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Research on Low Carbon Transformation Strategies for Post operation and Maintenance of Land Consolidation Projects from the Perspective of Carbon Efficiency Calculation

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Abstract

This study focuses on the later operation and maintenance stage of land consolidation projects. Against the backdrop of the "dual carbon" goal, from the perspective of carbon efficiency measurement, it deeply analyzes the factors affecting carbon emissions and constructs a corresponding low-carbon strategy system. Through literature research, case analysis, and a combination of quantitative and qualitative analysis, it was found that the carbon emissions during the later operation and maintenance of land consolidation projects are influenced by multiple factors such as energy consumption, land use patterns, and agricultural inputs. Based on this, a low-carbon strategy system covering energy structure optimization, land use optimization, agricultural production management, carbon compensation and trading has been constructed. This study contributes to enriching the research content of carbon effects in land consolidation projects, providing guidance for the practice of land consolidation projects, and promoting the green and low-carbon development of the land consolidation industry. However, research has data limitations and low-carbon strategies face various constraints in practical applications. Future research can expand the scope of cases, conduct in-depth analysis of constraints, and explore collaborative development across multiple fields.

Keywords

Land consolidation project; Post operation and maintenance; Carbon efficiency calculation; Low carbon strategy.

1. Introduction

1.1. Research Background and Significance

1.1.1. Research Background

The global climate change situation is severe, with greenhouse gas emissions causing global warming, and human activities greatly disrupting the balance of the Earth's carbon cycle. Since the Industrial Revolution, the concentration of greenhouse gases such as carbon dioxide in the atmosphere has sharply increased. According to data from the International Energy Agency, global carbon dioxide emissions increased from approximately 22 billion tons to over 31.5

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billion tons from 1990 to 2020, causing a series of ecological and environmental problems that seriously threaten human survival and sustainable development. In this context, the "dual carbon" goal has emerged. In September 2020, China pledged at the 75th United Nations General Assembly to peak carbon dioxide emissions before 2030 and strive to achieve carbon neutrality before 2060.

As an important land use activity, land consolidation projects have a significant impact on carbon emissions and carbon sequestration. The implementation process involves multiple links such as land leveling, irrigation and drainage, and field road construction, consuming a large amount of energy and generating carbon emissions. The total carbon emissions during the construction phase of large-scale land consolidation projects can reach thousands or even tens of thousands of tons. However, land consolidation projects can also increase carbon sinks by adjusting land use structure and methods, such as increasing arable land area, afforestation, etc. At present, most research focuses on carbon effect analysis during the construction stage of land consolidation projects, and there is relatively little research on low-carbon strategies in the later operation and maintenance stage. However, the later stage of operation and maintenance is a critical period for land consolidation projects to achieve long-term benefits. Its carbon emissions and carbon sequestration have a profound impact on the project's carbon balance and ecological benefits. Therefore, it is urgent to study low-carbon strategies for this stage(Chang and Fang 2025).

1.1.2. Research significance

From a theoretical perspective, this study contributes to enriching the research content of carbon effects in land consolidation projects. At present, there are deficiencies in the carbon effect calculation and low-carbon strategy of land consolidation projects in the later operation and maintenance stage. In depth research on carbon effect measurement methods for later operation and maintenance, analyzing the impact mechanisms of various operation and maintenance activities on carbon emissions and carbon sequestration, can improve the theoretical system of carbon effect in land consolidation projects, provide a more comprehensive and in-depth theoretical basis for subsequent research, and also help expand the research perspective of land consolidation projects in the field of climate change response, promoting interdisciplinary integration of related disciplines(Zhao et al. 2023).

At the practical level, studying low-carbon strategies for the later operation and maintenance of land consolidation projects has important guiding significance. The number and scale of land consolidation projects are large, and the total carbon emissions from later operation and maintenance cannot be ignored. Developing scientifically reasonable low-carbon strategies can effectively reduce energy consumption and carbon emissions, and minimize negative environmental impacts. The use of energy-saving irrigation equipment and intelligent irrigation systems can reduce irrigation energy consumption and carbon emissions; Promoting green fertilization technology and comprehensive pest control measures can reduce the use of agricultural inputs, lower agricultural non-point source pollution and carbon emissions. A reasonable low-carbon strategy can also improve the ecological benefits and sustainability of land consolidation projects, provide decision-making basis for project planning, design, implementation, and management, and promote the green and low-carbon development of the land consolidation industry(Liu, Zhang, and Wang 2025).

