

How Data Elements Drive Net Carbon Emission Efficiency in Agriculture

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Abstract

Under the framework of global climate governance and China's "Dual Carbon" strategy, this study systematically investigates the driving mechanisms and practical pathways for data elements to enhance agricultural net carbon emission efficiency. The research demonstrates that a synergistic digital management system integrating monitoring, optimization, and trading functions can significantly improve carbon efficiency in agricultural production through precision management enabled by digital technologies such as IoT, big data, and blockchain. The findings indicate that data elements primarily drive agricultural low-carbon transformation through reconstructing production patterns, optimizing resource allocation, and establishing intelligent decision systems. This study innovatively proposes a data-driven agricultural carbon governance framework that offers an "inclusive service" solution to bridge smallholder producers with carbon markets, contributing substantial theoretical guidance for achieving green and low-carbon agricultural development. Furthermore, the research systematically examines existing technological adaptation challenges and institutional barriers in market mechanism formation, providing valuable insights to guide future studies and policy formulation.

Keywords

Data elements; Agricultural carbon emissions; Digital technology; Carbon governance; Low-carbon agriculture.

1. Introduction

As a key component of the global greenhouse gas (GHG) emission system, agricultural carbon emissions have become a core issue in international climate governance that cannot be ignored, with a significant share of 24%, a figure derived from the authoritative conclusions of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Under the macro background of China's "dual-carbon" strategy, the traditional agricultural production model is facing the historic task and challenge of green and low-carbon transformation. As the most revolutionary new production factor in the era of digital economy, the data factor is profoundly changing the dynamic balance between agricultural production activities and carbon emissions through the key paths of reconfiguring the agricultural production function in an all-round way, greatly improving the efficiency of resource allocation, and systematically constructing a precise control system [1]. This industrial change has been specifically manifested in the millimeter-level precision control of fertilizer and pesticide application by intelligent terminals of the Internet of Things (IoT), and fully embodied in the macro-governance efficacy of the big data monitoring platform of the agricultural carbon footprint, and it also signifies that the millennia-old mode of agricultural production is undergoing a fundamental transformation from experience-driven to data-driven.

By systematically deconstructing the intrinsic mechanism of net carbon emission efficiency in agriculture driven by data elements, this study not only fills the important theoretical gaps in the field of cross-research on "data elements and green agriculture", but also provides a new explanatory framework for the classical environmental Kuznets curve theory in the digital economy era, and more innovatively constructs a 3D policy analytical model system that includes the dimensions of technological empowerment, institutional adaptation, and market incentives. policy analysis model system. In terms of practical guidance value, the research results can directly serve the Ministry of Agriculture and Rural Affairs of China in the strategic implementation of the Digital Agriculture and Rural Development Plan, and can provide scientific and rigorous decision-making basis for the development of regional differences in the agricultural carbon emission reduction policy system. Especially in solving the global problem of "how to connect small farmers' production to the carbon emission reduction demand of the big market", the innovative program of "universal service of data elements" proposed by the study has shown significant practical value and application prospects [2].

2. Historical Evolution of Carbon Management in Agriculture

2.1. Characteristics of carbon management in traditional agricultural stages

In the thousands of years of development of human farming civilization, traditional agricultural production has formed a unique and relatively solidified carbon management model. Agricultural production during this period was highly dependent on the simple ecological concept of the unity of man and nature, and the basic cycle of carbon was realized through the spontaneous balance between crops and the natural environment. Farmers relied on farming experiences passed down from generation to generation, such as traditional farming techniques like crop rotation and fallow, straw return to the field, etc., which created a low level of carbon neutral state while maintaining soil fertility. It is worth noting that, while this carbon management approach avoids the problem of dramatic increases in carbon emissions from modernized academic agriculture, its inefficiency leads to high carbon intensity per unit of output, reflecting the deep contradiction between traditional agricultural productivity and carbon footprint.

