

Article

Comprehensive Benefit Evaluation of Saline–Alkali Land Consolidation Based on the Optimal Land Use Value: Evidence from Jilin Province, China

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Abstract

China, facing severe saline–alkali land degradation, is grappling with the paradox of technically adequate but systemically deficient land consolidation. In response to the existing evaluation system's over-reliance on physicochemical indicators and neglect of socioeconomic value, this study proposes the use of the Optimal Land Use Value (OLV) to construct a comprehensive benefit evaluation indicator system for saline–alkali land consolidation that encompasses ecosystem resilience, supply–demand balancing, and common prosperity. Considering a case project implemented from 2019 to 2022 in the Western Songnen Plain of China—one of the world's most severely affected soda saline–alkali regions—this study combines the land use transition matrix with a comprehensive evaluation model to systematically assess the effectiveness and sustainability of land consolidation. The results reveal systemic deficiencies: within ecological spaces, short-term desalination succeeds but pH and organic matter improvements remain inadequate, while ecosystem vulnerability increases due to climate fluctuations and grassland conversion. In production spaces, cropland expansion and saline land reduction are effective, but water resource management proves unsustainable. Living spaces show improved infrastructure and income but face threats due to economic simplification and intergenerational unsustainability. For the investigated case, recommendations include shifting from technical restoration to systemic governance via three strategies: (1) biological–engineering synergy employing green manure to enhance soil microbial activity; (2) hydrological balancing through groundwater quotas and rainwater utilization; (3) specialty industry development for rural economic diversification. This study contributes empirical evidence on the conversion of saline–alkali land, as well as an evaluation framework of wider relevance for developing countries combating land degradation and pursuing rural revitalization.

Keywords: saline–alkali land conversion; land consolidation; comprehensive benefit evaluation; indicator system; land degradation; rural revitalization; ecosystem resilience



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1. Introduction

As the fundamental substrate of Earth's ecosystems, land directly governs food security, ecological equilibrium, and climate resilience [1]. However, under the dual pressures of intensified climate change and enhanced human activities, land degradation has evolved from a regional ecological issue into a global crisis threatening human survival [2]. Land salination and alkalization (LSA) is among the most serious of these issues, particularly in

arid and semi-arid zones. The Global Status of Salt-Affected Soils (2024) report released by The Food and Agriculture Organization of the United Nations (FAO) reveals that approximately 1.381 billion ha of cropland worldwide is threatened by LSA [3]. China is among the countries worldwide that are severely affected by LSA. According to a 2015 estimate by Yang and Yao, China possesses 36.67 million ha of utilizable saline–alkali land, of which approximately a third has potential for agricultural development [4]. To combat land degradation and ensure food security, China has pioneered an approach known as “comprehensive saline–alkali land consolidation” (SLC). Chinese SLC initiatives aim to rehabilitate and reclaim saline–alkali lands into productive croplands through systematic improvements in soil health, hydrological functions, and ecosystem services, thereby advancing the utilization of rehabilitated lands for sustainable agricultural purposes. In the present study, the terms SLC and comprehensive land consolidation are used in the sense of the terms in Chinese policy and the relevant literature. It should be noted, however, that the Chinese terminology differs from FAO definitions of land consolidation, which primarily concern plot redistribution (for more information on this topic, see, for instance, de Vries [5]). The Chinese government has invested over CNY 120 billion in SLC since 2015. Through saline–alkali soil improvement technologies such as subsurface salt drainage, biological improvement, and salt-tolerant crop cultivation [6–8], a series of scientific measures and engineering practices have been formed, significantly contributing to global SLC technology and solution design.

However, the status of SLC in China presents a complex scenario characterized by consolidation coexisting with latent degradation and coupled with accelerating natural and anthropogenic drivers. For instance, extensive irrigation practices and inefficient water resource utilization in the North China Plain have reduced soil productivity and triggered secondary soil salinization [9]. In the seasonally frozen ground regions of China’s Northeast Plain, soils exhibit notable alkalinity, with pH showing an increasing northward trend in certain areas [10]. LSA disrupts critical biogeochemical and ecological processes, severely compromising soil multifunctionality [11]. This signifies not only the loss of fertile soils but portends systematic collapse of soil ecological functions, manifested through drastic declines in microbial community diversity, diminished carbon sequestration capacity, and weakened pollutant self-purification capabilities. Multidimensional functional deterioration of soils is manifesting as a “silent crisis” threatening food security not only in China, but also globally [12,13].

The paradox of technically effective but systemically deficient approaches to SLC highlights the urgent need to reconsider evaluation frameworks that prioritize technical metrics while neglecting value-based assessments. In the present study, the authors consequently argue that China’s SLC comprehensive evaluation methodologies currently present several fundamental flaws: evaluations tend to simplify complex systemic evaluation issues into soil physicochemical indicators, compressing dynamic spatial value judgments into static soil quality issues, conflating engineering performance with SLC benefits while ignoring socioeconomic system adaptability. Crucially, inadequate attention has been paid to whether consolidated land achieves its optimal value as a multifunctional resource base [8,14,15]. Specifically, SLC faces three major challenges: firstly, there is a lack of targeted evaluation methods for SLC. For instance, while drought serves as a driver of saline–alkali land formation, current evaluations lack an examination of water use efficiency, obscuring SLC’s distinctive characteristics. Secondly, there is an unclear value orientation. According to the perspectives on the development and utilization of saline–alkali land issued by the Ministry of Natural Resources of China [16], the objective of SLC is to achieve ecosystem restoration such that the land can sustainably create economic and social value while avoiding future ecosystem degradation. We therefore wish to argue

that SLC assessments should consequently be designed to cover aspects that allow them to assess whether SLC can achieve this objective. However, no evaluation system yet exists that encompasses these objectives. Thirdly, there is a lack of socioeconomic evaluation tools. Existing frameworks fail to assess stakeholder benefit distribution and well-being safeguards post-consolidation, particularly in terms of whether residents directly gain economic and social benefits through land consolidation, which is a crucial issue that directly affects the sustainability of consolidation.

We propose an alternative evaluation approach in this study, which we call Optimal Land Use Value (OLV). To clarify how our proposed approach addresses the systemic deficiencies mentioned above, we outline the characteristics of land consolidation benefits assessment methodologies currently used in China in Section 2. Our approach aims to develop an adaptive indicator system for evaluating the benefits of SLC, utilizing a common analytical framework that considers the comprehensive benefits of land consolidation and the specific characteristics of SLC. Using an SLC project in Northeast China's soda saline-alkali regions as a case study, the feasibility and effectiveness of the indicator system are verified. By developing scientifically quantifiable methods for comprehensive SLC benefit evaluation, this study offers a theoretically innovative and practically applicable framework for global SLC practices.

This study makes the following contributions: first, OLV is introduced for value judgment. Transcending mere soil remediation, this approach conceptualizes land as a vital resource element within the "human-society-economy-ecology" life community, explicitly linking SLC outcomes to spatial planning, rural revitalization, and sustainable land use transitions. Second is this study's resilience-oriented design. Through evaluating indicators such as soil stability, groundwater overextraction rate, intergenerational sustainability, and social well-being improvement, this indicator system comprehensively evaluates the sustainability and risk resistance of the life community with land as the fundamental base, overcoming the evaluation myopia associated with the use of purely physicochemical indicators. Third, this study provides a comprehensive benefit evaluation paradigm for SLC. The case study selected in this study is located in one of the world's most severely affected soda saline-alkali regions, characterized by extreme salinization, high alkalinity, critically low organic matter, and recalcitrant salt leaching, representing the most challenging consolidation category. Therefore, comprehensive benefit evaluations of the area selected for our case study not only demonstrate the effectiveness of the indicator system constructed in this study but also provide operational proof and an evaluation paradigm for SLC with potentially broad applicability beyond the investigated case.

The remaining sections of this article are structured as follows: Section 2 focuses on the construction of the analytical framework and indicator system. Section 3 outlines the research methods, data sources, and an overview of the regions. Sections 4 and 5 present the results and a discussion, respectively. The conclusions and implications are outlined in Section 6 of this article.

2. Construction of Analytical Framework and Indicator System

2.1. Adaptive Transformation Process of Land Consolidation Benefit Evaluation

China's comprehensive land consolidation (LC) process has been implemented to promote ecological civilization, urban-rural integration, and the realization of rural revitalization strategies. It involves systematic governance of resource and environmental issues and land utilization conflicts within specific regions [17]. Reviewing the evolution of LC practices, the evaluation of its benefits has shifted from single-factor assessment to multidimensional adaptive evaluation. The current consensus is that benefit evaluations focusing on a single element, such as monitoring and cost-benefit analysis centered on construc-

tion progress or project performance, have limited relevance for evaluating the extent to which projects achieve policy objectives. Instead, comprehensive evaluations incorporating multidimensional indicator systems have become the mainstream approach [18,19]. LC evaluation frameworks consequently exhibit a progressively increasing scope of issues considered, complexity in objectives, integration of contents, and diversified methodologies, as illustrated in Figure 1. Crucially, adequately addressing interactions between the different elements evaluated entails a more systemic understanding of the issues involved, as well as more systemic approaches in the evaluation frameworks.

