Optimization Analysis of Carbon Emission Reduction Paths in Agricultural Transformation Driven by Intelligence

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Abstract. Against the backdrop of the advancement of the carbon peaking and carbon neutrality goals and the accelerated high-quality transformation of agriculture, the regulation of agricultural carbon emissions has become a key measure to realize the coordinated development of ecology and agriculture. Faced with the predicaments of extensive mode, low efficiency and continuously diminishing marginal benefits in traditional agricultural emission reduction, this study focuses on the enabling value of intelligent technologies for agricultural carbon emission reduction. We clarify the connotations of core concepts, analyze the influence paths and synergetic effects of intelligent technologies, and construct a dynamic carbon emission monitoring system, a path optimization model and a verification mechanism. Furthermore, an empirical study is conducted with cases such as the rice planting areas in the Yangtze River Delta to quantify emission reduction effects and explore regional differences and synergetic paths.The study finds that intelligent technologies can achieve significant emission reduction through whole-chain management and control, hybrid intelligent optimization algorithms can effectively screen the optimal emission reduction paths, and regional coordination can address the pain point of unbalanced emission reduction. This research can provide theoretical support and practical reference for the intelligent-driven low-carbon transformation of agriculture, and help the steady realization of agricultural carbon emission reduction goals.

1 Introduction

Agriculture is one of the important sources of carbon emissions, and its emission reduction effect is directly related to the overall advancement of the carbon peaking and carbon neutrality goals. Traditional agriculture has long relied on extensive production, resulting in persistently high carbon emission intensity, which also severely restricts the sustainable development of agriculture itself. At present, the deep integration of intelligent technologies and agriculture has become an irresistible trend of agricultural transformation, and also provides a new solution for agricultural carbon emission reduction. However, there are still obvious deficiencies in relevant research at present, such as the lack of precision in the optimization of emission reduction paths, poor adaptability to different regions, the homogenization of intelligent technology research without distinguishing heterogeneous emission reduction effects of specific technologies, and the disconnection between model construction and policy mechanism design.

From the perspective of intelligent-driven development, this paper systematically analyzes the internal mechanism of intelligent technologies promoting agricultural carbon emission reduction, constructs a scientific model system and conducts empirical tests, and explores optimized carbon emission reduction paths suitable for different regions. The core innovation of this study is reflected in three aspects: first, it constructs a "whole-chain technology empowerment-carbon emission dynamic regulation" theoretical analysis framework, clarifying the differentiated influence paths of different intelligent technologies on agricultural carbon emissions; second, it designs a hybrid intelligent optimization algorithm-based carbon emission reduction path optimization model, which realizes the balance of emission reduction effect, food security and economic benefits; third, it reveals the coupling mechanism between regional technological penetration differences and carbon emission reduction efficiency, and derives targeted cross-regional synergetic mechanisms based on model empirical results. The study aims to break through the practical bottlenecks of traditional agricultural emission reduction, promote the low-carbon and intelligent transformation of agriculture, and has both theoretical innovation and practical application value.

2 Research Foundation

2.1 Definition of Core Concepts

To clarify the research boundaries and standardize the research logic, the core concepts of this paper are precisely defined in combination with the cutting-edge practices of agricultural low-carbon transformation and

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the application of intelligent technologies. **Intelligent-driven** is essentially to rely on technologies such as the Internet of Things (IoT) and big data to promote the deep integration of the new generation of information technology with agricultural production, realize intelligent decision-making, precise management and control, and efficient operation in the whole process of agricultural production, and essentially solve the extensive predicament of agricultural production through data-driven development.Agricultural transformation specifically refers to the dynamic process of the industry transforming from the traditional high-carbon and extensive production mode to a low-carbon intensive, green and efficient, and sustainable mode, with the core of realizing the coordinated advancement of agricultural economic development, food security guarantee and ecological environmental protection[1].

