Review of Response of Cultivated Land Ecological Processes and Quality Enhancement Technologies in Henan Province's Core Grain Production Area under Climate Change

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Abstract Climate change-induced spatiotemporal restructuring of precipitation profoundly impacts the ecological processes of cultivated land in Henan Province's core grain production area. This paper systematically reviews the characteristics of ecological responses in cultivated land and the technological achievements in quality enhancement within this region. Studies reveal that the northward shift of precipitation isohyets has intensified the "spring drought and summer waterlogging" pattern, with prominent issues of soil erosion and secondary salinization; the cultivated land quality grade shows an annual average decline of 0.05 –0.10 grades. To address these challenges, the research team has developed a comprehensive technological framework encompassing "ecological process identification—zoned remediation—monitoring and early warning—big data support". Demonstration applications demonstrate that this system has led to an average improvement of 0.8 grades in cultivated land quality, an average grain yield increase of 750 –1 500 kg/ha, and a water-saving rate of 40% in irrigation. Current limitations include insufficient technological adaptability; future efforts require strengthening the development of adaptive technologies and intelligent upgrades.

Key words Climate change, Core grain production area, Cultivated land ecological process, Quality enhancement, Henan Province

0 Introduction

Food security is a cornerstone of national security. As the fundamental medium for grain production, the stability of cultivated land quality and the sustainability of its productivity directly influence regional agricultural development and the nation's food security capacity. Western Henan (Yuxi region), a vital component of Henan's grain production base, features diverse topography including mountains, hills, and plains, serving as a transitional zone from the Loess Plateau to the North China Plain. Its cultivated land resources are fragmented, and its ecological environment is fragile. In recent years, the global climate change-induced northward shift of precipitation isohyets has significantly altered the spatiotemporal distribution of rainfall in this region. The frequency of alternating droughts and floods has increased, profoundly affecting key ecological processes such as soil moisture dynamics and nutrient cycling in cultivated land. This exacerbates the risk of land quality degradation, posing severe challenges to regional grain production.

Against this backdrop, clarifying the mechanisms through which climate change affects cultivated land ecological processes and integrating and promoting scientifically effective quality enhancement technologies have become central imperatives for ensuring stable productivity in Henan's core grain area and fortifying the national food security shield. Based on years of research accumulation and demonstration outcomes from the Land Research Center of the Institute of Geography, Henan Academy of Sciences, this paper systematically reviews the response characteristics of cultivated land ecological processes, the innovation in integrated quality enhancement technologies, and their application effectiveness in Henan's core grain area under climate change. It analyzes the shortcomings in current research and practice, proposes future development directions, and aims to provide theoretical support and practical references for similar regions in coping with climate change and achieving cultivated land quality protection and productivity enhancement.

1 Response characteristics of cultivated land ecological processes to the northward shift of precipitation isohyets in Western Henan

1.1 Restructuring of water-soil-vegetation interaction processes

Climate change, particularly the alteration in precipitation patterns, directly restructures the material cycles and energy flows within cultivated land ecosystems. The core grain area of Henan Province exhibits a slight increasing trend in annual precipitation, but its seasonal distribution is highly uneven: the frequency of spring droughts has increased by 30% compared to twenty years ago, while summer short-duration heavy rainfall events have risen by 25%, forming a typical "spring drought and summer waterlogging" pattern. This change disrupts the water cycle in cultivated land: in the loess hilly areas of western Henan, the surface runoff coefficient on sloping farmland has increased by 15% –20%, the average annual soil erosion modulus has reached 3 500 t/km^2, and

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the annual loss of topsoil organic matter has increased by approximately 1 t/ha. In low-lying areas of the Huang – Huai – Hai Plain, groundwater level fluctuations have widened to 1.5 – 2.0 m, with secondary salinization appearing in some plots, and soil pH has increased by 0.3 – 0.5 compared to a decade ago.

The abnormal fluctuations in water conditions further disrupt the vegetation-soil feedback balance. Water supply-demand mismatches during critical growth stages, such as wheat jointing and maize tasseling, hinder crop root development, reduce soil microbial activity in the root zone by 10% – 15%, and decrease soil nitrogen, phosphorus, and potassium mineralization efficiency by approximately 20%, creating a cascading effect of "water stress-nutrient imbalance-productivity decline". Monitoring data indicate that climate change has caused the interannual variation coefficient of grain yield in the core area to reach 12% – 18%, with yield fluctuation in non-irrigated cultivated land in hilly areas as high as 23%.