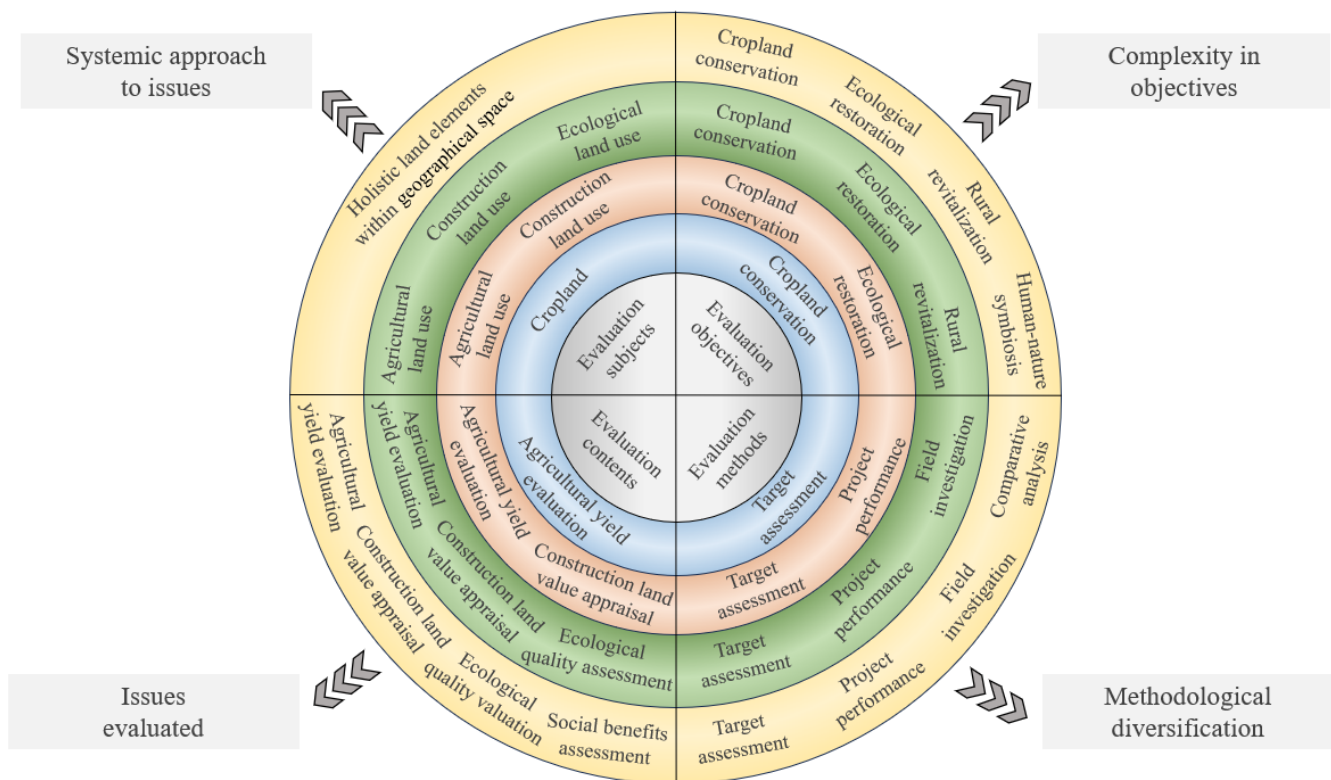


Figure 1. The evolution of China's land consolidation benefit evaluation frameworks. The concentric rings (gray circle at the center, followed by blue, orange, green, and yellow rings) represent the evolution of the evaluation framework from one-dimensional to multi-dimensional. The gray rectangular boxes denote the framework's characteristics. Source: original figure designed by the authors.

Although the LC comprehensive benefit evaluation methodologies used in China have widened their scope and multidimensional indicator systems have become mainstream, we believe that they nevertheless suffer from limited applicability. On one hand, although the frameworks may be theoretically sound, the indicators proposed in many existing frameworks are difficult to operationalize in ways that are relevant to their intended purposes. On the other hand, they tend to lack specificity, and the evaluations are therefore not sufficiently customized for distinct land degradation types.

Their limited applicability means that current LC-based evaluation systems, while theoretically sound, suffer from impractical indicators that prevent their practical implementation, thus confining them to the theoretical realm. This lack of specificity reflects insufficient evaluations customized for distinct land degradation types. While land degradation issues may be generally described as arising from nonlinear coupling between anthropogenic activities and natural drivers, different types of land degradation are fundamentally distinct. For instance, LSA is primarily induced by coupled water–salt transport, chemical fertilization, and improper irrigation practices [20–22], whereas desertification rep-

resents a systemic imbalance caused by climatic aridity, overgrazing, and other contributing factors [23]. Consequently, incorporating the distinctive signatures of specific degradation types into an analytical framework of LC is imperative. Cost–benefit bias manifests in LC evaluations prioritizing economic returns, leading to severe economic overweighting and temporal myopia. When utilizing core indicators focused on financial management and organizational management for acceptance assessments, SLC projects tend to pass acceptance inspections with outstanding ratings. However, subsequent rebound effects and even secondary degradation demonstrate the inadequacy of this conventional cost-driven paradigm for effectively evaluating and guiding LC practices.

2.2. OLV Common Analytical Framework and SLC Comprehensive Benefit Evaluation Indicator System

In recent years, spatial justice and spatial value have gained increasing prominence as core objectives in LC. Spatial justice emphasizes equitable access to land and other spatial resources across socioeconomic groups [24]. Spatial value denotes the composite worth generated through spatial production processes, encompassing economic, social, and cultural dimensions [25], whose optimization critically depends on resource allocation efficiency. Together, they constitute the dual pillars of contemporary land governance: spatial justice establishes ethical boundaries for spatial production to safeguard equity, while spatial value drives material growth to enhance comprehensive benefits. Against this backdrop, the prioritization of equity versus efficiency in land interventions remains a central academic debate. The prevailing consensus prioritizes balancing these dual objectives. Scholars affirm that efficiency gains—exemplified by land value appreciation—must primarily benefit the least advantaged, with multi-actor participation constituting the essential mechanism for reconciling equity and efficiency [26–28]. This theoretical consensus provides the foundation to construct the OLV framework from an equity–efficiency balance perspective, enabling us to incorporate structurally disadvantaged groups into the land consolidation benefit evaluation system.

2.2.1. The Connotations of OLV

The optimal value orientation necessitates balancing two dimensions: equity, which reflects the perceptions and priorities of local populations affected by land consolidation, and efficiency, which embodies the implementation of national policies through planning practices. In our approach to optimal value orientation, we therefore attempt to balance equity and efficiency rather than prioritizing either single dimension. This approach aligns well with the practical logic of China’s comprehensive land consolidation [29]. In this study, we propose OLV as a common analytical framework that aims to achieve an optimal equilibrium state in ecosystem resilience, resource supply–demand balancing, and common prosperity through scientific planning, rational utilization, and effective management under specific socioeconomic, environmental, and policy contexts. It embodies not only the equity and efficiency of land use but also incorporates long-term sustainability, resistance to risks, and adaptive flexibility, ensuring the fulfillment of contemporary needs without compromising the interests of future generations. Figure 2 illustrates how, based on the concepts of ecological spaces, production spaces, and living spaces, we utilize ecosystem resilience, supply–demand balancing, and common prosperity to assess implementation paths to achieve Optimal Land Use Value.

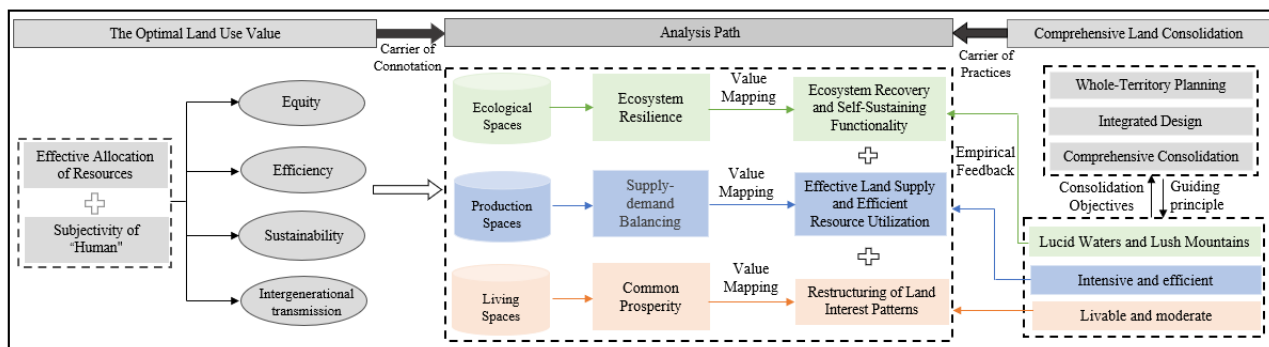


Figure 2. A common analytical framework used for comprehensive benefit evaluation of land consolidation based on OLV. Colors in Figure 2 are used to distinguish different conceptual groups. Green, blue, and orange boxes correspond to the dimensions of ecological spaces, production spaces, and living spaces and their associated pathways, respectively. Source: original figure designed by the authors.