Optimization of agricultural carbon emission reduction paths takes intelligent technologies as the core support. Aiming at the main sources of agricultural carbon emissions, it adjusts and upgrades the existing emission reduction paths through technological empowerment, model innovation and mechanism improvement, and constructs a carbon emission reduction system that balances feasibility, efficiency and sustainability, ultimately achieving the dual goals of reducing the total amount of agricultural carbon emissions and improving emission reduction efficiency[2].

2.2 Influence Paths of Intelligent Technologies on Agricultural Carbon Emissions

Intelligent technologies empower agriculture in an all-round way throughout the whole chain, effectively restrain and regulate carbon emissions, and form a clear transmission path. In the regulation of production factors, intelligent perception and big data decision-making technologies can accurately capture key information, and precisely supply chemical fertilizers, pesticides and irrigation water, reducing chemical emissions and energy consumption caused by excessive input of agricultural materials, thus curbing the growth of carbon emissions from the source[3].

In the management and control of the production process, intelligent agricultural machinery and equipment as well as intelligent livestock and poultry breeding systems can optimize the operation process, reduce fuel consumption of agricultural machinery, and decrease methane emissions generated by the fermentation of livestock and poultry manure. Through intelligent environmental regulation, the energy consumption of facility agriculture is optimized, and energy-based carbon emissions are reduced.

In the improvement of ecological carbon sequestration, intelligent remote sensing monitoring and carbon sink accounting technologies can accurately grasp the dynamic changes of carbon sinks in agricultural ecosystems such as farmland and forest land, provide data support for the optimization of carbon sequestration measures such as straw returning to the field and crop rotation and fallow, realize the coordinated advancement of emission reduction and sequestration, and construct a whole-process carbon emission management and control system[4].

3 Construction of Intelligent-Driven Agricultural Carbon Emission Reduction Models

3.1 Dynamic Carbon Emission Monitoring Model

To realize the precise management and control as well as dynamic tracking of agricultural carbon emissions, an intelligent technology-based dynamic agricultural carbon emission monitoring model is constructed, whose core is to realize real-time monitoring, precise accounting and risk early warning of carbon emissions through multi-source data fusion and scientific accounting methods[5]. As the basic support of the model, the data acquisition layer integrates multi-source data from remote sensing satellites, ground sensors, unmanned aerial vehicles and other sources, and adopts a weighted fusion algorithm to realize the standardized integration of multi-source data, with the formula as follows:

$$X=\sum_{i=1}^{n}\omega_i X_i \tag{1}$$

where ω is the weight of the i-th type of data, $X$is the standardized value of the i-th type of data, and n=3 is the number of data types[6].

The accounting method layer combines the Life Cycle Assessment (LCA) method with the carbon footprint accounting model. The formula for accounting agricultural carbon emissions throughout the whole life cycle under the LCA method is:

$$E_{LCA}=\sum_{k=1}^{m}E_k=\sum_{k=1}^{m}Q_k\times f_k \tag{2}$$

where E_{LCA} is the total carbon emissions throughout the whole life cycle, E_k is the carbon emissions of the k-th link, Q_k is the quantified value of the emission source in the k-th link, f_k is the corresponding emission factor, and m=4 is the number of core links[7].

Carbon footprint accounting focuses on specific production links, and the formula for carbon emissions of a single link is:

$$E_{CF}=Q\times f\times\eta \tag{3}$$

whereη is the loss coefficient.

The monitoring framework constructs a closed-loop system of "data acquisition - integration and analysis - carbon emission calculation - real-time early warning". The formula for the early warning threshold is:

$$T_E=\bar{E}\times(1+\alpha) \tag{4}$$

where$\bar{E}$s the historical average carbon emissions of the region, and$\alpha$is the early warning coefficient (taking the value of 0.1).

For case verification, a rice planting area in southern China is taken as an example. By deploying an intelligent monitoring system, data such as soil moisture and methane emission under the intermittent irrigation mode are accurately collected. Combined with the above formulas, it is calculated that the methane emission reduction of this mode reaches 18.3% compared with the traditional flooding irrigation mode, which verifies the practicability and accuracy of the model.