1.2. Current Research Status at Home and Abroad

1.2.1. Research progress abroad

Research on the carbon effect of land consolidation started earlier in foreign countries, and there have been fruitful achievements in carbon effect measurement methods and low-carbon strategies. In terms of carbon effect measurement methods, in the early days, the focus was mainly on carbon storage and flux measurement of a single land use type, using field surveys to

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measure vegetation biomass and soil organic carbon content of ecosystems to estimate carbon storage. With the deepening of research, model simulation methods are widely used, such as the InVEST model, which can comprehensively simulate and predict regional carbon stocks and fluxes based on multiple factors; The Life Cycle Assessment (LCA) method calculates energy consumption and carbon emissions throughout the entire lifecycle of a project, and evaluates the project's carbon footprint.

In terms of low-carbon strategy research, foreign countries focus on proposing measures from the aspects of land use planning and management. In land use planning, it is necessary to reasonably layout construction land, arable land, and ecological land, increase the proportion of ecological land, such as expanding forest and wetland areas, and improving regional carbon sequestration capacity; Develop strict forest protection policies and encourage afforestation. In agricultural land management, promote sustainable agricultural practices such as precision fertilization, no till or reduced tillage techniques to reduce carbon emissions from agricultural production. In recent years, foreign countries have also paid attention to the combination of land consolidation and carbon trading markets, quantifying the carbon sequestration of land consolidation projects and incorporating them into market transactions, opening up new avenues for project funding and sustainable development.

1.2.2. Domestic research progress

The research on the carbon effect of land consolidation in China has developed rapidly in recent years. In terms of carbon effect calculation, various methods are proposed based on the characteristics of land consolidation projects in China, such as using material balance algorithm during the construction phase, using ecosystem type method for carbon effect calculation of land use structure, calculating crop carbon fixation and agricultural input carbon emissions during the farmland management and protection phase, and using GIS and RS technology to improve the accuracy and efficiency of calculation(Al-Mansour and Jejcic 2017).

In terms of low-carbon strategy research, measures have been proposed from the perspectives of engineering technology, agricultural production, and ecological protection in China. In terms of engineering technology, research and promote energy-saving construction equipment and processes; Promote green agricultural technologies in agricultural production; In terms of ecological protection, we will strengthen ecological restoration and vegetation construction. However, existing research has shortcomings, with some parameters of carbon effect measurement methods lacking regional specificity and insufficient integration of measurements at different stages; There is little systematic research on low-carbon strategies in the later stages of operation and maintenance, lacking specificity, and the implementation effect evaluation and monitoring system is incomplete(Tu et al. 2019).

1.3. Research Methods and Innovation Points

1.3.1. Research Methods

This study comprehensively utilizes multiple research methods. The literature research method collects and sorts out relevant literature at home and abroad, understands the research status, cutting-edge dynamics, and development trends, summarizes relevant theories and methods, and clarifies the research entry point and direction. The case analysis method selects representative land consolidation projects, deeply analyzes the actual operation and maintenance situation in the later stage, collects data information, uses carbon effect calculation methods to quantitatively analyze carbon emissions and carbon sequestration, summarizes experience and problems, and provides practical basis for low-carbon strategies. The combination of quantitative and qualitative analysis methods is used to accurately calculate energy consumption, carbon emissions, and carbon sinks in carbon effect measurement. When analyzing the feasibility, implementation effectiveness, and influencing factors of low-carbon strategies, qualitative methods are used to obtain opinions and

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suggestions from relevant stakeholders, and comprehensively and objectively evaluate carbon effects and low-carbon strategies.

1.3.2. Innovation points

This study has multiple innovative aspects. Build a low-carbon strategy system based on carbon effect calculation, integrating carbon effect calculation throughout the entire operation and maintenance process of land consolidation projects, constructing a systematic low-carbon strategy system from multiple aspects, clarifying the potential of carbon emission sources and sinks, and proposing targeted strategies. Develop targeted low-carbon strategies based on regional differences, develop strategies that meet actual needs according to the characteristics of different regions, and improve the effectiveness and adaptability of strategy implementation. Introducing interdisciplinary research methods, breaking disciplinary boundaries, and comprehensively applying interdisciplinary theories and methods to conduct in-depth research on carbon effect measurement and low-carbon strategies, providing a comprehensive and in-depth perspective and solution for solving low-carbon problems(Li 2022).

