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Does New Rural Collective Economy Improve Cultivated Land Use Ecological Efficiency? Empirical Evidence from Yangtze River Economic Belt, China

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Abstract

Against China's tightening cultivated land ecological constraints, clarifying how the New Rural Collective Economy (NRCE) affects Cultivated Land Use Ecological Efficiency (CLUEE) is critical for advancing agricultural sustainability in the Yangtze River Economic Belt (YREB). Using 714 panel data observations from 42 prefecture-level cities in the YREB from 2009 to 2025, this study measures CLUEE efficiency via SBM-DEA and quantifies the NRCE via the entropy weight method. Two-way fixed effects models estimate the impact, while two-step mediation analysis explores underlying mechanisms. Results show NRCE significantly boosts CLUEE, with each 1-unit increase in NRCE level driving a 0.1633-unit improvement in CLUEE, and findings remain robust after endogeneity correction. Mediation analysis reveals indirect effects via land-scale management, agricultural socialized services, and green technology innovation. This study innovatively clarifies the endogenous institutional driving effect of rural collective economic reform on CLUEE, filling the research gap of ignoring rural organizational institutional factors in existing CLUEE research. The findings provide empirical evidence and theoretical support for optimizing the construction of rural collective economic organizations and formulating differentiated cultivated land ecological governance policies in the YREB, so as to effectively unlock the ecological dividend of rural institutional innovation and facilitate coordinated ecological and economic development of cultivated land.

Keywords: new rural collective economy; cultivated land use ecological efficiency; Yangtze River Economic Belt; SBM-DEA; sustainable agriculture



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1. Introduction

Confronted with the dual challenges posed by global climate change and increasingly stringent resource constraints, sustainable agricultural development has become an essential element of the UN Sustainable Development Goal (SDG) of Zero Hunger [1]. A historic transformation is taking place in China's agriculture, shifting from output prioritization to green high-quality development [2]. Cultivated Land Use Ecological Efficiency (CLUEE), as a core indicator for maximizing output per unit of ecological cost, is inextricably bound up with national food security and agricultural sustainability [3].

However, the long-standing smallholder-based decentralized farming model in China has inherent institutional and operational defects in green agricultural development. Frag-

mented cultivated land management not only restricts the scale application of modern green agricultural production technologies, but also leads to insufficient endogenous motivation of farmers for ecological protection and low governance efficiency of agricultural non-point source pollution, forming a prominent constraint on the improvement of cultivated land ecological utilization level [4,5]. Against this institutional background, the New Rural Collective Economy (NRCE), as an innovative rural economic organization based on collective land ownership and standardized property rights system, has become a crucial institutional carrier to break through the dilemma of small-scale peasant economy and realize the green transformation of agricultural land use. Different from traditional rural economic organizations and simple agricultural cooperatives, NRCE integrates economic operation, rural public service and ecological governance functions, providing a new institutional path for solving the ecological externality problems in cultivated land utilization [6].

CLUEE comprehensively considers expected outputs, including grain yield and agricultural added value, along with undesirable outputs, represented by carbon emissions and non-point source pollution [7–9]. As a result, it has become a key benchmark for the academic community and policymakers in evaluating the green transformation of agriculture [10,11]. Existing studies have focused on its measurement methods, influencing factors, and spatial characteristics [11–14]. The SBM-DEA model has emerged as the mainstream tool for measuring CLUEE due to its ability to effectively handle slack variables in input–output relationships while addressing the measurement challenges associated with undesirable outputs [11,15,16]. The research scale has expanded from macro-level perspectives, such as provincial and urban levels [17,18], to micro-level perspectives at the county and town levels [19,20]. In studies on driving factors, digital technology [21,22], policy regulations [23], farm size [24], and urbanization and socio-economic development [25] are regarded as key determinants of CLUEE. However, extant studies predominantly focus on the exogenous impacts of environmental conditions and material input factors on cultivated land ecological efficiency while ignoring the endogenous driving role of rural organizational institutional innovation in achieving sustainable development [26,27]. Few studies have systematically discussed the causal relationship and internal mechanism between NRCE institutional reform and CLUEE improvement, resulting in a missing institutional perspective in the research on green optimization of cultivated land use.

Since the reform of the Household Contract Responsibility System, China's rural operation and governance system has entered a period of unprecedented profound structural change. As the institutional link connecting farmers with modern agriculture, rural collective economic organizations have, following the reform of the rural collective property rights system, re-emerged as the NRCE at the center of rural governance and production organization [28,29]. A large amount of the literature indicates that organizational construction is a key driver of sustainable agricultural development [30–32]. Unlike traditional collective models, the NRCE is characterized by “clear property rights, scientific governance structures, stable operational models, and reasonable profit distribution,” endowing it with greater institutional resilience [33]. In practice, the NRCE has rationalized property rights relationships through the “Three Transformations” reform, converting resources into assets, funds into equity, and farmers into shareholders. By deepening the reform of the “three-right separation system”, namely land ownership, land contracting rights and land management rights, the NRCE has achieved unified planning and centralized management of fragmented cultivated land, optimized the structure and functions of land use, and fostered moderate land-scale operation [34,35]. Serving as intermediaries between farmers and the market, the NRCE can provide end-to-end agricultural socialized services or outsource such services, thereby lowering the barriers for rural households to adopt

green technologies and promoting their diffusion [36,37], thus laying the organizational foundation for enhancing CLUEE. However, the above theoretical logical deduction lacks systematic empirical verification, and whether the NRCE can effectively improve CLUEE and its specific transmission mechanism still needs quantitative scientific assessment.

The Yangtze River Economic Belt (YREB) traverses the east, central and west of China with important strategic significance. It is not only a core producing area for national food security but also a leading demonstration zone for agricultural sustainability [38]. Restricted by terrain conditions, economic foundation and resource endowment, the YREB presents obvious regional differences in rural economic development and cultivated land utilization, forming an ideal research sample for exploring the heterogeneous impact of the NRCE on CLUEE. Clarifying the differentiated driving effect of the NRCE in this basin can not only enrich the theoretical system of rural institutional innovation and agricultural ecological development but also provide targeted practical references for watershed agricultural green transformation and rural high-quality development.

Based on the above research gaps and practical demands, the marginal contributions of this study are clarified as follows. First, different from previous studies focusing on exogenous determinants of CLUEE, this study innovatively takes rural collective institutional innovation as the research entry point, filling the research gap regarding the endogenous organizational mechanisms driving cultivated land ecological efficiency improvements. Second, based on property rights theory and transaction cost theory, this study systematically explains the multi-dimensional transmission paths through which the NRCE affects CLUEE, clarifying the internal logical mechanism of the institutional empowerment of ecological land use. Third, combined with the dual heterogeneity of regional location and terrain characteristics of the YREB, this study reveals the context-dependent differential impact of the NRCE, providing empirical support for formulating differentiated rural collective economy development policies and cultivated land ecological protection strategies.

Accordingly, this study proposes the following core research questions: (1) Does the NRCE enhance CLUEE, and what is its core driving mechanism? (2) Do significant regional and terrain heterogeneous differences exist in this driving effect across the YREB?

