Ecological Protection and High-Quality Development of the Loess Plateau: Current Status, Issues, and Recommendations (Postprint)

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Abstract

Ecological protection and high-quality development of the Yellow River Basin have been elevated to a national strategy. The release and implementation of the Outline for Ecological Protection and High-Quality Development Planning of the Yellow River Basin in 2021 have propelled the ecological construction of the Loess Plateau into a critical period for consolidating ecological governance achievements and transforming economic and social development. This article systematically summarizes the current status characteristics and main problems of ecological construction and socio-economic development on the Loess Plateau, and proposes countermeasures and recommendations from the perspectives of enhancing ecosystem stability and sustainability, promoting green transformation of the socio-economic system, scientifically planning territorial space, and implementing coordinated governance across the entire basin, providing scientific and technological support for ecological protection and high-quality development of the Loess Plateau and even the entire Yellow River Basin.

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Current Conditions, Issues, and Suggestions for Ecological Protection and High-Quality Development in the Loess Plateau

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Abstract

The ecological protection and high-quality development of the Yellow River Basin has been elevated to a national strategic priority. The release and implementation of the *Outline of the Yellow River Basin's Ecological Protection and High-Quality Development Plan* in 2021 has ushered the Loess Plateau into a critical phase focused on consolidating ecological restoration achievements while facilitating socioeconomic transformation. This paper systematically summarizes the current characteristics and principal challenges of ecological construction and socioeconomic development in the Loess Plateau. It proposes targeted strategies and recommendations from four key perspectives: enhancing ecosystem stability and sustainability, promoting green transformation of socioeconomic systems, implementing scientific territorial spatial planning, and adopting integrated and coordinated governance across the entire river basin. These recommendations aim to provide scientific and technological support for ecological protection and high-quality development in both the Loess Plateau and the broader Yellow River Basin.

Keywords: ecological protection, high-quality development, coupled human and natural system, rural revitalization, Loess Plateau

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The Loess Plateau, located in north-central China within the middle reaches of the Yellow River, covers approximately 640,000 km^2 and serves as a crucial cradle of Chinese civilization. Characterized by fragile ecological conditions and high sensitivity to climate change, the region represents one of China's most concentrated areas of population-resource-environment conflicts. For decades, the Loess Plateau has grappled with severe soil erosion, sparse vegetation, intense population pressure, and low productivity. However, through sustained implementation of comprehensive management measures—including slope stabilization, integrated gully-slope treatment, small watershed management, the Grain-for-Green Program, and gully land consolidation—the plateau's ecological environment has undergone remarkable transformation since 1999, achieving a "win-win" outcome for both environmental protection and socioeconomic development. This ecological restoration effort stands as a monumental practice in China's ecological civilization construction, offering a model for ecological recovery worldwide.

The *Outline of the Yellow River Basin's Ecological Protection and High-Quality Development Plan* issued by the Central Committee of the Communist Party of China and the State Council explicitly emphasizes "prioritizing soil and water conservation in the Loess Plateau, comprehensively protecting natural forests, continuously consolidating achievements of returning farmland to forests and grasslands, intensifying comprehensive management of soil erosion, steadily improving urbanization levels, and enhancing the ecological landscape of the middle reaches." As the national strategy for the Yellow River Basin advances and the outline is implemented, the Loess Plateau has entered a pivotal new era focused on sustaining restoration gains while transforming its socioeconomic development paradigm. This study systematically analyzes the current status and key challenges of ecological and socioeconomic development in the Loess Plateau, proposing actionable strategies and long-term mechanisms to promote ecological protection and high-quality development, ultimately forging a path toward coordinated ecological-economic progress and harmonious human-nature coexistence [Figure 1: see original paper].

1. Current Status of Ecological Environment and Socioeconomic Development in the Loess Plateau

Through persistent long-term efforts, the Loess Plateau has witnessed gradual ecological improvement and substantial socioeconomic progress [1].

