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Methodology of Carbon Sink Accounting and Evaluation Model for the Full Chain of “Consolidation-Carbon Sequestration-Transaction” of Arable Land

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ABSTRACT

The urgent challenge of climate change has made carbon neutrality a central policy goal worldwide. Farmland soil in China holds significant potential for carbon sequestration, yet small-scale, scattered household management has constrained the development of large-scale farmland carbon sink projects. To address this gap, this study constructs a full-chain methodological framework of “Consolidation-Carbon Sequestration-Transaction,” integrating land consolidation theory, agroecological principles, and ecosystem service valuation. A “scale-cost-benefit” analysis model was developed to quantify the economic viability of farmland carbon sinks under different land-use conversion scenarios. Results show that under the current carbon price of 40 yuan/ton, the per-mu benefit of farmland carbon sequestration is only 8–12 yuan, which is insufficient to cover monitoring and transaction costs at small scales. However, when farmland is consolidated into contiguous plots, costs can be reduced by 30–40%, allowing the cost-benefit balance point to be reached. This study provides a standardized quantitative method for farmland carbon sink evaluation, offering practical guidance for designing large-scale carbon sequestration projects in

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China. Furthermore, the proposed framework has broader international relevance for countries with smallholder-dominated agricultural structures, where land consolidation and carbon sink standardization can similarly promote sustainable agricultural modernization and climate mitigation.

Keywords: Agricultural Land Consolidation; Contiguous Fertile Fields; Consolidation-Carbon Sequestration-Transaction Full Chain; Modeling the Scale-Cost-Benefit of Farmland Carbon Sinks

1. Introduction

The urgent challenge of climate change has made carbon neutrality a central policy goal worldwide. China has pledged to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, which requires innovative pathways to enhance carbon sequestration while ensuring food security. Among the potential solutions, farmland soil carbon sinks are recognized as one of the most cost-effective and scalable measures^[1,2]. However, effective carbon accounting and market-based trading mechanisms remain a prerequisite for transforming ecological functions into economic incentives, thereby linking agricultural production with climate mitigation.

Land consolidation, defined as the reallocation and spatial reorganization of fragmented farmland into larger and more efficient plots, plays a pivotal role in this context^[3]. The theoretical rationale is that consolidation improves agricultural productivity, reduces transaction costs, and facilitates the adoption of standardized ecological management practices. Successful international cases, such as the European Union's land consolidation programs, have demonstrated that integrated land management can generate both economic and environmental benefits^[4]. In China, nationwide land consolidation initiatives have created the institutional foundation for integrating ecological functions such as soil carbon sequestration into agricultural development.

The link between land consolidation and carbon sequestration is direct. By enabling contiguous fertile plots, consolidation provides the spatial conditions necessary for applying conservation tillage, organic fertilizer substitution, and crop rotation practices, all of which enhance soil organic matter and long-term carbon storage^[5]. Moreover, consolidation makes it feasible to implement standardized monitoring and accounting systems, thereby reducing the high costs associated

with scattered smallholder-based carbon trading. Despite these advantages, there is still a lack of systematic methodologies that connect consolidation, carbon sequestration, and transaction into a coherent analytical framework. Existing studies have often treated these elements separately, without providing an integrated approach to quantify costs, benefits, and trade-offs.

Against this background, this paper aims to fill the research gap by constructing a full-chain methodological framework of "Consolidation-Carbon Sequestration-Transaction." Specifically, it develops a "scale-cost-benefit" analysis model to evaluate the economic viability of farmland carbon sinks under different land-use conversion scenarios. By integrating theoretical perspectives from land consolidation, agroecology, and ecosystem service valuation, the study seeks to answer the following research questions: (1) How can land consolidation enhance the potential of farmland soil carbon sinks? (2) What are the cost-benefit thresholds for realizing carbon sink value under different scales and land-use types? (3) How can the accounting and evaluation of farmland carbon sinks be standardized to support market-based transactions? Addressing these questions contributes not only to China's carbon neutrality strategy but also offers reference for other countries with similar smallholder-dominated agricultural structures

2. Definition of Relevant Concepts

2.1. Integrated Comprehensive Land Governance and Agricultural Land Governance

The concept of comprehensive land consolidation originated from the "Million Village Construction" practice in Zhejiang Province, with townships as the basic implementing units and territorial spatial planning as the

basis. It is a systematic project to promote the integration of production, living and ecology and the optimization of territorial spatial layout by comprehensively promoting the improvement of rural land, the development of construction land and the protection and restoration of ecology, so as to promote the centralized and continuous use of agricultural land, the efficient agglomeration of construction land, and the improvement of ecological land functions. Agricultural land consolidation is an important part of the comprehensive land consolidation, which mainly involves the comprehensive arrangement of cultivated land, garden land, woodland, grassland, etc., focusing on the reasonable layout of land use and the optimization of the structure, the improvement of soil, the improvement of the quality of cultivated land, the increase of effective cultivated land area, and the improvement of comprehensive agricultural production capacity. In this paper, the research scope focuses on the comprehensive management of agricultural land in agricultural land consolidation, and the technical and methodological issues of centralized and continuous land consolidation in domestic and foreign regions are summarized, so as to lay a foundation for the realization of large-scale carbon sinks of cultivated land.

2.2. Cropland Carbon Sinks and Agricultural Soil Carbon Sinks

With the convening of the 2021 Central Economic Work Conference, the construction of China's "total carbon emission control" system has been put on the agenda. The "2022 Annual Report on China's Policies and Actions to Address Climate Change" released by the Ministry of Ecology and Environment in 2022^[6] pointed out that efforts should be made to increase carbon sinks in farmland soil and concentrate on building high-standard farmland. The "Implementation Plan for Emission Reduction and Carbon Sequestration in Agriculture and Rural Areas" issued by the Ministry of Agriculture and Rural Affairs and the National Development and Reform Commission in 2022^[7] pointed out that the focus should be on enhancing the organic matter in cultivated soil to strengthen the carbon sequestration capacity of farmland soil. On October 19, 2023, the Ministry of Ecology and Environment issued the "Interim Mea-

asures for the Administration of Voluntary Greenhouse Gas Emission Reduction Trading"^[8], providing a fundamental institutional guarantee for the orderly operation of China's voluntary greenhouse gas emission reduction trading market. On January 22, 2025, the Central Committee of the Communist Party of China and The State Council issued the "Comprehensive Rural Revitalization Plan (2024–2027)"^[9], proposing to steadily promote agricultural emission reduction and carbon sequestration, promote no-till and low-till seeding technology, reduce methane emissions from agriculture and odors from livestock and poultry breeding, accelerate the scrapping and renewal of old agricultural machinery and the application of green technology equipment, Carry out technological research and development on agricultural emission reduction and carbon sequestration. Compared with the internationally recognized and rigid quantified "targets" for agricultural emission reduction and carbon sequestration, there are relatively few legal norms in China's current legislation regarding conservation tillage and other measures that help increase soil carbon sinks in farmland. At present, policies have not yet proposed quantified indicators. The concept of cultivated land carbon sink involves the carbon absorption capacity of agricultural ecosystems, and also covers the conversion of the potential of cultivated land carbon sink into asset value through the carbon trading market, and then the establishment of a compensation mechanism for cultivated land protection, so that protecting cultivated land becomes a conscious act of farmers. Cultivated land carbon sinks include vegetation carbon sinks and agricultural soil carbon sinks, the former mainly refers to the carbon dioxide absorbed by crops during their growth, and the latter involves the accumulation and decomposition processes of organic matter in the soil. Since the vegetation carbon sink of cultivated land is not obvious due to the short crop maturity period, it is often considered to be zero, and the average value of cultivated land soil carbon sink is (0.017 ± 0.005) PgC/a, which is much greater than that of vegetation carbon sink. In terms of measurement methods, the current calculation of agricultural carbon emissions mainly relies on the coefficients of international and domestic models such as the IPCC inventory method and

the greenhouse gas inventory method^[10]. However, the coefficients of international methodological data models have strong regional characteristics^[11], which are significantly different from the actual conditions of domestic farmland, resulting in large errors in domestic localized applications. Moreover, the update cycle of the existing domestic soil organic carbon data and greenhouse gas inventories is relatively long, making it difficult to apply them directly. If the on-site detection method is adopted, due to the dispersed and dynamic characteristics of the carbon effect in farmland^[12], there are significant differences in the measured parameters among different regions. Moreover, the cumulative effect of carbon sinks after the implementation of management measures fluctuates with historical data, making it difficult to ensure the universality of the measured data.