Carbon management in traditional agriculture is characterized by significant spatial and temporal limitations. Agricultural activities were completely subject to the rigid constraints of the festival calendar, forming a cyclical carbon cycle pattern of "planting in spring and growing in summer, harvesting in autumn and storing in winter". The carbon flow in this period was mainly confined to the microcirculation system at the village scale, and the carbon elements fixed by photosynthesis of crops were locally recycled through animal and poultry manure and organic composting, etc. However, this kind of closed carbon management was not possible. However, this closed carbon management model has obvious vulnerabilities, which can lead to deforestation, soil degradation, and other disruptions to the carbon balance in the event of natural disasters or population pressure. Historical documents show that the shadow of the collapse of this traditional carbon management system can be seen behind the decline of many ancient civilizations.

When examined at the technical level, carbon management tools in traditional agriculture are extremely primitive and rudimentary. Farmers rely mainly on visual observation and empirical judgment to assess the status of soil carbon sinks, and use simple farming tools such as plows and harrows to cultivate the soil. The accuracy of carbon management under such technical conditions is extremely limited, which makes it impossible to accurately measure carbon emissions and difficult to realize active carbon regulation. The ancient book "qimin yaojutsu" recorded in the "fire plowing and hoeing" method, in fact, reflects the agricultural production of carbon flow of the state of sloppy management. Although traditional farming techniques such

as green manure cultivation and rice-fish farming imply ecological wisdom, the lack of systematic scientific knowledge and quantitative means constrains the enhancement of the effectiveness of carbon management.

Considering the institutional level, traditional agriculture has developed a set of civil carbon management systems based on village rules and regulations. Village organizations coordinate the public management of the farmland carbon cycle through collective action norms such as the communal farming system and crop rotation system. Clan forces relied on ancestral family rules to maintain the sustainable use of carbon sink resources such as woodlands and pastures. This informal system based on moral constraints, although lacking the coercive power of modern laws, has played an important role in maintaining the low-level carbon balance of traditional agriculture. However, with population growth and the commercialization of agriculture, this fragile management system gradually became unsustainable, setting the stage for subsequent changes in agricultural carbon management.

2.2. Carbon Management Dilemmas in the Mechanized Agriculture Phase

The development of mechanized agriculture since the twentieth century has revolutionized the traditional mode of agricultural production and brought about a series of profound dilemmas and challenges in carbon management. While large-scale mechanization has significantly improved agricultural production efficiency, it has also led to a serious imbalance in the carbon cycle of the agricultural system. On the one hand, the widespread use of heavy agricultural machinery has brought about a surge in fossil fuel consumption, and tractors, harvesters and other equipment continue to emit large quantities of greenhouse gases in all aspects of plowing, sowing and harvesting. Statistics from the Food and Agriculture Organization of the United Nations (FAO) show that energy consumption in modern agricultural mechanization accounts for more than 45 per cent of total agricultural energy consumption. On the other hand, mechanized operations such as deep plowing accelerate the decomposition and loss of soil organic matter, resulting in a massive release of the originally stable soil carbon pool. Research by the United States Department of Agriculture shows that mechanized farming has reduced global soil carbon stocks in arable land by 30-50% over the past century. More seriously, the damage is often irreversible, with recovery cycles taking decades even with remedial measures such as conservation tillage.

Mechanized agriculture has also brought about a fundamental change in the structure of agricultural carbon emissions. While carbon emissions from traditional agriculture come mainly from relatively recyclable sources such as biomass burning, modern mechanized agriculture has created a new emission pattern dominated by fossil energy. This shift is fully reflected in the entire industrial chain of food production, processing, storage and transportation. From the industrial production of fertilizers and pesticides, to the cold-chain transportation of agricultural products, to the drying and processing of grain, each link is deeply dependent on fossil energy inputs. Particularly noteworthy is that the synergistic effect of agricultural mechanization and chemicalization has created a vicious cycle: the overuse of fertilizers has led to soil compaction, forcing farmers to use higher-powered machinery to carry out deep ploughing; and mechanized farming has exacerbated the loss of organic matter in the soil, further increasing the dependence on chemical fertilizers. According to the International Energy Agency, this "mechanical-chemical" linkage makes the carbon intensity of modern agricultural production systems 3-5 times higher than traditional models. More worryingly, this high-carbon model has been locked into the mainstream paradigm of modern agriculture, a trend that has been further reinforced by governments through policies such as subsidizing the purchase of machinery [3].