Drawing on 714 panel data observations from 42 prefecture-level cities in the YREB (2009–2025), this study adopts the SBM-DEA to measure CLUEE and develops a comprehensive evaluation index system to assess the developmental level of the NRCE. To clarify the causal link and transmission path between the two variables, a two-way fixed effects model and a mediating effects model are utilized. Additionally, heterogeneity analysis is carried out by categorizing the research samples into the upper, middle, and lower reaches of the YREB, as well as plain and non-plain terrain. The remainder of this study is structured as follows: Section 2 presents the theoretical analyses and corresponding hypotheses of this study, elucidating the direct and indirect pathways through which the NRCE drives CLUEE; the research materials and methodological arrangements are detailed in Section 3, along with variable selection, model construction and data sources; Section 4 elaborates the results, covering baseline regression, robustness tests, mechanism analysis, and heterogeneity tests; and Section 5 summarizes the main findings and proposes reasonable policy recommendations.

2. Theoretical Analyses

2.1. Direct Mechanisms Through Which the New Rural Collective Economy Drives Cultivated Land Use Ecological Efficiency

In the context of existing transaction costs, the property rights system serves as the fundamental institutional guarantee for optimizing the distribution and utilization of resources [39]. The NRCE is essentially about ascertaining the ownership, contracting

rights, and management rights of collective assets, and this objective is accomplished by promoting the reform of rural collective property rights. By transforming collective resources into assets and capital through such reforms, the new rural collective economy quantifies these assets as farmers' equity shares, shifting households from mere land users to collective shareholders, thereby institutionally addressing the risk of the tragedy of the commons caused by excessive resource consumption [40,41]. Furthermore, the key function of property rights is to guide incentives and internalize external effects [42]. This identity shift enhances farmers' focus on the long-term value of collective assets, motivating them to self-regulate negative externalities like agricultural non-point source pollution. It also directs green credit and agricultural technologies toward cultivated land protection, thereby optimizing input structures and improving comprehensive utilization efficiency [43,44].

H1. *The improvement of the NRCE has a direct positive driving effect on CLUEE.*

2.2. Indirect Mechanism Through Which the NRCE Drives CLUEE

2.2.1. Land Management Scaling

Rural China has long suffered from severe cultivated land fragmentation, which not only increases labor input per unit of land but also limits the operational efficiency of large-scale, low-carbon agricultural machinery [36]. As vital intermediaries connecting smallholder farmers and large-scale business entities, the new rural collective economy relies on land transfer and land shareholding mechanisms. By conducting integrated asset management, the NRCE can effectively consolidate scattered land parcels, reduce the transaction costs of factor mobility, mitigate land fragmentation and cultivated land abandonment, and promote the centralized allocation of land management rights [45,46]. Moderate land-scale operation can improve management efficiency and create opportunities for green management practices, such as precision fertilization and unified pest control. This enhances efficiency on the output side while reducing emissions and resource consumption on the input side.

H2a. *The NRCE improves CLUEE by promoting land management scaling, optimizing production factor allocation, and reducing input intensity per unit area.*

2.2.2. Agricultural Socialized Services

The division of labor is a source of productivity improvement [47]. Firstly, the NRCE deepens the division of labor by outsourcing high-skill agricultural production activities, such as unified prevention and control of pests and diseases, as well as soil testing and formula fertilization, to professional organizations. These agricultural socialized services utilize professional talents and standardized equipment, effectively overcoming information asymmetry and technical thresholds for individual smallholders in green production decisions [48]. Secondly, the NRCE promotes the large-scale coverage of green inputs, including bio-fertilizers and low-residue pesticides, through unified procurement of agricultural materials and unified technical standards. This organized professional division of governance can significantly reduce chemical redundancy and environmental pollution caused by extensive operations [49].

H2b. *The NRCE improves CLUEE by developing agricultural socialized services and leveraging the professional division of labor and unified technical standards.*

2.2.3. Green Technological Innovation

Changes in resource scarcity will induce technological innovation to replace expensive factors [50]. Faced with dual constraints of limited resources and environmental pressures,

the NRCE, as a carrier of “new quality productive forces” and an introducer of advanced production technologies, can overcome smallholders’ cognitive biases and application thresholds for new technologies. Technologies such as plant protection drones, soil testing, formula fertilization, and precision irrigation actively guide agricultural production to transform into low-carbon and organic models proactively. This innovation-driven path directly optimizes the production function, reducing energy consumption while improving expected output.

H2c. *The NRCE achieves emission reduction and efficiency improvement in cultivated land use by stimulating green technological innovation and guiding the popularization and application of low-carbon production technologies.*

2.3. Heterogeneity Logic in the Yangtze River Economic Belt

Institutional change exhibits path-dependent characteristics, with social adaptive efficiency determining long-term economic performance [51,52]. In rural areas with relatively weak institutional environments, the core merit of collective organizations stems from their capacity to realize the organic coupling of formal institutional provisions and informal conventions, such as written contracts and village regulations, which can more effectively reshape the allocation path of production factors [51]. This offers a new perspective for enhancing CLUEE by the NRCE across different regions of YREB.

Across the upper, middle, and lower reaches of the YREB, significant variations are observed in economic foundation, geographical conditions, and institutional environment, which result in heterogeneous impacts of the NRCE on CLUEE [53,54]. Within the Yangtze River Delta area, a highly market-oriented and mature contractual framework has propelled collective economy into a phase of “deepened organizational development,” shifting the focus of efficiency enhancement toward advanced agricultural technologies and smart agriculture applications. The marginal driving force of the new rural collective economy demonstrates relatively stable performance, primarily manifested in achieving a harmonious balance between operational efficiency and ecological sustainability [55].

In the middle and upper reaches of the YREB, agricultural production still faces severe fragmentation and resource constraints [56]. The institutional intervention of the NRCE can produce a stronger “marginal improvement” effect. The middle reaches, as an important grain producing area, have superior cultivated land conditions but high production pressure. The core value of the NRCE in this region lies in ensuring grain yield while effectively mitigating non-point source pollution arising from long-term high-load farming. These areas play a crucial ecological role but lag behind economically [57]. Property rights system reform shows a stronger marginal effect in activating idle land resources and promoting the capitalization of ecological resources. In rugged terrains like Yunnan, Guizhou, and Sichuan, the organizational power of the NRCE is the only efficient way to overcome topographic barriers and achieve green technology diffusion.

H3. *The improvement effect of the NRCE on CLUEE is heterogeneous across different regions and topographies.*

H4. *The improvement effect of the NRCE on CLUEE is context-dependent, being more significant in areas with high marketization levels and high levels of fiscal agricultural support.*

Based on the assumptions, an analytical framework was constructed to analyze how the NRCE affects CLUEE (Figure 1).