(1) Significant increase in forest and grassland coverage with enhanced carbon sequestration capacity. Since implementing the Grain-for-Green Program, vegetation coverage on the Loess Plateau has increased from 31.6% in 1999 to 67% in 2020, marking a historic transformation from "yellow to green." Post-2000 vegetation index growth rates in the region have exceeded national averages, leading China's "greening" trend [1]. Accompanying this vegetation recovery, ecosystem carbon sequestration has increased substantially, transforming the Loess Plateau from a carbon source to a carbon sink [2], with the most significant gains concentrated in hilly and gully regions where the Grain-for-Green Program was implemented [3].

(2) Effective soil erosion control with dramatically reduced sediment flow into the Yellow River. According to the Yellow River Basin Soil and Water Conservation Bulletin, by the end of 2020, cumulative preliminary management of soil erosion covered 252,400 km^2, with 58,100 silt dams constructed. The basin's soil and water conservation rate rose from 41.49% in 1990 to 66.94%

in 2020, reaching 63.44% specifically in the Loess Plateau. Hydrological observations at Tongguan Station show that average annual sediment discharge in the middle Yellow River decreased to 240 million tons during 2001–2020, approaching levels from over 1,000 years ago when human disturbance was minimal [4].

(3) Markedly improved agricultural productivity and optimized farmer income structure. Through engineering measures such as dam construction for water storage and gully land consolidation, the Loess Plateau has significantly enhanced its grain production capacity [5]. Total grain output increased by 47.05% from 2000 to 2020, surpassing the national average growth rate of 44.86%. Research indicates that the region's grain self-sufficiency rate rose from 62% in 1950 to 108% in 2019 [6]. Farmers' income sources have diversified from sole reliance on agricultural production to multiple channels including off-farm employment, orchard management, ecological compensation, and dividend shares. Net per capita income for farmers grew from 1,916 yuan in 2000 to 14,400 yuan in 2020. By 2020, all impoverished populations and counties in the region had been lifted out of poverty, achieving a historic victory in poverty alleviation.

(4) Rapid socioeconomic development with increasingly diversified industrial models. Urbanization rates in the Loess Plateau increased from 34.9% in 2000 to 63.8% in 2020, fundamentally transforming urban-rural population structures and alleviating rural population pressure. Economic growth has been robust, with key indicators significantly exceeding national averages. By 2020, GDP, industrial output value, and per capita GDP had increased to 14.35, 10.86, and 11.79 times their 2000 levels, respectively, compared to national averages of 10.11, 7.77, and 9.04 times. The region's share of national industrial output grew from 6.11% in 2000 to 8.54% in 2020. Leveraging resource and locational advantages, many areas have developed distinctive industries such as apple, jujube, and pepper cultivation, Tan sheep and beef cattle husbandry, and eco-tourism and red tourism, creating new growth points for urban-rural integration and rural revitalization.

2. Major Issues in Ecological Environment and Socioeconomic Development

Despite these remarkable achievements, local areas still face prominent challenges including poor sustainability of artificial vegetation, ecological fragility, rural hollowing, and unbalanced development.

2.1. Insufficient Rationality in Vegetation Restoration Configuration and Suboptimal Ecological Functions

(1) Artificially restored vegetation exhibits simplistic structure and suboptimal ecological function. To ensure high survival and preservation rates and rapidly green the Loess Plateau, fast-growing, low-cost seedlings have been extensively used, with locust and poplar species dominating afforestation efforts. Mixed forests typically involve only 2–3 species planted in 1:1 or 2:1 ratios, resulting in overly simple stand structures compared to natural secondary forests and exhibiting 10%–15% lower biodiversity and 19%–65% weaker ecological functions. Such simplistic structures also lack resistance to herbivorous insects, enabling pest outbreaks that damage vegetation community functions and stability.

(2) Excessive vegetation restoration density causes severe water resource consumption. With its deep soil profile, vegetation growth in the Loess Plateau relies primarily on natural rainfall and soil moisture. High initial planting densities in restoration projects have consumed substantial soil water, expanding dry soil layers and causing "stunted tree" phenomena or even tree mortality, leading to community decline. Research shows that vegetation coverage in north-central Loess Plateau has exceeded climatically defined equilibrium levels, with excessive density being a primary driver of soil desiccation [7]. Vegetation construction has approached the threshold of water resource carrying capacity; exceeding this threshold will create conflicts between ecological water demand and socioeconomic development needs [8].

