overall, ecological protection and restoration are also decentralized, fragmented, and inefficient. The “local improvement and overall ecosystem degradation” trend has not been fundamentally reversed.

3.2.2 Insufficient investment in ecological protection and restoration, and difficulties realizing the ecological value

According to *China Forestry and Grassland Statistical Yearbook 2020* [33], the expenditure on ecological protection and restoration was approximately RMB 65.63 billion in the fields of forest, grasslands, and wetlands in nine provinces (regions) along the Yellow River in 2020. While the ecological damage loss was approximately RMB 321.0 billion [34], which is still far lower than the latter. There are many historical arrears of ecological damage. The national financial transfer payment for key ecological functional areas does not cover over 50% of the extra important and important ecological areas and over 50% of the extra sensitive and sensitive ecological areas within the basin. In addition, the existing fund source is limited to ecological engineering, which is still based on national investment, and long-term and stable investment mechanisms and channels are still absent [11]. Meanwhile, the imbalance and disharmony are very prominent between economic-social development and ecological protection in the upper, middle, and lower reaches of the Yellow River. In 2020, the seven provinces (regions) in the upper and middle reaches served as key ecological function areas and ecologically sensitive and vulnerable areas of the whole basin; the value of their natural ecosystem products and services accounted for nearly 80% of the nine provinces (regions) in the basin. However, their regional GDP accounts for below 50% of the nine provinces (regions) in the basin [34]. The ecological value of lucid waters and lush mountains has not been effectively transformed, and a large number of inputs for the protection of lucid waters and lush mountains have not been effectively compensated, which caused the prominent problem of "ecological poverty." In this dilemma, the extensive development mode continues in some areas, and the vicious cycle of poverty–ecological degradation intensifies. Many challenges will be faced during ecological protection, restoration, and rural revitalization.

3.2.3 Ecological engineering effects are uncertain and lack systematic evaluation

At present, some studies have evaluated the effect of ecological engineering in the Yellow River basin, such as ecological protection and construction of the Three-River Sources area [3,4], water and soil conservation [10,11], Three-North Forest Shelterbelt [35], natural forest resource protection [36], Grain for Green program [37,38], returning grazing to grassland [39], and Beijing–Tianjin sandstorm source control [40]. Some national standards have been formulated and released to evaluate projects by the forestry department [41–43]. The national report on the evaluation of engineering benefits has been issued [44,45], all of which draw the conclusion that the degradation trend of watershed ecosystems has been initially curbed. However, the local ecological degradation has not been fundamentally reversed, and the effect of ecological engineering is still unstable. However, some studies have focused on the effect of single ecological projects, in which the evaluation indicators are limited to the originally expected objectives of the project, such as the area of closed forestation, area of soil and water loss control, or a number of dam system works; only a few studies have focused on the indicators of ecosystem service functions [3,39,40]. Generally, a systematic and comprehensive evaluation of the effects of various ecological projects in the whole basin is still lacking [3]. There is also a lack of unified standards and norms for the effective evaluation of ecological projects at the national level.

4 Overall strategy of ecological protection and restoration in the Yellow River basin

Given the issues above, future ecological protection and restoration should focus on key areas and prominent problems. This should be based on a systematic evaluation of the results of major ecological projects in the Yellow River basin. Then we should implement a new round of ecological projects according to actual conditions, and establish a long-term mechanism by innovating the value realization mechanism of ecological products in the whole basin, to effectively promote the ecological protection and high-quality development of the Yellow River basin.

4.1 Systematical evaluation on the effectiveness of ecological engineering

The competent authority shall explore and establish a comprehensive decision-making mechanism for ecological protection and restoration, formulate evaluation methods and standards systems specific to the ecological engineering, and systematically evaluate the effectiveness of existing ecological projects, which can be used as a scientific basis for adjusting and optimizing ecological engineering at the national level in the future.

First, a comprehensive decision-making mechanism for ecological protection and restoration should be established. It is suggested that such work shall be led by the Ministry of Finance, with cooperation from the Ministry of Natural Resources, Ministry of Ecology and Environment, Ministry of Agriculture and Rural Areas, Ministry of Water Resources, and State Forestry and Grassland Administration. Subsequently, the effectiveness evaluation can be systematically carried out by each provinces (autonomous regions) specific to major projects (e.g., to natural

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forest resources protection, Grain for Green, Three-North Forest Shelterbelts, returning grazing to grassland, grasslands protection, construction and utilization, national wetlands protection, construction of Three-River Source Nature Reserve, and construction of important ecological function reserve) and pilot ecological engineering of mountains–rivers–forests–farmlands–lakes–grasslands, to evaluate the ecological benefits of various projects, and identify the prominent problems and constraints.

