

AGROECOLOGICAL TRANSITION OF IRRIGATED AND DRAINAGED SYSTEMS IN THE YELLOW RIVER BASIN: MULTI-LEVEL CHARACTERISTICS AND PATHWAYS

TRANSITION AGROÉCOLOGIQUE DES SYSTÈMES IRRIGUÉS ET DRAINÉS DANS LE BASSIN VERSANT DE JAUNE : CARACTÉRISTIQUES MULTI-NIVEAUX ET TRAJECTOIRES

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ABSTRACT

The Yellow River Basin (YRB) is one of China's most important agricultural regions, supporting extensive irrigated agriculture under conditions of severe water scarcity, ecological degradation, and increasing climate uncertainty. This study examines the characteristics of irrigated and drained agroecological systems in the YRB and explores pathways for agroecological transition toward sustainable, resilient, and climate-adaptive agricultural development.

Using a multi-level analytical framework that integrates agroecology, Integrated Water Resources Management (IWRM), and irrigation modernization principles, the study synthesizes scientific literature, policy documents, irrigation district experiences, and basin-scale management practices. At the farm level, irrigated systems are characterized by strong dependence on irrigation, uneven water productivity, intensive agrochemical use, and growing adoption of precision irrigation technologies. At the territorial level, irrigation districts exhibit complex canal–drainage networks, conjunctive use of surface water and groundwater, and increasing challenges associated with salinization, nutrient runoff, and ecological degradation. At the basin level, agricultural development is influenced by interprovincial water allocation mechanisms, ecological flow requirements, and growing pressures from climate change and socio-economic development.

The findings indicate that agroecological transition requires coordinated technological, ecological, and institutional interventions. Key approaches include precision and deficit irrigation, controlled drainage, agricultural drainage water reuse, soil carbon enhancement, crop diversification, digital water allocation systems, and participatory governance mechanisms such as Water User Associations (WUAs). Basin-scale measures, including ecological compensation, ecological flow regulation, climate-adaptive water allocation, and integrated watershed governance, are also essential.

The study demonstrates that sustainable transformation of irrigated and drained systems extends beyond engineering modernization and requires the integration of ecological restoration, digital technologies, open science-based monitoring, and governance reforms. The proposed framework offers practical insights for enhancing food security, ecological integrity, and climate resilience in the YRB and provides a useful reference for irrigated river basins facing similar water–energy–food–ecosystem challenges worldwide.

Keywords: Yellow River Basin; agroecological transition; irrigation and drainage; water scarcity; IWRM; climate resilience; sustainable agriculture.

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RESUME

Le bassin versant de Jaune (YRB) est l'une des régions agricoles les plus importantes de la Chine, soutenant une agriculture irriguée extensive dans des conditions de grave pénurie d'eau, de dégradation écologique et d'incertitude climatique croissante. Cette étude examine les caractéristiques des systèmes agroécologiques irrigués et drainés dans le YRB et explore les voies de la transition agroécologique vers un développement agricole durable, résistant et adapté au climat.

En utilisant un cadre analytique multi-niveaux intégrant l'agroécologie, la gestion intégrée des ressources en eau (GIRE) et les principes de modernisation de l'irrigation, l'étude synthétise la littérature scientifique, les documents politiques, les expériences menées dans les districts d'irrigation et les pratiques de gestion à l'échelle du bassin. Au niveau de la parcelle, les systèmes irrigués sont caractérisés par une forte dépendance de l'irrigation, de la productivité de l'eau inégale, de l'utilisation agrochimique intensive et de l'adoption croissante des technologies d'irrigation de précision. Au niveau territorial, les districts d'irrigation présentent des réseaux complexes de drainage par canaux, une utilisation conjointe des eaux de surface et souterraines, ainsi que des défis croissants liés à la salinisation, au ruissellement des nutriments et à la dégradation écologique. Au niveau du bassin, le développement agricole est influencé par les mécanismes interprovinciaux d'allocation de l'eau, les exigences de débit écologique et les pressions croissantes liées aux changements climatiques et au développement socio-économique.

Les résultats indiquent que la transition agroécologique exige des interventions technologiques, écologiques et institutionnelles coordonnées. Les approches clés incluent l'irrigation de précision et l'irrigation déficitaire, le drainage contrôlé, la réutilisation des eaux de drainage agricoles, l'amélioration du carbone du sol, la diversification des cultures, les systèmes numériques d'allocation de l'eau et les mécanismes de gouvernance participative tels que les Associations d'Usagers de l'Eau (AUE). Les mesures à l'échelle du bassin, y compris la compensation écologique, la régulation des débits écologiques, l'allocation de l'eau adaptée au climat et la gouvernance intégrée des bassins versants, sont également essentielles.