2.2.2. SLC Comprehensive Benefit Evaluation Indicator System

Using the OLV framework established in Section 2.2.1, we construct an indicator system that accounts for the specific properties of saline–alkali lands. This system evaluates whether such lands can achieve short-term effectiveness, long-term sustainability, and controllable risks.

- (1) **Ecosystem resilience (ECRE).** This dimension emphasizes the capacity of ecosystems to recover and maintain self-sustaining states post-consolidation. Long-term land degradation compromises the functionality of ecosystem services. Well-designed SLC initiatives enhance ecosystems with disturbance resistance, adaptability, and sustainability. In contrast, unreasonable SLC may further impair already vulnerable ecosystems by neglecting ecological complexity, excessive engineering, and deficient long-term management. Specifically, neglecting the complexity of ecosystems manifests as a reliance on chemical fertilizers to boost fertility, which damages soil microbial communities and results in a persistent decline in land ecological functions [30]. Excessive engineering, characterized by large-scale land leveling, alters terrestrial environments and ecosystems, damages soil structure, and impairs the land's capacity to perform functions [31]. The short-term acceptance inspection orientation implies that SLC projects often prioritize acceptance inspections, with designs lacking consideration for risk resistance and ecological resilience. Therefore, the ECRE dimension evaluates soil quality improvement and the ecosystem restoration capacity. Soil improvement incorporates saline-specific indicators, including salinity content, pH, and salt-tolerant vegetation coverage. Regarding ecological restoration capacity, the framework assesses environmental impacts on sustainable land management effectiveness, particularly the risk of secondary degradation arising from insufficient ecosystem stability. This authentically reflects SLC outcomes under unavoidable ecological constraints.
- (2) **Supply–demand balancing (SDB).** This dimension examines whether human subjective needs are effectively mapped onto land governance. Evidently, effective SLC fulfills production and development demands by improving agricultural conditions, enhancing productivity, and optimizing resource utilization. However, mismanaged planning causing land fragmentation [32] and hydrological disruption from groundwater overextraction exacerbate human–land conflicts, severely compromising land use efficacy and sustainability [33]. Therefore, land supply capacity and resource utilization efficiency become key to assessing whether SLC promotes supply–demand balance in production spaces. Specifically, the construct is designed to examine

whether SLC adapts land use types to local conditions and effectively utilizes critical resources in saline–alkali lands, thereby assessing the potential for post-consolidation overexploitation and resource depletion.

- (3) Common prosperity (CP). This dimension emphasizes the restructuring of land benefit distributions and assesses whether all stakeholders share the gains derived from SLC. Effective SLC typically delivers shared benefits through economic advancement, spatial optimization, and infrastructure enhancement [34]. However, residents’ structural disadvantages predispose SLC to imbalanced benefit allocation and risks of social stratification. Manifestations include land value appreciation failing to translate into tangible household income gains, alongside differential infrastructure supply between industrial zones and residential settlements. As the economic benefits and social welfare brought by SLC fail to genuinely benefit residents, residents lack motivation to protect or rationally utilize the consolidated land, ultimately severely shortening the lifespan of SLC outcomes. Therefore, within the CP dimension, the evaluation encompasses economic development and social welfare. This evaluation reflects the extent of benefit penetration and benefit-sharing linkages derived from SLC through metrics including residents’ direct income growth, labor force structure, intergenerational transmission levels, and social security improvements. Since saline–alkali lands are predominantly distributed in rural areas, the residents involved in the indicator system are rural residents.

The specific indicator selections are presented in Table 1, mainly including deterministic and adaptive indicators. Deterministic indicators do not require adaptive adjustments based on the actual situation of the project area, whereas adaptive indicators should be adjusted according to the country, region, natural conditions, land utilization orientation, and actual problems faced.

Table 1. The SLC comprehensive benefit evaluation indicator system.

Criterion Layer	Objective Layer	Solution Layer		Rationale for Indicator Selection
ECRE	Soil Quality Improvement	Status Quo Performance	A1. Soil Salinity Reduction Performance (SRP)	A core objective of SLC; reflects desalination performance.
		Sustainability Capacity	A2. pH Improvement Level (PHL)	A long-term objective for SLC; reflects alkaline consolidation performance.
		Risk Resistance	A3. Soil Stability Index (SSI)	Reflects the resilience of soil against external disturbances.
	Ecosystem Restoration	Status Quo Performance	A4. Organic Matter Accumulation Capacity (OMA)	A key indicator of phaeozem sustainable management.
		Sustainability Capacity	A5. Salt-tolerant Vegetation Coverage (STV)	Reflects the sustainability of ecological restoration.
		Risk Resistance	A6. Ecosystem Risk Resistance Index (ERRI)	Reflects the capacity of ecosystems to sustain their structure and functionality under external disturbances.
SDB	Land Supply Capacity	Status Quo Performance	B1. Cropland Area Expansion Level (CAE)	A core demand of food security; Reflects the reclamation performance.
		Sustainability Capacity	B2. Land Stress Index (LSI)	Reflects the exploitation pressure on land.
		Risk Resistance	B3. Land Productivity Resilience (LPR)	Reflects the stability of land productivity under extreme climate conditions.
	Resource utilization Efficiency	Status Quo Performance	B4. Water-saving Irrigation Coverage Rate (WIC)	Reflects the capacity to cope with water resource shortages.
		Sustainability Capacity	B5. Groundwater Overdraft Rate (GOR)	Reflects the status of water cycle balancing and water resource carrying capacity.
		Risk Resistance	B6. SLC Area Improvement Level (SAI)	Reflects the expansion trends of saline–alkali land and management level.

Table 1. Cont.

Criterion Layer	Objective Layer	Solution Layer		Rationale for Indicator Selection
CP	Economic Development	Status Quo Performance	C1. Direct Income Growth Rate (DIG)	Reflects the direct economic growth induced by SLC.
		Sustainability Capacity	C2. Per Capita Residents Income Growth Rate (RIG)	Reflects the economic benefit penetration capacity and income distribution patterns; a core targets of rural revitalization.
		Risk Resistance	C3. Labor Force Structure (LFS)	Reflects economic development potential.
	Social Welfare	Status Quo Performance	C4. Infrastructure Coverage Rate (ICR)	Reflects the advancement level of production conditions.
		Sustainability Capacity	C5. Intergenerational Transmission Level (ITL)	Reflects intergenerational transmission capacity of production resources and social security.
		Risk Resistance	C6. Low Income Population Reduction Rate (LIR)	Reflects the advancement level of social security.

3. Materials and Methods

3.1. Regional Overview

This study evaluates an SLC project (2019–2022) implemented in Taobei District, Baicheng City, Jilin Province. Led by the Taobei District Government with the participation of social capital, the project aimed to advance rural revitalization through ecological restoration and optimized land use allocation. In evaluating this project, we examine the fundamental status of a concrete example of China’s SLC practices. This project contributes to a more fine-grained understanding of the current status of SLC in China, and we used the Taobei SLC project as a case study. The profile of the project area is characterized as follows:

The SLC project (122°19′–123°10′ E, 45°2′4′–45°55′2′ N) in Taobei District is located in northwest Baicheng City, Jilin Province, at the western terminus of the Songnen Plain—one of the world’s most severely affected soda saline–alkali soil regions. Drought disasters occur frequently, and the terrain is flat. Pre-consolidation soil characteristics: the soil exhibits strongly alkaline conditions (pH 9.0–10.0) with an elevated exchangeable sodium percentage (ESP > 30%, reaching 60–70% in severe cases). The surface layer shows textural lightening, forming a laminated–structured eluvial horizon with salt accumulation exceeding 5 g/kg. Figure 3 shows the land use patterns in the project area before (2019) and after (2022) the implementation of SLC.

Based on China’s national standard, *Current Land Use Classification* [35], issued by the Ministry of Natural Resources, this study reclassifies saline–alkali land (SA) from unused land into an independent analytical category. It retains the land use types of forest land (FA), grassland (GA), cropland (CA), and water areas (WA). Concurrently, built-up land, artificial surfaces, bare land, and other types are consolidated into an “Other” category (OA). Since no forest land exists in the project area, ecological land is exclusively classified as grassland.

3.2. Research Methods

To verify the feasibility and adaptability of the indicator system while investigating the current status of SLC in China, this study employed the SLC project as a case study. First, land use transfer matrix (LUTM) analysis was employed to examine the dynamic change processes in land use before and after project implementation. The specific temporal scope is defined as follows: the SLC project was officially launched in October 2019, with acceptance procedures completed in December 2022. Feasibility study report preparation occurred between October and December 2019, while actual land consolidation work com-

menced in January 2020. Therefore, this study designates December 2019 as the temporal node. December 2016 to December 2019 represents the pre-consolidation period. The consolidation period covers December 2019 to December 2022, capturing the effects of SLC. Second, a comprehensive evaluation model was adopted to conduct an overall assessment of the status and benefits of the SLC project. Finally, the evaluation results were analyzed and discussed. This study thereby aims to synergistically reveal the multidimensional change characteristics and effectiveness of consolidation of the land system in the project area through the dynamic change trajectories unveiled by the land use transfer matrix and the comprehensive status assessment provided by the evaluation model.