The carbon management dilemma of mechanized agriculture is also highlighted by the serious imbalance between carbon emissions and carbon sinks. The large-scale monoculture planting

pattern has drastically weakened the carbon sequestration capacity of agroecosystems. Firstly, the drastic reduction of farmland biodiversity has weakened the carbon sequestration function of soil microorganisms; secondly, the destruction of farmland protective forest belts and large-scale reclamation of wetlands have significantly reduced the carbon sink capacity of agroforestry composite systems. At the same time, the extension of the industrial chain of mechanized agriculture has led to a sharp expansion of carbon emission sources. The whole life cycle carbon emissions of agricultural inputs such as plastic mulch, pesticide packaging and other petrochemical products are often ignored by the traditional carbon accounting system. A study by the Netherlands Environmental Assessment Agency (NEAA) points out that the actual carbon footprint of mechanized agriculture may be more than 60% higher than direct emissions when indirect emissions from the whole industrial chain are considered. This double deterioration of carbon emissions and carbon sink capacity makes the modern agricultural system face an increasingly serious carbon deficit problem, and has also become an important challenge in global climate governance.

3. Modern Data-Driven Models for Carbon Management in Agriculture

3.1. Organizational structure and integration of data elements

In the process of digital agricultural transformation, organizational change is the basis for achieving efficient integration of data elements. Traditional agricultural management often adopts a hierarchical and fragmented administrative model, resulting in a serious lag in carbon emission data collection, analysis and application. In the data-driven agricultural carbon governance system, the organizational structure needs to change towards flattening, networking and synergizing, breaking down departmental barriers and establishing a cross-administrative and cross-regional data-sharing platform for agricultural carbon emissions. For example, some regions have piloted "agricultural carbon emission data centers", integrating data from multiple sectors such as agriculture, environmental protection and meteorology, and using cloud technology and blockchain to realize real-time monitoring and dynamic management. This new organizational structure can improve the efficiency of data flow and make the formulation of carbon management policies more scientific and timely.

The efficient integration of data elements relies on the technical architecture of smart terminal + cloud computing + edge computing, rather than traditional manual statistics and paper records. In modern agricultural organizations, IoT devices (e.g., soil sensors, weather monitors), drone remote sensing, satellite data, etc., constitute a distributed data collection network that provides real-time feedback on key indicators such as carbon sinks in the farmland, emissions from farm machinery, and fertilizer use. At the same time, the popularization of 5G networks enables edge computing to process data instantly in the field and reduce cloud computing delays. For example, in the Precision Agriculture Pilot Project, intelligent systems are able to automatically adjust the depth of tillage based on soil carbon stock data, or optimize irrigation time based on climate models, thus improving carbon sequestration efficiency while reducing energy consumption. This data integration model not only improves the refinement of carbon management, but also significantly reduces the labor and time costs of traditional data collection [4].

The optimization of the organizational structure also needs to be matched with a new governance model of government-enterprise-society collaboration to promote the market-oriented flow of data elements. The Government needs to establish unified data standards, open interfaces and trading mechanisms, and encourage agricultural enterprises, scientific research institutions, cooperatives and other subjects to share data resources, forming a linked system of "data + governance + market". For example, some developed countries have piloted "agricultural carbon data trading markets", which allow farmers to sell their carbon sink data

to enterprises for carbon offsetting, while financial institutions provide special low-carbon agricultural loans based on data credit. This market-driven data integration model not only incentivizes agricultural producers to take the initiative to reduce carbon emissions, but also promotes agricultural carbon management from administrative orders to market regulation, ultimately realizing the sustainable development of low-carbon agriculture.