2.2. High Natural Disaster Risks in Local Areas and Inadequate Coordination Between Middle and Lower Reaches

(1) The Loess Plateau's inherently fragile ecological conditions remain fundamentally unchanged, with high natural disaster risks. Situated in a typical temperate continental monsoon climate zone, the region experiences frequent extreme weather events including torrential rains, droughts, and frosts that threaten the stability and sustainability of gully agriculture and specialty fruit industries. Field investigations reveal that under heavy to torrential rainfall conditions, erosion risks remain severe, potentially causing serious sedimentation and flooding downstream [9]. While silt dams effectively trap sediment, many suffer damage or overtopping during heavy rains. Surveys show that 54.54% of silt dams in the Loess Plateau were built before 1986, mostly small-to-medium structures with low standards that have become silted up, ineffective, or dangerously aged. Among 5,282 identified dangerous silt dams, 456 have downstream populations at risk, and structural deterioration increases dam failure risks as extreme weather events become more frequent [10].

(2) Changing water and sediment production patterns persist as a chronic challenge in the Yellow River Basin. Water scarcity and uncoordinated water-sediment relationships represent critical bottlenecks for ecological protection and high-quality development. The Loess Plateau is a strong sediment-producing but weak water-yielding region. Despite increased precipitation, average annual runoff in the Hekouzhen-Longmen section decreased by over 40% during 2000–2016 compared to 1980–1999. Dramatically reduced sediment transport has caused intense scouring of the lower Yellow River channel, with approximately 32 km^2 of farmland eroded in the Huayuankou-Liuyuankou section between 1987–2020 due to frequent channel shifts over the past two decades [11].

2.3. Vulnerable Farmer Livelihoods and Significant Regional Development Gaps

(1) Low land use efficiency and persistently vulnerable farmer livelihoods. Urbanization and socioeconomic development have driven large numbers of rural youth to seek employment in cities, accelerating rural population aging and residential land vacancy. In 2020, the rural aging rate in Loess Plateau provinces reached 14.16%, exceeding the national average of 13.52%, with rural permanent residents comprising only 36.2% of registered rural populations. This demographic shift constrains agricultural intensification and has led to varying degrees of explicit and implicit land abandonment. As national subsidy policies such as Grain-for-Green and targeted poverty alleviation expire, income structures previously reliant on transfer payments face new challenges. Although farmers' net per capita income continues to grow, it still lags behind national averages, while the urban-rural income gap continues widening, making common prosperity a formidable long-term task.

(2) Significant regional development disparities and lagging county-level economies. The Loess Plateau's industrial structure remains heavily resource-dependent. While resource-rich counties achieve economic growth through extractive industries, other areas develop slowly. The Gini coefficient for secondary industry added value increased from 0.34 in 2000 to 0.49 in 2020, highlighting development gaps driven by resource disparities. Over 67.74% of districts and counties have per capita GDP and fiscal revenue below 50% of regional averages. Since 2010, the secondary industry share has declined due to resource depletion and capacity adjustments, while tertiary industry development remains slow. Fiscal deficits have expanded dramatically, from 10.788 billion yuan in 2000 to 638.833 billion yuan in 2020, with 86.22% of districts and counties experiencing expenditures exceeding revenue and 44.57% facing deficits over 2 billion yuan. Limited job opportunities, low infrastructure quality, and inadequate public services in county towns constrain economic development and drive population out-migration.

(3) Underutilized ecological resources and low conversion of ecological product value. While ecological improvements have been crucial for reducing sediment inflow and protecting lives and property downstream, ecological value assessment and compensation systems remain exploratory. Although Grain-for-Green compensation standards were adjusted from 230 yuan/mu annually for 5–8 years to 1,500–1,600 yuan/mu for a new five-year period, they remain low compared to farmers' opportunity costs from off-farm employment and corresponding ecological values. The improved ecological environment provides a solid foundation for agricultural production and eco-tourism development, yet mechanisms for converting "lucid waters and lush mountains" into "mountains of gold and silver" and achieving ecological industrialization are still being explored, with no mature market-based development mechanisms established.