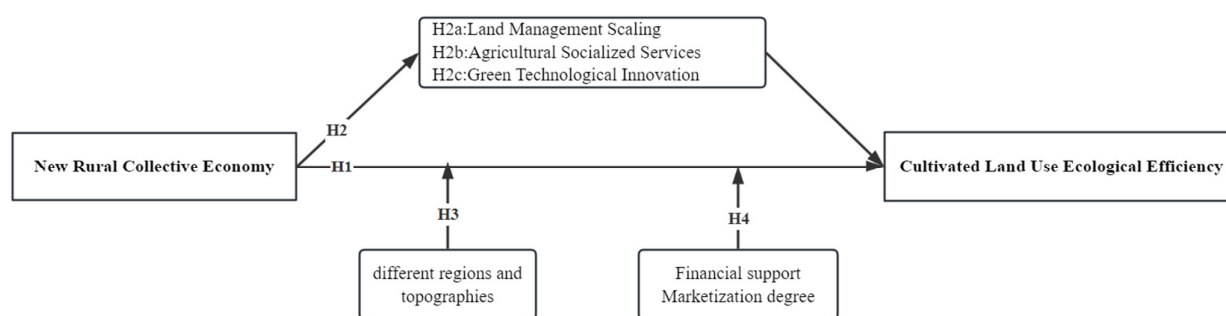


Figure 1. Analytical framework of the impact of NRCE on CLUEE.

3. Materials and Methods

3.1. Variable Selection

3.1.1. Dependent Variable: Cultivated Land Use Ecological Efficiency (CLUEE)

The essence of CLUEE is to maximize expected outputs, such as economic and social outputs, while minimizing undesirable outputs, such as resource input and environmental burden. Referencing previous studies [17,58,59], this study developed an indicator system for evaluating CLUEE (Table 1).

Table 1. Indicator system for evaluating CLUEE.

Dimension	Indicator Name	Unit	Indicator Explanation and Data Sources
Input indicators	Labor input	10,000 people	Employment figures in the primary sector
	Land investment	Thousand hectares	Total sown cultivated land area
	Fertilizer input	10,000 tons	Agricultural fertilizer application rate (pure)
	Pesticide input	ton	Actual amount of pesticides used
	Mechanical input	10,000 kilowatts	Mechanical power for agricultural production
	Water resource input	Thousand hectares	Effective irrigation area
	Energy input	10,000 tons	Diesel consumption for agricultural production
Expected output	Economic output	100 million yuan	Economic output of the primary sector (flattened based on 2009)
	Social output	10,000 tons	Total grain output
Unexpected output	Carbon emission load	10,000 tons (CO ₂ e)	Total greenhouse gas emissions during cultivated land use
	Non-point source pollution load	ton	Estimated values of nitrogen and phosphorus losses and residual agricultural film

The standards for agricultural carbon emission accounting are as follows (Table 2):

Table 2. Compositions and measurements of undesirable outputs in cultivated land use.

Emission Sources	Coefficient (in C)	Official Data Sources
Chemical fertilizer	0.8956 kgC/kg	Oak Ridge National Laboratory (ORNL)
Pesticide	4.9341 kgC/kg	Oak Ridge National Laboratory (ORNL)
Agricultural film	5.1800 kgC/kg	Institute of Agricultural Resources and Ecological Environment (IREEA) at Nanjing Agricultural University
Diesel oil	0.5927 kgC/kg	<i>Greenhouse Gas Emissions Accounting and Reporting Requirements Part 23: Crop Production</i>
Agricultural irrigation	20.476 kgC/hm ²	<i>Trial version of Provincial Greenhouse Gas Inventory Compilation Guidelines</i>
Farming	3.126 kgC/hm ²	College of Agronomy and Biotechnology, China Agricultural University

Referencing previous studies [60–62], this study employed the SBM-DEA model to measure CLUEE, as illustrated in the following formula:

$$\rho^* = \min \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{\bar{D}_i}{x_{ik}}}{1 + \frac{1}{a+b} \left(\sum_{r=1}^a \frac{D_r^e}{y_{rk}^e} + \sum_{h=1}^b \frac{D_h^n}{y_{hk}^n} \right)} \quad (1)$$

where ρ^* represents the value of CLUEE. When $\rho^* = 1$, it indicates that the evaluation unit is on the efficiency frontier, achieving coordination between ecology and economy; when $\rho^* < 1$, there is room for improvement. There are n decision-making units, each including m inputs, a expected outputs, and b undesired outputs; $\bar{D}_i$, D_r^e , D_h^n respectively represent variables for the inputs, expected outputs, and unexpected outputs.

3.1.2. Independent Variables: New Rural Collective Economy (NRCE)

Based on institutional economics and rural endogenous development theory, the connotation of the NRCE covers organizational coverage, operational scale, and functional benefit, which constitutes a multi-dimensional complex system different from traditional rural collective economy. Referencing the research by Liu Chuanming et al. [63], this study constructs an evaluation index system based on the breadth, scale, and benefits of development (Table 3). This multi-dimensional framework fully captures the essential characteristics of the NRCE with clarified property rights, standardized organization, and market-oriented operation, effectively avoiding the measurement bias caused by single-dimensional indicators and matching the multi-level operational complexity of rural collective economic organizations in the YREB. This indicator system has been widely verified in relevant watershed rural economic empirical studies with strong scientific validity and applicability. It employs the entropy weighting method to weight and aggregate indicators reflecting “new” characteristics, thereby providing a comprehensive measure of the NRCE level.

Table 3. Construction of the indicator system for the NRCE level.

Indicator Dimensions	Calculation Method	Variable Unit	Indicator Attributes
Development breadth	Number of new rural collective economy/area	Units per square kilometer	+
	Number of enterprises related to new rural collective economy/area	Units per square kilometer	+

Table 3. Cont.

Indicator Dimensions	Calculation Method	Variable Unit	Indicator Attributes
Development scale	Total registered capital of enterprises related to new rural collective economy	100 million yuan	+
Development benefits	Total collective assets of new rural collective economy	100 million yuan	+

3.1.3. Mediator Variables

According to existing studies [64–68], the ratio of sown crop area to the rural population is selected to measure Land Management Scaling (Sca); the ratio of the service output in agriculture, forestry, animal husbandry and fishery to crop sown area is selected to quantify Agricultural Socialized Services (Ass); and the number of granted green patents is selected to measure Green Technological Innovation (Gti).

3.1.4. Control Variables

To minimize estimation bias caused by omitted variables, six control variables are included in the model based on previous studies and theoretical analyses [69–71]: economic development level (c1), measured by city GDP (log); village-level governance structure (c2), measured by the proportion of administrative villages with “one-shoulder” (yijiantiao) village heads; urban-rural income gap (c3), measured by the urban–rural resident income ratio; rural human capital (c4), measured by average years of education; rural public cultural service (c5), measured by the number of cultural stations; and rural economic vitality (c6), measured by rural social electricity consumption.

3.1.5. Moderating Variables

Two moderating variables are constructed in this section: financial support for agriculture (Fin), calculated as the share of local government expenditures on agriculture, forestry, and water resources in total fiscal outlays [72]; marketization degree (Mar), measured by the marketization index reported in the *China Provincial Marketization Index Report* [73].