3.2 Carbon Emission Reduction Path Optimization Model

Centering on the core goal of intelligent-driven agricultural carbon emission reduction, a carbon emission reduction path optimization model that balances emission reduction effects, food security and economic benefits is constructed to minimize agricultural carbon emissions throughout the whole chain and maximize comprehensive benefits[8]. The objective function of the model is set to minimize the total agricultural carbon emissions throughout the whole chain, with the formula:

$$\min E_{total} = \sum_{j=1}^{4} E_j = \sum_{j=1}^{4} \sum_{i=1}^{n_j} Q_{ji} \times f_{ji} \tag{5}$$

where E_{total} is the total carbon emissions throughout the whole chain; j=1-4 corresponds to the planting, breeding, processing and transportation links respectively; Q_{ji} is the number of emission sources in the j-th link; f_{ji} is the consumption of the i-th type of emission source in the j-th link; and f_{ji} is the corresponding emission factor.

The constraint conditions are set in line with the actual agricultural production, and the formula for the food security output constraint is:

$$\sum_{s=1}^{t} Y_s \geq Y_{mir} \tag{6}$$

where Y_s is the output of the s-th crop, t is the number of crop types, and Y_{mir} is the minimum grain output for regional food security.

The emission reduction amounts under different scenarios are calculated, and the optimal carbon emission reduction path is selected through comparison as show in figure 1.

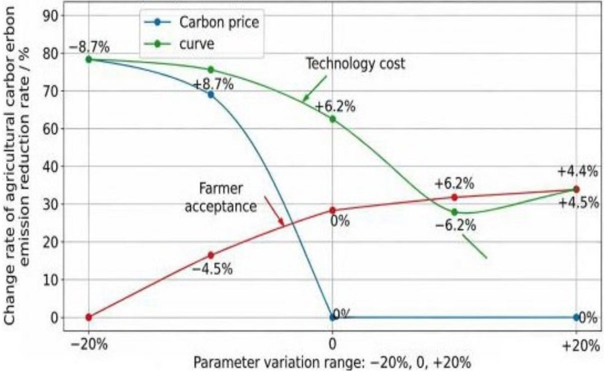

Figure 1 Sensitivity Analysis of Agricultural Carbon Emission Reduction Model Parameters

4 Empirical Analysis of Intelligent-Driven Agricultural Carbon Emission Reduction

4.1 Case Selection

To verify the practicability and universality of the intelligent-driven agricultural carbon emission reduction model, typical cases are selected for empirical analysis. The research focuses on the rice planting areas in the Yangtze River Delta, covering core producing areas such as Suzhou in Jiangsu Province, Jiaxing in Zhejiang Province and Wuhu in Anhui Province. The rice planting area in this region reaches 12 million hectares. As both a major rice producing area in China and a concentrated pilot area for intelligent agricultural technologies, it has been widely applying technologies such as intelligent irrigation, straw returning to the field and UAV plant protection, with a solid empirical foundation. Its planting mode and technical application level are highly representative, which can provide a reference for carbon emission reduction in rice planting areas across the country[9].

4.2 Quantitative Analysis of Emission Reduction Effects

The direct emission reduction effect is mainly reflected by comparing the carbon emission intensity per unit output before and after the application of intelligent technologies. In the case, the intelligent irrigation technology applied in the rice planting areas of the Yangtze River Delta refers to the integrated technology system based on IoT soil moisture sensors, meteorological monitoring stations and automatic water control valves, which realizes real-time monitoring of soil moisture, rice growth period water demand and meteorological conditions, and adopts intermittent irrigation with dynamic water quantity adjustment and water depth control (the water depth is controlled at 3-5cm in the tillering stage, and dry-wet alternating irrigation is implemented in the booting stage). After the application of this technology, methane emissions have decreased by 30%-50% compared with the traditional mode of flooding irrigation plus straw burning. Among them, the methane emission reduction in the Suzhou pilot, a core producing area, reaches 48.6%, and the carbon emission intensity per unit output also drops from 1.23kg CO_2-eq/kg to 0.63kg CO_2-eq/kg, showing a prominent direct emission reduction effect.as show in table 1.