1.2 Spatiotemporal evolution of key limiting factors for cultivated land quality Based on long-term monitoring data of cultivated land quality in Henan Province and field trial results, the limiting factors for cultivated land quality in the core area exhibit significant spatiotemporal heterogeneity under the background of climate change. Among natural factors, irrigation conditions have become the primary limiting factor: cultivated land without irrigation facilities accounts for over 40% in the hilly areas of western Henan and the mountainous areas of southern Henan, and precipitation fluctuations cause the interannual yield variation coefficient on such land to exceed 20%. The limiting effects of soil texture and organic matter content continue to intensify. The sand particle content in sloping farmland soil has increased by approximately 4% compared to ten years ago, and the proportion of cultivated land area with organic matter content below 10 g/kg has expanded to 33%, leading to a significant decline in soil water and nutrient retention capacity.

The superposition of anthropogenic factors and climate change exacerbates the risk of quality degradation. Traditional farming practices like conventional tillage and extensive irrigation lack sufficient adaptability to the altered ecological processes. Excessive tillage leads to shallower plow layers and increased soil bulk density, further diminishing soil water storage capacity. Fragmented land management hinders the large-scale application of technologies like water-saving irrigation and conservation tillage, resulting in insufficient resilience of the cultivated land ecosystem to climate change. In key areas such as the salinization zones of the eastern Henan plain and the erosion-prone hilly areas of western Henan, the cultivated land quality grade declines by 0.05 – 0.10 grades annually, directly threatening the stability of grain production.

2 Integration and innovation of core technologies for cultivated land quality enhancement in Henan's core grain area

To address the disorder of ecological processes and quality degradation in cultivated land triggered by climate change, the research team, using Henan's core grain area as a research platform and after more than a decade of technological research, has constructed a comprehensive "ecological process identification—zoned precision remediation—dynamic monitoring and early warning—big data support" technological framework for cultivated land quality enhancement.

2.1 Precision identification technology for the cultivated land quality-productivity relationship This technology overcomes the bottleneck in traditional research where it is difficult to isolate the interactive effects of factors. It establishes grading standards for 11 categories of cultivated land quality influencing factors tailored to different geomorphological units in Henan (mountains, hills, plains). Using a combination of GIS spatial analysis and quantitative modeling, it develops response relationship models linking changes in single factors and combined patterns with grain productivity. Research shows that improvement in irrigation conditions contributes most significantly to productivity enhancement; a unit change in its indicator grade can increase standard grain yield by 1 600 kg/km^2, followed by factors like gravel content and topographic slope. The natural quality score of cultivated land exhibits an "inverse S-shaped" relationship with productivity; within the natural quality score range of 0.75 – 2.00, every 0.01 unit increase yields an average production growth of 75 kg/ha. This technology is the first to quantify the impact thresholds of changing water conditions on productivity in western Henan's cultivated land under the northward shift of precipitation isohyets, providing a scientific basis for formulating targeted quality enhancement measures. Related research findings have been published in core journals such as *Chinese Journal of Agricultural Resources and Regional Planning* and *Areal Research and Development*, and won the First Prize for Scientific and Technological Achievements from the Henan Academy of Sciences.

2.2 Zoned comprehensive remediation technology for medium- and low-yield farmland Based on the spatial variations in natural conditions (climate, geomorphology, soil) and quality-limiting factors within Henan's core grain area, using techniques such as GIS layer overlay and patch synthesis, the core area was delineated into 3 primary and 9 secondary remediation and improvement zones for medium- and low-yield farmland, establishing a "location-specific, categorized strategy" remediation model. For medium-yield dryland farmland in the hilly areas of western Henan, a comprehensive "water harvesting engineering + water-saving irrigation + soil improvement" technical system was developed. By constructing water harvesting facilities like terraces and fish-scale pits, coupled with drip and sprinkler irrigation systems, combined with organic fertilizer application and straw return, soil water content increased by 20% – 25%, and productivity improved by 420 – 2 400 kg/ha. For waterlogged saline-alkali farmland in the eastern Henan plain, the "drainage-irrigation infrastructure + soil desalination + vegetation restoration" technology was promoted, involving the improvement of field irrigation and drainage pipe networks, and the combined use of subsurface pipe drainage and flue gas desulfurization gypsum amendment to control soil salt content below 0.3%. For low-yield farmland with restrictive layers in the mountainous areas of southern Henan, the "land leveling + soil layer thickening + profile optimization" project was implemented to break through restrictive layers such as gravel layers and clay pans, resulting in an improvement of cultivated land quality grade by 0.5 – 1.0 grades. This technology has transformed the remediation of medium- and low-yield farmland from a "unified model" to "precision adaptation". It has been incorporated into the *Henan Province Technical Standards for Land Development and Consolidation Engineering*, serving as a core technical foundation for regional integrated land consolidation.