3.2. Empirical Model Construction

3.2.1. Benchmark Regression Model

To test H1, this study formulated a panel model with two-way fixed effects to analyze the influence of the NRCE on CLUEE:

$$CLUEE_{it} = \alpha_0 + \alpha_1 NRCE_{it} + \sum \beta X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (2)$$

where $CLUEE_{it}$ corresponds to the cultivated land use ecological efficiency for province i in year t ; $NRCE_{it}$ reflects the degree of development of new rural collective economy; X_{it} represents control variables, μ_i and λ_t are the fixed effects of region and year, respectively.

3.2.2. Model for Assessing Mediation Effect

To test H2, the stepwise regression method of Preacher and Hayes [74] is used to construct a mediation effect model:

Step 1: Regression of mediating variables on the independent variable.

$$M_{it} = \beta_0 + \beta_1 NRCE_{it} + \sum \beta X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (3)$$

where M_{it} represents the mediating variables, including land management scaling (Sca), agricultural socialized services (Ass), and green technology innovation (Gti).

Step 2: Regression of CLUEE on both the NRCE and the mediating variable.

$$CLUEE_{it} = \gamma_0 + \gamma_1 NRCE_{it} + \gamma_2 M_{it} + \sum \beta X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (4)$$

where γ_2 captures the impact of the mediating variable M_{it} on $CLUEE_{it}$ after controlling for $NRCE_{it}$. The coefficient γ_1 represents the direct effect of $NRCE_{it}$ on $CLUEE_{it}$. The definitions of other variables are consistent with those in Equation (2). The proportion of the mediation effect is $\beta_1 \times \gamma_2 / \alpha_1$.

3.2.3. Moderating Effect Model

By introducing moderating variables Reg_{it} , including Market (the marketization degree) and Finance (intensity of fiscal support for agriculture), an interaction term model is constructed:

$$CLUEE_{it} = \delta_0 + \delta_1 NRCE_{it} + \delta_2 Reg_{it} + \delta_3 NRCE_{it} \times Reg_{it} + \sum \beta X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (5)$$

If δ_3 is significantly positive, then the moderating variable positively moderates the relationship between collective economy and ecological efficiency.

3.3. Data Sources

The empirical analysis in this study employed a panel dataset of 42 prefecture-level cities in the YREB over the period 2009–2025. This study adopted prefecture-level cities as the basic analytical unit for rigorous theoretical and empirical considerations. Compared with provincial-level units that obscure intra-regional spatial heterogeneity and average out localized institutional and ecological variations, prefecture-level cities constitute the core administrative and operational units for implementing rural collective economic reforms, cultivated land management policies, and agricultural ecological governance in China. Meanwhile, county-level samples suffer from severe lack of data, inconsistent statistical caliber, and poor long-term panel continuity, which cannot support reliable long-span empirical analysis. As a moderate mesoscale research unit, prefecture-level cities can effectively capture the differentiated interactive relationships between institutional innovation (NRCE) and cultivated land use ecological efficiency, matching the spatial governance characteristics and gradient development differences of the Yangtze River Economic Belt basin. In line with the *National Yangtze River Economic Belt Development Plan Outline*, the sample was divided into three sub-regions: (1) Yangtze River Delta: 18 prefecture-level cities across Shanghai, Jiangsu, Zhejiang, and Anhui; (2) Middle Reaches: 16 prefecture-level cities in Jiangxi, Hubei, and Hunan; (3) Upper Reaches: 8 prefecture-level cities in Chongqing, Sichuan, Guizhou, and Yunnan. After removing observations with missing data or extreme values, a balanced panel with 714 city-year observations was constructed.

Data for this study were primarily obtained from the China Statistical Yearbook, the China Rural Statistical Yearbook, the China Rural Management Statistics Annual Report, the China Agricultural Statistics Annual Report and Statistical Bulletins by province and municipality. Carbon emission and pollution coefficients refer to IPCC, ORNL, and related academic standards. Minor missing values were handled using linear interpolation and mean imputation. To account for inflation, all nominal monetary variables were converted to real terms using the GDP deflator, with 2009 as the base year. The descriptive statistics for the variables are presented in Table 4.

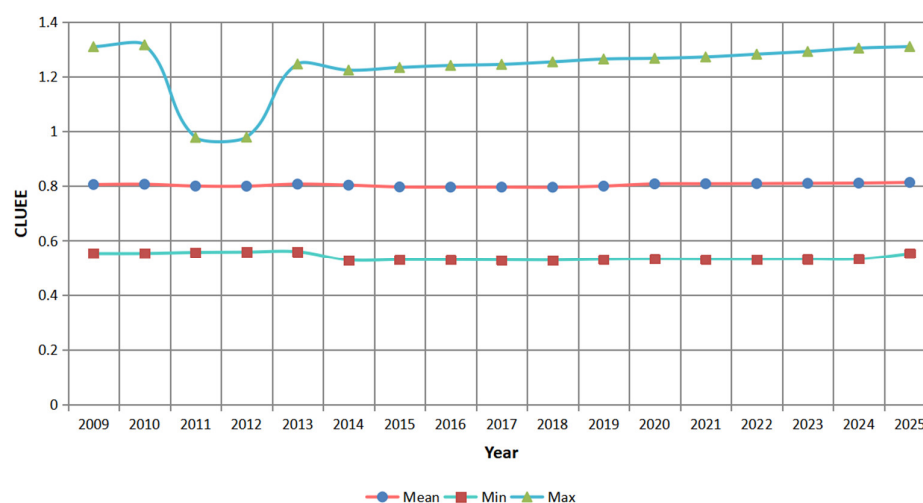
Table 4. Descriptive statistical analysis of variables (N = 714).

Variable Type	Variable Name	Mean	SD	Min	Max
Dependent variable	Cultivated land use ecological efficiency	0.962	0.265	0.553	1.923
Independent variables	New rural collective economy	0.099	0.090	0.001	0.577
Mediator variables	Land management scaling	1.340	1.795	0.0001	8.380
	Agricultural socialized service	8.271	1.201	5.628	16.80
	Green technology innovation	6.169	1.961	0.693	10.77
Control variables	Economic development level	25.91	3.001	15.11	29.66
	Village-level governance structure	2.731	0.339	1.100	3.649
	Urban–rural income gap	0.643	0.167	0.001	1.258
	Rural human capital	1.330	0.420	−0.552	2.363
	Rural public cultural service	4.186	0.907	1.609	7.959
	Rural economic vitality	14.07	1.643	9.920	18.25

4. Results

4.1. Spatiotemporal Characteristics Analysis of CLUEE

Measured by the SBM-DEA model, CLUEE in the YREB from 2009 to 2025 shows obvious dynamic evolution characteristics in Figure 2. Temporally, the mean value of CLUEE in the YREB fluctuated between 0.795 and 0.813, overall showing a “U-shaped” evolutionary trend. 2009–2018 was a stage of shock and decline, with efficiency bottoming out in 2018 (0.7955), related to increased pressure on the cultivated land system caused by rapid expansion of urbanization and agricultural production intensity. After 2019, the efficiency value continued to rise and reached its peak in 2025 (0.8130), reflecting the increasingly prominent success of the shift of agricultural production toward low-carbon and intensive patterns under the guidance of the green development strategy.