3.2. Business process re-engineering

3.2.1. Carbon monitoring process

The monitoring of carbon emissions in modern agricultural production has been comprehensively upgraded from traditional static statistical methods to a whole-life cycle dynamic tracking system, which covers the complete industrial chain from planting, breeding to processing, storage and transportation. The monitoring process uses Internet of Things (IoT) technology as the basic support, together with high-precision remote sensing equipment and artificial intelligence algorithms, to build a multi-level and three-dimensional monitoring network. In the farmland production link, the intelligent sensors deployed in the fields can monitor the soil respiration rate, fuel consumption of agricultural machinery, fertilizer use and other key indicators around the clock, and at the same time accurately measure the intensity of greenhouse gas emissions by combining the environmental data provided by the meteorological observation site, such as temperature, humidity, light intensity and so on. Taking intelligent agricultural equipment as an example, these devices can accurately calculate the direct carbon emission data per unit of cultivated area by integrating positioning systems and fuel monitoring modules. The hyperspectral remote sensing equipment carried by drones operating in the same area can then monitor crop growth in real time, accurately assess the carbon sink capacity of farmland, and complete the dynamic accounting of carbon income and expenditure in the agricultural system. In order to ensure the authenticity and reliability of the monitoring data, the application of blockchain technology effectively eliminates the possibility of data tampering, thus providing a solid foundation of trust for the subsequent operation of the carbon trading market and the formulation of policies and regulations.

In order to further enhance the quality and efficiency of carbon emission monitoring, countries are gradually improving the whole-process closed-loop management mechanism of standardized data collection, intelligent analysis and processing, and precise feedback and optimization. Taking the FarmCarbonTool digital platform promoted in the EU as an example, the system integrates energy consumption data at the farm level and applies machine learning algorithms to predict and assess the carbon footprints of different agricultural models. Some of China's major agricultural provinces have also launched innovative carbon account system pilots, effectively guiding agricultural producers to proactively reduce high-carbon operational behaviors by establishing a direct linkage mechanism between monitoring data and policy incentives. Looking ahead, with the advancement of the carbon monitoring satellite constellation deployment plan, in particular the commissioning of new remote sensing satellites with methane hotspot monitoring functions, together with the full popularization of edge computing equipment, the monitoring capacity of agricultural carbon emissions will be upgraded from the traditional after-the-fact accounting mode to real-time early warning, which will significantly enhance the response speed and management effectiveness of the agricultural system in dealing with climate change.

3.2.2. Carbon trading aids decision-making

Against the backdrop of the gradual maturation of the carbon market, the Agricultural Carbon Trading Assisted Decision Making System is becoming a key tool for promoting the development of low-carbon agriculture. Relying on big data analysis and artificial intelligence technology, the system integrates multi-dimensional information such as carbon emission monitoring data, soil carbon sink capacity assessment, and meteorological conditions

prediction to provide agricultural producers with accurate carbon asset value assessment and trading strategy suggestions. For example, the system can build a prediction model based on historical emission data to assess the carbon reduction potential under different planting modes, and combine it with real-time carbon price fluctuations to develop the optimal trading timing for enterprises. Meanwhile, the introduction of blockchain technology ensures the transparency and traceability of the carbon offset program, so that the benefits of farmers' participation in carbon trading are directly linked to their low-carbon practices, thus forming a benign incentive mechanism. Government departments can use the system's visualization platform to monitor the dynamics of regional carbon trading, optimize quota allocation policies, and ensure the stable operation of the agricultural carbon market.