Second, the evaluation method and standards system specific to the effect of ecological engineering should be established. It is suggested to rely on the comprehensive decision-making mechanism mentioned above, study and formulate such evaluation methods and standards system, and mainly focus on the index system and technical standards under the overall framework of ecosystem area, quality, and function.

4.2 Protection and restoration of the ecology according to local conditions

4.2.1 Prioritizing ecological protection and restoration of upstream areas to improve water conservation function

Owing to its water conservation function, the upstream area is vital to water resource supply in the whole basin. It is also the fundamental guarantee to maintain ecosystem health in the whole basin. Therefore, priority must be given to the protection and restoration of upstream areas to improve water conservation.

First, adhering to the principle of "natural restoration first, supplemented by artificial restoration," it is recommended to protect and restore the degraded grasslands. The emphasis should be on the important ecological functional areas, such as the source area of the Yellow River, the Three-River Source area, Qilian Mountains, Ruoergai grassland wetland, and the Ecological Supply Area of Yellow River in Southern Gansu Province. Grassland protection should be strengthened by means of enclosure, grazing prohibition, and conservation, and the relevant systems for grazing prohibition, rest grazing, rotational grazing, and grass-livestock balance should be implemented. Additionally, lowering the livestock-carrying amount to restore the ecological function of grassland. It is also necessary to strengthen the biological control specific to rodents, pests, and poisonous weeds on degraded grasslands. The treatment of black soil beaches should be promoted through various measures, such as artificial grassland reconstruction, semi-artificial grassland supplementary sowing, and enclosure and conservation. It is recommended to improve and raise the eco-compensation criteria of grasslands, guide herders to participate in ecological management and protection, and implement resettlement and relocation in areas with extremely important and fragile ecological functions.

Second, the sandstorm control of the Ordos Plateau should be strengthened. Successful experiences and typical models should be summarized from desertification control in the Kubuqi Desert and Maowusu Sandy Land, to orderly promote key projects, such as desertification control, Three-North Forest Shelterbelts, and Grain for Green; it is recommended to adopt biological sand fixation and engineering sand fixation to effectively curb the expansion of the Ulan Buh Desert and Tengger Desert, constantly consolidate and improve the effectiveness of desertification control, so as to reduce sediment inflow into the Yellow River. It is necessary to actively explore and promote new models, such as sand land management and utilization and green industry development, to coordinate ecological management and economic development in sand areas.

Third, it is recommended that the Hetao irrigation area be restored and managed. It is necessary to further treat urban domestic and agricultural non-point source pollution, strictly apply fertilizers and pesticides, and reduce pollutant discharge into the trunk. Engineering measures could be implemented, such as drainage ditch treatment, constructed wetlands, and ecological water replenishment. It is also necessary to optimize the water supply and drainage network and water transfer and supply mode in the Hetao irrigation area to lower the waste of water resources. It is suggested that the water ecology of some lakes, such as Ulansuhai and Shahu Lakes should be continuously restored. Along with enhancing the intensity of external water transfer, it is also necessary to vigorously control backwater pollution in irrigation areas and reduce endogenous pollution in lakes in combination with biological and engineering measures to restore the biodiversity and health of lakes.

4.2.2 Protecting and restoring the ecology of the middle and lower reaches according to local conditions to maintain the stability of ecosystem

In the Yellow River basin, the middle and lower reaches are affected by relatively intensive human activities; meanwhile, they need to provide high-quality ecological products, safe human settlements, and an ecological environment. Therefore, ecology should be protected and restored by region and by classifications specific to the prominent issues to effectively improve the ecological environment and ensure the safety of human settlements.

First, vigorous control of soil and water loss in the Loess Plateau is recommended. It is necessary to further strengthen mountain closure, grazing prohibition and enclosure protection, and prevent and protect against soil erosion. Moreover, comprehensive treatment should be carried out specifically for ridges, tablelands, slopes, ditches, and rivers according to the local conditions, and some national key water and soil conservation projects should be continuously promoted, such as comprehensive treatment of sloping farmland, protection of tablelands on the Loess Plateau, removal and reinforcement of dangerous check dams, and comprehensive treatment of small watersheds in poverty-stricken areas. Water and soil loss should be comprehensively prevented and controlled in sandy and coarse sand areas. It is also suggested to strengthen the management and protection of forest resources, transform low quality and inefficient forests, and improve the water and soil conservation function of forest ecosystems. Following the zonal law and regional water resources carrying capacity, the scale and layout of vegetation restoration engineering should be scientifically set, such as returning farmland to forests in the future to balance regional water conservation and supply. The integrated development model should be actively explored to balance soil erosion control and rural revitalization to promote coordinated development between regional ecology and the economy.