L'étude démontre que la transformation durable des systèmes irrigués et drainés s'étend au-delà de la modernisation technique et exige l'intégration de la restauration écologique, des technologies numériques, du suivi ouvert basé sur la science et des réformes de la gouvernance. Le cadre proposé offre des perspectives pratiques en ce qui concerne l'amélioration de la sécurité alimentaire, l'intégrité écologique et la résistance au climat dans le YRB et constitue une référence utile pour les bassins versants irrigués confrontés à des défis similaires en matière de lien entre eau-énergie-alimentation-écosystèmes à travers le monde.

Mots-clés : Bassin versant de Jaune; Transition agroécologique; Irrigation et drainage; Pénurie d'eau; GIRE; Résistance au climat; Agriculture durable.

1. INTRODUCTION

Irrigated agriculture plays a critical role in global food production, accounting for approximately 20% of cultivated land while contributing nearly 40% of global food supply (FAO, 2021). However, conventional irrigation systems have increasingly faced challenges associated with water scarcity, salinization, soil degradation, nutrient pollution, biodiversity loss, and climate variability. These pressures are particularly severe in arid and semi-arid river basins where agricultural production depends heavily on regulated irrigation and drainage systems.

The Yellow River Basin (YRB), known as the "Mother River" of China, is among the country's most important agricultural production regions. Covering approximately 795,000 km² and spanning nine provinces, the basin supports major grain-producing areas, including extensive wheat, maize, cotton, and horticultural systems (Liu and Xia, 2004). Despite its strategic significance, the YRB contains only about 2% of China's total water resources while supporting around 12% of the national population and 15% of cultivated land (Wang et al., 2019). Long-term overexploitation of water resources has resulted

in severe ecological and hydrological problems, including reduced river discharge, groundwater depletion, wetland degradation, and salinity accumulation.

The modernization of irrigation infrastructure in the YRB has traditionally focused on engineering efficiency improvements, including canal lining, reservoir regulation, and water-saving irrigation technologies. Although these measures have improved irrigation efficiency in many regions, increasing evidence suggests that engineering-based approaches alone are insufficient for ensuring long-term sustainability. Agroecological transition has therefore emerged as an integrated framework combining ecological principles, sustainable water management, climate adaptation, and participatory governance. Agroecological transition in irrigated and drained systems refers to the transformation of agricultural water management from resource-intensive and environmentally damaging practices toward ecologically resilient, socially inclusive, and climate-adaptive systems. Such transition emphasizes efficient resource utilization, ecosystem restoration, biodiversity conservation, circular nutrient management, and improved resilience against climate and hydrological uncertainties (Wezel et al., 2020).

This paper aims to:

1. Analyze the characteristics of irrigated and drained agroecological systems at farm, territorial, and system levels in the Yellow River Basin;
2. Examine key environmental and institutional challenges affecting sustainable irrigation development;
3. Identify methods and pathways supporting agroecological transition in the basin; and propose an integrated framework for sustainable management of irrigated agroecosystems under climate change.

2. MEGHOCLOGY

This study adopts a qualitative and systems-based analytical framework integrating agroecology, integrated water resources management (IWRM), and irrigation modernization theory.

2.1 Study Area

The Yellow River Basin (YRB) is China's second-longest river basin and one of the country's most important ecological, agricultural, and socio-economic regions (Liu and Xia, 2004). Covering approximately 795,000 km² and extending 5,464 km from the Bayan Har Mountains on the Tibetan Plateau to the Bohai Sea, the basin traverses nine provincial-level administrative regions and supports more than 100 million people (Yellow River Conservancy Commission, 2021). It plays a critical role in national food security, energy production, and economic development (Wang et al., 2019).

The basin exhibits substantial geographical and climatic diversity. Elevation decreases from the high-altitude upstream regions to the alluvial plains downstream, while climatic conditions range from alpine climates in the upper reaches to arid and semi-arid environments in the middle reaches and humid monsoon climates in the lower reaches (Chen et al., 2007). Annual precipitation varies from less than 200 mm in the northwest to over 800 mm in the southeast and is highly seasonal, with approximately 60–70% occurring during the summer monsoon period between June and September (Liu and Xia, 2004).

Despite supporting approximately 15% of China's cultivated land, the basin possesses only about 2% of the nation's water resources, making water scarcity one of its most critical constraints (Wang et al., 2019). Irrigated agriculture is therefore essential for sustaining the production of wheat, maize, rice, cotton, vegetables, orchards, and forage crops (Kang et al., 2017). However, increasing water demand from agriculture, industry, urbanization, and ecosystem conservation, combined with climate change impacts, has intensified pressure on water resources and ecological systems (Piao et al., 2010).