Therefore, the focus of this article is on the cultivated land soil carbon sink in the cultivated land carbon sink, and the practical experience of domestic and foreign regions in the promotion of cultivated land soil carbon sequestration capacity, the construction of cultivated land carbon sink system, and the successful trading cases are summarized.

3. Methodology

3.1. Research Framework

This study establishes a comprehensive methodology framework encompassing the entire process of “land consolidation-carbon sequestration-trading” to evaluate the feasibility of farmland carbon sequestration projects. Integrating theories from land consolidation, agroecology, and ecosystem service value assessment, the framework connects land use transformation, soil carbon sequestration enhancement, and carbon trading into a systematic analytical procedure. It aims to assess how land consolidation enhances the carbon sequestration potential of farmland soils and quantifies the cost-benefit balance across different scales and land use scenarios.

3.2. Data Sources

The empirical data in this study were obtained from representative land consolidation projects in

Guangzhou, Jiangmen, Maoming, Shantou, Meizhou, and Shanwei in Guangdong Province. These cases provide cost information related to farmland improvement, soil fertility enhancement, and newly developed land. Carbon emission and carbon sequestration coefficients were referenced from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and the Guidelines for Compiling Provincial Greenhouse Gas Inventories in China, supplemented with local agricultural data.

3.3. Analytical Procedures

3.3.1. Carbon Effects of Land-Use Conversion

Different types of land-use conversion (e.g., to garden plots, grassland, facility farmland, or ponds) generate distinct carbon effects. These impacts can be quantified using the carbon emission coefficient method, see formula (1)^[13,14]:

$$E = \sum A_k * f_k \quad (1)$$

E represents the emission (removal) of carbon from all land-use types; A_k is the area of the k th land type; f_k is the emission coefficient of the k th land-use type.

Carbon emissions calculated based on the carbon emission coefficient (Unit: tons):

- Cultivated land and garden plots: 0.497A1–0.730A2
- Cultivated land and grassland: 0.497A1–0.021A3
- Permanent cropland and water surface of potholes: 0.497*A1–0.248A5
- Cultivated land and facility agricultural land: 0.497*A1

Notes: A1 denotes the original cultivated land area (hectares) before remediation, and A_n ($n = 1, 2, 3, 4$) denotes the area of land types remediated.

3.3.2. Enhancement of Soil Carbon Sequestration

The increase in soil carbon storage was estimated based on the Duke’s Law, which relates soil organic matter (SOM) content to carbon accumulation. An increase of 0.1% in SOM content in the top 40 cm of soil corresponds to an addition of 0.217 tons of organic carbon per mu, equivalent to a reduction of 0.796 tons of CO₂ emissions.

Nitrous oxide (N₂O) emissions resulting from fertilizer inputs were incorporated using IPCC emission factors.

Furthermore, considering the N₂O emissions generated during this process, increasing the SOM content by 1 percentage point requires the application of 15–20 tons of organic fertilizer. With reference to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and the Guidelines for Compiling Provincial Greenhouse Gas Inventories in China, the following parameters were applied: nitrogen content of 46%, mineralizable nitrogen proportion of 30%, nitrous oxide emission factor (EF) of 0.0178, N₂O molar mass of 44 g/mol, and atomic mass of nitrogen of 14 g/mol. The resulting value was converted to CO₂ equivalence using a global warming potential (GWP) factor of 298.

The equations and conversions related to Duke's Law and IPCC coefficients are provided in the following table.

3.3.3. Cost Assessment

The costs associated with land consolidation include:

The total remediation cost consists of two parts, one is the improvement of arable land, that is (e.g., land leveling, irrigation, drainage, road construction, and soil amelioration.), the construction and renovation of high-quality farmland; the other is the change of land use types, such as the remediation cost required for orchards to become arable land;

15 is the conversion from hectares to mu; 0.3 is the content of high-quality farmland construction and renovation, including land leveling, irrigation and drainage works, field road works, farmland protection, soil improvement, etc., with a construction cost of about 0.3 yuan/mu; 12 is the estimated construction investment of newly added arable land (including the price of land improvement, 20,000 yuan/mu); The total consolidation cost (C) is calculated as follows:

$$C = (15 \times 0.3)A_1 + (15 \times 12)A_2 = 4.5A_1 + 180A_2 \quad (2)$$

where A_1 represents the original cropland area (hectares), and A_n denotes the area of newly converted land (hectares).

3.3.4. Benefit Assessment

The benefit assessment primarily considers two categories:

Ecological benefits (R_1): Refers to the benefits derived from the net carbon sequestration post-consolidation, monetized based on the current carbon market price.

Production benefits (R_2): Refers to the increased crop yield from the consolidated farmland, calculated based on the per-hectare yield and current grain market prices.

The total benefit is defined as $R = R_1 + R_2$, and the net benefit is calculated as $P = nR - C$, where n represents the number of years required for the production benefits to be realized after consolidation.

3.3.5. Model Integration

Integrating the above steps, a "Scale-Cost-Benefit" model was developed to analyze the trade-offs among land use scale, carbon sequestration increment, costs, and benefits. This model can generate two-dimensional and three-dimensional representations of cost-benefit relationships and identify threshold conditions under which large-scale farmland consolidation achieves a positive net benefit (Figure 1).

3.4. Analytical Tools

All calculations were performed using a spreadsheet-based methodology, supported by dynamic simulation models for visualization. These tools facilitate sensitivity analyses across different land-use scenarios and carbon price assumptions, providing a transparent basis for evaluating project feasibility.

3.5. Assumptions and Limitations

The methodology is based on the following key assumptions:

Carbon coefficients are assumed to remain constant across regions, despite potential spatial variations.

Long-term ecological feedbacks, such as soil degradation and climate change impacts, are not considered within the scope of this study.

Economic benefits are limited to carbon trading and crop production, excluding broader ecosystem services (e.g., biodiversity, water conservation).

While these limitations may affect the generaliz-

ability of the results, the framework offers a replicable method for evaluating cropland carbon sequestration, particularly in regions dominated by smallholder farming systems.