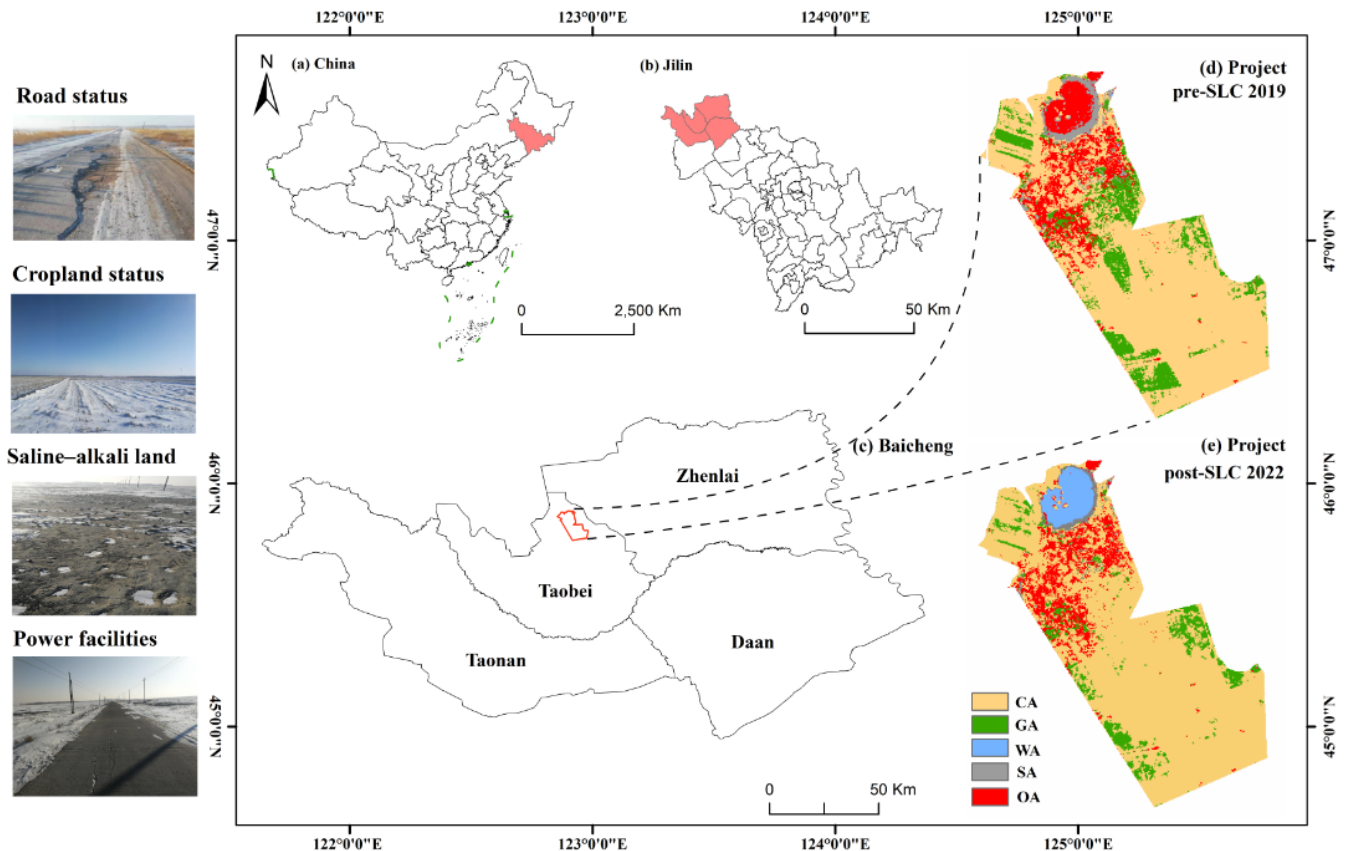


Figure 3. The location of Jilin Province, China (a); the location of Baicheng City, Jilin Province (b); the location of the project area within Baicheng City (c); land use types pre-SLC (2019) (d); land use types post-SLC (2022) (e).

3.2.1. Land Use Transition Matrix

The LUTM can describe the characteristics of land use changes and reflect the direction of land use changes caused by human activities. It not only reflects the static area data of each land use type in a certain area at a certain time point but also reflects the dynamic situation of area transfer out and transfer in of each land use type, as shown in Equation (1).

$$S_{ij} = \begin{pmatrix} S_{11} & S_{12} & \dots & S_{1n} \\ S_{21} & S_{22} & \dots & S_{2n} \\ \dots & \dots & \dots & \dots \\ S_{n1} & S_{n2} & \dots & S_{nn} \end{pmatrix} \quad (1)$$

where i and j indicate land use types. n refers to the number of land use types. S_{ij} indicates the area of transformation from type i to type j in the project area.

3.2.2. Comprehensive Evaluation Model

We first need to assign weights to the indicators in the indicator system constructed in Section 2.2.2. Given that the comprehensive benefit evaluation of SLC in practice typically evaluates consolidation effects only at specific timepoints for targeted projects, objective weighting methods such as Principal Component Analysis (PCA) and the Entropy Weight Method (EWM) are inadequate for calculating weights. Therefore, considering the principles of rationality and convenience in weighting, this study combines the actual status of SLC with the Analytic Hierarchy Process (AHP) and Equal Priority Method (EPM) to assign weights to the indicators. The fundamental principle of AHP is to decompose complex problems into multiple layers, allocate weights within each layer, and multiply the weights at each layer to obtain the final weight. There are three advantages of EPM. First, it can reflect the fairness assumption under noninformative priors. Second, the value orientation is balanced. ECRE, SDB, and CP are considered to be of equal importance to the evaluation objectives under the connotation of OLV. Third, interpretability can avoid disputes caused by complex weighting methods for actual project evaluation. The weighting process is as follows:

- (1) Weighting of the criterion layer and objective layer. ECRE in ecological spaces, SDB in production spaces, and CP in living spaces are equally important in terms of OLV. Any deficiency in an evaluation objective above can directly impact the land value output and consolidation effectiveness. Therefore, using EWM, the weights of ECRE, SDB, and CP are weighted by 1/3, and the objective layer is weighted by 1/2.
- (2) Weighting of the solution layer. The difficulty in evaluating SLC lies in assessing the sustainability and risk resistance of the governance results. Therefore, a higher weight is assigned to indicators of sustainability and risk resistance. Simultaneously, the operational convenience of the indicator system is considered. Therefore, in our methodology, weights of 1/5, 2/5, and 2/5 are assigned to status quo performance, sustainability capacity, and risk resistance, respectively, to reflect the focus on evaluating sustainability and risk resistance.
- (3) The final comprehensive weight is determined by the multiplication synthesis method, as shown in Equations (2) and (3).

$$p_{A1}, p_{A4}, p_{B1}, p_{B4}, p_{C1}, p_{C4} = \frac{1}{3} \times \frac{1}{2} \times \frac{1}{5} = \frac{1}{30} \quad (2)$$

The remaining indicators are

$$\frac{1}{3} \times \frac{1}{2} \times \frac{2}{5} = \frac{1}{15} \quad (3)$$

The calculation methods of indicators are described below. According to different indicator settings, the methods can be divided into the Direct Comparison Method, Threshold Method, and Index Evaluation Method.

(1) Direct Comparison Method

This method directly compares the values of similar indicators at different time points or conditions and reflects the differences or change trends through the difference or ratio. Indicators calculated using this method must satisfy the preconditions of dimensional consistency, metric alignment, and unit uniformity. The specific indicators are shown in Table 2.

Table 2. Indicators calculated using the Direct Comparison Method.

Calculation Methods	Definition and Specification
A5. $STV = S_{STV}/S_{GL}$	S_{STV} and S_{GL} represent the salt-tolerant plant coverage area and the total grassland area upon SLC completion, respectively.
B4. $WIC = S_{WIC}/S_{TI}$	S_{WSI} and S_{TI} represent the water-saving irrigation area and the total cropland area upon SLC completion, respectively.
B5. $GOR = 1 - V_{GRE}/V_{TGR}$	V_{GRE} and V_{TGR} represent the actual groundwater extraction volume and the permitted groundwater extraction volume upon SLC completion, respectively.
B6. $SAI = S_{SL}/(S_{TS} + S_{NT})$	S_{SL} , S_{TS} , and S_{NT} represent the successfully SLC area, the total SLC area, and the newly converted area of saline-alkali land, respectively.
C1. $DIG = (DI_a - DI_b)/DI_b$	DI_a and DI_b represent the direct income generated by consolidation upon SLC completion and during the SLC initiation period, respectively.
C3. $LFS = LF_{YP}/LF_T$	LF_{YP} and LF_T represent working-age workers and total labor force counts, respectively.
C4. $ICR = S_I/S_T$	S_I and S_T represent the infrastructure covers the production area and the total area of the production area upon SLC completion, respectively.