The Loess Plateau in the middle reaches is globally recognized for severe soil erosion and sediment transport, contributing to the Yellow River's exceptionally high sediment load and creating significant challenges for irrigation and drainage infrastructure management (Fu et al., 2011). Representative irrigation districts, including Hetao, Ningxia, Fen River, and the lower Yellow River irrigation systems, illustrate diverse challenges such as salinization, groundwater overexploitation, drainage congestion, and competing water demands (Li et al., 2018; Qin et al., 2013; Zhang et al., 2020).

With the implementation of China's strategy for the Ecological Protection and High-Quality Development of the Yellow River Basin, increasing emphasis has been placed on integrating agricultural productivity, ecological conservation, climate resilience, and sustainable water management. Consequently, the YRB serves as an important case study for understanding agroecological transition in irrigated and drained systems under conditions of water scarcity and environmental change.

2.2 Analytical Framework

This study adopts a multi-level analytical framework integrating agroecology, Integrated Water Resources Management (IWRM), irrigation modernization, and socio-ecological systems theory to investigate the agroecological transition of irrigated and drained systems in the Yellow River Basin (YRB). The framework is designed to capture the complex interactions among agricultural production, water resources management, ecological conservation, and institutional governance across different spatial and management scales. Agroecological transition is inherently a cross-scale process involving biophysical, technological, economic, social, and governance transformations, requiring coordinated actions from farm-level management to basin-wide policy interventions (Wezel et al., 2020).

The analytical framework is structured around three interconnected levels: the farm level, the territorial level, and the basin-system level. These levels are linked through water flows, ecological processes, institutional arrangements, and socio-economic interactions, providing a comprehensive perspective on irrigation sustainability and agroecological transformation in the YRB. The framework further incorporates key agroecological principles, including resource-use efficiency, ecosystem resilience, biodiversity conservation, circular nutrient management, and participatory governance (Altieri and Nicholls, 2017).

At the farm level, the analysis focuses on field-scale agricultural production systems and water management practices. Particular attention is given to irrigation technologies, soil-water interactions, crop systems, nutrient management, and drainage practices. This level examines how irrigation methods, soil moisture dynamics, salinity processes, crop selection, fertilizer use, and drainage management influence agricultural productivity, environmental performance, and resilience to climate variability. Farm-level indicators include irrigation water productivity, soil health, nutrient-use efficiency, reduction of agrochemical inputs, and adaptive capacity under changing climatic conditions (Perry et al., 2009).

At the territorial level, the framework examines irrigation districts as intermediate management units connecting individual farms with larger basin-scale water allocation systems. The analysis focuses on irrigation district governance, canal and drainage infrastructure, water allocation mechanisms, and landscape-scale ecological interactions. Particular emphasis is placed on institutional arrangements, participatory irrigation management, water user associations, sediment and salinity management, conjunctive use of surface water and groundwater, and ecological restoration along irrigation and drainage networks. This level highlights the importance of integrating agricultural production with ecosystem conservation and water resource management (Wang et al., 2015).

At the basin-system level, the framework adopts an integrated watershed perspective consistent with IWRM principles and China's ecological civilization strategy. Analysis focuses on interprovincial water allocation, ecological flow management, climate adaptation, and integrated watershed governance. This level addresses basin-wide challenges arising from competing agricultural, industrial, urban, and ecological water demands. It further evaluates the role of policy coordination, ecological compensation mechanisms, digital water governance, and climate adaptation planning in supporting sustainable

agroecological transition across the YRB (Global Water Partnership, 2000; Piao et al., 2010; Zhang et al., 2020).

Overall, the framework provides a comprehensive multi-scale approach for understanding the interactions among irrigation modernization, agroecological sustainability, and integrated river basin governance, thereby supporting the development of effective transition pathways for sustainable irrigation and drainage management in the Yellow River Basin.

2.3 Data Sources

This study employs a comprehensive literature review and policy analysis approach to investigate the agroecological transition of irrigated and drained systems in the Yellow River Basin (YRB). Multiple data sources were integrated to ensure the scientific rigor, reliability, and policy relevance of the analysis. The selected sources provide information on hydrology, irrigation engineering, agroecology, climate adaptation, water governance, ecological restoration, and agricultural sustainability within the basin.

The primary sources include peer-reviewed academic literature from both international and Chinese journals focusing on irrigation management, integrated water resources management (IWRM), agroecological transition, drainage systems, climate adaptation, and water-use efficiency. These studies provide evidence on irrigation technologies, crop-water relationships, groundwater dynamics, salinity evolution, and ecological restoration practices, particularly in representative irrigation districts such as Hetao and Ningxia (Perry et al., 2009).

