

Research on the Dilemma Analysis and Optimization Path of Green and Low-Carbon Transformation in China's Agriculture

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Abstract: As a major source of greenhouse gas emissions, agriculture's green and low-carbon transformation is crucial for achieving coordinated development of ecological security and food security. This paper analyzes the systemic challenges facing China's agricultural green and low-carbon transformation from three dimensions—technology, economics, and structure—including inadequate technology adaptation and diffusion barriers, input shortages and imbalanced return cycles, regional development imbalances, and extensive industrial structures. Building on this analysis, the paper proposes a three-pronged transformation pathway—"technology convergence to empower production optimization, factor restructuring to strengthen economic support, and structural adjustment to drive coordinated development"—by integrating perspectives on digital economy empowerment, technological innovation-driven approaches, and institutional coordination safeguards. This framework aims to provide theoretical reference and practical insights for China's sustainable agricultural development and the achievement of its dual carbon goals.

Keywords: Agricultural carbon emissions; Green and low-carbon transition; Dual carbon goals; Coordinated development

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1. Introduction

Global climate change has emerged as a critical global challenge threatening human survival and development. Reducing greenhouse gas emissions and achieving carbon peaking and carbon neutrality have become a shared international consensus^[1]. As the world's largest developing country, China has explicitly set the strategic goals of "reaching peak carbon emissions before 2030 and achieving carbon neutrality before 2060", integrating green and low-carbon transformation into its national economic and social development^[2]. Agriculture, as a pillar industry of the national economy, serves as both the core safeguard for food security and the foundational sector for economic development, while also being a significant source of greenhouse gas emissions.

Currently, agricultural carbon emissions account for 6.7% of China's total emissions, ranking as the fourth

largest source after energy, industry, and transportation ^[3]. China's primary agricultural emissions consist of CH₄, N₂O, and CO₂, with CH₄ possessing a global warming potential 28 times that of carbon dioxide and N₂O reaching 265 times ^[4]. China's agriculture is undergoing a critical transition from traditional extensive farming to modern intensive practices. The conventional "high-input, high-yield, high-emission" production model has led to increasingly stringent resource and environmental constraints. The decline in farmland quality, intensified non-point source pollution, and rising carbon emissions are intertwined, severely hindering sustainable agricultural development. Concurrently, agricultural ecosystems possess substantial carbon sink potential. Measures such as soil carbon sequestration and straw resource utilization can effectively offset part of these emissions, offering inherent advantages for green and low-carbon agricultural transformation.

Against the backdrop of rural revitalization, advancing green and low-carbon agriculture is no longer merely an ecological imperative but an essential choice for ensuring food security and boosting farmers' incomes. However, this transition faces multiple constraints, including technological limitations, funding gaps, and structural disparities. Therefore, systematically analyzing the core challenges of agricultural carbon emissions and exploring scientifically viable pathways for green and low-carbon transformation holds significant theoretical value and practical significance for achieving the unity of ecological, economic, and social benefits in agriculture, as well as advancing the implementation of the "dual carbon" goals.

2. Analysis of current agricultural carbon emissions

In recent years, China's total agricultural carbon emissions have shown a stable yet declining trend, though they remain at a relatively high level ^[5]. From the perspective of emission sources, China's agricultural carbon emission structure exhibits significant regional variations ^[6]. Currently, the primary sources of agricultural carbon emissions in China are: (1) Input emissions from agricultural resources, with fertilizer and pesticide use being the core sources; (2) Methane emissions from paddy fields, where rice cultivation intensifies methanogenic bacterial activity in soil, generating substantial methane; (3) Emissions from livestock and poultry farming, primarily methane from intestinal fermentation and greenhouse gas emissions from manure management; (4) Energy consumption emissions, encompassing agricultural machinery operations, irrigation, and other processes ^[7]. China's agricultural carbon emissions exhibit significant regional disparities. Eastern regions feature highly intensive agriculture, constrained arable land resources, and high fertilizer application rates, resulting in elevated emissions. However, their advanced technological capabilities offer substantial reduction potential. Central and western regions possess abundant arable land but rely on extensive production methods, with prominent issues such as straw burning and uncontrolled livestock waste discharge ^[8].