Notes: -Following the International Labor Organization (ILO), the working-age population is 15–64 years old, and the demographic dividend theory suggests that a country or region has a higher potential for economic growth when it has a higher proportion of the population approximately 15–64 years old.

(2) Threshold Method

This method assesses whether objectives or specific states are achieved by comparing indicator values against one or more predefined thresholds. For indicators with absolute standards, merely tracking the magnitude of change may fail to accurately reflect actual outcomes, as achieving compliance requires values to fall below critical thresholds. Both discrete indicators and range-based indicators are designed as piecewise continuous functions, converting actual values into a normalized [0,1] interval. This approach not only embodies threshold-based criteria, but also ensures comparability with indicators derived from the Direct Comparison Method and the Index Evaluation Method. The indicators calculated using this method are all adaptive indicators, and different countries or regions can design thresholds according to their actual situations.

A1. SRP is shown in Equation (4). To facilitate comparisons with other studies on saline soils in China, the soil salinity threshold was taken from *Soil Agrochemical Analysis* [36], which is widely used as a reference work in the country. Soils with salinity levels higher than 0.5% are classified as highly saline, while those less than 0.1% are considered non-saline soil, where V_S indicates the maximum soil salinity level of all sampled soils upon SLC completion, and % denotes mass percentages.

$$SRP = \begin{cases} 0 & , V_S \geq 0.5\% \\ 1 - \frac{V_S - 0.1\%}{0.4\%} & , 0.1\% < V_S < 0.5\% \\ 1 & , V_S \leq 0.1\% \end{cases} \quad (4)$$

A2. PHL is shown in Equation (5). Optimal nutrient availability for most crops is in the soil pH range of 6.0–8.0, as this range optimizes nutrient availability for most agricultural production [37]. Therefore, the optimal lower limit is 6.0 in this article. $\overline{V_{PH}}$ denotes the

average pH value of all soil samples tested upon project completion, and PH_L and PH_H denote the upper and lower limits of the objective pH for soil samples.

$$PHL = \begin{cases} 0 & , \overline{V_{PH}} > PH_H; \overline{V_{PH}} < 6.0 \\ 1 - \frac{\overline{V_{PH}} - PH_L}{PH_H - PH_L}, PH_L < \overline{V_{PH}} \leq PH_H & \\ 1 & , 6.0 \leq \overline{V_{PH}} \leq PH_L \end{cases} \quad (5)$$

A4. OMA is shown in Equation (6). The soil organic matter content threshold comes from the *China Nutrient Grading Standards for the Second Soil Census* [38] issued by the China Soil Survey Office. A high soil organic matter content is classified as greater than 4%, while levels less than 0.6% are considered extremely deficient. V_O indicates the average organic matter content of sampled soils upon project completion, and % denotes mass percentages.

$$OMA = \begin{cases} 0 & , V_O \leq 0.6\% \\ \frac{V_O - 0.6\%}{3.4\%}, 0.6\% < V_O < 4\% & \\ 1 & , V_O \geq 4\% \end{cases} \quad (6)$$

B1. CAE is shown in Equations (7) and (8). C denotes the annual average growth rate of cropland. CL_a and CL_b indicate the cropland area upon SLC completion and the SLC initiation period, respectively. T denotes the average annual growth rate of cropland in the higher-level administrative region where the project is located.

$$C = (CL_a / CL_b)^{1/n} - 1 \quad (7)$$

$$CAE = \begin{cases} 0, C \leq 0\% \\ C/T, 0\% < C < T \\ 1, C \geq T \end{cases} \quad (8)$$

B2. LSI is shown in Equation (9). C_{SU} and C_{ST} indicate the per capita supply of grain and the food security line in the current project area upon SLC completion, respectively. This study adopts the per capita grain yield of 400 kg as the food security line [39]. Different countries should determine their own standards based on actual dietary structures and caloric requirements. For nations lacking established studies, researchers can estimate the food security threshold as follows: first, calculate the demand for three primary grain categories: ration, feed, and seed. This calculation should be based on a daily caloric intake of 2330 kcal per “representative” adult [40] and the dietary structures of their countries. Second, summing these quantities with industrial utilization grain yields the total grain demand, and dividing this aggregate by the national population produces the per capita food security benchmark.

$$LSI = \begin{cases} 1 & , C_{SU}/C_{ST} \geq 1 \\ C_{SU}/C_{ST}, \text{ otherwise} \end{cases} \quad (9)$$

B3. LPR is shown in Equations (10) and (11). This involves selecting extreme climate types and determining source thresholds for the grain yield coefficient of variation (CV) standard. The selection of extreme climate types should be based on actual conditions within the project area. There is no unified international standard for grain yield CV thresholds. In Europe and North America, with stable, highly intensive agriculture, crop CVs typically fall below 10%. China’s main grain-producing regions generally exhibit CVs between 8% and 15%, while CVs in arid Northwest China or mountainous Southwest regions can exceed 25%. Based on this analysis, this study establishes a general empirical standard for grain yield CV.

$$\sigma_{C_t} = \sqrt{\frac{\sum_{t=1}^n (C_t - \sum C_t / n)^2}{n}}; CV_L = \frac{\sum C_t / n}{\sigma_{C_t}} \quad (10)$$

$$LPR = \begin{cases} 0 & , CV_L \geq 25\% \\ 1 - \frac{CV_L - 10\%}{15\%}, 10\% < CV_L < 25\% \\ 1 & , CV_L \leq 10\% \end{cases} \quad (11)$$

where C_t and σ_{C_t} represent the grain yield and its standard deviation over n years, respectively. n is the consecutive years before LC, which include the selected extreme climate types. CV_L denotes the CV of grain yield. The smaller the CV, the smaller the fluctuation of grain yield in natural conditions, and the stronger the resilience of land productivity. CV_L greater than 25% indicates poor resilience of land productivity.

C2. RIG is shown in Equation (12). Comparing the per capita income growth rate in the project area with that of urban residents reflects the core objective of eliminating the urban–rural income gap in China’s pursuit of common prosperity. This comparison directly measures the degree of benefit delivered to residents. FI_{per-a} and FI_{per-b} represent the per capita income of residents in the project area upon SLC completion and the SLC initiation period, respectively. GR_{CI} denotes the ratio of urban resident per capita income growth rates during the same period.

$$RIG = \begin{cases} 1, \frac{FI_{per-a}}{FI_{per-b}} \geq GR_{CI} \\ 0, \text{otherwise} \end{cases} \quad (12)$$

C6. LIR is shown in Equation (13). P_{LI-a} and P_{LI-b} represent the low-income population upon SLC completion and the SLC initiation period of the project area, respectively.

$$LIR = \begin{cases} \frac{|P_{LI-a} - P_{LI-b}|}{P_{LI-b}}, P_{LI-a} \leq P_{LI-b} \\ 0, \text{otherwise} \end{cases} \quad (13)$$

(3) Index Evaluation Method

Given that many indicators encompass multiple inter-related dimensions, a single indicator cannot fully represent the overall situation. Thus, this study constructs these as composite indices to comprehensively reflect their multidimensional nature.

The Soil Stability Index (A3.SSI), calculated using Equations (14)–(16), includes slope and land use types as crucial factors of soil erosion and stability. Slope critically influences soil integrity, where steeper gradients intensify erosion risks. Prime agricultural land occurs on slopes below 2° , characterized by minimal erosion, high productivity, and optimal mechanization potential. Land use types exert equally significant impacts on stability [41]: forestland delivers superior erosion resistance through deep root systems, canopy protection, organic matter accumulation, and enhanced soil aggregation; water bodies enhance stability by regulating soil moisture, facilitating root development, sustaining vegetation productivity, and supporting ecological cycles that mitigate drought; grassland provides effective topsoil stabilization via dense shallow roots but offers moderate long-term stability due to the absence of woody structural biomass; cropland exhibits reduced stability stemming from tillage-induced organic matter depletion and soil structure disruption; and bare soils, artificial surfaces, and salinity-affected soils demonstrate extreme vulnerability when devoid of vegetative cover, directly exposing them to erosive forces.

$$SSI = 0.5 \times SL + 0.5 \times L \quad (14)$$

$$SL = \sum SL_i \omega_i; L = \sum P_j \omega_j \quad (15)$$

$$\omega_i = \begin{cases} 1, & SL_1 \leq 2^\circ \\ 0.75, & 2^\circ < SL_2 \leq 6^\circ \\ 0.50, & 6^\circ < SL_3 \leq 15^\circ \\ 0.25, & 15^\circ < SL_4 \leq 25^\circ \\ 0, & SL_5 > 25^\circ \end{cases}; \omega_j = \begin{cases} 1, & j = \text{FA} \\ 0.75, & j = \text{WA} \\ 0.50, & j = \text{GA} \\ 0.25, & j = \text{CA} \\ 0, & j = \text{SA and OA} \end{cases} \quad (16)$$

where SL and L indicate the influence of slope and land use type on land stability, respectively. SL_i and P_j represent the proportion of land area within slope grade range i and land area representing land type j to the total area of the project area, respectively. ω_i and ω_j are the weights corresponding to slope i and land use type j , respectively. Following *Technical regulation of the third nationwide land survey* [42] issued by the Ministry of Natural Resources, slopes are classified into five grades with decreasing weights to account for their negative impact on SSI. For computational simplicity and feasibility, SSI assigns equal decay weights to slope and land use types.