In addition, reports and policy documents from international organizations, including the Food and Agriculture Organization of the United Nations (FAO), the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the Global Water Partnership (GWP), were reviewed to provide conceptual frameworks and global perspectives on sustainable irrigation development, agroecology, climate resilience, and integrated river basin management (FAO, 2021; UNESCO, 2020; Global Water Partnership, 2000).

National policy documents and strategic plans were also analyzed to understand China's evolving policy framework for water management and ecological protection, particularly the "Ecological Protection and High-Quality Development of the Yellow River Basin" strategy (Zhang et al., 2020). Furthermore, irrigation district management reports and technical assessments were consulted to obtain practical insights into irrigation modernization, drainage management, salinity control, and agricultural water allocation. Together, these diverse sources provide a robust scientific and institutional foundation for evaluating sustainable irrigation and agroecological transition pathways in the Yellow River Basin.

3. RESULTS AND DISCUSSION

3.1 Characteristics of Irrigated and Drained Agroecological Systems

3.1.1 Farm-Level Characteristics

At the farm level, agricultural production in the Yellow River Basin (YRB) is highly dependent on irrigation due to uneven precipitation distribution, high evapotranspiration rates, and increasing climate variability (Liu and Xia, 2004). In arid and semi-arid regions such as Ningxia, Inner Mongolia, Gansu, and northern Shaanxi, regulated surface water diversions and groundwater abstraction are essential for maintaining stable crop yields and supporting rural livelihoods.

The dominant cropping pattern in the basin is the wheat–maize double-cropping system, which requires substantial irrigation during critical growth stages (Kang et al., 2017). In recent decades, the expansion of cash crops, orchards, greenhouse vegetables, and forage production has further increased agricultural water demand. Traditional flood and surface irrigation methods remain widely used because of their low investment costs and long history of application. However, these systems are often

associated with low irrigation efficiency, high conveyance losses, excessive deep percolation, and non-uniform water distribution (Perry et al., 2009).

Another important characteristic of farm-level systems is the intensive use of fertilizers and agrochemicals. To maximize crop yields, many farmers apply nitrogen fertilizers beyond crop requirements, resulting in nutrient leaching, groundwater contamination, and non-point source pollution. Combined with excessive irrigation, these practices increase the risk of nitrate accumulation and eutrophication in downstream water bodies.

In saline-prone areas such as the Ningxia and Hetao irrigation districts, inadequate drainage infrastructure and improper irrigation management have contributed to secondary soil salinization and waterlogging. These problems reduce soil fertility, restrict root development, and ultimately lower agricultural productivity.

To address these challenges, irrigation modernization programs have increasingly promoted water-saving technologies, including drip irrigation, sprinkler irrigation, soil moisture monitoring, deficit irrigation, and precision fertigation systems. These technologies improve irrigation uniformity, optimize water application according to crop demand, and enhance nutrient-use efficiency while reducing water consumption and environmental impacts. Although significant improvements in agricultural water productivity have been achieved, adoption remains uneven due to financial, technical, and infrastructural constraints. Therefore, continued investment in farmer training, extension services, and policy incentives is essential to accelerate agroecological transition and improve the sustainability of farm-level irrigation systems throughout the YRB.

3.1.2 Territorial-Level Characteristics

At the territorial level, irrigated and drained agroecological systems in the Yellow River Basin (YRB) are organized around large-scale irrigation districts that integrate canals, reservoirs, diversion structures, pumping stations, drainage networks, and groundwater abstraction systems. These irrigation districts serve as critical management units linking farm-level production with basin-scale water allocation and ecological management. Representative systems such as the Hetao and Ningxia Irrigation Districts rely heavily on Yellow River diversions and play a vital role in regional food production and water resource regulation (Li et al., 2018).

Water distribution within these districts is achieved through hierarchical canal networks consisting of main canals, branch canals, lateral canals, and field channels. Parallel drainage systems are designed to remove excess irrigation water, regulate groundwater levels, and mitigate soil salinization risks. Such integrated irrigation-drainage infrastructure is essential for maintaining agricultural productivity in the arid and semi-arid regions of northern China where precipitation is insufficient to support reliable crop production.

Despite their importance, territorial irrigation systems face several significant challenges. Sediment accumulation caused by the exceptionally high sediment load of the Yellow River reduces canal conveyance capacity, increases maintenance costs, and lowers water delivery efficiency. In addition, inadequate drainage capacity in low-lying areas often leads to waterlogging and secondary salinization, particularly in the Hetao and Ningxia irrigation districts, where long-term irrigation and strong evaporation contribute to salt accumulation in soils.