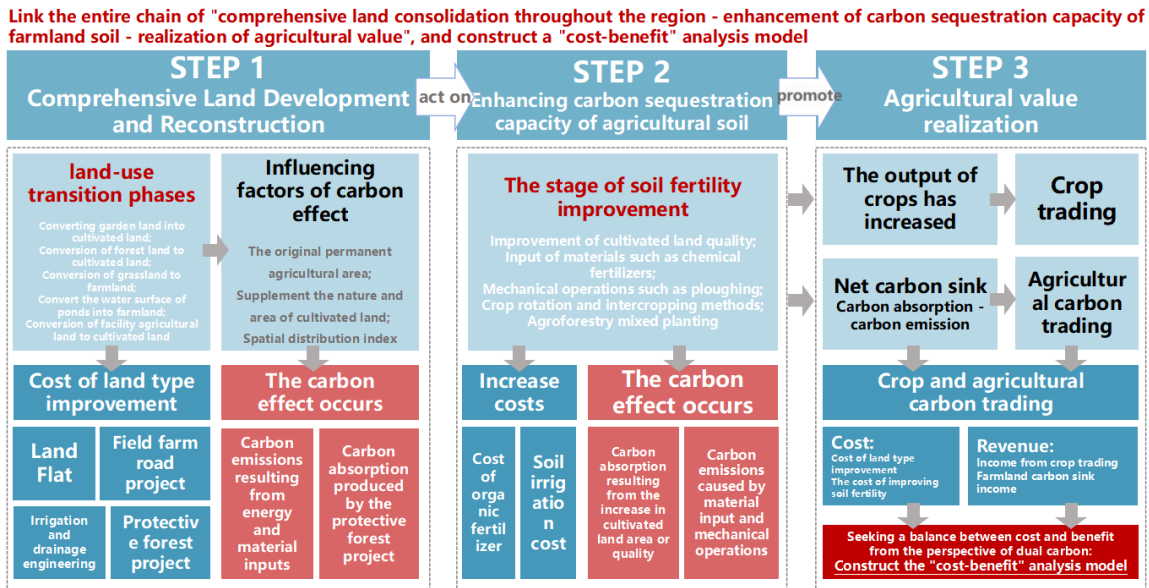


Figure 1. Model roadmap.

4. International Experience on Farmland Consolidation and Farmland Carbon Sinks

4.1. Summary of the Connotation of Land Consolidation Abroad

The history of land consolidation in western countries is much longer than that in China^[15]. In Europe, land consolidation has been implemented since the Middle Ages, and relevant legislation appeared in the mid-18th century^[16]. Since then, it has become an important part of land policy in most European countries^[17]. A long period of practice has made the connotation of land consolidation in European countries richer and richer: in the early stage, based on the German experience, Bronstert et al. believed that land consolidation mainly refers to land consolidation projects, including rearranging and combining scattered plots, eliminating pollution, flattening terraces, building rural roads, repairing local streams, soil improvement and so on^[18]. With the continuous expansion of the later land consolidation, Jiang

et al.^[13] believed that land consolidation is a collection concept, including land reclamation, land redistribution, land adjustment and land planning implemented in rural areas^[19,20]. The Food and Agriculture Organization of the United Nations (FAO) released the Legislative Guide on Land Consolidation in 2021, defining land consolidation as: an initiative led by public authorities and regulated by law, which coordinates the interests of landowners and users by adjusting and allocating plots in an overall or partial manner, and ultimately achieves multiple public goals, such as improving land fragmentation, developing agricultural scale, restoring the natural environment and building infrastructure^[19]. By now, the goals of international modern land consolidation involve land spatial distribution and adjustment, and improvement of material conditions of farmland itself (such as roads, Ditch, terrace improvement), the reconfiguration of rural land property rights (land use rights, ownership and other rights), and solving agricultural environmental problems (such as landscape fragmentation, soil erosion, insufficient soil fertility and loss of biodiversity) in many dimensions^[13].

defined as the basis for the consideration of the owners' equity in the event of reallocation of agricultural land^[23].

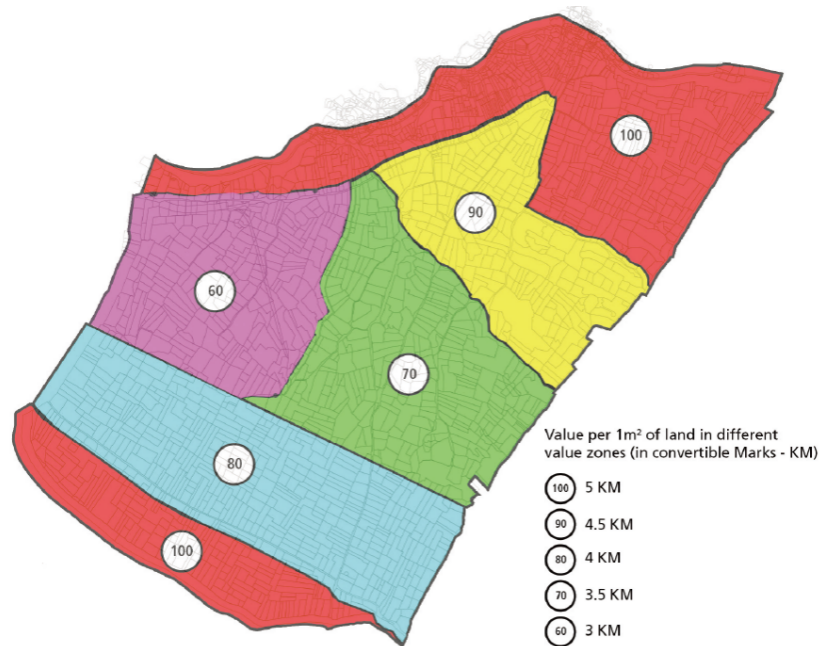


Figure 3. Agricultural land value assessment and classification—BiH land consolidation pilot project^[24].

Farmland re-allotment: Farmland re-allotment mainly includes the re-allotment of ownership and the shape of the land parcel, the main goal is to reduce the fragmentation of land ownership and land use, each land owner's farmland land parcel should be merged into a complete land parcel which is as few in number and ad-

acent as possible, the location should be as close as possible to the owner's homestead, and the shape of the land parcel should be as regular as possible, so as to facilitate the later comprehensive renovation projects such as the repair of tractor road and the perfection of irrigation system (**Figure 4**).



Figure 4. Pilot farmland consolidation project in Shorsulu village, Azerbaijan^[23] (left before and right after).

Improvements to agricultural infrastructure: Following the demarcation of the above-mentioned land allocation maps, the land was leveled and rehabilitated. The figure below shows the changes that were made to

agricultural land in the village of Egri, North Macedonia, as part of the agricultural land consolidation project. In the 336-hectare project area, the project consolidated the 874 plots (left) into 260 plots (right) and im-

proved agricultural infrastructure (by constructing new access roads, constructing new and rehabilitating existing drainage ditches, and upgrading the existing irrigation system) (Figure 5). The average plot size after the

implementation of the project was 1.30 hectares, compared to 0.38 hectares before the implementation of the project^[24].

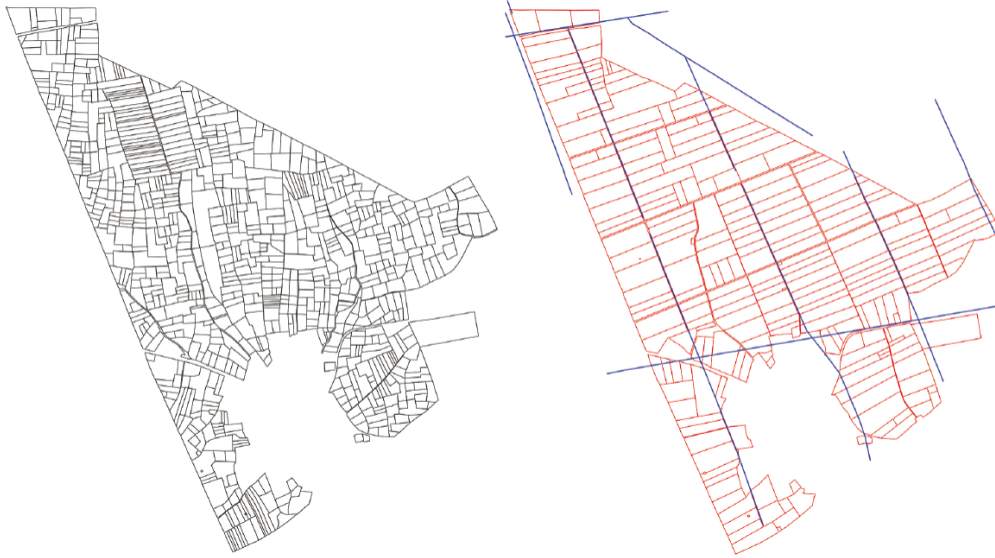


Figure 5. North Macedonia Agricultural Land Rehabilitation Enhancement Pilot Project^[24].