A6. ERRI, as shown in Equations (17)–(19), includes climate stability (CI), the land disturbance intensity (LI), and habitat quality (HI) to comprehensively assess ecosystem stability, security, and resilience. CI quantifies regional climate variability, requiring indicator selection based on the actual climatic conditions of the project area. LI measures human interference levels through actual disturbance types in the project area, such as ecological land loss from development activities. HI evaluates an ecosystem's capacity to provide suitable habitat conditions for species survival.

$$\text{ERRI} = \frac{1}{3} \times \text{CI} + \frac{1}{3} \times (1 - \text{LI}) + \frac{1}{3} \times \text{HI} \quad (17)$$

$$\text{CI} = \max(0, 1 - \frac{CV_{temp} + CV_{prec}}{2}) \quad (18)$$

$$\text{HI} = A_{bio} \times \frac{0.35 \times A_F + 0.21 \times A_G + 0.28 \times A_W + 0.11 \times A_C + 0.04 \times A_T + 0.01 \times A_U}{A} \quad (19)$$

CV_{temp} and CV_{prec} represent the CV of the annual average temperature and precipitation upon SLC completion, respectively. LI refers to the actual interference upon SLC completion. In this article, the reduction in ecological land caused by land exploitation and utilization is used as a variable. A_{bio} is the normalized coefficient of the HI . The reference value for China is 511.264, which comes from *The Technical Criterion for Ecosystem Status Evaluation* [43] issued by the Ministry of Ecological Environment. A_F , A_G , A_W , and A_C indicate the area of FA, GA, WA, and CA. A_T denotes the built-up land area within the OA. A_U represents the sum of the non-built-up area within the OA and the SA area. A indicates the total area of the project.

C5. ITL, as shown in Equation (20), includes intergenerational transmission of production resources and living security, reflecting intergenerational sustainability. Representative resources should be selected based on the project area's actual conditions. These resources must be indispensable, face significant constraints or high consumption in the project area, and incur high maintenance costs.

$$\text{ITL} = \frac{1}{M} \sum_{m=1}^M \frac{\text{CRC}_m}{\text{SRA}_m} \quad (20)$$

where M denotes the total number of resource types. CRC_m indicates the usage or possession of the m -th resource in the project area, while SRA_m represents its sustainable availability or ownership.

Finally, the comprehensive benefits evaluation score of SLC is calculated using Equation (21). As all indicators are positive and scaled to [0,1], no standardization

is required. The optimal value is set to 1, meaning scores closer to 1 indicate better comprehensive benefits.

$$F_{score} = \sum_{Z=1}^{18} p_Z A_Z \quad (21)$$

where F_{score} denotes the comprehensive benefit evaluation score for SLC, with p_Z and A_Z representing the weight and value of the z -th indicator, respectively. For interpretability, Table 3 provides a conventional scoring reference standard.

Table 3. Scoring evaluation criteria used for the comprehensive benefit evaluation of SLC.

Project Evaluation Results	Unqualified	Moderate	Good	Excellent
F_{score}	[0,0.25)	[0.25,0.50)	[0.50,0.75)	[0.75,1)

To deliver actionable computational guidance, Section 4.2 (including Sections 4.2.1–4.2.3) provides necessary details on the selection process of adaptability indicators and computational implementation of all indicators.

3.3. Data Sources

Meteorological data (temperature and precipitation) and land use data were obtained from the Resource and Environment Science and Data Center, the Institute of Geographic Sciences and Natural Resources Research, and the Chinese Academy of Sciences (<https://www.resdc.cn>). Digital Elevation Model (DEM) data were sourced from Geospatial Data Cloud (<https://www.gscloud.cn>). Data on soil physicochemical properties, income, population, hydrology, labor force, grain yield, infrastructure, and engineering technology applications were cross-validated through project acceptance reports, field survey verification, and official government websites. The land use data and DEM elevation data cover the period from 2016 to 2022, while meteorological data and grain yield data span 2014–2022. Slope gradients were derived from the DEM elevation data. Both land use and DEM datasets were clipped to the project area using ArcGIS based on longitude and latitude coordinates, with the World Geodetic System 1984 (WGS84) coordinate reference system applied throughout the processing.

4. Results

4.1. Land Transfer and Utilization Analysis

As shown in Table 4, progressive deterioration of land use conditions occurred in the project area before SLC, characterized by a 30.86% increase in saline–alkali land and 16.44% cropland expansion, reflecting intensifying agricultural–ecological conflicts, alongside severe ecological degradation marked by a 42.83% reduction in ecological land. There are several key observations: First, we consider cropland dominated land use. The total area of cropland increased from 3776.67 ha in 2016 to 4397.4 ha in 2019, a net increase of 620.73 ha, mainly transferred from grassland (735.03 ha), indicating that agricultural reclamation encroached on ecological land. Meanwhile, even under China’s policy of grain for green, only 65.97 ha of cropland was converted to grassland, which aligns with the trend in Northeast China, where the area of ecological land converted to cropland is much greater than the area of cropland converted to ecological land [44]. Second, water areas sharply decreased, leading to severe deterioration of the ecological environment. The water area decreased from 149.04 ha in 2016 to 1.06 ha in 2019 (a reduction of 99.29%), resulting in a severe shortage of water resources. The direct cause was a severe drought that struck Jilin Province in May 2017. In Taobei District, where the project area is located, precipitation was 49.24% lower than the annual average for Jilin Province. Thirdly, saline–alkali lands exhibited

accelerated expansion. The total area increased from 217.35 ha in 2016 to 284.42 ha in 2022, with diversified conversion sources: 48.42 ha from croplands, 12.42 ha from grasslands, and 6.23 ha from water. Given the geographical and climatic conditions, this study primarily attributes saline–alkali land formation to drought-induced salinization. Specifically, drought lowers groundwater levels, causing salts to rise to the surface through capillary action. Poor drainage and improper agricultural irrigation methods further exacerbate salt accumulation under natural conditions, ultimately forming saline–alkali lands.

Table 4. LUTM from 2016 to 2019. Unit: ha.

Land Use Types		2016					Total
		Cropland	Grassland	Water	Saline–Alkali Land	Other	
2019	Cropland	3662.28	735.03	0.09	-	-	4397.40
	Grassland	65.97	846.54	-	-	-	912.51
	Water	-	-	1.06	-	-	1.06
	Saline–alkali land	48.42	12.42	6.23	217.35	-	284.42
	Other	-	2.16	141.66	-	724.14	867.96
	Total	3776.67	1596.15	149.04	217.35	724.14	6463.35

As shown in Table 5, after SLC, conflicts between cropland uses and the ecological environment eased, and the effects of SLC have been remarkable. Specifically, the sources of cropland are diversified, the risk of water shortage has been reduced, and saline–alkali land has been significantly reduced. First, cropland expansion has occurred with diversified sources, and the dependence on grassland conversion has decreased. The area of cropland increased from 4397.4 ha in 2019 to 5002.22 ha, a net increase of 604.82 ha. The trend observed in this project area during the 2019–2022 period aligns with China’s nationwide pattern of achieving net cropland expansion through land consolidation [45], suggesting that increasing cropland has remained one of China’s approaches to ensuring food security during this period. Compared to pre-project reliance on grassland conversion for cropland expansion, saline–alkali land consolidation provided an alternative source through which 199.69 ha of rehabilitated land was converted to cropland. This diversification of land sources simultaneously promoted an 87.21 ha increase in cropland-to-grassland reversion and a 140.13 ha reduction in grassland-to-cropland conversion compared to pre-consolidation, indicating a decrease in land use conflicts and that pressures on ecosystems crucial to ecological resilience in the region have been alleviated. These findings indicate that effective SLC reconciles land use demands with ecological conservation. Second, although restored water areas increased 284.22 ha since 2019, ecological security remains insufficient. This recovery resulted from 2020’s river connectivity project diverting Nenjiang River water for targeted replenishment. Notably, during the 2022 drought, water areas remained stable, indicating enhanced risk resistance. However, the proportion of grassland area decreased from 26.70% in 2016 to 7.3% in 2022, reflecting an absolute reduction that continues to threaten ecological security in the project area. Third, saline–alkali land decreased by 263.14 ha. The newly rehabilitated lands have provided conversion sources for cropland, grassland, and water, significantly alleviating land resource pressures in the project area. However, 0.3% of consolidated lands remained saline–alkali, and 0.36 ha of grasslands underwent salinization and alkalization, reflecting a somewhat common relationship between SLC and land degradation, where apparent gains in some areas are accompanied by losses in others, as well as increased latent vulnerability. This suggests potential consolidation rebound and sustainability challenges.

Table 5. LUTM from 2019 to 2022. Unit: ha.