Table 1: Quantitative Analysis of Smart-Driven Carbon Emission Reduction Effects in the Case Study Area

Dimension	Key Indicator	Traditional Mode (Baseline)	Post-Smart Technology Application
Direct Emission Reduction	Methane Emission Change Rate	Baseline (Traditional flooding + straw burning)	Decreased by 30%-50% compared to traditional mode
Direct Emission Reduction	Core Area (Suzhou) Methane Reduction	Baseline	Reduction reached 48.6%
Direct Emission Reduction	Carbon Intensity per Unit Yield	1.23 kg CO_2-eq/kg	Reduced to 0.63 kg CO_2-eq/kg

Overall Effectiveness	Comprehensive Evaluation	High emissions, high pollution	Direct emission reduction results are highly significant

The indirect emission reduction effect is mainly realized by improving the efficiency of resource utilization. Combined with regional monitoring data, after the application of intelligent technologies, the application of nitrogen fertilizer is reduced by 10%, corresponding to a reduction of 6.7 tons of CO_2 equivalent per hectare in nitrous oxide emissions; the utilization efficiency of irrigation water is increased by 25%, reducing indirect carbon emissions caused by agricultural irrigation energy consumption by about 8.2 tons of CO_2 equivalent per hectare; at the same time, the operation efficiency of agricultural machinery is improved by 30%, fuel consumption is reduced by 18%, and the contribution of indirect emission reduction reaches 22.3%[10].

The economic feasibility analysis focuses on the break-even point. Taking the intelligent emission reduction system for integrated farming and breeding in the case area as an example, its initial investment in intelligent technologies is 1,200 yuan per hectare, with an annual operation and maintenance cost of 300 yuan per hectare. Combined with the current carbon price of 80 yuan per ton of CO_2-eq, the break-even point is calculated to be an annual emission reduction of 18.75 tons of CO_2-eq per hectare. However, the actual annual emission reduction of the system reaches 42.5 tons of CO_2-eq per hectare, and the carbon emission reduction benefit reaches 3,400 yuan per hectare, far exceeding the input cost. In addition, carbon emissions are 40% lower than those of the traditional farming and breeding mode, which fully verifies the economic feasibility and sustainability of the intelligent emission reduction path as show in figure2.

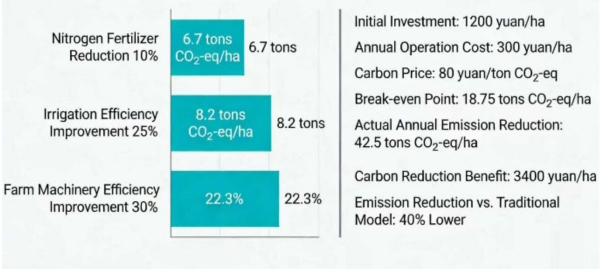

Figure 2 Sensitivity Analysis

4.3 Regional Differences and Synergetic Mechanisms

Combined with the differences in the level of agricultural development and the penetration rate of intelligent technologies in the eastern, central and western regions, a regional comparative analysis is carried out, and a cross-regional synergetic mechanism is constructed at the same time to promote the large-scale popularization of intelligent-driven agricultural carbon emission reduction.

The differences between the eastern, central and western regions are mainly reflected in three core dimensions: in terms of technology penetration rate, it reaches more than 65% in the eastern region (such as the Yangtze River Delta and the Pearl River Delta), 40%-55% in the central region (such as Henan and Hubei), and less than 30% in the western region (such as Gansu and Guizhou); in terms of policy support, the annual low-carbon agricultural subsidy in the eastern region reaches 200 yuan per hectare, 120 yuan per hectare in the central region, and only 80 yuan per hectare in the western region; in terms of farmers' acceptance, it is 78% in the eastern region, 62% in the central region and 45% in the western region. These differences directly lead to the carbon emission intensity per unit output in the eastern region being 52.3% lower than that in the western region, with a significant gap in emission reduction effects as show in figure3