**Figure 2.** Time-series changes in CLUEE in the YREB from 2009 to 2025.

Spatially, efficiency levels show significant non-equilibrium and gradient differentiation. Regionally, it generally presents a “downstream > middle reaches > upstream” stepped distribution in Figure 3. Middle and upper reaches have shown robust growth momentum in recent years, exhibiting a clear catch-up trend. Figure 4 shows that efficiency levels are significantly constrained by topography; efficiency in plain cities is always higher than in non-plain cities. However, the efficiency gap between the two narrowed from 0.0316 in 2009 to 0.0211 in 2025, showing a spatial convergence trend. This suggests that

with the improvement of cross-regional agricultural mechanization services and ecological compensation mechanisms, the constraint of topography on CLUEE is weakening, and CLUEE in the YREB exhibits clear spatial synergy and optimal convergence characteristics.

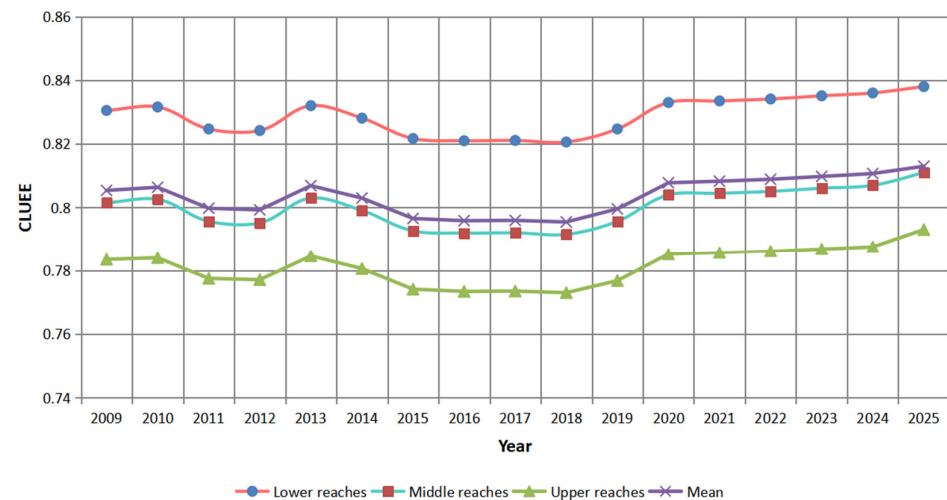


Figure 3. Changes in the CLUEE in the upper, middle, and lower reaches of the YREB from 2009 to 2025.



Figure 4. Changes in the CLUEE in plains and non-plains along the YREB from 2009 to 2025.

4.2. Analysis of Model Regression Results

Table 5 reflects the regression results of the impact of the NRCE on CLUEE. Model (1) is the baseline regression with only core explanatory variables; Model (2) adds city and year fixed effects; Model (3) adds control variables without fixed effects; and Model (4) is the full model with independent variables, control variables, and two-way fixed effects.

The results show that the regression coefficient of the NRCE is positive and statistically significant at the 1% confidence level across Models (1) to (4), indicating that the NRCE exerts a notable enhancing effect on CLUEE in the YREB. The coefficient for the NRCE in the fully controlled Model (4) is 0.1633. This result shows that, with a comprehensive set of control variables incorporated, including economic development level, village-level governance structure, urban–rural income gap, rural human capital, rural public cultural services and rural economic vitality, each additional unit rise in the NRCE is associated with a significant increase of 0.1633 units in CLUEE, providing empirical support for Hypothesis H1.

Table 5. Benchmark Regression Results.

Variables	CLUEE			
	(1)	(2)	(3)	(4)
NRCE	0.2291 *** (32.9159)	0.1652 *** (3.7997)	0.1781 *** (24.5410)	0.1633 *** (5.5077)
c1			0.0015 (0.3191)	−0.0149 ** (−2.2898)
c2			−0.3880 *** (−5.5841)	−0.1636 ** (−2.0362)
c3			0.2239 * (1.6869)	0.5908 *** (3.8454)
c4			0.5111 *** (8.6622)	0.9062 *** (11.7597)
c5			0.0219 ** (2.4184)	−0.2453 *** (−3.9999)
c6			0.0023 (0.4684)	0.0414 ** (2.2853)
Constant	0.7357 *** (79.1759)	0.7988 *** (18.5933)	0.8609 *** (3.4062)	0.4926 (1.4555)
Controls	NO	NO	YES	YES
Observations	714	714	714	714
Firm fixed effects	NO	YES	NO	YES
Year fixed effects	NO	YES	NO	YES
Adjusted R ²	0.603	0.817	0.757	0.872

t-statistics in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Different from pure statistical significance, this result also presents clear economic significance. Economically, the coefficient of 0.1633 suggests that the institutional progress of rural collective economic reform yields a non-trivial improvement in cultivated land green utilization performance. After eliminating the interference of individual heterogeneity, time trends, and socioeconomic confounding factors, a 1-unit increase in the comprehensive development level of the NRCE can independently drive a 16.33% marginal improvement in CLUEE. This magnitude is economically meaningful in the field of agricultural ecological efficiency research, confirming that the NRCE is not only statistically correlated with CLUEE but also produces substantial practical ecological and economic benefits. Such observable marginal improvement further verifies that rural collective economic institutional innovation is a core, effective, and economically valuable driving factor for promoting sustainable cultivated land use, rather than a spurious statistical association.

Further analysis of the data reveals several socio-economic factors significantly influence CLUEE. Rural human capital (c4) is the strongest factor, with a coefficient of 0.9062, which implies that higher educational attainment facilitates the adoption of green agricultural technologies and efficient resource allocation. The urban–rural income gap (c3) also shows a positive correlation of 0.5908, which may be attributed to labor migration driving factor reallocation and more capital-intensive management within the Yangtze River Economic Belt. Conversely, village-level governance structure (c2) and regional economic development (c1) exhibit negative impacts of −0.1636 and −0.0149, respectively, reflecting potential inefficiencies in collective decision-making and a “growth-first” lag in ecological protection. Furthermore, while rural economic vitality (c6) contributes positively

to efficiency with a coefficient of 0.0414, rural public cultural service (c5) presents an inverse relationship of -0.2453 , possibly due to resource diversion or competition effects. Collectively, these results highlight the complex interplay between institutional, human, and economic factors in shaping agricultural sustainability.

4.3. Model Robustness Tests

To assess the robustness of H1, four robustness strategies were employed: replacing the estimation model, excluding special time points, strengthening the control variables, and implementing stricter fixed effects. To avoid the estimation bias caused by the linear hypothesis of the traditional fixed-effect model, this study further adopted a non-parametric machine learning approach for re-estimation. Table 6 presents the results of robustness analysis.

Table 6. Results of robustness analysis.