Groundwater overexploitation has become another major concern as farmers increasingly rely on groundwater during periods of surface water shortage. Excessive pumping has contributed to declining groundwater tables, ecosystem degradation, and growing sustainability concerns (Qin et al., 2013). Furthermore, irrigation return flows and drainage water frequently contain elevated concentrations of nutrients, pesticides, and dissolved salts resulting from intensive agricultural production, thereby increasing risks of eutrophication and downstream ecological degradation.

To address these challenges, territorial-scale management increasingly promotes ecological drainage systems, drainage water reuse, constructed wetlands, and integrated surface water–groundwater management. The conjunctive use of groundwater and surface water, combined with optimized water allocation and reservoir regulation, has emerged as a key strategy for improving drought resilience and enhancing the long-term sustainability of irrigated agriculture in the YRB (Qin et al., 2013).

3.1.3 Basin-System Characteristics

At the basin-system level, the Yellow River Basin (YRB) is characterized by severe water scarcity, high ecological vulnerability, and increasing competition among agricultural, industrial, urban, and environmental water users (Liu and Xia, 2004). Despite its critical role in supporting national food production and economic development, the basin possesses limited water resources, with agricultural irrigation accounting for more than 70% of total water withdrawals (Wang et al., 2019). As a result, balancing water demands among different sectors while maintaining ecological sustainability remains a major challenge.

The basin experiences substantial spatial and temporal variability in precipitation and runoff, making water resource management inherently complex. Climate change has further increased hydrological uncertainty through rising temperatures, greater evapotranspiration demand, and more frequent drought events (Piao et al., 2010). Changes in glacier melt and runoff generation in the upper reaches, combined with declining streamflow in the middle and lower reaches, have increased the vulnerability of irrigation systems and agricultural production to water shortages (Chen et al., 2007).

A defining characteristic of the YRB is the strong interdependence between upstream and downstream regions. Upstream provinces prioritize hydropower generation, ecological conservation, and local development, whereas downstream regions depend heavily on stable river flows for irrigation, industry, and domestic water supply. Consequently, water allocation conflicts frequently emerge, particularly during drought periods when water availability declines (Yellow River Conservancy Commission, 2021). Ecological degradation remains another significant basin-scale concern. Historical overexploitation of water resources and excessive river diversions contributed to river flow intermittency, wetland degradation, desertification, biodiversity loss, and declining ecosystem resilience (Fu et al., 2011). Wetland shrinkage has been particularly pronounced, reducing the basin's capacity for flood regulation, groundwater recharge, nutrient retention, and habitat conservation.

In response, China's "Ecological Protection and High-Quality Development of the Yellow River Basin" strategy has strengthened ecological flow regulation, water allocation controls, pollution reduction measures, and climate adaptation planning (Zhang et al., 2020). However, increasing climate uncertainty and growing water demand continue to pose substantial risks. Therefore, integrated water resources management (IWRM), ecological restoration, adaptive governance, and cross-sector coordination are essential for ensuring long-term water security and promoting sustainable agroecological transition across the basin.

3.2 Methods Supporting Agroecological Transition

3.2.1 Technological Innovations

Technological innovation is a key driver of the agroecological transition of irrigated and drained systems in the Yellow River Basin (YRB). Faced with severe water scarcity, climate variability, ecological degradation, and growing agricultural demand, the basin increasingly relies on advanced technologies to improve water-use efficiency, strengthen climate resilience, and reduce environmental impacts (Kang et al., 2017).

Smart irrigation systems have emerged as one of the most important innovations. By integrating sensors, automated control systems, wireless communication technologies, and decision-support platforms, smart irrigation enables real-time optimization of water application according to crop requirements and environmental conditions (Zhang et al., 2021). Soil moisture monitoring, weather

forecasting, and crop growth assessment improve irrigation scheduling and reduce unnecessary water use while maintaining agricultural productivity.

Remote sensing-based evapotranspiration (ET) monitoring has also become an important tool for irrigation management. Satellite imagery, unmanned aerial vehicles (UAVs), and geographic information systems (GIS) provide continuous monitoring of crop water consumption, soil moisture conditions, vegetation health, and drought stress. These technologies support more accurate water allocation and facilitate basin-scale monitoring of agricultural water use and ecological conditions.

Artificial intelligence (AI)-assisted irrigation scheduling further enhances water management efficiency. By integrating meteorological information, soil moisture data, crop growth stages, and historical irrigation records, AI-based systems can generate adaptive irrigation recommendations and improve decision-making under climate uncertainty (Li et al., 2022). Such systems are particularly useful in large irrigation districts where water allocation is complex and dynamic.