2. Theory Related to The Operation and Maintenance of Land Consolidation Projects in The Later Stage and Carbon Effect

2.1. Overview of Land Consolidation Projects

2.1.1. Concept and Content of Land Consolidation Projects

Land consolidation project is a series of engineering activities aimed at improving the efficiency of land use, improving land quality and ecological environment by rectifying inefficient, unreasonable, unused, and damaged land due to production, construction, and natural disasters. Agricultural land consolidation is an important component, including the consolidation of cultivated land, gardens, forests, and other areas. In the process of farmland consolidation, land leveling projects make the fields orderly, facilitating mechanized cultivation and irrigation, and improving the efficiency of farmland utilization; The improvement of irrigation and drainage engineering construction ensures the water demand of farmland, and water-saving irrigation technologies such as drip irrigation and sprinkler irrigation improve water resource utilization efficiency and reduce irrigation energy consumption. Land reclamation aims to restore and utilize land damaged by production, construction, and natural disasters through a series of measures, increasing land resources and improving the ecological environment. The renovation of construction land focuses on optimizing the layout and intensive use of urban and rural construction land, improving land use efficiency and comprehensive carrying capacity. Unutilized land development refers to the development of barren grasslands, saline alkali land, etc., and their conversion into usable land resources. The development process should pay attention to ecological environment protection(Li et al. 2022).

2.1.2. Importance of post operation and maintenance of land consolidation projects

The operation and maintenance of land consolidation projects in the later stage are crucial for maintaining the effectiveness of consolidation, improving land use efficiency, promoting ecological environment protection, and ensuring the sustainable development of projects. Effective maintenance can ensure the long-term effectiveness of the project and avoid damage to the remediation results. Good post operation and maintenance can help improve land use efficiency and transform the potential efficiency of land consolidation into actual benefits. Post operation and maintenance are of great significance for ecological environment protection, as they can promote ecosystem stability and restoration, and protect biodiversity(Li et al. 2024).

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2.2. Carbon effect related theories

2.2.1. Concept and connotation of carbon effect

The carbon effect refers to the comprehensive impact of the emission, absorption, storage, and transformation of carbon elements on the ecological environment, climate system, and human socio-economic processes in natural ecosystems and human activities. Human activities are the main factor contributing to the increase in carbon emissions, with industrial production, transportation, agricultural production, and land use changes all producing significant amounts of carbon emissions. Natural ecosystems play a crucial role in carbon absorption, with forests, grasslands, wetlands, and other ecosystems being important carbon sinks. The carbon effect also has significant impacts on the ecological environment and human socio-economic development, such as causing climate change, affecting energy utilization and industrial development patterns.

2.2.2. Carbon Cycle Process in Land Consolidation Projects

The carbon emissions, absorption, and transformation processes in various stages of land consolidation projects are intertwined. During the construction phase, the operation of construction machinery and the production and transportation of building materials generate significant carbon emissions. During the stage of land use structure adjustment, the conversion of construction land into arable land increases carbon sinks, but the cultivation and cultivation of arable land may lead to the decomposition and emission of soil organic carbon; Forest destruction reduces carbon sinks and increases carbon emissions. In the later stage of operation and maintenance, activities such as farmland management and maintenance, irrigation and drainage facility operation and maintenance, field road use and maintenance will all affect carbon cycling, and the process is complex.

2.3. Carbon Effect Calculation Method

2.3.1. Material balance algorithm

The material balance algorithm is based on the law of conservation of matter and is used to calculate the carbon emissions generated during the later operation and maintenance of land consolidation projects due to energy consumption and material use. Calculate the total carbon emissions by calculating the amount of energy and material consumption, combined with carbon emission factors. This method is simple to calculate and relatively easy to obtain data, but there may be errors for carbon emission sources that are difficult to accurately measure(Luo and Lin 2023).

2.3.2. Ecological System Type Method

The ecosystem type method estimates carbon sequestration by measuring and analyzing ecosystem area and carbon density based on the differences in carbon sequestration capacity of different ecosystems. In the later operation and maintenance of land consolidation projects, the impact of changes in land use structure on carbon sinks can be evaluated. However, this method requires high accuracy in the classification of ecosystem types and carbon density data(Ma et al. 2023).

2.3.3. Other Common Methods

The life cycle method comprehensively evaluates the energy consumption and environmental impact of land consolidation projects throughout their entire life cycle, and can account for carbon emissions and sinks at each stage of the project. However, data collection is difficult and the calculation process is complex. The model simulation method uses mathematical models to simulate and predict the carbon effects of land consolidation projects, such as the InVEST model and DNDC model, but the accuracy of the model depends on the quality of input data and the rationality of parameters.