Land Use Types		2019					Total
		Cropland	Grassland	Water	Saline–Alkali Land	Other	
2022	Cropland	4238.5	594.9	0.36	199.69	-	5002.22
	Grassland	153.18	316.35	-	2.79	-	472.32
	Water	0.09	0.18	0.25	59.58	193.95	285.28
	Saline–alkali land	-	0.36	-	20.92	-	21.28
	Other	5.63	0.72	0.45	1.44	674.01	682.25
	Total	4397.4	912.51	1.06	284.42	867.96	6463.35

4.2. Evaluation Process of Comprehensive Benefits of SLC

Based on the analysis of land use conversion status in the project area, this section includes a comprehensive evaluation to demonstrate the applicability and feasibility of the indicator system. The results are presented in Table 6.

Table 6. Comprehensive benefit scores of SLC.

Criterion Layer	Indicators Score						Within-Layer Score
ECRE	A1	A2	A3	A4	A5	A6	0.47
	1	0.29	0.51	0.41	0.58	0.28	
SDB	B1	B2	B3	B4	B5	B6	0.67
	0.40	1	0.80	0.84	0	0.93	
CP	C1	C2	C3	C4	C5	C6	0.63
	0.16	1	0.76	1	0.50	0.32	
F_{score}	0.59						

4.2.1. Evaluation Process of ECRE

- (1) Deterministic indicators. The salinity content, pH, and organic matter content required for calculating A1. SRP, A2. PHL, and A4. OMA were assigned the maximum value, mean value, and mean value, respectively, from the corresponding datasets of the three sampled plots submitted for analysis. According to the acceptance report, soils in the project area showed no signs of salinization, with an average pH of 8.3 (within the target range of 7.8–8.4) and organic matter content averaging 2% (20 g/kg). Using the method outlined in Equations (4)–(6), the corresponding indicator scores can be calculated. For A3. SSI, the stability index of slope and land use types was calculated using remote sensing monitoring data, yielding values of 0.72 and 0.30, respectively. Using Equations (14)–(16), the A3 score was 0.51. For A5.STV, cross-validation of project acceptance data and field surveys revealed that salt-tolerant vegetation (including *Allium polyrhizum*, *Artemisia anethifolia*, and *Suaeda glauca*) covered 272.20 ha in the project area. When calculated as a proportion of the total grassland area (472.32 ha), this indicator yielded a score of 0.58.
- (2) Adaptive indicators. For A6. ERRI, based on 2022's average annual precipitation and temperature, the CV for indicator CI was calculated as 123.0% and 304.7%, respectively. LI, in this case study, manifested as cropland expansion encroaching upon grassland resources, quantified by the ratio of net grassland-to-cropland conversion area to total cropland expansion area (yielding 0.73). HI was calculated at 0.58 based on normalized land use area and habitat quality indices. Using Equations (17)–(19), the A6 score was calculated to be 0.28.

4.2.2. Evaluation Process of SDB

- (1) Deterministic indicators. B1. The CAE score is 0.40, calculated as the ratio of the average annual growth rate of cropland area in the project area (4.3%) during the project implementation period to the average annual growth rate of cropland area in the city where the project is located (10.70%). B4. WIC is based on the project acceptance results. The project area implemented water-saving supporting projects only on concentrated contiguous cropland, with a water-saving irrigation area of approximately 4207.87 ha. This accounts for 84.12% of the total cropland area. B5. GOR shows that the groundwater in the project area is severely overexploited; therefore, the score is 0. B6. SAI is calculated using the successful SLC area (263.5 ha), total SLC area (284.42 ha), and newly converted saline–alkali land area (0.36 ha), yielding a score of 0.93.
- (2) Adaptive indicators. B2. LSI is derived from the ratio of per capita grain production in the project area to the per capita food security line of 400 kg, resulting in a score of 1. For B3. LPR, the first step is to select extreme weather conditions. In this case, the average annual temperature in the project area is below 5 °C. During the 37 years recorded in local chronicles from 1949 to 1985, droughts occurred for a total of 27 years, with an average of once every 1.36 years. Therefore, extremely low temperatures and droughts were chosen. The second step is time period selection. In the project area, severe drought conditions affecting agricultural production occurred in 2014 (causing complete crop failure), 2016, 2017, 2020, and 2022, while extreme cold events below −30 °C were recorded in 2018 and 2021. Consequently, the continuous period from 2014 to 2022 was selected for analysis. Using annual grain yield data from this period, the CV reached 13.01%. Based on this, the B3 score is 0.80.

4.2.3. Evaluation Process of CP

- (1) Deterministic indicators. C1. DIG originates from agricultural income generated by converting rehabilitated saline–alkali land into cropland. The DIG score of 0.16 was calculated as the ratio of the newly cropland-derived grain income (CNY 6.43 million) to the pre-consolidation income (CNY 40.00 million). C2. RIG is derived from the ratio between the 5.7% growth rate of per capita disposable income for residents in the project area and the 2.4% growth rate for urban residents in Taobei District (the superior administrative region) in 2022. Using Equation (12), the C2 score was calculated to be 1. C3. LFS was calculated as the ratio of the working-age population (3868 persons aged 15–64) to the total resident population (5085 persons) in the project area, yielding a value of 0.76. C4. ICR was obtained from a 100% coverage rate of water, electricity, internet, roads, pipelines, irrigation and drainage facilities in the production area of the project area. C6. LIR necessitates the identification of low-income populations. Due to challenges related to income privacy protection and the high costs associated with household surveys, this study proposes using the number of basic living allowance participants in the project area for low-income population identification. The C6 score was calculated based on the decrease in participants from 601 persons in 2019 to 410 persons in 2022 within the project area.
- (2) Adaptive indicators. C5. ITL requires selecting representative intergenerational transmission resources. This study used water resources, agricultural labor force, and *residential* infrastructure for the following reasons: Water resources represent the most critically constrained resources in the project area, directly affecting the effectiveness of SLC and agricultural production capacity. Intergenerational changes in the agricultural labor force reflect the alignment between residents' production willingness and the dominant direction of land utilization. The infrastructure in

residential resettlement zones is the most direct living security service enjoyed by residents. Before SLC implementation, electricity and internet coverage reached 100%, but most roads remained unpaved (earthen/gravel). Irrigation relied on self-built wells with primitive channels, while domestic sewage was discharged untreated. These conditions directly undermined resident enthusiasm for agricultural production and environmental protection. In 2022, the actual water usage in the project area was 601 million m³, while the sustainable water supply equaled the sum of the allowable groundwater extraction (478 million m³) and the annual runoff of transit water (1.127 billion m³). The intergenerational transmission rate of agricultural labor was calculated by normalizing the ratio between the actual number of agricultural workers aged ≤ 35 (20.92%) and those aged ≥ 55 (75.21%). Water, electricity, internet, irrigation facilities, sewage treatment, and road accessibility rates in residential zones constituted the living infrastructure assessment system. The calculated transmission levels were 0.37 for water resources, 0.22 for labor resources, and 0.92 for living infrastructure. The C5 score of 0.50 was derived using Equation (20).

Finally, the within-layer scores and the comprehensive benefits score of SLC were calculated based on the results of each indicator using Equations (2), (3) and (21).

5. Discussion

5.1. Discussion and Analysis

This section includes a comprehensive discussion based on the evaluation scores presented in Section 4.2 to provide a systematic analysis of the current status and challenges of the SLC. The project's overall score of 0.59 indicates progress in the remediation efforts while revealing specific dimensional deficiencies. Specifically, the SDB dimension achieved the highest score (0.67), followed by the CP dimension (0.63); while the ECRE dimension demonstrated the weakest performance (0.47). The score variations reflect the typical characteristics of SLC: short-term engineering achievements, yet requiring further improvement in long-term ecological resilience and social equity. The success of SLC is primarily manifested in achieving explicit objectives such as cropland expansion, reduction of saline–alkali land areas, and improved infrastructure coverage. However, it has not yet fully addressed implicit challenges, including ecosystem restoration sustainability, rational water resource management, and intergenerational equity of economic benefits.

- (1) Short-term desalination is effective, but long-term resilience is insufficient.

The low ECRE score primarily stems from the short-sightedness of consolidation technologies and the inherent vulnerability of ecosystems, reflecting contradictions between ecological sustainability and economic imperatives in governance objectives. Although soil salinization (A1) in the project area has been controlled, the consolidation effect on alkalization (A2) remains limited. The elevated alkalinity of soda saline–alkali soils originates from sodium ion accumulation, requiring gradual neutralization through long-term organic matter application or bioremediation technologies [46]. However, current SLC strategies prioritize rapid results through excessive reliance on chemical amendments while neglecting biological approaches like agropastoral cycles. Soil fertility (A4) improvement progresses slowly. This indicates hidden costs: although chemical amendments accelerate desalination, they suppress microbial activity, weakening the ecosystem's self-restoration capacity. Such technological choices fundamentally arise from the preference for short-term metrics within administrative appraisal mechanisms; consequently, local governments pressured by land remediation acceptance deadlines prioritize rapid engineering solutions while neglecting long-term benefits such as soil health improvement. More critically, ecological space is being compromised: Section 4.1 shows a drastic 42.83% reduction in grassland

area, with cropland expanding into ecological zones. Despite introducing salt-tolerant plants (A5), grassland fragmentation persists, indicating structural neglect of ecological protection in remediation planning. This stems from distorted economic incentives: newly created cropland qualifies for fiscal subsidies and political achievements, while ecological maintenance lacks compensation mechanisms, driving communities toward reclamation over conservation. A6 reveals persistent ecosystem vulnerability, demonstrating that the project area remains under dual pressures of drought risk and anthropogenic disturbances.