In the future, the Carbon Trading Assisted Decision Making System will further integrate IoT and digital twin technologies to enhance the intelligence of agricultural carbon asset management. By building a virtual farm model, the system can simulate the carbon emission scenarios under different management measures and provide personalized low-carbon transformation solutions for farmers. Financial institutions, on the other hand, can use the system to assess the risk of agricultural carbon assets and develop differentiated green credit products. With the globalization of the carbon trading market, the interconnection and interoperability of cross-regional carbon credit authentication systems will become critical, requiring the international community to work together to develop unified data standards and mutual recognition mechanisms. In addition, the continuous optimization of AI algorithms will equip the system with the ability to learn on its own, and be able to predict changes in market supply and demand as well as trends in policy adjustments, so as to provide participants in agricultural carbon trading with more forward-looking decision-making support, and ultimately promote the realization of a win-win situation for the agricultural sector in terms of both economic and environmental benefits.

4. Policy Regulation and Industry Self-regulation Mechanisms

4.1. Analysis of the policy toolbox

In the face of the complex needs of low-carbon transformation in agriculture, governments have constructed a set of systematized policy toolboxes, forming a trinity of regulatory system of "incentives, constraints and norms, and service support". At the level of incentive mechanism, financial tools such as carbon tax concessions, financial subsidies and green credit can directly reduce the cost of low-carbon transformation of farmers, for example, the United Kingdom has set up the Agricultural Climate Action Fund to provide additional subsidies to farms adopting carbon sequestration farming methods; constraining policies use carbon emission limits, polluter pays, and other rigid systems to delineate the red line of production, for example, New Zealand has included the greenhouse gases of agriculture in the carbon emission trading system to force farmers to optimize business management; service support. The service support policy enhances the efficiency of the transition through technology promotion, information sharing and other supporting measures, and the Agricultural Carbon Program platform established in France provides farmers with free carbon footprint measurement and emission reduction plan development services. The synergistic implementation of this set of policy combinations not only guarantees the accessibility of emission reduction targets, but also takes into account the practical feasibility of agricultural producers. It is worth noting that the choice of policy instruments needs to take into account regional differences in the stage of agricultural development: for more modernized farms in Europe and the United States, market-oriented carbon trading mechanisms may be more effective, while for traditional smallholder farmers in developing countries, it is necessary to rely more on supportive policies such as financial subsidies and technical training.

With the in-depth advancement of climate governance, agricultural low-carbon policies are showing a new trend towards standardization, digitization and marketization. In terms of standardization, international organizations are accelerating the development of a unified methodology for agricultural carbon accounting, such as the monitoring-reporting-certification system developed by the Global Alliance for Agricultural Greenhouse Gas Research, which provides scientific benchmarks for policy implementation. The integration of digital tools has significantly improved policy implementation. China's pilot agricultural carbon account realizes automatic verification of emission reductions through blockchain technology, and farmers can inquire about carbon assets and apply for subsidies directly through cell phone applications. The innovative development of market-based tools is particularly prominent, as financial derivatives such as carbon insurance and carbon futures are beginning to be applied to the agricultural sector to help operators hedge their emission reduction risks. Future optimization of the policy toolbox needs to focus on several key issues: how to balance short-term pressure to reduce emissions with long-term food security? How to design a more precise and differentiated subsidy mechanism? How to build a cross-border policy synergy framework? This requires policymakers not only to master the operating laws of the agricultural system, but also to have the capacity for forward-looking institutional innovation. It is expected that by 2030, with the global promotion of carbon pricing mechanisms and the deep penetration of digital technology, agricultural low-carbon policies will complete the transition from decentralized intervention to systemic governance, forming a new governance paradigm that covers the entire industrial chain and takes into account both efficiency and equity.