Note: before rehabilitation on the left; after rehabilitation on the right.

4.3. Technical Means to Enhance the Carbon Sink Capacity of Agricultural Soil in the World

In terms of how to enhance the carbon sequestration capacity of agricultural soil, various countries have also put forward relevant technical guidelines to guide farmers to improve the carbon reduction and sequestration capacity of farmland soil. If the United States is the country with the most widespread no-till technology and the largest no-till area in the world^[25], with conservation tillage accounting for over 40% of the cultivated land area, and the corn belt in the Midwest adopts no-till combined with straw mulching, the average annual increase in soil organic carbon is 0.1 to 0.3 tons per hectare. In 2025, the United States Department of Agriculture (USDA) released a public version of the carbon intensity calculator. Guide farmers to independently calculate soil carbon storage under different farming models, fertilization strategies, and crop selections^[26]; The EU also encourages farmers to adopt sustainable land management measures to increase soil carbon sinks. For instance, in 2023, the EU updated the Common Agri-

cultural Policy (CAP), requiring member states to allocate at least 25% of their agricultural budgets to “Eco-schemes”. To encourage climate-friendly agricultural practices (such as organic agriculture, agroecology, carbon agriculture, etc.), France thus requires farmers to implement conservation tillage (to reduce soil disturbance) and rotate leguminous crops (for nitrogen and carbon fixation), promoting the transformation of agricultural land into carbon sinks and laying the foundation for the next step of member states paying carbon subsidies to farmers^[27] Organic farmers in Germany have adopted a 4-year crop rotation system of “marigold-oat-head-wheat”, reducing the incidence of marigold late blight by 70%^[28]; Other countries such as India have achieved zero chemical input in organic rice fields through a combination of “rice-legume-mustard” rotation and duck-rice co-culture^[29].

On the technical means and policy measures to enhance the carbon sequestration capacity of agricultural soils, American scholars studied how to improve the carbon sink capacity of agricultural soils by improving agricultural technology and management practices, and paid attention to the impact of different agricultural man-

agement measures on soil carbon sinks, and believed that measures such as conservation tillage, organic farming and crop rotation were conducive to increasing soil carbon storage capacity^[30]; Australian scholars studied how to improve soil carbon sink capacity by soil management and ecosystem restoration, focusing mainly on the relationship between soil carbon sinks and land use changes; The focus of the EU's common agricultural policy shifted from emphasizing grain production to placing more emphasis on the ecological sustainability of crop land, encouraging farmers to adopt sustainable land management measures to increase soil carbon sinks^[31]. Various countries and regions have taken a series of measures to promote the carbon sinks of agricultural soils: in terms of technical means, the adoption of conservation tillage, organic farming, crop rotation and intercropping, soil improvement, pasture restoration, cover crops, and agro-forestry complex systems; in terms of policy measures, the adoption of carbon emissions trading, agricultural subsidies, ecological compensation, and legal regulations^[32]. Recently, the VCS released a revised "Improved Agricultural Land Management Methodology", which quantified the greenhouse gas emissions reduced and the soil organic carbon removal by improving land management practices.

In addition, agricultural water management, especially drainage systems, has a significant impact on greenhouse gas emissions. Özçelik and Kuhnert^[33] constructed a quantitative model framework based on cases in Lincolnshire, UK, systematically assessing the differ-

ences in greenhouse gas emissions from agricultural lands under drained and undrained conditions. The results indicate that drainage management not only alters soil moisture conditions and crop yields but also significantly affects the emission levels of N₂O and CH₄. Similarly, field trials by Hwang et al.^[34] in Korean paddy fields found that reasonable drainage can effectively reduce CO₂ and CH₄ emissions, verifying the potential of drainage measures in reducing emissions in sustainable agricultural management. Research by Islam et al.^[35] suggests that implementing intermittent drainage during the early stages of rice growth can significantly reduce greenhouse gas emissions without causing yield loss. These research findings provide beneficial references for the carbon sink assessment method proposed in this study, suggesting that in land reclamation and carbon accounting models, agricultural water management should be considered one of the key influencing factors. The technical means to enhance the carbon sink capacity of agricultural soil in the world include conservation tillage, organic agriculture rotation, and agro-forestry complex system in the field of agricultural management. In the field of agricultural technology, these include direct agricultural technical measures such as soil improvement technology, organic material input and fertilizer management, and water and nutrient coordinated management, as well as precise monitoring and intelligent management technologies that help achieve carbon reduction indirectly. The specific summary is shown in the following **Table 1**.

Table 1. Overview of International Technological Approaches to Enhance the Carbon Sink Capacity of Agricultural Soils.

Type	Method	Specific Content	Achieve Results	Case Study
Agricultural management measures	Conservation tillage	The approaches adopted on a majority of acres for corn, soybeans, and wheat in US. Through methods such as no-till (planting directly into residue without any tillage) or mulch-till (involving some tillage in a narrow strip where seeds are planted), permanent surface residue cover, and crop rotation, soil disturbance can be reduced and the accumulation of organic carbon in the soil surface can be achieved.	The amount of carbon sequestered per hectare per year can reach <u>0.1–1 tons</u> ^[36] .	<p>·US: In 2016, 65% of corn field and 67% of wheat used conservation tillage techniques^[37]. Conservation tillage accounts for more than 40% of cropland. No-till farming with straw cover is adopted in the US Midwest Corn Belt, enabling the organic carbon to increase by <u>0.1–0.3 tons per hectare per year</u>^[38].</p> <p>·China: The promotion of no-till farming with straw cover in the Northeast China Black Soil Region has curbed black soil degradation and increased yield by 10%–15%^[39].</p>

Table 1. Cont.

Type	Method	Specific Content	Achieve Results	Case Study
Agricultural management measures	Organic Farming Crop Rotation	A sustainable farming system that involves the periodic and sequential rotation of different crops (or a combination of green manure and forage grasses) on a specific plot of land, in order to maintain soil fertility, control pests and diseases, and ensure the organic quality of agricultural products. Its essence is to manage biodiversity instead of chemical inputs, and to achieve a balance in the agricultural ecosystem in accordance with the laws of nature.	Reduce external fertilizer input, maintain soil health, prevent diseases and pests ecologically, and meet the organic certification requirements (international organic standards such as EU EC 834/2007, US NOP mandate crop rotation, prohibit long-term monoculture).	<p>Germany: Organic farmers used a four-year potato-oat-clover-wheat rotation, which <u>reduced the incidence of late blight of potato by 70%</u> [40].</p> <p>India: The rice-legume-mustard rotation combined with duck rice farming realized <u>zero chemical input of organic rice fields</u> [41].</p> <p>China: The rotation of “solanaceae-leafy vegetables-allium” was promoted in the organic vegetable base of North China, with the occurrence of monoculture obstacle <u>decreased by 50%</u> [42].</p>
	Agroforestry Systems	A purposefully integrated, artificially managed system consisting of two or more species of animals or plants and at least two production systems. By arranging perennial woody plant cultivation (such as trees, shrubs, palms, and bamboos) with crop cultivation (such as agricultural crops, medicinal plants, cash crops, and fungi) and/or livestock and poultry in a spatial or temporal sequence on the same land management unit, the system’s overall productivity is increased, improving overall ecosystem quality.	Tree roots stabilize soil and reduce erosion (by <u>50%–80% less soil loss compared with monoculture farmland</u>); the annual <u>carbon sequestration of the tree layer can reach 5–15 tons per hectare</u> , which is far higher than pure farmland; tree shade reduces the need for irrigation, and nitrogen-fixing tree species (such as Leucaena) can replace chemical fertilizers; Diversify agricultural and forestry products, improve unit land use efficiency and crop yields, thereby reducing the various types of material energy consumed per unit crop yield and achieving improved carbon sequestration capacity.	<p>Meenangadi village in Kerala: The government-supported carbon-neutral village project aims to enhance carbon sinks by increasing tree cover on farmlands [43].</p> <p>African Fertilizer Tree system: Intercropping nitrogen-fixing tree species, such as Leucaena, with corn fields, leading to a <u>30–50% increase in corn yields</u> [44].</p>
Direct agricultural technical measures	Organic Material Input and Fertilizer Management	Straw returning and carbonization returning, green manure planting and turning pressing.	The annual carbon sequestration of returning straw and carbonizing <u>returning straw could reach 0.5–1.2 tons C/hectare</u> (IPCC Tier 2 data); the annual carbon sequestration of green manure planting and turning pressure could be <u>0.3–0.8 tons C/hectare</u> , and it could reduce the N ₂ O emission of chemical fertilizer by 20%–30%. Application of biochar at the rate of 10–30 tons/hectare resulted in <u>20%–50% increase in SOC</u> , and its carbon sequestration effect can last for decades [45].	<p>India: By converting organic waste from cities and rural areas into biochar and substituting it for chemical fertilizers applied to cropland, not only has the dependency on chemical fertilizers been reduced, but also the content of organic carbon in the soil has increased by 20%–30% [46].</p> <p>Brazil: The promotion of the application of biochar with phosphate fertilizer in acidic soil has <u>increased the carbon sequestration efficiency by more than 50%</u> [47].</p> <p>China: Through straw returning and the application of organic fertilizers, the content of organic carbon in cropland soil has increased by an average <u>0.1%–0.3% per year</u>, and in some black soil project areas, the increase has reached more than 0.5%.</p>