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3. Factors Affecting Carbon Emissions During the Later Operation and Maintenance of Land Consolidation Projects

3.1. Energy consumption

3.1.1. Use of mechanical equipment

In the later operation and maintenance of land consolidation projects, the use of mechanical equipment is an important source of energy consumption and carbon emissions, with irrigation equipment and agricultural machinery having a significant impact. In terms of irrigation equipment, the operation of water pumps consumes a large amount of electricity or fuel, and different irrigation methods have significant differences in energy consumption and carbon emissions. Flood irrigation has high energy consumption, while water-saving irrigation methods such as drip irrigation and sprinkler irrigation can reduce energy consumption and emissions. Agricultural machinery uses diesel as fuel, and the frequency and intensity of use affect carbon emissions. Large agricultural machinery consumes more energy.

3.1.2. Power Supply

Electricity supply plays a crucial role in the later operation and maintenance of land consolidation projects, and its source and use process affect carbon emissions. China has diverse forms of power supply, with high carbon emissions from thermal power generation and relatively low carbon emissions from hydropower, wind power, and solar power generation. During the use of electricity, the unreasonable use of irrigation systems, lighting facilities, and agricultural processing equipment can increase carbon emissions. The use of energy-saving equipment can reduce carbon emissions.

3.2. Land use mode

3.2.1. Land use intensity

The impact of changes in land use intensity on soil carbon emissions is complex, with cultivation frequency and planting system being key factors. An increase in farming frequency will accelerate the decomposition of soil organic carbon, leading to an increase in carbon emissions and potentially weakening soil carbon sequestration capacity. Different planting systems have varying impacts on soil microbial community structure, nutrient cycling, and plant root exudates, which in turn affect soil carbon emissions. Crop rotation and intercropping are beneficial for reducing carbon emissions, while continuous cropping may increase carbon emissions.

3.2.2. Changes in vegetation cover

The increase or decrease in vegetation coverage affects the carbon sequestration capacity of the region, while changes in forest and grassland areas have a significant impact on carbon sequestration. An increase in forest area can significantly enhance carbon sequestration capacity, as trees fix a large amount of carbon dioxide through photosynthesis. Changes in grassland area also affect carbon sequestration. Reasonable grassland management measures can improve carbon sequestration capacity, while a decrease in grassland area reduces carbon sequestration capacity.

3.3. Agricultural inputs

3.3.1. Use of fertilizers and pesticides

The application of fertilizers and pesticides in agricultural production generates carbon emissions and has a negative impact on the environment. The production process of fertilizers has high energy consumption and emission amplification. During the use process, nitrogen transformation produces nitrous oxide emissions, and excessive application of nitrogen fertilizer will increase emissions. The production, transportation, and use of pesticides all

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generate carbon emissions, and their use can also damage the ecological environment and affect the carbon cycle.

3.3.2. Irrigation Water Management

Irrigation water management is crucial for the later operation and maintenance of land consolidation projects. Unreasonable irrigation can lead to water resource waste and increased carbon emissions. The flood irrigation requires a large amount of water and has a low utilization rate. The water lifting process consumes a lot of energy and generates carbon emissions. Unreasonable irrigation can also affect soil physical and chemical properties, leading to methane emissions and soil salinization, reducing soil carbon sequestration capacity.

4. Low Carbon Strategy Construction for Post Operation and Maintenance of Land Consolidation Projects

4.1. Energy Structure Optimization Strategy

4.1.1. Promote the utilization of renewable energy

In the later operation and maintenance of land consolidation projects, promoting the use of renewable energy is of great significance in reducing carbon emissions. Solar energy is widely used, and solar irrigation equipment and photovoltaic power generation systems can reduce dependence on traditional energy sources and lower carbon emissions. Wind energy can play an important role in areas with abundant wind resources, and the complementary utilization of wind and solar energy can improve the stability and reliability of energy supply. The government should increase policy support to promote the application of renewable energy in the later operation and maintenance of land consolidation.

4.1.2. Improve energy utilization efficiency

Improving energy efficiency is an important aspect of low-carbon strategies. Choosing energy-saving equipment such as variable frequency water pumps, new energy-saving agricultural machinery, and electric agricultural machinery can reduce energy consumption and carbon emissions. Optimizing the energy management system, establishing an intelligent energy management system, strengthening energy management training, improving the energy management awareness of project managers and farmers, arranging equipment operation time reasonably and regularly maintaining equipment can improve energy utilization efficiency.

4.2. Land use optimization strategy

4.2.1. Reasonable planning of land use layout

Reasonable planning of land use layout can enhance the carbon efficiency of later operation and maintenance of land consolidation projects. Based on the results of land suitability evaluation, scientifically layout land use types such as cultivated land and forest land, leverage the carbon sink advantages of different land use types, form a good ecosystem structure, promote the benign development of carbon cycle, and improve regional carbon sink capacity.