Variables	Change Machine Learning Model (1)	Remove the Epidemic (2)	High-Dimensional Covariate Control (3)	Fixed Individual Interactions Over Time (4)
NRCE	0.1195 *** (7.9120)	0.1570 *** (5.5457)	0.1511 *** (4.6661)	0.1838 *** (3.9300)
c1		-0.0290^{**} (-2.5151)	0.0689 (1.2522)	0.0115 (1.5158)
c2		-0.1448^{**} (-2.1071)	0.3599 (1.1888)	-0.0323 (-0.6705)
c3		0.5761 *** (3.4789)	1.0461 *** (3.3548)	0.4497 *** (2.7613)
c4		0.8732 *** (11.2654)	0.1907 (1.1320)	0.3576 *** (3.7406)
c5		-0.2352^{***} (-3.1823)	-0.0780 (-0.7619)	-0.0233 (-0.2774)
c6		0.1077 *** (2.7037)	0.0039 (0.0485)	0.0145 ** (2.2781)
Constant	0.0007 (0.1974)	-0.1103 (-0.2334)	-1.5525 (-1.6317)	-0.3024 (-1.2889)
Control variables			YES	
Year fixed effect			YES	
Individual fixed effects			YES	
Adjusted R ²	/	0.871	0.881	0.958
N	714	588	714	672

*** $p < 0.01$, ** $p < 0.05$.

Model (1) re-estimated the specification via machine learning methods. Based on a Random Forest model, the random seed was set to 42 and five-fold cross-validation was adopted for sample partitioning and model training. The estimated coefficient of the NRCE was 0.1195, significant at the 1% level, indicating that the core positive driving effect still holds after relaxing the linear assumption and adjusting the estimation weights. Model (2) excluded the COVID-19 pandemic years from the sample, reducing the sample size from 714 to 588. The NRCE coefficient remained at 0.1570 with 1% significance, demonstrating time-stable improvement effects unaffected by temporary fluctuations. Model (3)

introduced high-dimensional covariates to mitigate omitted variable bias. The estimated coefficient of the new rural collective economy was 0.1511 without substantial changes in statistical significance, confirming strong exogeneity of the promotion effect. Model (4) incorporated urban–year interaction fixed effects. The coefficient was 0.1838, which closely aligns with baseline regression results while effectively eliminating interference from time-varying regional unobserved factors. In summary, the improvement effect of the NRCE on CLUEE maintained high stability across different estimation models, sample intervals, and control strategies, demonstrating robust reliability and consistency in research conclusions.

4.4. Model Endogeneity Test

To rule out potential endogeneity issues from unobserved confounding factors or bidirectional causality, the present study utilized the instrumental variable technique. The number of local ordinary higher education institutions was selected as the instrument variable. Strictly following the exclusion restriction and correlation requirements of instrumental variables, the rationality of this IV was elaborated as follows: In terms of correlation, local universities can significantly drive the standardized and high-quality development of the NRCE through agricultural intellectual spillover, rural talent training, and rural industrial model promotion, forming a stable and positive correlation with the regional NRCE development level. In terms of exogeneity and exclusion restriction compliance, although university resources are closely related to regional technological innovation and human capital accumulation, such agricultural green technologies and high-end human resources cannot directly act on micro-level cultivated land use ecological efficiency. The transformation of university scientific and technological achievements and talent dividends into cultivated land green utilization improvement must rely on the organizational carrier of rural collective economic organizations to complete resource integration, technology promotion and standardized production guidance. There is no direct transmission path from the number of local universities to CLUEE, which effectively satisfies the core exogeneity requirement for instrumental variables. The rationale is that universities significantly drive the standardized development of the NRCE through intellectual spillover, talent training, and model promotion, and have a strong correlation; while the establishment of universities is mostly based on historical accumulation and urban planning, hardly affecting micro-level cultivated land use ecological efficiency directly, thus meeting the exogenous requirement.

Results from the instrumental variable regressions are reported in Table 7. The first-stage estimates show that the instruments are positive and statistically significant, confirming the positive impact of universities on the NRCE. Statistically, the Kleibergen–Paperrk LM statistic is 47.97, and the first-stage F-statistic is 34.71, both exceeding the relevant critical values to rule out under-identification and weak instrument concerns. In the second-stage regression, the estimated coefficient of the NRCE is 1.215, significant at the 1% level. Although the coefficients fluctuate slightly compared to the baseline regression, the consistency of their positive impact indicates that, after correcting for endogeneity bias, the driving effect of the NRCE on CLUEE in the YREB remains robust.

Table 7. Results of endogeneity test.

	Phase 1 Return	Second Phase of Return
	NRCE	CLUEE
TOOL	0.739 *** (5.890)	
NRCE		1.215 *** (2.650)

Table 7. Cont.

	Phase 1 Return	Second Phase of Return
Kleibergen–Paap rk LM		47.97 *** [0.000]
First-stage F value		34.71
N	714	714

*** $p < 0.01$.

4.5. Mechanism Tests

Based on the confirmation that the NRCE has a significant positive driving effect on CLUEE, this study further examines its internal influence pathways. Different from simple stepwise regression, this study formally divides the total effect into direct effects and indirect effects and further discusses the interdependent correlation among the three mediating variables, so as to ensure a rigorous and complete mechanism analysis. Table 8 presents the mechanism test results using land management scaling (Sca), agricultural socialized service (Ass), and green technology innovation (Gti) as mediating variables.

Table 8. Results of mediating effect test.

VARIABLES	Sca	Ass	Gti
	(1)	(2)	(3)
NRCE	1.3406 *** (3.8259)	0.4653 *** (3.6292)	0.3281 ** (2.6943)
c1	−0.0529 (−0.6527)	−0.0392 (−1.4778)	0.0229 (0.7080)
c2	−1.0441 * (−1.9657)	−0.1767 (−0.6245)	0.2426 (1.1695)
c3	−0.5114 (−0.2727)	0.1047 (0.1495)	−0.0202 (−0.0260)
c4	0.7849 (0.5480)	−0.2291 (−0.7218)	−0.2983 (−0.8644)
c5	0.1395 (0.2049)	0.5539 ** (2.3420)	0.2828 (1.3374)
c6	−0.1901 (−0.9371)	0.1068 * (1.6858)	−0.0695 (−1.1588)
Constant	5.6148 (1.4298)	5.7259 *** (4.2166)	4.7928 *** (3.5751)
Controls	YES	YES	YES
Observations	714	714	714
City fixed effects	YES	YES	YES
Year fixed effects	YES	YES	YES
Adjusted R ²	0.736	0.906	0.975

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Model (1) shows that the estimated coefficient of the NRCE on land management scaling is 1.3406, which is significant at the 1% level. This indicates that the NRCE has effectively integrated scattered land through methods such as coordinated transfer and contiguous management, which optimizes resource allocation and creates the necessary spatial conditions for modern agricultural production, thus validating H2a.

Results from Model (2) indicate that the estimated coefficient of NRCE on agricultural socialized services is 0.4653, which is positive and statistically significant at the 1% level. This confirms that the NRCE serves as an essential institutional platform for providing standardized and professionalized production services to smallholder farmers, effectively substituting traditional, resource-intensive production modes with more ecologically sustainable practices, such as unified pest prevention and mechanized operations. H2b is verified.