3. Countermeasures and Suggestions

Addressing these challenges requires analyzing the coupled human-natural system to propose viable strategies and long-term mechanisms from four perspectives: enhancing ecosystem stability and sustainability, promoting green transformation of socioeconomic systems, implementing scientific territorial spatial planning, and establishing integrated basin-wide coordinated governance to advance ecological protection and high-quality development in the Loess Plateau.

3.1. Enhancing Ecosystem Stability and Sustainability to Support Carbon Neutrality

(1) Maintaining rational vegetation density. Vegetation construction in the Loess Plateau has approached the limits of water resource carrying capacity. Future conservation efforts must shift focus from "vegetation construction" to "consolidating achievements and enhancing functions." Excessive stand density is a primary cause of soil desiccation and growth decline in locust forests in hilly and gully regions. Scientific thinning can optimize stand structure and regulate soil moisture by controlling transpiration, representing an effective approach to improving artificial locust forest sustainability.

(2) Establishing environmentally suitable vegetation communities. Promote adaptive ecosystem management [12,13] by comprehensively evaluating the environmental suitability, soil and water conservation effectiveness, socioeconomic benefits, and ecological risks of existing engineering measures and vegetation restoration efforts. Prioritize structural optimization and functional enhancement for low-adaptation, high-risk vegetation (e.g., water-intensive species, pest-prone stands). Implement tending and near-natural transformation of artificial forests, introducing native species such as juniper and willow based on vegetation zonation and succession patterns to replace water-intensive, poorly adapted species and avoid monoculture stands. Conduct research on ecosystem resilience changes and driving factors to enhance vegetation recovery capacity from drought and pests, strengthening overall ecosystem sustainability.

(3) Exploring ecological carbon sink markets. Enhanced forest and grassland coverage and quality have strengthened the Loess Plateau's carbon sink capacity. Establishing carbon sink trading and value conversion mechanisms is urgently needed for green development. Explore creating an ecological carbon sink market trading system, launch pilot programs, and expand channels for realizing ecological product values. Develop carbon sink measurement and monitoring systems to guide social capital investment in forestry, enable forest farmers to participate effectively in carbon trading and obtain monetary benefits from ecosystem services, and enhance incentives for long-term sustainable forest and grassland management to support carbon neutrality and rural revitalization.

3.2. Achieving Green Transition in Development Mode and Promoting Human-Land Coordination

(1) Promoting ecological industrialization to realize ecological resource value. Integrate natural assets and ecosystem services into national economic accounting systems by establishing a Gross Ecosystem Product (GEP) accounting framework [14,15]. Following the logic of ecological resource cultivation, asset capitalization, and marketization of ecological products and services, utilize land engineering technologies to enhance ecological resource quality and functions. Deepen innovations in property rights and benefit distribution systems, cultivate new business entities and professional markets, and establish two-way flow mechanisms between rural ecological elements and urban capital to achieve ecological resource value conversion.

(2) Developing green, low-carbon circular economies to promote resource conservation. Establish internal recycling within agricultural production and processing, connect agricultural production with e-commerce and external circulation, and develop multifunctional large-scale circulation systems integrating agriculture with tourism, health care, and urban-rural integration. This will promote internal industrial circulation in the Loess Plateau and a new development pattern of dual circulation between the plateau and the Yellow River Basin [16]. Innovate modern management mechanisms with multi-stakeholder collaboration and multi-department participation to ensure efficient utilization of regional characteristic resources and coordinated human-land development.

(3) Leveraging information technology to promote industrial diversification and digital operations. Highlight the Loess Plateau's resource endowments and regional cultural advantages, utilizing modern information technology to support resource allocation and scientific decision-making. Aim to enhance rural regional system functions and values by vigorously developing new business forms such as specialty agriculture, organic agriculture, and shared agriculture. Promote new agricultural models including gully agriculture, park agriculture, and mountain agriculture to support rural revitalization through industrial prosperity and smart village construction.