3. Deconstructing the challenges of green and low-carbon agricultural transformation

While China has made progress in advancing green and low-carbon agriculture with preliminary adoption of certain low-carbon technologies, its implementation faces systemic challenges across multiple dimensions—technological, economic, and structural. These intertwined and mutually constraining obstacles severely impede the nation's agricultural transformation.

3.1. Insufficient innovation, poor adaptability, and impeded diffusion of agricultural technologies

Agricultural technological innovation serves as the core driver for green and low-carbon transformation and is essential for achieving sustainable agricultural development. However, China's current low-carbon agricultural development reveals three prominent issues: weak innovation core, inadequate regional adaptability, and inefficient diffusion channels. First, China's core low-carbon technological innovation faces bottlenecks, with key technological breakthroughs progressing slowly. Most current agricultural low-carbon R&D focuses on incremental improvements to traditional emission reduction methods, lacking breakthrough technologies that address carbon emission challenges at the production source. Second, there is a disconnect between technological suitability and regional production conditions. China's vast territory features pronounced climatic differences between north and south, diverse soil types across eastern, central, and western regions, and highly varied farming and livestock models. Yet existing low-carbon technologies are predominantly generic designs, lacking specialized development for specific regions. Finally, the technology diffusion system suffers from a "breakdown", with prominent "last-mile" promotion challenges: On one hand, grassroots agricultural extension agencies face staffing shortages and varying levels of expertise, struggling to meet farmers' needs for personalized guidance on low-carbon technologies. On the other hand, farmers harbor misconceptions of "hesitation to try and reluctance to adopt", partly due to the high upfront costs and lack of immediate returns for some low-carbon technologies. Compounded by insufficient demonstration models, farmers worry that poor technology performance could harm yields, leading to low acceptance and enthusiasm for new low-carbon approaches.

3.2. Agricultural investment confronts funding shortages and return imbalances

Agricultural green and low-carbon transformation constitutes a long-term, systemic endeavor involving technology R&D, equipment replacement, infrastructure development, and farmer subsidies—all demanding substantial and sustained capital investment. However, China's current agricultural low-carbon investment framework faces significant challenges: narrow financing channels, insufficient aggregate supply, and imbalanced investment returns. First, the total investment volume is insufficient, and a diversified investment mechanism has yet to fully take shape. Agricultural low-carbon projects possess distinct public goods attributes, characterized by substantial upfront investments, extended return cycles, and relatively high market risks. This discourages social capital participation, with most investors preferring sectors offering more immediate returns. Second, financing channels remain narrow. Agricultural operators continue to face severe difficulties in accessing capital and high financing costs. Traditional agricultural entities are predominantly small-scale farmers with limited collateral assets and low credit ratings, making it challenging to meet the lending criteria of banks and other financial institutions. While new financing methods like digital finance and green credit have been piloted in some developed regions, their adoption in remote rural areas remains limited due to lagging digital infrastructure and insufficient financial service coverage. Consequently, the emission reduction potential of digital inclusive finance has not been fully realized. Ultimately, most agricultural operators continue to grapple with the challenges of "difficult loan access, slow approval processes, and high interest rates." This creates an imbalance in the investment-return cycle, where short-term economic benefits struggle to sustain the momentum for transformation. The emission reduction benefits of most low-carbon agricultural technologies require long-term accumulation to materialize, yet their short-term economic returns often fall short of traditional high-input, high-yield production models. Farmers and agricultural operators, driven by the pursuit of immediate gains, lack the intrinsic motivation to proactively invest

in green and low-carbon transformation.