Table 1. Cont.

Type	Method	Specific Content	Achieve Results	Case Study
Direct agricultural technical measures	Integrated management of water and nutrients	Water-saving irrigation, optimization of N and P application, and synergistic regulation of microbial communities (e.g., fungi/bacteria ratio) by water and nutrients, promote the formation of mineral-organic complexes (e.g., iron oxide-associated carbon), and enhance C stability.	<p>·In Xinjiang cotton fields, subsurface drip irrigation under plastic film can <u>increase the soil carbon stock by 0.2 t/hm²/year</u> compared with flood irrigation.·Appropriate use of fertilizers (such as slow-release nitrogen fertilizer) can reduce carbon loss caused by carbon-nitrogen imbalance. Experiments show that <u>nitrogen fertilizer use efficiency can be increased by 10% and soil carbon sequestration can be increased by 5%–8%</u>.</p>	<p>·China: Urban bare soil management by fermenting organic solid waste into nutritious soil, planting drought-resistant plants, and fixing 1650 tons of carbon per year; rice-shrimp co-culture combined with optimized fertilization reduces fertilizer use, increases soil carbon and nitrogen sequestration, and significantly enhances the sustainability of the system.</p>
	Soil improvement technology	A series of methods to adjust the physicochemical properties, biological activity and structural functions of the soil through physical, chemical, biological or comprehensive means, so that it is more suitable for crop growth or ecological restoration. Its core goal is to solve the problem of soil degradation (such as compaction, salinization, decline in fertility, and pollution) to improve soil productivity and ecological service capacity.	<p>·Physical improvement: straw, ground film covering reduces evaporation, regulating soil temperature (e.g., water-holding rate of corn straw covering in arid areas <u>increased by 20%</u>).·Chemical improvement: adding zeolite, biochar, etc. adsorbs heavy metals (e.g., applying biochar to cadmium-contaminated paddy fields, which makes the effective cadmium <u>decreased by 30%–50%</u>).·Biological improvement: turning and pressing purple clover, alfalfa and other leguminous plants, immobilizing nitrogen and increasing carbon (green manure can <u>provide 150–200 kg nitrogen per hectare</u>).</p>	<p>·China: The model of “deep tillage returning straw to the field + organic fertilization” was promoted in the black soil area of Northeast China, which increased the organic matter of the soil by <u>0.1%–0.3% per year</u> on average^[39];</p> <p>·Netherlands: The saline-alkali land affected by seawater intrusion realized agricultural reuse through “drainage-planting salt-resistant potatoes-drip irrigation to control salt”^[48].</p> <p>·Brazil: The degraded area of the Amazon rainforest adopted “fast-growing tree species + nitrogen-fixing leguminous plants” to quickly restore soil fertility^[47].</p>
Indirect agricultural technical measures	Precise Monitoring and Smart Management	Intelligent supervision is achieved by using remote sensing and geographic information technology, ground sensor networks, intelligent management platforms, etc., and accurate tracking, regulation and early warning of material and energy consumption are achieved based on data-driven methods to prevent material and energy waste caused by improper manual operation or untimely pest and disease control measures, thereby promoting carbon reduction and achieving soil carbon sink enhancement.	Monitoring accuracy is improved, and the platform will analyze various monitored data and provide management and control suggestions, such as watering and fertilizing; a single farmer can manage and care for all 1000 acres of wheat fields.	<p>·US: Developed COMET-Farm model where farmers can input tillage and fertilization data to automatically generate a carbon sequestration potential report to guide policy subsidy allocation^[49].</p> <p>·China: Smart agriculture demonstration site in Guangshui uses soil sensors and AI models to optimize management, <u>reducing the occurrence of wheat diseases and pests by 40% and achieving a 90% quality rate</u>. Climate-smart technologies (e.g., water-saving irrigation, quick-rot technology for straw) developed that <u>reduce methane emission intensity by 20%–30%</u> for rice-growing areas.</p>

5. Model Application and Results

Based on the methodological framework established in Chapter 3, this section applies the scale-cost-

benefit model to analyze land consolidation projects in Guangdong Province. Through simulations of various land-use conversion scenarios, the study identifies threshold conditions under which carbon sequestration

benefits outweigh the associated costs.

Drawing on field survey data, a comprehensive cost-benefit accounting process for farmland carbon sequestration is conducted from a full-chain perspective (Table 2). The analysis focuses on four primary conversion types: reclamation of garden land to cropland, reclamation of grassland to cropland, reclamation of facility

agricultural land to cropland, and reclamation of pond surfaces to cropland. The calculation formulas are developed based on actual conditions in Guangdong Province, with empirical data sourced from 42 study units across practical land consolidation projects in cities including Guangzhou, Jiangmen, Maoming, Shantou, Meizhou, and Shanwei.

Table 2. Analysis of the “cost-effectiveness” of Reclaimed Garden Land as Cultivated land.