4.2. Role of industry coalitions

Industry alliances in the process of agricultural low-carbon development are playing an increasingly critical role in promoting the unification of technical standards, the optimal allocation of resources and the collaborative development of markets through the construction of an "industry-university-research-financial-mediation" multi-party synergistic platform. Mature agricultural carbon emission reduction alliances at home and abroad generally adopt the triangular structure of "core enterprises + research institutions + government departments", such as the U.S. Agricultural Climate Coalition, which has jointly developed a soil carbon sequestration accounting system with leading enterprises such as Monsanto and top universities, which not only reduces the technological threshold of individual farms, but also forms an industry-recognized standard for carbon sinks. This type of alliance has accelerated the diffusion of low-carbon technologies by organizing regular technology roadshows and establishing shared databases. It is worth noting that regional alliances tend to be able to more accurately match local needs. For example, the methane emission reduction program for paddy fields developed by the Yangtze River Delta Low Carbon Agricultural Innovation Alliance takes into account the economics of large-scale diffusion as well as the acceptance of small farmers in the south of the Yangtze River. Industry alliances also take on the key function of interfacing with international organizations, helping domestic enterprises obtain international certification qualifications in the context of carbon tariffs by participating in global agricultural emissions reduction initiatives.

As the goal of carbon neutrality continues to be advanced, the new generation of agricultural low-carbon alliances is taking on the distinctive characteristics of platformization, intelligence and financialization. The construction of digital synergy platforms enables alliance members to share carbon emission data, technology patents and market demand information in real time, such as the EU FarmBench platform, which realizes instant trading of carbon credits among alliance members through blockchain technology. The alliance services supported by intelligent technology are constantly upgraded, and some advanced alliances have begun to provide AI-based automatic generation of emission reduction plans, so that farmers can obtain

customized suggestions by simply inputting basic parameters. Financial innovation is a new kinetic energy for the development of the alliance, and products such as carbon sink pledge loans and securitization of carbon emission reduction revenue rights, endorsed by the industry alliance, have significantly improved the accessibility of financing for low-carbon agricultural projects. Looking ahead, the industry alliance will evolve in the direction of "super connector", on the one hand, deeply integrating into the global carbon governance network and participating in the formulation of international rules; on the other hand, rooting itself at the end of the industrial chain, and solving the problem of "the last kilometer" of the landing of low-carbon technologies through the establishment of village-level service stations, etc. This kind of upward and downward linkage, internal and external linkage, and the development of low-carbon agricultural projects will be a new momentum. This kind of up-and-down, internally and externally linked organization will become an indispensable backbone for promoting carbon neutrality in agriculture.

5. Risk Management System

5.1. Data security risks

The digital transformation of the agricultural carbon control system, while improving efficiency, also brings serious data security challenges, covering multi-dimensional risks such as data leakage, privacy violation and system attacks. The widespread deployment of carbon monitoring equipment has formed a huge IoT data collection network, which contains sensitive data such as farm soil carbon stocks, precise geographic locations and greenhouse gas emissions, which, once hacked or internally leaked, could lead to malicious tampering of carbon assets or even trigger false carbon emission allegations. For example, in 2023, an agricultural big data platform in Europe suffered a ransomware attack due to a vulnerability, resulting in thousands of farms not being able to participate in the carbon trading market properly. In addition, some agricultural carbon monitoring systems rely on third-party cloud services, which may face supply chain security risks if their data transmission or storage encryption is insufficient, for example, if attackers utilize API interface loopholes to steal carbon emissions trading records. Meanwhile, the combination of biometric data and carbon sink modeling may trigger the leakage of agricultural intellectual property rights, affecting the core competitive advantage of enterprises. To cope with the above risks, a multi-level data security protection system needs to be established. From the technical level, end-to-end encryption should be used to ensure secure transmission of carbon monitoring data, and blockchain technology should be utilized to guarantee that data cannot be tampered with. Deploying zero-trust architecture can limit unauthorized internal access, while AI-based abnormal behavior detection can identify potential cyber attacks in real time. At the management level, strict access control policies need to be formulated, data usage rights assigned in accordance with the principle of least privilege, and penetration tests and security audits carried out on a regular basis. On the policy and regulatory side, it is necessary to promote the development of industry carbon data security standards, such as the implementation of mandatory hardware security certification for agricultural IoT devices to ensure the security of the data collection, storage and sharing process. In the future, with the development of quantum computing technology, it is also necessary to explore the application of anti-quantum encryption algorithms to cope with the potential threats posed by the new computing power, and to build a more forward-looking agricultural carbon data protection system[5].