Controlled drainage systems represent another important innovation. By regulating groundwater levels and drainage discharge through adjustable structures, controlled drainage can reduce nutrient losses, improve soil moisture retention, and mitigate salinity accumulation. In addition, drainage water reuse has gained increasing attention as a strategy for supplementing irrigation supplies in water-scarce regions, although careful management is required to prevent salinity and pollution problems.

Salt balance modeling technologies also contribute to sustainable irrigation management by simulating salinity accumulation and leaching processes under different irrigation and drainage conditions. These models support the design of appropriate water management strategies, particularly in saline-prone areas of the YRB.

Overall, the integration of precision irrigation, digital water management, AI applications, controlled drainage, and salinity management technologies has significantly improved water productivity and environmental performance. However, wider adoption will require continued investment in infrastructure, technical training, financial support, and institutional capacity building.

3.2.2 *Ecological Approaches*

Ecological approaches have become increasingly important in supporting the agroecological transition of irrigated and drained systems in the Yellow River Basin (YRB). Unlike traditional irrigation modernization, which focuses primarily on engineering efficiency and infrastructure development, ecological approaches aim to restore ecosystem functions, improve biodiversity, enhance environmental resilience, and strengthen the long-term sustainability of agricultural landscapes (Wezel et al., 2020). Such approaches are particularly relevant in the YRB, where intensive agricultural development and prolonged water resource exploitation have contributed to wetland degradation, soil erosion, salinization, biodiversity loss, and agricultural pollution.

Wetland restoration and rehabilitation are among the most important ecological interventions. Natural and constructed wetlands provide multiple ecosystem services, including water purification, nutrient retention, flood regulation, groundwater recharge, and biodiversity conservation (Mitsch and Gosselink, 2015). In many irrigation districts, restored wetlands help intercept nutrients, sediments, and salts transported by agricultural drainage water, thereby reducing downstream pollution and enhancing ecological resilience.

The establishment of biodiversity corridors is another important strategy for improving habitat connectivity and ecosystem stability. Ecological corridors linking rivers, wetlands, riparian zones, shelterbelts, and agricultural landscapes facilitate species movement, enhance biological pest control, and support pollination services while strengthening climate adaptation capacity.

Conservation tillage practices, including reduced tillage and no-tillage systems, contribute to soil conservation by minimizing erosion, improving soil structure, increasing soil organic carbon, and enhancing soil moisture retention (Lal, 2004). These practices are particularly valuable in the Loess Plateau region, where soil erosion has historically posed significant challenges to agricultural sustainability.

Organic amendments such as compost, manure, biochar, and crop residues further improve soil fertility, nutrient cycling, microbial activity, and water-holding capacity while reducing dependence on synthetic fertilizers. Agroforestry systems, which integrate trees and shrubs into agricultural landscapes, provide additional benefits including carbon sequestration, wind erosion control, microclimate regulation, and biodiversity enhancement.

Ecological buffer zones established along canals, drainage ditches, and riverbanks help reduce nutrient runoff and sediment transport while improving water quality and providing habitats for wildlife. Collectively, these ecological approaches enhance ecosystem services, strengthen agricultural resilience, and complement technological and institutional innovations. Their integration into irrigation modernization programs is essential for achieving sustainable agroecological transition in the Yellow River Basin under increasing environmental and climate pressures.

3.2.3 *Institutional and Governance Reforms*

Institutional and governance reforms are critical for supporting the long-term agroecological transition of irrigated and drained systems in the Yellow River Basin (YRB). While technological innovations and ecological restoration measures improve water-use efficiency and environmental performance, their effectiveness depends largely on appropriate governance structures, policy frameworks, and stakeholder participation (Ostrom, 1990). Given the complex interactions among agriculture, water resources, ecological protection, and climate adaptation, integrated institutional arrangements are essential for achieving sustainable water management across the basin.

One of the most important governance mechanisms is the establishment of Water User Associations (WUAs), which enable farmers and local water users to participate in irrigation management, infrastructure maintenance, fee collection, and conflict resolution. In many irrigation districts of the YRB, WUAs have improved water allocation efficiency, strengthened communication between farmers and irrigation authorities, and enhanced transparency and accountability in water management.

Volumetric water pricing has also emerged as an effective policy instrument for promoting water conservation. Unlike traditional area-based charging systems, volumetric pricing links water fees directly to actual water consumption, thereby encouraging farmers to adopt water-saving technologies and improve irrigation practices. Pilot projects in northern China have demonstrated the potential of this approach to reduce agricultural water withdrawals while maintaining crop productivity.