Reclaiming The Garden Plot Into Cultivated Land “Cost-Benefit” Calculation Process	
C (Total Remediation Cost)	$C = (15 \times 0.3)A_1 + (15 \times 12)A_2$ $\text{--- } C = 4.5A_1 + 180A_2$ <p>① The total remediation cost consists of two parts, one is the improvement of arable land, that is, the construction and renovation of high-quality farmland; the other is the change of land use types, such as the remediation cost required for orchards to become arable land; ② 15 is the conversion from hectares to mu; 0.3 is the content of high-quality farmland construction and renovation, including land leveling, irrigation and drainage works, field road works, farmland protection, soil improvement, etc., with a construction cost of about 0.3 yuan/mu; 12 is the estimated construction investment of newly added arable land (including the price of land improvement, 20,000 yuan/mu);</p>
K (Net Carbon Sink)	$K = (15 \times 5 \times (0.796/40 \times 30))A_1 + (15 \times 10 \times (0.796/40 \times 30))A_2 - (0.497 \times A_1 - 0.730 \times A_2) - 6.21$ $\text{--- } K = 44.28A_1 + 90.28A_2 - 6.21$ <p>Referring to Duke’s Law and the carbon emission coefficient method, the process of increasing soil organic matter by 1 percentage point for orchards and farmland, and the process of increasing soil organic matter by 0.5 percentage point for permanent farmland, with a carbon emission coefficient of 0.497 for cultivated land and 0.730 for orchards (which act as carbon sinks). ① Carbon sink amount calculated according to Duke’s Law (Unit: tons): $(15 \times 5 (0.796/40 \times 30))A_1 + (15 \times 10 (0.796/40 \times 30))A_2$ ② Carbon emission amount calculated according to the carbon emission coefficient (Unit: tons): $(0.497A_1 - 0.730A_2)$, which belongs to soil mineralization. ③ Considering the carbon emission from organic fertilizer (Unit: tons) (Check the “carbon dioxide emission coefficient” from the “oxidized ammonia emission from organic fertilizer input”), for each 1 percentage point increase, 15 tons–20 tons of organic fertilizer need to be invested. (According to the need to invest 18 tons of organic fertilizer for each 1 percentage point increase), calculated by nitrogen content of 46%, it can mineralize nitrogen by 30%, with an emission coefficient of 0.0178, N₂O molecular weight 44, N atomic weight 14, converted into carbon dioxide *298 farmland organic fertilizer input introduces the content of nitrous oxide-carbon dioxide emission: $2710000.460.30.017844/14/10000 \times 298 = 6.21$ tons of net carbon sink amount $K = (15 \times 5 \times (0.796/40 \times 30))A_1 + (15 \times 10 \times (0.796/40 \times 30))A_2 - (0.497A_1 - 0.730A_2) - 6.21$</p>
R1 (Ecological Benefits)	$R_1 = K \times 39.30 / 10,000$ $\text{--- } R_1 = 0.17A_1 + 0.35A_2 - 0.02$ <p>① Ecological value benefit: After the comprehensive land consolidation, a large amount of soil carbon sinks are newly added, and the average carbon trading price is calculated according to the transaction volume and transaction amount from January 1, 2025 to March 18, 2025 in the national carbon trading market. From January 1 to March 18, 2025, the national carbon market carbon emission allowance transaction volume was 402,411.4 tons, and the transaction amount was 36,325,210.27 yuan, and the carbon average price was 90.27 tons/yuan. The closing price on April 1 was 39.30 yuan/ton (which can be referred to later). ② 10000 is the unit conversion between tons and ten thousand tons.</p>
R2 (Production Revenue)	$R_2 = 15 \times 783 \times 1.62 (A_1 + A_2) / 10,000$ $\text{--- } R_2 = 1.90A_1 + 1.90A_2$ <p>Note: 15 is the unit conversion from hectares to mu, 783 is the number of catties of grain produced per mu, and 1.62 is the grain unit price: 1.62 yuan/catty, 10,000 is the unit conversion from yuan to ten thousand yuan</p>
R (Total Revenue)	$R = R_1 + R_2$ $\text{--- } R = 2.07A_1 + 2.25A_2 - 0.02$ <p>Note: Total benefits are the sum of ecological benefits and production benefits</p>
P (Net Profit)	$P = nR - C = n(2.07A_1 + 2.25A_2 - 0.02) - (4.5A_1 + 180A_2)$ $\text{--- } P = nR - C = (2.07n - 4.5)A_1 + (2.25n - 180)A_2 - 0.02n$ <p>Note: Net benefits = Total benefits R - Total costs C, considering that it takes a certain number of years to generate production benefits after remediation, a variable n is added</p>

Table 2. Cont.

Reclaiming The Garden Plot Into Cultivated Land “Cost-Benefit” Calculation Process

Total cost of reclamation: $C = 4.5A1 + 180A2$
 Net carbon sink: $K = 44.28A1 + 90.28A2 - 6.21$
 Total revenue: $R = 2.07A1 + 2.25A2 - 0.02$
 Net profit: $P = nR - C = (2.07n - 4.5)A1 + (2.25n - 180)A2 - 0.02n$

The same algorithm can lead to the conclusion that: $180)A5 - 0.03n$

- Grassland Reclamation into Arable Land “Cost-Benefit” Calculation Process:

Total cost of reclamation $C = 4.5A1 + 180A3$
 Net carbon sink $K = 44.28A1 + 89.57A3 - 6.21$
 Total benefit $R = 2.07A1 + 2.25A3 - 0.02$
 Net benefit $P = nR - C = (2.07n - 4.5)A1 + (2.25n - 180)A3 - 0.02n$

- Conversion of facility farmland into cultivated land “Cost-benefit” calculation process

Total cost of reclamation of facility farmland into cultivated land $C = 4.5A1 + 180A4$
 Net carbon sink $K = 44.28A1 + 134.33A4 - 8.28$
 Total revenue $R = 2.07A1 + 2.43A4 - 0.03$
 Net profit $P = nR - C = (2.07n - 4.5)A1 + (2.43n - 180)A4 - 0.03n$

- Converting Pond Surface into Farmland “Cost-Benefit” Calculation Process

Total cost of reclamation of converting Pond Surface into cultivated land $C = 4.5A1 + 180A5$
 Net carbon sink $K = 44.28A1 + 134.57A5 - 8.28$
 Total revenue $R = 2.07A1 + 2.43A5 - 0.03$
 Net profit $P = nR - C = (2.07n - 4.5)A1 + (2.43n -$

Based on the computational results, a two-dimensional analysis of “area-carbon sink-cost” relationships was developed (Figure 6). The corresponding chart delineates variations in original cultivated land area, newly added cultivated land area, consolidation costs, and farmland carbon sink changes across the 42 study units. Results indicate that greater newly added cultivated land area corresponds to higher consolidation costs, while larger original cultivated land area implies better baseline conditions and enhanced carbon sequestration capacity. Moreover, under identical newly added area conditions, a larger original cultivated area is associated with higher net benefits, whereas expanding new cultivated area on the same original land base increases costs.

Analysis of “Total Newly Added Cultivated Land Area vs. Net Soil Carbon Sink” reveals an exponentially increasing trend in carbon sequestration with expanded cultivation area. Conversely, “Total Newly Added Cultivated Land Area vs. Consolidation Cost” displays a linear relationship, indicating proportionally rising costs with area expansion.

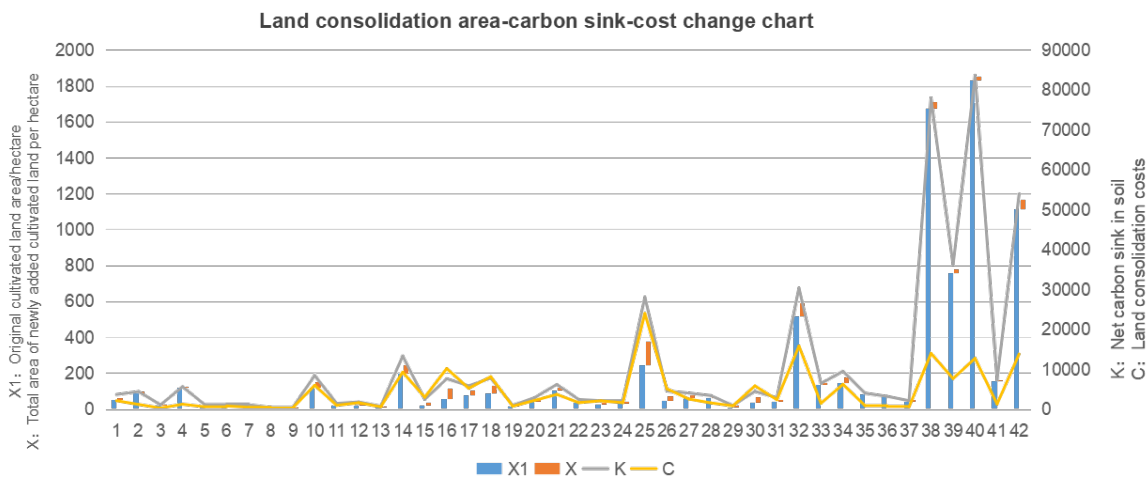


Figure 6. Cont.