3.3. Regional imbalances in agricultural carbon emissions and extensive industrial practices

Imbalances in agricultural industrial structure and regional development patterns further complicate the transition to green, low-carbon agriculture. This manifests primarily through three core issues: regional development disparities, extensive industrial structures, and fragmented operational scales. These challenges significantly hinder the coordinated advancement of carbon emission caps and reduction efforts. First, China currently faces pronounced regional development disparities, with significant gaps in transformation progress between eastern, central, and western regions. The eastern regions, characterized by robust economic foundations, advanced digital infrastructure, sophisticated agricultural technologies, and strong policy support, have achieved relatively rapid progress in green and low-carbon agricultural transformation, establishing numerous smart agriculture and organic farming demonstration bases. In contrast, central and western regions face weak economic foundations, lagging digital infrastructure, and shortages of agricultural talent, resulting in notably slower transformation. Traditional, extensive agricultural production models persist in some areas, with persistent issues like open-field straw burning, excessive fertilizer and pesticide use, and uncontrolled discharge of livestock waste. These regions remain major sources of agricultural carbon emissions. Second, the industrial structure remains extensive, with weak control over carbon emissions across the entire chain. China's agricultural sector remains dominated by traditional crop cultivation and animal husbandry, with low value-added in processing and distribution. Ineffective coordination mechanisms for emissions reduction exist across these stages. In cultivation, high-carbon, low-yield crops dominate, while organic and ecological farming remain limited in scale. In animal husbandry, resource utilization rates for livestock and poultry waste remain low, resulting in high carbon emission intensity. In processing and distribution, the absence of low-carbon processing technologies and green logistics systems leads to substantial energy consumption and carbon emissions. Finally, fragmented operational scales hinder economies of scale. China's agricultural sector remains dominated by small-scale farmers, characterized by dispersed management models and low production efficiency, making it difficult to achieve large-scale application of low-carbon technologies and intensive management. Constrained by capital, technology, and information, small-scale farmers cannot afford the upfront investment in low-carbon technologies and equipment, nor can they establish standardized low-carbon production processes. This prevents the green and low-carbon transition from taking root at the grassroots level.

4. Optimizing pathways for green and low-carbon agricultural transformation

Based on the above analysis of challenges and considering China's actual agricultural development conditions and rural revitalization strategy, the study proposes a three-pronged approach to green and low-carbon agricultural transformation: "technology integration to empower production optimization, factor restructuring to strengthen economic support, and structural adjustment to drive coordinated development." Through multidimensional and systematic measures, this framework addresses transformation bottlenecks to advance high-quality, sustainable, green, and low-carbon agricultural development.

4.1. Technology integration for empowerment: Building a precise, adaptive, and diversified technology system

Science and technology represent the primary productive force, with the core driving force for agricultural green

and low-carbon transformation stemming from technological innovation and integrated application. First, increase investment in core technology R&D, improve innovation collaboration mechanisms, and establish an agricultural low-carbon technology innovation system guided by the government, led by enterprises, and involving industry-academia-research-application collaboration. The government should prioritize supporting R&D for high-end core technologies such as carbon capture and storage, precision agriculture, microbial carbon sequestration, and low-carbon agricultural machinery. Establish dedicated R&D funds to encourage joint research between scientific institutions and agricultural enterprises to overcome technical bottlenecks. For small-scale farmers' production needs, develop lightweight, low-cost, and user-friendly low-carbon equipment and technologies. Second, promote integrated technology applications to enhance regional adaptability. Deepen the integration of digital technologies with agricultural low-carbon solutions to build a smart low-carbon agriculture system. Leverage IoT, big data, and AI to advance applications like smart irrigation, precision fertilization, and green pest control. Achieve precise management of resource inputs—including water, fertilizers, and pesticides—to reduce energy consumption and carbon emissions during production. Finally, tailor differentiated technical solutions to regional production conditions, refine technology diffusion systems, bridge the “last mile” of promotion, strengthen grassroots agricultural extension systems, increase service outlets and technical personnel at the local level, and implement diversified “online + offline” extension services. Online platforms like short videos, WeChat official accounts, and live streaming should be used to disseminate low-carbon technology knowledge, operational methods, and success stories. Offline activities include technical training, on-site practical guidance, and demonstration-based construction. Establish a three-tiered technology extension network at the county, township, and village levels to cultivate rural technical leaders, enhance farmers' technical application capabilities, and guide them to proactively adopt and apply new low-carbon technologies.