Water rights allocation and quota systems are additional institutional tools for addressing the basin's severe water scarcity. Clearly defined water rights can improve allocation efficiency, prevent overexploitation, and facilitate flexible water management through mechanisms such as water trading and transferable water-use permits. These reforms support the reallocation of water resources toward more efficient and sustainable uses.

Ecological compensation mechanisms have also become increasingly important for promoting environmental protection and ecosystem restoration. Through financial incentives and policy support, upstream communities and farmers are encouraged to undertake conservation activities that generate downstream ecological benefits, including wetland restoration, ecological flow protection, and water-saving agriculture.

Participatory governance further strengthens agroecological transition by involving farmers, local communities, researchers, irrigation managers, and government agencies in decision-making processes. Such participation improves policy legitimacy, enhances local adaptive capacity, facilitates

knowledge exchange, and promotes long-term sustainability. Overall, institutional reforms provide the governance foundation necessary to integrate technological innovation, ecological restoration, and sustainable water allocation, thereby supporting resilient and sustainable agroecological development in the Yellow River Basin.

3.3 *Integrated Transition Pathways*

The agroecological transition of irrigated and drained systems in the Yellow River Basin (YRB) requires an integrated framework that simultaneously addresses water scarcity, ecological degradation, climate change, and increasing socio-economic demands. Given the complex interactions among agricultural production, water resources, ecosystem conservation, and governance systems, isolated interventions are insufficient to achieve long-term sustainability. Instead, coordinated actions across technological, ecological, and institutional dimensions are necessary to promote resilient and sustainable agricultural development (Wezel et al., 2020).

Three major transition pathways are proposed to support agroecological transformation in the YRB: digital and smart water management, ecological irrigation modernization, and integrated basin governance.

The first pathway, Digital and Smart Water Management, focuses on the application of advanced information technologies to improve irrigation efficiency and adaptive management. The integration of big data, artificial intelligence (AI), remote sensing, cloud computing, and digital twin technologies enables real-time monitoring and optimization of water allocation (Li et al., 2022). Big data platforms can combine hydrological, meteorological, agricultural, and socio-economic information to support evidence-based decision-making and drought management. Remote sensing technologies, including satellites and unmanned aerial vehicles (UAVs), facilitate large-scale monitoring of crop water use, soil moisture, vegetation health, and ecological conditions. AI-assisted irrigation scheduling further improves irrigation precision by generating adaptive recommendations based on weather forecasts, crop growth conditions, and soil moisture data (Zhang et al., 2021). In addition, digital twin river basin systems provide dynamic simulation platforms for flood forecasting, drought management, ecological flow regulation, and climate adaptation planning.

The second pathway, Ecological Irrigation Modernization, emphasizes the integration of engineering improvements with ecosystem restoration and sustainable agricultural practices. Water-saving technologies such as drip irrigation, sprinkler systems, canal lining, and precision fertigation remain essential for improving irrigation efficiency (Kang et al., 2017). However, ecological modernization extends beyond infrastructure by incorporating soil restoration, wetland conservation, biodiversity enhancement, and circular nutrient management. Conservation tillage, organic amendments, crop rotation, and biochar application can improve soil fertility, water retention, and carbon sequestration (Lal, 2004). Wetland restoration and ecological buffer zones contribute to nutrient retention, flood regulation, biodiversity conservation, and groundwater recharge (Mitsch and Gosselink, 2015). Furthermore, recycling crop residues, livestock manure, and treated drainage water supports circular nutrient management while reducing environmental pollution.

The third pathway, Integrated Basin Governance, addresses the institutional dimension of agroecological transition. Effective governance is required to balance agricultural production, ecological protection, and climate adaptation across the basin. Strengthening coordination among water, agriculture, environmental, energy, and land management sectors can improve policy coherence and reduce institutional fragmentation (Global Water Partnership, 2000). Climate adaptation planning should incorporate drought preparedness, flexible water allocation mechanisms, and ecosystem-based adaptation strategies to address increasing hydrological variability (Piao et al., 2010). Maintaining ecological flows is also critical for protecting river ecosystems, wetlands, and downstream environmental functions (Zhang et al., 2020). In addition, multi-level governance involving government agencies, irrigation districts, water user associations, scientific institutions, and local communities can enhance stakeholder participation, transparency, and adaptive management capacity.

Together, these three pathways provide a comprehensive framework for promoting resilient, climate-adaptive, and sustainable agroecological transition in irrigated and drained systems throughout the Yellow River Basin.