4.2.2. Strengthen the protection and construction of ecological land

Strengthening the protection and construction of ecological land is crucial for improving carbon sequestration capacity. Wetlands and green spaces play a unique role in carbon sequestration, and wetland protection should be strengthened by establishing nature reserves and carrying out wetland restoration work. Increase green space area, plan and construct park green spaces, road green spaces, and farmland protective forests, improve vegetation coverage, and enhance carbon sequestration capacity.

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4.3. Agricultural Production Management Strategies

4.3.1. Promoting low-carbon agricultural technologies

Promoting low-carbon agricultural technologies can reduce carbon emissions during the later operation and maintenance of land consolidation projects. Precision fertilization technology is based on a precise understanding of soil nutrients and crop fertilizer requirements, reducing fertilizer waste and carbon emissions. The no till and minimal tillage technology reduces soil disturbance, lowers the rate of soil organic carbon decomposition, reduces carbon emissions, improves soil structure, and enhances the sustainability of agricultural production.

4.3.2. Optimizing Irrigation and Water Resource Management

Optimizing irrigation and water resource management is a key link in achieving low-carbon development. Drip irrigation, sprinkler irrigation and other water-saving irrigation methods accurately control water volume and irrigation range, improve water resource utilization efficiency, reduce energy consumption and carbon emissions. Measures for water resource recycling, such as rainwater collection, irrigation and drainage treatment and reuse, and reclaimed water reuse, reduce the amount of fresh water used, lower energy consumption and carbon emissions.

4.4. Carbon compensation and trading strategy

4.4.1. Carry out carbon compensation projects

Carrying out carbon offset projects is an important means to achieve carbon neutrality. Planting trees and afforestation can increase carbon sequestration and improve the ecological environment. Suitable tree species should be selected according to regional characteristics, and planting density and layout should be reasonably planned. Forest management can improve the carbon sequestration capacity of forests, including measures such as thinning, pruning, and fertilization, while strengthening forest protection to prevent fires and pests.

4.4.2. Participation in the carbon trading market

Participating in the carbon trading market provides new opportunities for the later operation and maintenance of land consolidation projects. The carbon sequestration generated by land consolidation projects can be quantified and traded in the market, realizing economic value and providing financial support for the sustainable development of the projects. The project implementation entity needs to accurately calculate and certify the carbon sequestration amount, register and list for sale in the carbon trading market, and conduct transactions in accordance with market rules.

5. Conclusion and Prospect

5.1. Research Conclusion

This study focuses on the operation and maintenance of land consolidation projects in the later stage, and from the perspective of carbon effect calculation, it is concluded that there are significant differences in carbon emissions and carbon sinks at different stages. The construction phase is mostly characterized by net carbon emissions; In the stage of land use structure adjustment, if carbon sequestration land is increased, the increase in carbon sequestration will be prominent; In the stage of farmland management and protection, while crops fix carbon, agricultural inputs and mechanical operations generate carbon emissions, and some projects can achieve net carbon sink growth. Most projects can achieve carbon break even after a period of implementation, indicating that reasonable measures in the later stage are of great significance for carbon balance.

The carbon emissions during the later operation and maintenance of land consolidation projects are influenced by multiple factors. In terms of energy consumption, the use of

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mechanical equipment and power supply have a significant impact, and different irrigation methods, agricultural machinery usage, and power sources can all change carbon emissions; In terms of land use, the frequency of cultivation, planting system, and changes in vegetation cover affect soil carbon emissions and regional carbon sequestration capacity; In agricultural inputs, the entire process of chemical fertilizers and pesticides, as well as improper management of irrigation water, can increase carbon emissions.

The low-carbon strategy system constructed for this purpose is feasible. In terms of optimizing the energy structure, promoting the utilization of renewable energy and improving energy efficiency; In terms of optimizing land use, scientific planning and layout should be carried out to strengthen the protection and construction of ecological land; In terms of agricultural production management, promote low-carbon technologies, optimize irrigation and water resource management; In terms of carbon compensation and trading, carry out carbon compensation projects and participate in the carbon trading market to realize the value of carbon sinks.

5.2. Research Shortcomings and Prospects

This study has certain limitations, with a narrow scope of data collection, making it difficult to comprehensively reflect the carbon effects of different types of projects. And low-carbon strategies are constrained by factors such as policies, technology, economy, and society in practical applications.

Future research should expand the scope of cases, analyze regional differences, and improve low-carbon strategies. Conduct in-depth research on constraining factors, propose solutions, and strengthen strategy evaluation and monitoring. At the same time, utilizing advanced technology to explore the inherent mechanism of carbon effect, promoting the integration of land consolidation projects and carbon trading markets, paying attention to their coordinated development with other fields, and assisting regional sustainable development.

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