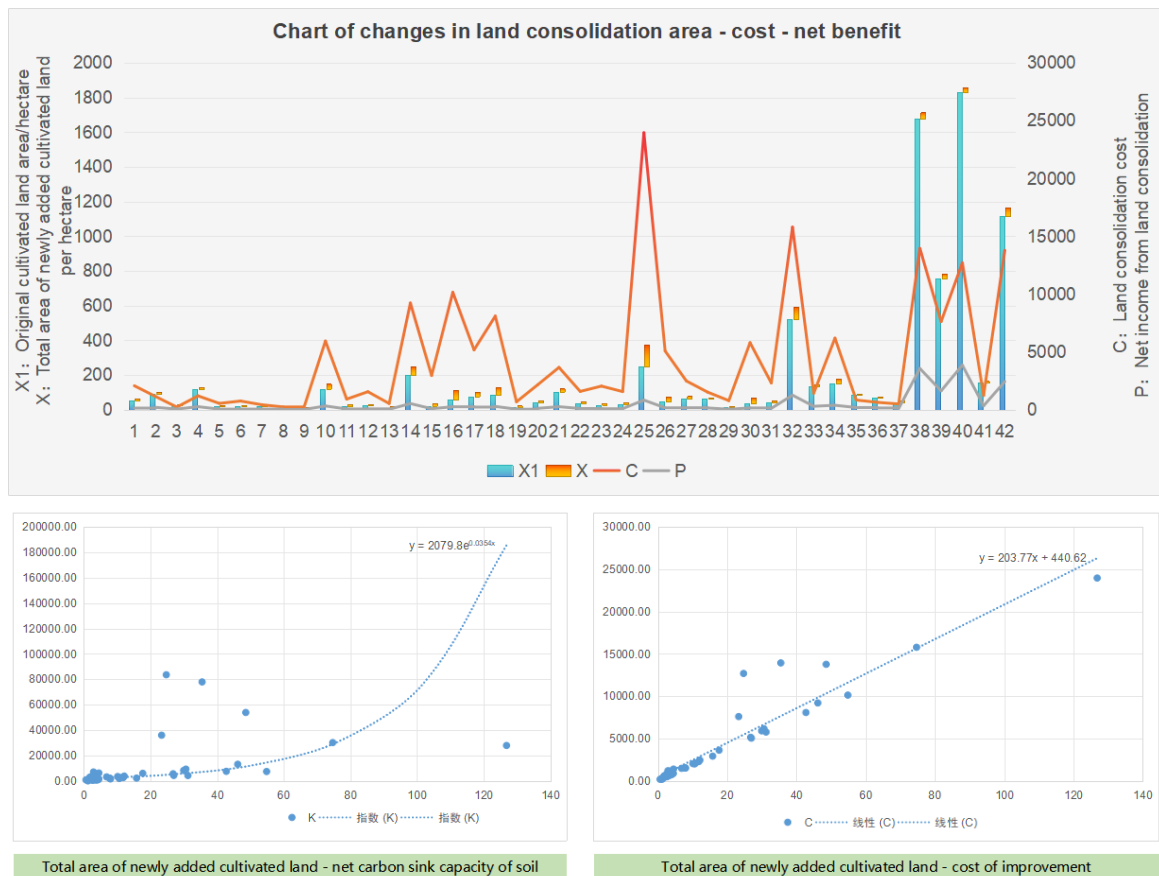


Figure 6. Analysis of the two-dimensional Relationship between “scale-cost-benefit” of Soil Carbon Sink in Cultivated Land.

A three-dimensional “area-cost-benefit” model was further established (Figure 7), with Y representing comprehensive consolidation cost, P denoting comprehensive benefits, X_1 indicating original cultivated area, and X_2 representing newly added area. Within this frame-

work, cost and benefit functions generate an intersection curve that dynamically shifts along the X_1 and X_2 axes. This curve represents the break-even point where costs equal benefits, enabling determination of optimal conditions for equilibrium.

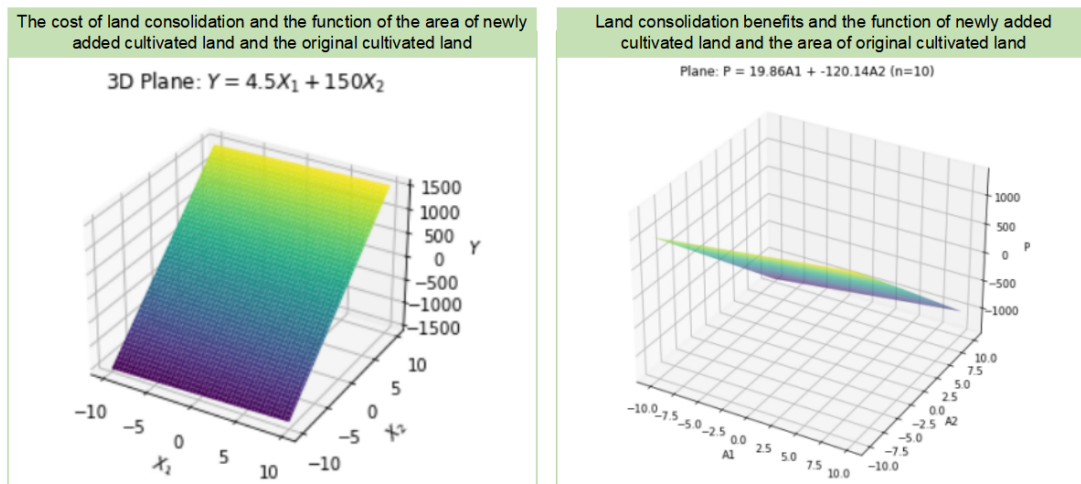


Figure 7. Cont.

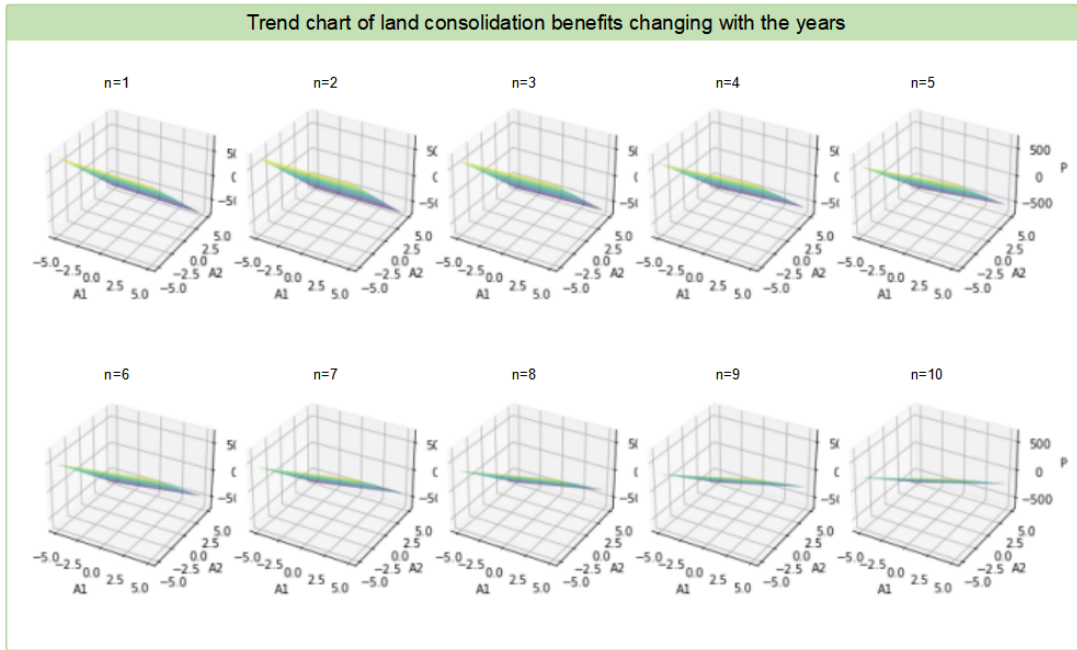


Figure 7. Analysis of the three-dimensional Relationship between “scale-cost-benefit” of Soil Carbon Sink in Cultivated Land.