4. CONCLUSIONS

The Yellow River Basin represents one of the world's most complex irrigated agroecological systems under severe water scarcity and ecological stress. Irrigated and drained agricultural systems in the basin exhibit interconnected challenges across farm, territorial, and basin-system scales, including inefficient water use, salinization, ecological degradation, and climate vulnerability.

This study demonstrates that agroecological transition requires more than conventional irrigation engineering modernization. Sustainable transformation depends on integrating precision irrigation, ecological restoration, digital technologies, institutional reforms, and climate-adaptive governance. Controlled drainage, drainage water reuse, wetland rehabilitation, biodiversity-based landscape management, and participatory water governance provide important opportunities for improving resilience and sustainability.

Future development in the YRB should prioritize integrated water resources management (IWRM), ecological flow protection, open science-based monitoring systems, and digital water governance. Artificial intelligence, remote sensing, and smart irrigation systems can significantly enhance adaptive capacity under climate uncertainty.

Ultimately, the agroecological transition of irrigated and drained systems in the Yellow River Basin provides valuable lessons for other water-scarce river basins globally. Building resilient socio-ecological systems capable of balancing food production, environmental sustainability, and climate adaptation will be essential for achieving long-term sustainable development.

REFERENCES

- Altieri, M.A. and C.I. Nicholls. 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change*. 140(1): 33–45.
- Chen, J., Wang, H. and Li, S. 2007. Climate change and hydrological variability in the Yellow River Basin. *Journal of Hydrology*. 334(3–4): 374–388.
- FAO. 2021. *The State of the World's Land and Water Resources for Food and Agriculture – Systems at Breaking Point*. Food and Agriculture Organization of the United Nations, Rome.
- Fu, B., Y. Liu, L. Lü, C. He, Y. Zeng and B. Wu. 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. *Ecological Complexity*. 8(4): 284–293.
- Global Water Partnership. 2000. *Integrated Water Resources Management*. TAC Background Papers No. 4. Global Water Partnership, Stockholm.
- Kang, S., X. Hao, H. Du, L. Tong, X. Su, H. Lu and R. Li. 2017. Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. *Agricultural Water Management*. 179: 5–17.
- Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*. 304(5677): 1623–1627.
- Li, X., Y. Li and H. Wang. 2018. Irrigation modernization and salinity management in the Ningxia irrigation region of China. *Irrigation and Drainage*. 67(5): 654–666.
- Li, Y., H. Wang and X. Zhao. 2022. Artificial intelligence-assisted irrigation scheduling for sustainable agriculture under climate variability. *Agricultural Systems*. 198: 103376.
- Liu, C. and X. Xia. 2004. Water problems and hydrological research in the Yellow River and the Huai and Hai River basins of China. *Hydrological Processes*. 18(12): 2197–2210.
- Mitsch, W.J. and J.G. Gosselink. 2015. *Wetlands*. 5th Edition. John Wiley & Sons, Hoboken.
- Ostrom, E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press, Cambridge.

- Perry, C., P. Steduto, R.G. Allen and C.M. Burt. 2009. Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management*. 96(11): 1517–1524.
- Piao, S., P. Ciais, Y. Huang, Z. Shen, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma and Y. Ding. 2010. The impacts of climate change on water resources and agriculture in China. *Nature*. 467(7311): 43–51.
- Qin, D., S. Kang and R. Li. 2013. Conjunctive use of surface water and groundwater in the Yellow River Basin. *Water Resources Management*. 27(2): 379–392.
- UNESCO. 2020. *United Nations World Water Development Report 2020: Water and Climate Change*. UNESCO Publishing, Paris.
- Wang, Y., X. Chen and L. Guo. 2019. Water scarcity and agricultural sustainability in the Yellow River Basin under changing climate conditions. *Sustainability*. 11(18): 4872–4888.
- Wezel, A., H. Herren, J. Kerr, E. Barrios, A. Rodrigues Gonçalves and F. Sinclair. 2020. Agroecological principles and elements and their implications for transitioning to sustainable food systems: A review. *Agronomy for Sustainable Development*. 40(6): 1–13.
- Yellow River Conservancy Commission. 2021. *Yellow River Water Resources Bulletin 2020*. Yellow River Conservancy Commission Press, Zhengzhou.
- Zhang, X., Y. Liu and B. Wang. 2020. Ecological protection and high-quality development in the Yellow River Basin: Policy framework and implementation pathway. *China Population, Resources and Environment*. 30(10): 1–10.
- Zhang, Y., S. Kang and J. Liu. 2021. Smart irrigation technologies and water-saving agriculture in China: Progress and future prospects. *Agricultural Water Management*. 249: 106801.