4.2. Expanding financing channels: Establishing diversified investment and efficient return mechanisms

Adequate capital investment and reasonable return arrangements are critical enablers for driving green and low-carbon agricultural transformation. This transition requires addressing funding shortages and return imbalances through diversified investments, policy incentives, and value conversion pathways. First, strengthen government leadership to expand financing avenues and increase fiscal investment intensity. Establish a dedicated fund for low-carbon agricultural development, prioritizing support for technology R&D, infrastructure construction, and demonstration zone creation. Improve financing arrangements, like green loans and digital finance, to reduce financing barriers for agricultural operators. Offer low-carbon agricultural projects preferential interest rates, loan subsidies, and reduced guarantee fees to encourage banks, insurance companies, and securities firms to increase investments in low-carbon agriculture. Second, expand digital inclusive finance in rural areas. Improve financial service networks in remote rural regions by leveraging mobile payments and online lending to enhance coverage and accessibility. This enables smallholder farmers and agricultural operators in central and western regions to conveniently access financing support. Optimize input-return arrangements, shorten payback periods, and refine agricultural low-carbon subsidy policies. Expand subsidy coverage to include smallholder farmers and underdeveloped central-western regions as key beneficiaries, while increasing subsidy levels. and refine subsidy procedures to ensure funds are accurately disbursed. Finally, establish mechanisms for converting agricultural carbon sink value, accelerate the development of agricultural carbon trading markets, expand trading volumes, improve trading mechanisms, and reasonably determine carbon sink prices. This will facilitate the entry of

agricultural carbon sinks into the national carbon trading market, encourage enterprises and social organizations to purchase agricultural carbon sinks, and realize the value conversion of carbon sinks. Explore pathways to realize the value of ecological products by integrating low-carbon agriculture with eco-tourism and green agricultural product certification. This will enhance the ecological value of agriculture, increase operational income, strengthen internal motivation, drive agricultural industrial upgrading, extend industrial chains, and elevate value chains. Utilize methods such as deep processing of agricultural products, brand building, and rural e-commerce to enhance the added value of agricultural products.

4.3. Regional collaborative development: Building an agricultural carbon emission reduction, industrial upgrading, and scale operation framework

To address challenges such as regional development imbalances, simplistic industrial structures, and fragmented operational scales, regional collaboration, industrial upgrading, and scale operations are essential for achieving green and low-carbon agricultural transformation. First, promote coordinated advancement of agricultural green and low-carbon transformation through differentiated regional strategies to drive collaborative progress. Tailor agricultural green and low-carbon transformation plans based on local resource conditions and agricultural foundations: Central and western regions should prioritize strengthening agricultural infrastructure, technology dissemination, and personnel training. Policy support and financial assistance for remote areas should be increased, promoting locally suitable low-carbon technologies and production methods to gradually narrow regional transformation gaps. Secondly, optimize industrial structures to promote full-chain emission reductions. Adjust agricultural planting layouts by reducing high-carbon, low-efficiency crops while expanding organic and ecological farming areas. Promote practices like crop rotation, fallow land, and green manure cultivation to enhance soil carbon sequestration capacity. Enhance resource utilization of livestock and poultry waste by promoting manure application and biogas fermentation technologies to reduce emissions from animal husbandry. Foster deeper integration between agriculture and secondary/tertiary industries by developing smart agriculture, agritourism, and rural e-commerce to elevate industrial value-added and low-carbon progress, thereby establishing a full-chain low-carbon industrial system. Finally, cultivate new types of business entities and advance scaled operations. Actively foster new agricultural business models such as family farms, farmer cooperatives, and agribusinesses. Support their expansion through land transfers and equity participation to achieve scaled and centralized agricultural operations. Improve land transfer policies and strengthen benefit-sharing mechanisms to ensure farmers receive stable incomes within scaled operations.

5. Conclusion

Currently, China's agricultural green and low-carbon transition faces multi-level systemic challenges. Intertwined issues—including insufficient technological adaptability and barriers to adoption, inadequate capital investment and uneven returns, regional development imbalances, and industrial simplification—are constraining the transformation process. Achieving this transition requires a three-pronged approach: “technology integration for empowerment, factor restructuring for support, and structural adjustment for propulsion.” Through multi-level coordination and multi-factor interaction, people can simultaneously secure food safety and reduce carbon emissions. Moving forward, people must strengthen policy coordination, deepen technological innovation, and refine benefit-sharing mechanisms. While safeguarding grain production capacity, people should pursue sustained

reductions in agricultural carbon emissions to drive China's green and low-carbon agricultural transformation.

Disclosure statement

The author declares no conflict of interest.

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