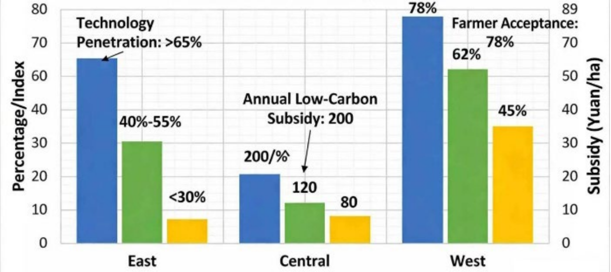

Figure 3 Regional Comparison ofSmart Agriculture Carbon Reduction

Based on the empirical results of the carbon emission reduction path optimization model, the study finds that the superposition of technological, policy and acceptance differences leads to the low overall efficiency of national agricultural carbon emission reduction, and the marginal emission reduction benefit of a single region is showing a diminishing trend. On this basis, two cross-regional synergetic mechanisms are derived by taking the optimal solution of the model for balanced regional emission reduction efficiency as the target. To address the problem of unbalanced emission reduction caused by regional differences, this paper constructs two major cross-regional synergetic mechanisms: on the one hand, the rice methane emission reduction cooperation zone in the Yangtze River Economic Belt, which integrates the intelligent technological advantages of the east, the planting resource advantages of the central region and the ecological advantages of the west, and builds a technology sharing platform. The eastern region exports intelligent monitoring and precise management and control technologies to the central and western regions, while the central and western regions provide pilot scenarios and data support. On the other hand, the horizontal compensation model in the Yellow River Basin, which relies on the carbon emission reduction amount obtained by intelligent monitoring to establish a carbon emission reduction compensation mechanism between the eastern, central and western regions, with a compensation standard of 100 yuan per ton of CO_2-eq. At the same time, a cross-regional carbon sink trading docking platform is built to promote the rational distribution of emission reduction benefits.

The implementation of the above two mechanisms needs to address three core obstacles: first, the administrative division barrier, the inconsistent agricultural carbon emission accounting standards and management systems among different provinces lead to the difficulty of cross-regional data interconnection and mutual recognition; second, the difficulty of compensation standard verification, the differences in regional agricultural production costs and carbon sink values may lead to disputes on the rationality of the 100 yuan/ton CO_2-eq compensation standard; third, the technical popularization barrier, the low digital infrastructure level in the central and western regions leads to the slow landing of intelligent technologies exported from the eastern region. To overcome the above obstacles, it is necessary to formulate a unified national agricultural carbon emission accounting specification, establish a dynamic compensation standard adjustment mechanism based on regional carbon emission reduction costs, and increase the investment in digital agricultural infrastructure in the central and western regions. Ultimately, a cross-regional coordinated emission reduction pattern is formed to improve the overall efficiency of national intelligent-driven agricultural carbon emission reduction.

5 Conclusions

This paper conducts a systematic study on the path optimization of smart-driven agricultural carbon emission reduction. It clarifies the whole-chain heterogeneous impact paths and synergistic effects of different intelligent technologies on agricultural carbon emissions, and constructs a dynamic carbon emission monitoring model and a path optimization model with the balance of emission reduction effect, food security and economic benefits. The constructed models have been empirically verified to be of high accuracy and practicality in the rice planting areas of the Yangtze River Delta. Case analysis confirms that specific intelligent technologies (e.g., the integrated intelligent irrigation technology system) can achieve significant emission reduction with economic feasibility. Based on the model empirical results, the study reveals the coupling mechanism between regional development differences and carbon emission reduction efficiency, and derives cross-regional synergetic mechanisms while analyzing their core implementation obstacles.

This research makes up for the deficiencies of homogeneous research on intelligent technologies and the disconnection between model construction and policy mechanism design in existing studies, and the constructed "technology heterogeneity-carbon emission efficiency-policy synergy" analysis framework enriches the interdisciplinary research on smart agriculture and low-carbon agriculture. However, the research still has limitations, such as limited case coverage and insufficient verification of long-term emission reduction effects of different intelligent technologies. In the future, the scope of cases can be expanded to cover different crop planting areas and animal husbandry breeding areas, combined with long-term monitoring data to compare the long-term emission reduction effects and cost changes of different intelligent technologies, further optimize model parameters, improve the cross-regional coordinated emission reduction mechanism by targeting implementation obstacles, and promote the large-scale and differentiated implementation of smart-driven agricultural carbon emission reduction.