As regional consolidation progresses, the gradual expansion of cultivated area drives continuous evolution of the cost-benefit intersection curve. Ultimately, a dynamic “scale-cost-benefit” visualization model was developed for cultivated land carbon sinks (Figure 8), capable of estimating corresponding costs and benefits

based on input land-type areas and timeframes. The model captures the dynamic interaction between cost and benefit surfaces within a three-dimensional space, projecting a consistent year-on-year increase in net benefits over time.

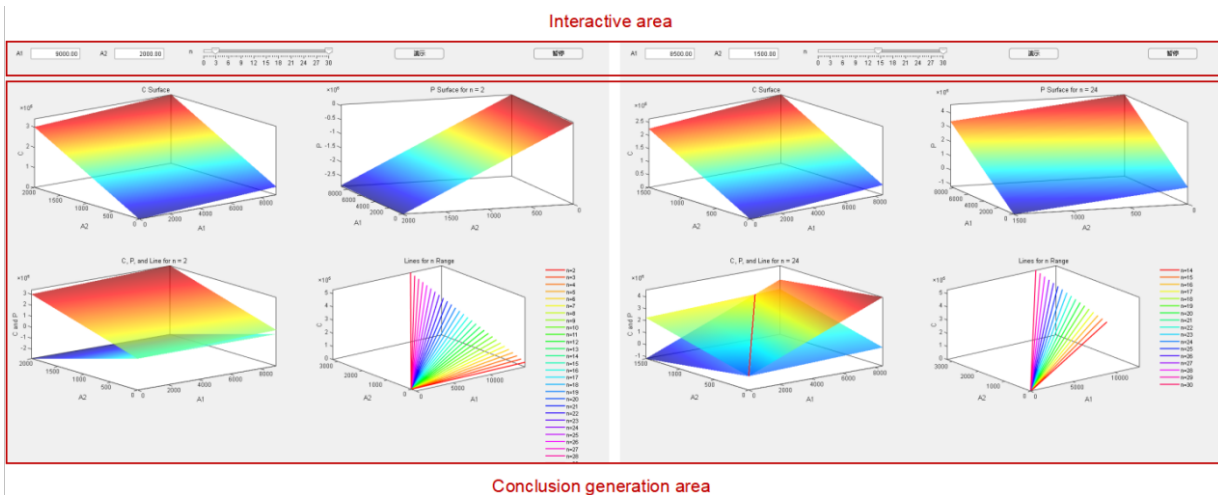


Figure 8. Generating a dynamic visualization analysis model for the “scale-cost-benefit” of the global cropland soil carbon sink.

6. Discussion

This study contributes methodologically by constructing a full-chain “land consolidation-carbon sequestration-trading” framework and developing a

“scale-cost-benefit” model. Unlike previous studies that examined land consolidation, carbon accounting, or trading mechanisms in isolation, this integrated framework enables a systematic assessment of the economic feasibility of farmland carbon sequestration. The

methodological innovation provides a replicable tool applicable not only in China but also in other agricultural systems dominated by smallholder farmers.

Empirical results demonstrate that scale is a prerequisite for economic feasibility. At the current carbon price of 40 yuan per ton, the average carbon benefit per mu of farmland is only 8–12 yuan, which is not enough to offset the small-scale monitoring and transaction costs. However, consolidating farmland into contiguous plots can reduce costs by 30–40%, enabling projects to achieve cost-benefit equilibrium. This finding aligns with international practices: land consolidation projects in the European Union emphasize the importance of standardization and scaled management, while conservation tillage and no-till practices in the United States demonstrate that centralized farmland management can enhance both productivity and carbon benefits. Thus, these results resonate with broader international experiences and provide guidance for countries with fragmented farmland structures.

From a policy perspective, this study offers three key insights. First, carbon sequestration considerations should be integrated into the comprehensive planning stage of land consolidation to achieve scaled aggregation of carbon sinks. Second, a full-chain mechanism encompassing farmland consolidation, soil carbon enhancement, and carbon trading should be established, with multi-stakeholder involvement from farmers, enterprises, and governments to reduce transaction costs. Third, while national standards provide necessary consistency, localized criteria must be developed to reflect regional variations in soil conditions, farming practices, and market readiness. Together, these measures can strengthen the institutional foundation for farmland carbon sequestration.

7. Conclusions and Prospects

Based on the perspective of the whole chain of “remediation-carbon sequestration-trading”, this study constructed a “scale-cost-benefit” analysis model for farmland soil carbon sequestration and conducted a systematic calculation based on the transformation scenarios of different land types. The study reached the follow-

ing main conclusions:

- (1) Scale is the core condition for achieving carbon sequestration benefits. Under the current carbon trading market price level, the carbon sequestration benefits of a single mu of farmland are limited. Only under the conditions of large-scale and continuous land remediation can the detection, remediation and transaction costs be effectively diluted, forming a balance point where benefits exceed costs, thereby realizing the value of carbon sequestration.
- (2) Different land types show differentiated benefits. After gardens, grasslands, facility agricultural land and pond water surfaces are converted into arable land, there are significant differences in carbon sequestration increments and benefits. Among them, the carbon sequestration benefits of facility agriculture and water surface transformation projects are higher, but the cost input is also higher; in contrast, the cost-benefit ratio of grassland and garden conversion is relatively better. Therefore, the land remediation path needs to be adapted to local conditions and classified.
- (3) The study emphasizes the necessity of establishing an integrated “consolidation–sequestration–trading” mechanism to reduce market entry barriers for smallholder farmers through unified accounting standards and transactional procedures. Simultaneously, it advocates for the development of differentiated local standards that align with national guidelines while accounting for regional variations in soil conditions and agricultural practices. This approach enhances both the scientific rigor and practical applicability of carbon accounting.
- (4) The model has application value and promotion potential. The “scale-cost-benefit” model proposed in this study can not only predict the carbon sequestration costs and benefits under different scale and time conditions, but also provide a quantitative basis for the expansion of project investment and financing paths and the judgment of the applicability of carbon trading, thereby providing tool support for policy formulation and local practice.

The model in this paper still has certain limitations in the application process: First, the parameters depend on existing statistical and case data, and the soil conditions and agronomic measures in different regions vary greatly, which may affect the universality of the model; second, the model has not yet incorporated long-term ecological feedback effects and climate change uncertainties, making it difficult to fully reflect the dynamic process; third, the economic calculation mainly considers carbon sequestration trading and food production benefits, and does not cover broader value dimensions such as ecological compensation and social benefits. Future research should combine long-term monitoring data to improve the localization accuracy of parameters and incorporate multi-dimensional benefits into the comprehensive evaluation system to promote the sustainable development of farmland carbon sequestration projects under the dual goals of ecology and economy.

Author Contributions

M.Y.: Project management, idea building and overall article writing; C.C.: Data collection, writing of domestic and international review analyses, and article proof-reading; Y.L. (Yueqi Li): Method Construction and writing; F.W.: Model building and writing; Y.L. (Yanping Liu): Domestic and International review analysis and writing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

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