2.3 Precision monitoring and early warning technology for cultivated land quality An innovative monitoring sample layout method based on the spatial variability within control zones was developed. Homogeneous monitoring control zones were delineated within the core area. The Neyman allocation method was used to determine the optimal total number of sample points, and the number of points per zone was allocated based on the spatial variation coefficient of cultivated land quality, achieving the monitoring goal of "obtaining maximum information with the fewest samples". Empirical studies show that this method achieves a monitoring accuracy of over 95%, with a 40% increase in efficiency compared to traditional random sampling methods, effectively solving the problems of high cost and low accuracy in monitoring caused by the fragmented distribution of cultivated land in the core area.

Simultaneously, a comprehensive early warning system was established, taking cultivated land productivity as the core warning indicator, overcoming the limitations of traditional single-indicator warnings. By quantifying the impact of changes in cultivated land area (increase or decrease) and quality on productivity, four-level warning thresholds ("No Warning", "Light Warning", "Medium Warning", "Heavy Warning") were defined, enabling the scientific identification of key drivers of cultivated land quality degradation. Applied in areas such as the eastern Henan plain and western Henan hills, this early warning system successfully predicted the erosion risk on sloping farmland triggered by the summer rainstorm in 2021 and the productivity decline caused by the spring drought in 2022. It provided decision support for timely emergency measures like straw mulching and irrigation scheduling, limiting grain yield reduction in affected areas to within 5%.

2.4 Big data integration technology for cultivated land quality To address issues like dispersed data sources and heterogeneous formats, a multi-source heterogeneous data integration model based on GML/KML was proposed. This model converts monitoring data from departments such as agriculture, natural resources, and environmental protection, along with real-time sensor monitoring information and expert knowledge data, into a unified format, enabling efficient data integration and sharing. Leveraging big data storage and processing technologies, the Henan Cultivated Land Quality Big Data Platform was constructed, reducing data redundancy by over 30%, promoting data standardization, and significantly enhancing data analysis and application efficiency. This platform enables dynamic tracking and assessment of cultivated land quality in the core area. By integrating multi-year monitoring data, it can precisely identify the patterns of climate change impacts on cultivated land quality in different regions, providing data support for technology optimization and policy formulation.

3 Technology application effectiveness and socioeconomic benefits

3.1 Significant productivity enhancement effects Demonstration applications of this technology system in over 10 counties/cities within Henan's core grain area show an average improvement of 0.8 grades in cultivated land quality, an average grain yield increase of 750 – 1 500 kg/ha, resulting in an annual grain production increase of 240 500 t across the 2 million ha demonstration area. Specifically, after remediation of medium- and low-yield farmland in the hilly areas of western Henan, irrigation assurance rate increased from 58% to 85%, with the wheat-maize rotation system achieving an average yield increase of 1 800 kg/ha. In the salinization remediation zones of the eastern Henan plain, precision fertilization and optimized drainage/irrigation led to an annual average increase in soil organic matter content of 0.5 g/kg and a 25% improvement in productivity stability. Simultaneously, the application of these technologies reduced agricultural production costs by 5% – 30% and achieved a water-saving rate of 40% in irrigation, realizing the dual goals of productivity enhancement and resource conservation.

3.2 Extensive application scope and strong spillover effect The research outcomes have been incorporated into the regional land consolidation guidance system by the Land Consolidation Center of the Ministry of Natural Resources, providing core technical support for Henan Province's territorial spatial planning and high-standard farmland construction initiatives. Within the province, the technological achievements are widely applied in fields such as integrated land consolidation, medium- and low-yield farmland improvement, and cultivated land quality evaluation. They have guided the implementation of multiple key projects, including high-standard farmland construction in Zhoukou City, cultivated land fertility enhancement in Luoyang City, and medium- and low-yield farmland improvement in Xunxian County and Lingbao City. Furthermore, the results have provided a scientific basis for the Henan Provincial Committee of the China Association for Promoting Democracy in formulating policy consultation topics and CPPCC proposals related to cultivated land protection, fostering a virtuous cycle of "technological innovation-practical application-policy refinement".