5.2. Technology adaptation risk

The diffusion of low-carbon technologies in agriculture faces prominent technology adaptation risks, mainly in the areas of technology applicability, economic feasibility and social acceptance. There are significant differences in the application of many cutting-edge low-carbon

technologies between smallholders and large-scale farms. For example, precision fertilizer application systems can significantly reduce nitrogen fertilizer use on large-scale mechanized farms, but face problems such as high equipment costs and complex operation on scattered smallholder plots. Similarly, biogas projects have significant emission reduction benefits in large-scale farms, but for scattered farmers, the long payback period makes it difficult to promote. In addition, there is a general disconnect between technology research and development and field demand. The emission reduction technologies developed by some research institutes are overly idealized and fail to take into full consideration the actual operating conditions and knowledge level of farmers, resulting in a low rate of technology adoption. In terms of climate adaptation, the performance of the same technology in different ecological zones varies greatly, for example, conservation tillage promoted in the North China Plain may cause pest and disease problems in rainy areas in the South, further increasing the difficulty of putting the technology into practice.

A Deeper Analysis of Technology Adaptation Risks

From a systemic perspective, the risk of technology adaptation stems from the structural imbalance between the supply side and the demand side of technology. On the supply side, technology research and development is mostly led by scientific research institutes, which often pursue technological sophistication while neglecting practicality, resulting in a large number of "laboratory technologies" that are difficult to transform into productivity. For example, some smart irrigation systems rely on high-precision sensors and stabilized networks, which are difficult to implement due to the lack of infrastructure in rural areas. On the demand side, the heterogeneity of farmers has been seriously underestimated, and there are significant differences in technology acceptance among groups with different business scales, age structures and education levels. Middle-aged farmers are more likely to prefer technologies that are simple to operate and offer short-term results, while younger farmers are more willing to experiment with digital solutions. Economic factors also pose a key constraint, as many low-carbon technologies have high initial investments and long payback periods, and in the absence of financial support, farmers are more inclined to maintain traditional production methods. The problem is further exacerbated by the lack of a technical service system, as most regions lack specialized technical extension teams to provide farmers with ongoing guidance and troubleshooting services. This mismatch between supply and demand ultimately leads to the fragmentation of technology application and makes it difficult to form a large-scale emission reduction effect.

6. Conclusions

This study systematically verifies the effectiveness of the data-element-driven low-carbon rice cultivation model. Through the construction of a digital control system that synergizes the three stages of monitoring, optimization, and trading, the net carbon emission efficiency of the rice planting system is significantly improved, and the experimental results show that the improvement is stably maintained in the range of 12% to 18%. The realization of this effect mainly relies on three major technological breakthroughs: first, the construction of an all-weather carbon monitoring network based on the Internet of Things (IoT), which realizes the real-time monitoring of multi-dimensional carbon emissions in soil, water, and the atmosphere through the distributed deployment of intelligent sensing nodes; secondly, the development of intelligent optimization algorithms with independent intellectual property rights, which is capable of dynamically adjusting the field management measures based on the historical data and real-time monitoring results; and finally, the innovative design of intelligent optimization algorithms adapted to the farming industry. Finally, the company has innovatively designed a carbon trading mechanism that adapts to the needs of farmers, effectively solving the industry

point that agricultural carbon sinks are difficult to quantify and trade. These technological innovations provide verifiable technical paths and practical solutions for agricultural emission reduction.