Models (3) indicates that the NRCE exerts a notable promoting effect on green technology innovation, yielding a coefficient of 0.3281 that is significant at the 5% level. This supports the notion that collective institutional arrangements effectively mitigate information asymmetry and the financial barriers to adopting sustainable agricultural technologies, including precision fertilization and water-saving irrigation. Hypothesis H2c is thus validated.

To quantify the pathway contribution, this study further decomposes the total effect, direct effect, and indirect effects. The total effect of the NRCE on CLUEE is 0.1633 (consistent with the baseline regression result). After controlling for mediating variables, the direct effect of the NRCE remains significantly positive, verifying that the NRCE can directly improve cultivated land ecological efficiency through institutional optimization. Meanwhile, the three indirect pathways jointly constitute the complete mediating effect: land-scale management acts as the foundational intermediate pathway, agricultural socialized services serve as the operational carrier pathway, and green technology innovation functions as the core driving pathway.

Crucially, the three mediating variables are not independent and parallel but present obvious interdependence and progressive linkage. Land-scale management eliminates the constraint of fragmented land, providing basic scale conditions for the large-scale promotion of agricultural socialized services and green technologies. Standardized agricultural socialized services further reduce the application cost and technical threshold of green innovative technologies, forming a synergistic evolution logic of “scale expansion-service empowerment-technology greening”. This interactive coupling relationship jointly constructs the multi-level transmission mechanism through which the NRCE affects CLUEE, rather than three isolated single paths.

4.6. Heterogeneity Analysis

Considering the notable disparities in economic development levels, resource endowments, and natural geographic conditions across different regions of the YREB, standard baseline regressions may fail to reveal the structural heterogeneity in how the NRCE affects CLUEE. Therefore, this study further examines its heterogeneous impact from two dimensions: regional location and topographic features. The regression results are shown in Table 9.

Results from the regional heterogeneity analysis indicate that the impact of the NRCE varies significantly across the YREB, with clear differences in both magnitude and statistical significance among the three reaches. The midstream and upstream regions see the strongest positive effects of the NRCE, with coefficients of 0.2067 and 0.2374, both of which are statistically significant at the 1% level. In comparison, the downstream region yields a much smaller coefficient estimate of 0.0688, which does not reach statistical significance at conventional levels. The group difference test yields a statistic of 24.52, which is significant at the 1% level, thereby confirming that the role of the NRCE in enhancing CLUEE is significantly stronger in the middle to upper reaches than in the downstream areas. This discrepancy likely stems from the higher degree of marketization and non-agricultural employment opportunities in the downstream region, which may dilute the dependency of

farming households on the NRCE for agricultural production. Conversely, in the midstream and upstream areas, where agricultural development faces more severe capital and social constraints, the NRCE plays a critical role in aggregating fragmented resources, improving collective action, and coordinating ecological infrastructure investment, thus leading to more substantial improvements in CLUEE.

Table 9. Heterogeneous regression results.

Variables	Regional Heterogeneity			Topographic Heterogeneity	
	Downstream	Midstream	Upstream	Non-Plain	Plains
NRCE	0.0688 (1.3712)	0.2067 *** (5.6007)	0.2374 *** (9.5707)	0.2242 *** (11.2120)	0.1092 ** (2.7269)
c1	0.0016 (0.1122)	−0.0235 (−0.8588)	−0.0574 (−1.8671)	−0.0031 (−0.4590)	−0.0182 (−1.3938)
c2	−0.1275 (−0.9393)	−0.1767 (−1.0277)	−0.0511 (−0.7702)	0.0804 (1.0552)	−0.2018 * (−1.8052)
c3	0.4237 * (1.9198)	0.6096 (1.6566)	0.7859 *** (4.4336)	0.8720 *** (3.9712)	0.5612 *** (2.8087)
c4	0.9448 *** (8.4717)	0.7597 *** (4.7195)	0.2402 * (2.0178)	0.2084 * (1.9440)	1.0087 *** (12.2507)
c5	−0.4297 *** (−3.0799)	−0.1533 (−0.8723)	0.2457 *** (4.3479)	0.1071 (1.3392)	−0.3090 *** (−2.8309)
c6	0.0180 (0.6177)	0.0575 * (1.9328)	0.2180 (1.8530)	0.0323 *** (4.2971)	0.0490 (1.3364)
Constant	1.1729 *** (3.4425)	0.3130 (0.4728)	−2.4897 ** (−2.5906)	−1.1368 *** (−3.9825)	0.7267 * (1.7717)
Controls	YES	YES	YES	YES	YES
Observations	289	289	136	238	476
Firm fixed effects	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES
Group difference test	24.52 *** [0.0000]			22.14 *** [0.0000]	
Adjusted R ²	0.834	0.883	0.939	0.946	0.820

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Regarding topographic heterogeneity shows that the impact of the NRCE is positive and significant in both non-plain and plain areas, yet the marginal effect is considerably more pronounced in non-plain regions. The coefficient estimate for non-plain areas is 0.2242, significant at the 1% confidence level, which is more than double the coefficient of 0.1092 observed for plain areas, significant at the 5% level. Results from the group difference test support the moderating effect of topography: with a test statistic of 22.14 that is significant at the 1% level, the analysis confirms that topography significantly shapes the nexus between the NRCE and CLUEE. In hilly or mountainous non-plain regions, the NRCE is better equipped to overcome the inherent disadvantages of land fragmentation and high transaction costs through land consolidation and the dissemination of specialized agricultural technology. In terms of control variables, rural human capital (c4) shows a consistent and significant positive influence across all regional and topographic sub-samples, underscoring the fundamental role of education in driving the adoption of green farming practices and improving resource allocation. The urban–rural income gap (c3) also demonstrates a significant positive impact in the upstream and topographic groups, suggesting

that labor migration out of rural areas may incentivize a shift toward more organized, collective-led scale operations to maintain efficiency. Furthermore, rural economic vitality (c6) and rural public cultural services (c5) exhibit varying degrees of influence, reflecting the complexity of the rural socioeconomic environment.

Overall, the findings suggest that the NRCE serves as a more powerful driver of CLUEE in regions characterized by lower economic development levels and more complex terrains, highlighting the necessity of localized policy interventions to maximize the potential of the NRCE.

4.7. Moderating Effect Analysis

To examine the moderating mechanism, this study adopted financial support for agriculture (Fin) and marketization degree (Mar) as moderating factors. By creating cross-interaction terms between the core explanatory variable and the above moderators, relevant regression tests were implemented. All estimated moderating effect results are displayed in Table 10.

Table 10. Moderation effect analysis.