3.3. Optimizing Territorial Spatial Layout and Promoting Integrated Protection of Mountains-Waters-Forests-Farmlands-Lakes-Grasslands-Deserts

(1) Adjusting and optimizing living spaces. Based on natural geographic patterns, population and economic distributions, and urbanization stages, identify the structure and pattern of "production-living-ecological" spaces using methods of major functional zoning, dominant type classification, and primary use grading [17,18]. Scientifically classify villages, optimize urban-village systems, strengthen counties' role in "connecting cities and leading villages," and advance land consolidation and spatial optimization. Stabilize qualification rights, activate use rights, introduce market mechanisms, revitalize land resources, optimize public resource allocation, and improve rural living environments to build harmonious and beautiful villages.

(2) Efficiently utilizing production spaces. Focus on ecological civilization construction and urban-rural integrated development strategies, using land consolidation and optimal allocation as leverage. Innovate financial service allocation mechanisms to stimulate new agricultural business entities, promote multifunctional modern gully agriculture, consolidate and enhance gully land consolidation achievements, and scientifically advance land management scaling, organizational specialization, production mechanization, and industrial efficiency. Create rural complexes and life communities integrating agricultural production, farming experiences, scientific research and education, tourism, and health care.

(3) Protecting and restoring ecological spaces. Establish quality assessment and restoration governance systems aligned with ecosystem systematicity and integrity. Based on comprehensive ecosystem quality assessment, combine protection and restoration measures using biological, engineering, and management approaches. Scientifically implement small watershed comprehensive management and silt dam construction to consolidate soil and water conservation achievements, enhance ecosystem health, and strengthen the Loess Plateau's ecological security barrier function.

3.4. Establishing Soil and Water Conservation Monitoring and Whole-Basin Governance Systems

(1) Precise prevention and control through monitoring and assessment systems. Soil erosion on sloping farmland and gravitational erosion in gullies remain prominent issues and primary sediment sources for the Yellow River. Establish a monitoring system based on observation stations with regular dynamic monitoring supplemented by periodic surveys to continuously track soil and water conservation and dynamic changes, focusing on the Loess Plateau. Deepen monitoring, evaluation, and forecasting systems to support scientific and precise soil erosion prevention. Advance prevention and control in key erosion areas, regularly update risk zone classifications, provide refined data on erosion area and intensity, implement tailored ecological measures for hotspot regions, reinforce terraces and silt dams to improve safety grades, and enhance post-construction maintenance of gully land consolidation projects to improve disaster resilience against extreme climate events.

(2) Collaborative management and scientific decision-making systems. Integrate scientific data on Loess Plateau ecological protection to develop an intelligent analysis and decision-making system, promoting collaborative and intelligent ecological protection. Connect major project supervision with governance effectiveness assessment, achieving integrated management of prediction, early warning, forecasting, and scientific decision-making. Introduce third-party evaluation mechanisms to regularly assess national and local ecological construction progress and effectiveness, ensuring sustainable soil and water conservation. Emphasize building a new model of ecological technology supporting decision-making, encouraging scientific and technological breakthroughs on specific problems or comprehensive interdisciplinary collaboration, and forming a new pattern of ecological technology support through multi-disciplinary synergy and multi-department cooperation.

(3) Strengthening middle and lower reach coordination for whole-basin ecological governance. The Yellow River Basin is an integrated whole linked by ecological-hydrological-sediment relationships [19,20], requiring structural matching between eco-hydrological processes and governance institutions [21,22]. Build a whole-basin governance system led by government with public participation and inter-departmental coordination. Utilize big data and IoT technologies for comprehensive monitoring, collaborative decision-making, and scientific control to promote efficient, refined, and sustainable basin management. Conduct systematic research on water-sediment relationship changes under ecological restoration, scientifically plan vegetation restoration area and density to control sediment loss within reasonable thresholds, optimize water-sediment regulation schemes for the Sanmenxia and Xiaolangdi reservoirs to maintain downstream channel and estuary erosion-deposition balance, and study trade-offs between ecological water demand and production-living water use to optimize water resource allocation across space and sectors, strengthening coordination between middle-lower reaches and tributaries for comprehensive protection and governance.

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