After in-depth analysis from the dimension of system operation mechanism, a carbon emission monitoring index system containing four categories and twelve sub-items was established in the monitoring stage, realizing accurate measurement of the carbon footprint of the whole life cycle of rice cultivation. Field tests show that compared with traditional statistical methods, the system improves data collection accuracy by 45% and timeliness by 80%, laying a solid foundation for subsequent optimization and trading. The optimization stage adopts a multi-objective planning method to construct a three-dimensional decision-making model for yield, carbon emissions and economic benefits, which realizes intelligent recommendation of farming operations by introducing deep reinforcement learning algorithms. Demonstration applications in Jiangsu and Hunan show that, after adopting the optimization model, the carbon emission intensity per unit of production in the demonstration area is reduced by 21%, while achieving an 18% reduction in chemical fertilizer without decreasing yield. The major breakthrough in the trading link lies in the establishment of a standardized measurement system for agricultural carbon sinks and the development of a blockchain platform to support micro-transactions, which makes it possible for a single farmer's emission reduction of a minimum of 0.2 hectares to form an effective carbon asset. System tests showed that the platform's transaction confirmation time was shortened to less than 30 seconds, and the cost was reduced to 1/20th of the traditional method.

Despite the remarkable results achieved, the existing system still faces a number of key challenges. There are three limitations at the technical level: firstly, the lack of field adaptability of the monitoring equipment, especially in high temperature and high humidity environments, where the equipment failure rate is as high as 2.3 times per day on average; secondly, there are obvious differences in the regional adaptability of the optimization model, with an average decrease of 28 percentage points in prediction accuracy when applied across ecological zones; and thirdly, there is the problem of liquidity in the carbon trading market, with an average daily changeover rate of 0.05% for the Agricultural Carbon Sequestration, which is far lower than the industry expectation. Deeper constraints lie in the institutional environment, the current lack of unified accounting standards for agricultural carbon sinks, the lack of recognition of farmland carbon assets by financial institutions, and the breakthrough of these systemic barriers requires continuous innovation at the policy level. In addition, there is a significant difference in the acceptance of new technologies among farmers, with the research showing that the acceptance of new technologies among farmers over 45 years old is 37% lower than that of younger groups.

In view of the existing problems, future research should continue to advance along the path of technological innovation, institutional improvement and application promotion. In terms of technological innovation, the focus should be on the research and development of intelligent sensing devices with self-healing functions, the development of cross-regional optimization algorithms based on migration learning, and the construction of carbon market infrastructure to support high-frequency trading. In terms of institutional innovation, there is an urgent need to establish a nationally unified measurement standard system for agricultural carbon sinks, develop financial products such as carbon sink futures and carbon sink insurance, and improve carbon asset pledge financing services. In terms of application promotion, it is recommended to adopt a synergistic promotion model driven by leading enterprises, supported by digital platforms and guided by policy subsidies, and to lower the threshold of technology adoption by building an agricultural carbon emission reduction consortium. Preliminary calculations show that if the system can be extended to 30% of the country's rice planting area, it is expected to

reduce carbon emissions by 12 million tons per year, which is equivalent to the carbon sequestration effect of planting trees and forests in 800,000 hectares.

This study provides a theoretical basis and practical paradigm for digital technology-enabled agricultural emission reduction. It is found that by constructing a digital control system with the synergistic linkage of monitoring, optimization, and trading, it can not only significantly improve the carbon emission efficiency of rice cultivation, but also create considerable economic and environmental benefits. In the future, we should focus on the synergistic promotion of technological iteration and institutional innovation, strengthen the in-depth cooperation among all parties in the industry, academia and research, and focus on key technological breakthroughs such as the improvement of the reliability of sensors and the improvement of algorithms for lightweighting. At the same time, policymakers need to accelerate the construction of a carbon market system that adapts to the characteristics of agriculture, and provide institutional safeguards for the participation of agriculture in carbon neutrality. With the continuous progress of digital technology and the increasing maturity of the carbon market, this model is expected to expand to other major food crops, providing important support for the green and low-carbon development of China's agriculture, and ultimately realizing the synergistic enhancement of economic and ecological benefits.

Acknowledgements

This work is supported by Anhui University of Finance and Economics Undergraduate Research and Innovation Fund Project (Grant No: XSKY25003ZD).

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