Acknowledgment:

Self-funded projects of the Research Center for Meteorological Disaster Prediction, Early Warning and Emergency Management, Key Research Base of Humanities and Social Sciences of Sichuan Provincial Department of Education, Chengdu University of Information Technology, 2025.

Project Number: ZHYJ24-ZC18

Project Name: Analysis of Carbon Reduction Path Optimization in Agricultural Transformation Driven by Intelligence

Reference:

1. Xia Zhiye. Satellite High-Resolution Inversion of Anthropogenic Carbon Emissions in the Chengdu-Chongqing Economic Circle and Quantification of the Carbon Emission Reduction Driving Mechanism of Typical Industries Under Carbon Neutrality. Chengdu University of Information Technology, Sichuan Province, 2024-06-10.
2. Zhang Jun, Fang Shiqi, Tian Ya. The Carbon Emission Reduction Effect of E-Commerce Going to the Countryside: A Quasi-Natural Experiment Based on the Comprehensive Demonstration Policy of E-Commerce in Rural Areas[J]. Journal of Central South University of Forestry & Technology (Social Sciences), 2024, 18(06):22-35. DOI:10.14067/j.cnki.1673-9272.2024.06.003.
3. Li Zhiguo, Kong Weijia, Li Zhaozhe. The Carbon Emission Reduction Effect of Enterprise Digital Transformation Under a Common Supply Chain Network: Two-Way Spillover and Double Dividend[J]. Economic Perspectives, 2024, (12):36-54.
4. Han Qingxiao, Li Xiaotong, Guan Jian. Optimal Monetary Policy Choice Under the Impact of Carbon Emission Reduction: Influence Mechanism and Welfare Effect[J]. Journal of Financial Development Research, 2024, (12):16-30. DOI:10.19647/j.cnki.37-1462/f.2024.12.002.
5. Shi Weiting. Analysis of ESG Performance of Chinese State-Owned Enterprises Under Carbon Emission Reduction Policies[J]. Modern Industrial Economy and Informationization, 2024, 14(12):158-161. DOI:10.16525/j.cnki.14-1362/n.2024.12.052.
6. Shen Xinglin, Xu Jing, Yan Qiming, et al. Economic Modeling and Evaluation of Photovoltaic Power Stations Considering Carbon Emission Reduction Benefits[J]. Journal of Chongqing Electric Power College, 2024, 29(06):31-35.

7. Xu Jia, Liu Sha. Research on the Carbon Emission Reduction Effect of Green Credit: From the Perspective of the Intermediary Role of Technological Innovation in Energy Enterprises[J]. Coal Economic Research, 2024, 44(12):23-30. DOI:10.13202/j.cnki.cer.2024.12.009.
8. Yao Xiaojian, Huang Siying. Research on the Carbon Emission Reduction Path of China’s Oil and Gas Resource Development Industry: Analysis Based on the Kaya-LMDI Method[J]. Price: Theory & Practice, 2025, (11):103-109+291. DOI:10.19851/j.cnki.CN11-1010/F.2025.11.409.
9. Peng Huatao, Yang Ming. How Does Corporate Carbon Emission Reduction Promote Sustainable Entrepreneurship? Empirical Evidence Based on Microdata of Chinese Enterprises[J]. Journal of Management Studies, 2025, 10(03):1-24+139.
10. Luo Bu. Research on Green Building Design Methods and Life-Cycle Carbon Emission Reduction Optimization Driven by Digital Technology[C]// China Tendering Journal Co., Ltd. Forum on the Development of Secondary Industry Driven by New Quality Productivity and Innovation in Bidding and Procurement - Special Topic on Green Intelligent Manufacturing and Procurement Innovation. Tibet Architectural Design and Research Institute, 2025: 96-100.