Second, ecological governance should be carried out in downstream beach areas. It is necessary to scientifically study and reasonably delimit the functional zone for administration by zone, and actively explore and implement the governance scheme of beach areas, including immigration, centralized residence, intensive planting, and policy compensation, to realize the separation of humans and water. The protection and utilization of beach areas should be incorporated into the territorial space planning of all provinces to standardize the development and protection layout of the territorial space.

Third, it is recommended that wetland ecosystems in the Yellow River Delta be protected and restored. According to the ecological water demand of the estuary, a regulation scheme should be scientifically formulated to implement the ecological flow (water) index and process management of the estuary to stabilize the estuarine flow path. It is necessary to assess the evolution trend of estuarine wetlands and scientifically analyze the environmental impact caused by the reduction of sediment from the upper reach to put forward effective countermeasures. It is also necessary to return farmland to wetlands and grasslands, further protect and restore the ecology of riparian zones and beach shorelines and prevent and control alien harmful invasive species to effectively restore the functions of wetland ecosystems in estuarine deltas.

4.3 Establishment of a value realization mechanism of ecological products

First, it is recommended to increase the scope and intensity of financial transfer payments to key ecological functional areas. It is suggested to expand the scope of the original key ecological function areas for soil and water conservation in the hills and gullies of the Loess Plateau, prioritize areas with important ecological functions and underdeveloped economies (e.g., the Ordos Plateau, Helan Mountain, Yinshan Mountain range, the grassland north of Yinshan Mountain, and the mountainous area of central Shandong), and include them in the scope of financial transfer payment. Based on fully considering the regional natural background, it is suggested to explore and enhance the evaluation coefficient of grassland and wetland areas with important ecological functions, such as the source area of the Yellow River, to further optimize the calculation method of financial transfer payment in key national ecological function areas.

Second, an eco-compensation mechanism between the upper and lower streams in the basin should be established. Based on an in-depth summary of pilot experiences from the eco-compensation mechanism in Ningxia and other places, it is possible to explore and study the cross-provincial (regional) eco-compensation scheme based on water quantity and quality and explore how to establish diversified compensation methods, such as capital compensation, counterpart cooperation, industrial transfer, and talent training. It is recommended to carry out a pilot water trading system, establish a water-trading platform for the Yellow River basin, and study the policy feasibility of ensuring ecological water in the river basin by purchasing water rights by the central government. The value of ecological products should be realized in the source area of the Yellow River through a diversified value-realization mechanism.

Third, it is recommended that the paid use and trading systems of natural resources be improved. Given the background characteristics of natural resources and prominent ecological issues in the basin, it is suggested to prioritize establishing and improving the paid use system of water resources in the Yellow River basin and reasonably adjust the levy criteria of water resource fees, especially for areas with water shortage and excess water use. It is also suggested to establish a paid use system to standardize the transfer of state-owned forest and grassland resources and actively develop ecological industries (e.g., understory economy and characteristic tourism) through leasing and franchising.

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5 Conclusions

A systematic evaluation of ecosystem changes in the Yellow River basin showed that the ecosystem structure was generally stable, and the ecological quality has improved in the past 20 years. However, various ecological issues and challenges still exist among the upper, middle, and lower reaches. Therefore, it is suggested to vigorously protect and restore the ecology of the Yellow River basin in the future through systematic evaluation of the effect of ecological engineering, promoting environmental protection and restoration according to local conditions, and innovating and establishing the value realization mechanism of environmental products to ensure regional environmental security.

Based on the assessment of the macro-ecological situations of the Yellow River basin, as well as the diagnosis and identification of regional issues, this study proposes a comprehensive strategy for ecological protection and restoration of the whole basin, which can provide support for the environmental protection and high-quality development of the Yellow River basin. Considering the sensitivity and vulnerability of the watershed ecosystem and the significant differences among the upstream, middle, and downstream areas, the key research directions should be focused on in the next step. These include determining the key threshold of the ecosystem under the interference of human activities to accurately warn against the early ecological security issues, and how to select appropriate technologies to restore the ecosystem of typical damaged and degraded areas in the basin.

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