3.3 Synergistic highlighting of social and ecological benefits During the technology promotion process, through models like land transfer and shareholding cooperatives, over 2 700 farmers in the core area achieved increased income, and village collectives saw an average annual income increase exceeding 300 000 yuan. This has effectively stimulated farmers' enthusiasm for participating in cultivated land protection and quality enhancement. Ecologically, the zoned remediation technologies reduced soil erosion on sloping farmland. Wetland protection and irrigation system optimization in the plain areas improved the regional water cycle. This led to a 10% increase in biodiversity and a 15% – 20% increase in the ecosystem service value of farmland in demonstration zones, achieving a sustainable development model of "cultivated land protection-ecological restoration-agricultural development".

4 Existing problems and future prospects

4.1 Major current challenges Despite the significant achievements of the cultivated land quality enhancement technology system, three prominent problems persist under the dynamic context of climate change: First, regional adaptability of technologies needs optimization. Precise water-saving technologies for the complex mountainous terrain of western Henan and technologies for coping with extreme precipitation in the eastern Henan plain are still inadequate, and the integration of technologies across different remediation zones is insufficient. Second, technology promotion efforts are limited. Affected by fragmented operations and farmers' knowledge levels, the adoption rate of advanced technologies like conservation tillage and big data monitoring is only around 35%, hindering large-scale application. Third, there is a lack of long-term monitoring and dynamic adjustment mechanisms. Data accumulation on the long-term impacts of climate change on cultivated land ecological processes is insufficient, and the dynamic adaptability of the technology system to climate change needs strengthening.

4.2 Future development directions

4.2.1 Strengthening climate change adaptation technology R&D. Focus should be placed on core influencing factors like precipitation pattern changes and extreme weather events. It is necessary to develop integrated water harvesting and moisture conservation technologies for the mountainous and hilly areas of western Henan, and rapid waterlogging drainage and soil remediation technologies for the eastern Henan plain, optimize the coordinated regulation model of "water-nutrient-crop" to enhance the resilience of the cultivated land ecosystem.

4.2.2 Promoting technology integration and intelligent upgrading. It is necessary to integrate technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) to enhance the cultivated land quality big data platform and develop dynamic fertilization and irrigation decision support systems based on precipitation forecasting, promote miniaturized, low-cost monitoring devices to address the challenge of monitoring fragmented cultivated land, achieving full-chain intelligence of "precision monitoring-intelligent early warning-efficient regulation".

4.2.3 Improving the technology promotion and policy support system. It is necessary to establish a collaborative promotion mechanism involving "research institutions + government + enterprises + farmers", enhance farmers' application capabilities through technical training and demonstration base construction, refine cultivated land protection compensation policies, incorporate technology application effectiveness into local government assessments, and encourage social capital participation in cultivated land quality enhancement projects.

4.2.4 Deepening cross-regional collaborative research. It is necessary to expand the research scope to conduct comparative studies on cultivated land quality between Henan's core grain area and regions like the North China Plain and the Loess Plateau, reveal the differential impacts of climate change on cultivated land ecological processes across different regions to form replicable and scalable regionally adapted technological models.

5 Conclusions

Under climate change, the ecological processes of cultivated land in Henan's core grain area have undergone significant restructuring. Fluctuations in water conditions and degradation of soil quality have become key factors constraining the stability of grain productivity. Addressing this challenge, the research team has achieved innovative breakthroughs in key technologies including precision identification of the cultivated land quality-productivity relationship, zoned comprehensive remediation of medium- and low-yield farmland, quality monitoring and early warning, and big data integration. The application of this technology system has effectively enhanced cultivated land quality and grain productivity in the core area, yielding significant economic, social, and ecological benefits. It provides a successful model for similar regions to cope with climate change and ensure food security.

In the future, it is necessary to further strengthen the regional adaptability and intelligence level of the technologies, improve the promotion and support mechanisms, deepen cross-regional collaborative research, and continuously refine the cultivated land quality enhancement technology system. This is not only an essential requirement for ensuring stable productivity in Henan's core grain area and promoting sustainable agricultural development, but also provides crucial reference for major grain-producing areas in northern China to cope with climate change and achieve cultivated land quality protection and productivity enhancement. It holds significant strategic importance for fortifying the national food security shield.

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