- (2) The supply capacity of cropland is outstanding, but the management capacity of water resources requires long-term monitoring.

The supply–demand imbalance manifests as an institutional contradiction between cropland expansion and water resource depletion. Although converting saline–alkali land to cropland alleviates food security pressures, and concurrent river connectivity projects promote aquatic ecosystem restoration, structural flaws persist in the governance system: First, the absence of water rights allocation rules exacerbates resource overexploitation. Despite constructing water-saving irrigation infrastructure, the lack of supporting water rights governance has sustained severe groundwater overdraft, directly contravening the water conservation priority principle. Second, rebound risks persist. While increased cropland area (B1) and reduced saline–alkali land (B6) demonstrate the feasibility of saline–alkali land conversion, concurrent water overextraction indicates the project area’s water-for-grain approach remains fundamentally unaltered. The degradation of 0.36 ha of grassland into saline–alkali land reveals the coexistence of consolidation and land deterioration. This likely stems from concentrated investments in visibly saline–alkali areas while neglecting concurrent preventive measures for ecologically vulnerable zones such as grasslands with salinization tendencies.

- (3) Social welfare has improved, but intergenerational equity is insufficient.

The deficiency in CP primarily stems from a mono-economic structure and discontinuity in intergenerational transfer. While infrastructure improvements have enhanced residents’ quality of life, excessive reliance on agricultural income (C1) has intensified systemic economic vulnerability. This manifests in two key ways. First, industrial ecology is imbalanced. Newly converted cropland contributes 13.8% to total economic revenue, highlighting the dominance of traditional crop farming and a lack of diversified industrial support. Secondly, a crisis of intergenerational transmission is evident. Young people constitute only 20.92% (C5) of the agricultural workforce, compared to 75.21% of those aged 55 and above. This significant disparity indicates a clear trend of younger generations disengaging from agricultural skills transmission, heightening the risk of future land abandonment. Although the number of individuals receiving subsistence allowances decreased by 31.8% (C6), indicating that newly added cropland provides alternative income sources, this income is primarily concentrated among the elderly population. These workers, lacking modern agricultural training, depend on extensive farming practices. This reliance risks secondary degradation of reclaimed land due to potential overuse of chemical fertilizers. Ultimately, low-efficiency production may prove unsustainable for maintaining income growth, counteracting initial poverty alleviation gains.

5.2. Sensitivity Analysis

To verify the robustness of the evaluation system, a single-factor sensitivity analysis was conducted using the Chain Ratio Adjustment Method for sensitive indicators. Based on the evaluation results in Table 6, indicators with high weight and high scores (B2, B6, and C2) and indicators with high weight but low scores (A2, B5, and C6) were selected for sensitivity analysis. The methodology was as follows: the weights of the target indicators

were changed by -20% , -10% , $+10\%$, and $+20\%$. The weights of other indicators within the same layer were then scaled proportionally using a scaling factor to obtain adjusted intra-layer scores and total scores. Weight sensitivity was determined by evaluating the score variation rate before and after perturbation. Using indicator A2 as an illustrative case, when the original intra-layer weight of A2 (0.20) was reduced by 20% to 0.16, the aggregate weight of peer indicators A1 and A3 increased from 0.30 to 0.34. This necessitated the calculation of a scaling factor ($0.34/0.30 = 1.13$), which was subsequently applied to the original weights of A1 (0.10) and A3 (0.20) to yield adjusted weights of 0.113 and 0.227, respectively, while maintaining constant weights for other indicators. Consequently, the changed $ECRE_{score_new}$ reached 0.488, representing a 3.24% increase relative to the baseline. Similarly, the total score F_{score_new} rose to 0.596, corresponding to a 1.04% enhancement. Comprehensive perturbation outcomes for all sensitive indicators are documented in Table 7. Under $\pm 20\%$ weight variations, the maximum fluctuation range of F_{score_new} remained within $[-2.03\%, +2.04\%]$, indicating that the weight setting of the evaluation system is robust.

Table 7. Sensitivity analysis of F_{score_new} .

Indicators	-20%	Variation Rate	-10%	Variation Rate	$+10\%$	Variation Rate	$+20\%$	Variation Rate
B2	0.586	-0.75%	0.588	-0.38%	0.592	$+0.38\%$	0.595	$+0.75\%$
B6	0.581	-1.47%	0.586	-0.73%	0.595	$+0.73\%$	0.599	$+1.47\%$
C2	0.585	-0.88%	0.588	-0.38%	0.594	$+0.61\%$	0.597	$+1.11\%$
A2	0.596	$+1.04\%$	0.593	$+0.60\%$	0.588	-0.26%	0.586	-0.70%
B5	0.602	$+2.04\%$	0.596	$+1.02\%$	0.584	-1.02%	0.578	-2.03%
C6	0.595	$+0.90\%$	0.593	$+0.50\%$	0.588	-0.28%	0.585	-0.67%

5.3. Limitations

This study has the following limitations that must be considered when interpreting its results and implementing its findings:

- (1) Weight allocation strategy. First, the framework may inadequately capture the depth of critical element influence. Second, the multiplication synthesis method offers a limited capacity to model complex synergistic/antagonistic interactions between indicators or identify critical tipping points. Finally, quantification challenges exist for specific agronomic measures, limiting precision in assessing management efficacy for refined land decision making.
- (2) Capturing long-term dynamics and risk. Due to project's timeline and data availability constraints, an additional limitation to this study should be noted: negative effects such as secondary salinization and biodiversity loss resulting from the agricultural use of saline-alkali land exhibit lagged and cumulative characteristics, meaning that assessments might underestimate long-term risks.
- (3) Analysis of extreme weather. First, despite recurrent droughts in the project area, analysis of *limited* years cannot fully capture multiyear delayed cascading effects and cumulative impacts. Second, under the influence of climate change, extreme weather conditions and patterns are expected to undergo transformations. Therefore, if the climatic conditions in the project area have experienced structural changes, historical data may not provide a sufficient basis for estimating future extreme weather events.
- (4) Characterization accuracy of remote sensing data. Although 30 m resolution data satisfy the *research* requirements for LUTM and comprehensive evaluation models, limitations may persist at the micro-scale, such as inadequate resolution of fine-grained spatial patterns.

6. Conclusions and Implications

This study is based on the theoretical framework of Optimal Land Use Value. We constructed a comprehensive benefit evaluation indicator system of comprehensive saline–alkali land consolidation encompassing ecosystem resilience, supply–demand balancing, and common prosperity. Using a comprehensive saline–alkali land consolidation project in Northeast China as a case study, the scientific validity and practical value of this indicator system were verified, and a systematic assessment of the status of typical saline–alkali land management was conducted. The main conclusions follow.

In terms of ecological spaces, soil salinity decreased significantly; however, pH and organic matter content remained outside healthy thresholds. The Ecosystem Risk Resistance Index further revealed synergistic pressures from drought stress and anthropogenic disturbances, indicating coexisting characteristics of short-term project effectiveness and long-term vulnerability. In terms of production spaces, the consolidation of saline–alkali land coexists with degradation risk. The project successfully expanded cropland (16.44%) and enhanced food security. However, groundwater overdraft and high crop yield variability ($CV = 13.01\%$) reflect unsustainable water management and climate sensitivity. Although 92.7% of saline–alkali land was consolidated, the concurrent degradation of grasslands into saline–alkali land signals potential rebound risks. In terms of living spaces, improved infrastructure coverage and increased resident incomes substantiate socioeconomic benefits. However, excessive reliance on agriculture and inadequate intergenerational succession may undermine the long-term revitalization of the project area.

The practical implications of this study are as follows: In technological innovation, priority should be given to bio-engineering synergy strategies that couple engineering desalination with biological measures such as green manure cultivation. This approach enhances the climate adaptation resilience of ecosystems by boosting soil microbial diversity and carbon sequestration capacity. For resource management, groundwater extraction quota systems and ecological land use redline regulatory mechanisms should be established to curb hydrological imbalances and prevent encroachment on ecological spaces. Regarding socioeconomic dimensions, the cultivation of salt-tolerant cash crops and reskilling programs should be integrated into the planning phases of saline land projects for residents. Finally, to support rural population revitalization strategies and attract prime-age labor to agricultural production contexts, diversified industries—including ecotourism and carbon sink agriculture—should be developed.

In summary, this study provides a scalable model for assessing complex global land degradation issues based on an optimal land value analytical framework. Future research should (1) employ higher-resolution imagery or UAV-acquired data to analyze the micro-dynamic mechanisms of SLC through cross-regional governance comparative studies; (2) establish long-term monitoring networks to track land system evolution trajectories; and (3) conduct surveys targeting youth and young adults in regions characterized by aging populations and insufficient intergenerational transmission of resources, in order to better understand residents' priorities and the factors influencing their choices. These advancements are expected to enhance the comprehensiveness and applicability of the evaluation framework.

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