Variables	CLUEE	
	(1)	(2)
NRCE	0.1304 *** (3.5929)	0.1577 *** (5.3455)
Fin	1.0967 ** (2.1035)	
Mar		0.0377 ** (2.2441)
c1	−0.0201 *** (−2.9739)	−0.0172 ** (−2.6153)
c2	−0.1547 * (−1.8426)	−0.1406 * (−1.7302)
c3	0.5468 *** (3.3054)	0.5213 *** (3.4993)
c4	0.8956 *** (11.4367)	0.8631 *** (11.1579)
c5	−0.2734 *** (−4.2012)	−0.2589 *** (−4.4963)
c6	0.0458 ** (2.4662)	0.0454 ** (2.5757)
Constant	0.6460 * (1.7100)	0.6928 * (1.8940)
Controls	YES	YES
Observations	714	714
Firm fixed effects	YES	YES
Year fixed effects	YES	YES
Adjusted R ²	0.873	0.874

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The main effect coefficients of the NRCE in models (1) and (2) are still significantly positive, and the coefficients of the interaction terms are also significantly positive. These results strongly support Hypothesis H4, namely that the effect of the NRCE on improving

CLUEE exhibits significant context dependence. This demonstrates that financial support for agriculture intensity plays a significant positive moderating role in improving ecological efficiency through agricultural infrastructure development, green production technology adoption, and ecological restoration projects. Regions with stronger fiscal support enable the NRCE to more effectively integrate ecological resources, thereby amplifying their capacity to enhance CLUEE. Higher marketization levels strengthen the positive impact of the NRCE on CLUEE. This may be attributed to more frequent factor mobility and optimized resource allocation efficiency in marketized regions. By aligning with mature market mechanisms, these organizations can more effectively market green agricultural products and achieve higher ecological premiums, incentivizing farmers to adopt eco-friendly farming practices. In conclusion, regions with substantial fiscal support for agriculture and favorable market conditions can more effectively unleash the governance efficacy of NRCE, thereby significantly driving the green transformation of cultivated land utilization patterns.

5. Conclusions and Policy Implications

5.1. Conclusions

This study utilizes 714 panel data observations from 42 prefecture-level cities in the YREB spanning 2009–2025, measuring CLUEE efficiency via SBM-DEA and quantifying the NRCE via the entropy weight method. Employing econometric methods, including two-way fixed-effects models, mediation effect models, heterogeneity analysis, and instrumental variable techniques, we have systematically examined the impact effects, underlying mechanisms, and heterogeneity characteristics of the new rural collective economy on cultivated land use ecological efficiency. Key findings are summarized as follows:

First, the NRCE serves as a primary driver for enhancing CLUEE. Empirical results demonstrate that the NRCE optimizes resource allocation and mitigates the negative environmental externalities of production factors. These findings remain robust across various tests, including model re-specification, exogenous shock controls, and the inclusion of high-dimensional fixed effects. Furthermore, the instrumental variable (IV) approach confirms that the positive impact is not biased by endogeneity, establishing the NRCE as a core catalyst for ecological efficiency.

Second, the mechanism analysis identifies three pathways through which the NRCE empowers FUEE: land management scaling, agricultural socialized services, and green technology innovation. By consolidating fragmented landholdings and providing professional services, the NRCE reduces transaction costs and input intensity. Moreover, it facilitates the implementation of eco-friendly low-carbon techniques, which helps achieve both carbon mitigation and the upgrading of agricultural productivity.

Third, the impact of the NRCE exhibits significant spatial and topographical heterogeneity. The driving effect is more pronounced in the middle and upper reaches of the Yangtze River and in non-plain regions. In the middle and upper reaches, where agriculture remains a dominant sector, the NRCE has greater potential for resource integration. Topographically, the NRCE provides a higher marginal benefit in non-plain areas by overcoming severe land fragmentation, whereas its incremental impact is limited in plain regions where large-scale operations are already established.

Finally, the external environment significantly moderates the ecological performance of the NRCE. Increased financial support for agriculture and higher levels of marketization significantly amplify the positive influence of the NRCE on CLUEE. This suggests that the synergy between institutional support and market mechanisms is crucial for maximizing the ecological potential of the NRCE.

5.2. Policy Implications

In light of the above empirical conclusions, a series of policy implications are presented, aiming to utilize the NRCE to accelerate CLUEE.

First, it is essential to optimize the institutional role of the NRCE, thereby underpinning the green development and transformation of agricultural production. Local agricultural and rural authorities and village collective organizations are designated as the primary responsible subjects for this institutional optimization. Specifically, this requires promoting the deepening of rural collective property rights reform and improving the operational mechanisms of collective asset shareholding cooperatives. Such efforts should aim to revitalize underutilized cultivated land and enhance the capacity for resource integration and public service provision. Furthermore, a long-term “university–village partnership” mechanism should be established. By leveraging the intellectual spillover effects of local universities, collective organizations can access advanced management expertise and technical talent. Programs such as professional farmer training and the deployment of tech-commissioners can improve the scientific rigor of collective decision-making, effectively nudging smallholder farmers toward adopting eco-friendly production practices. In terms of practical implementation, local governments can launch special rural talent support projects and regular training sessions; regarding potential costs and risks, grassroots organizational operation and talent introduction will bring fiscal and human resource costs, and targeted government subsidies are required to reduce grassroots operational burdens and avoid formalistic and inefficient cooperation.

Second, a synergistic mechanism should be developed to integrate land management scaling, agricultural socialized services, and green technology innovation. Prefecture-level agricultural departments and township governments shall take charge of mechanism construction and supervision. Local governments should facilitate moderate-scale operations by standardizing rural land transfer markets and improving pricing transparency, thereby systematically addressing land fragmentation. Simultaneously, the NRCE should be encouraged to provide professional services, such as production hosting, technical extension, and green input supply, to internalize environmental externalities through economies of scale in service delivery. To empower this transition, NRCE-led technology platforms should be established to accelerate the R&D and dissemination of low-carbon agricultural technologies and ecological farming models. In practical implementation, hierarchical land transfer approval standards and unified agricultural service specifications can be formulated. Critically, this study highlights the potential risk of excessive land centralization caused by blind large-scale land consolidation, which may lead to single agricultural structure, insufficient smallholder participation, and land resource mismatch. To avoid such risks, land-scale thresholds should be scientifically set based on regional endowments, and the principle of farmers’ voluntary participation must be adhered to, balancing scale operation efficiency and diversified agricultural development.

Third, differentiated development strategies must be implemented to align with regional and topographical endowments. River basin management departments and local agricultural departments are responsible for formulating and implementing region-specific policies. In the middle and upper reaches of the Yangtze River and non-plain regions, the NRCE should be prioritized as the primary driver for ecological efficiency. In these areas, the focus should be on land consolidation and overcoming the “collective action dilemma” inherent in fragile ecological environments. Conversely, in the downstream plain regions where markets are more mature, the NRCE should focus on high-quality farmland protection and the deep integration of collective organizations with modern ecological agriculture and market mechanisms to maximize incremental efficiency gains. In terms of risk and cost control, land consolidation in ecologically fragile upstream areas entails

high ecological governance costs; therefore, regional ecological compensation mechanisms should be improved to share governance costs and alleviate the pressure on rural collective organizations. Plain areas should prevent blind scale expansion and avoid marginal ecological efficiency losses caused by over-commercialization of cultivated land use.

Finally, the external support system must be optimized to amplify policy synergy. Fiscal departments and rural financial supervision departments serve as the main responsible bodies for external guaranteed optimization. Enhancing the market-driven allocation of key production factors such as land, capital, and labor is essential to provide a stable institutional environment for the NRCE. Financial support should be expanded through targeted fiscal subsidies and improved credit access for collective entities. Crucially, the structure of agricultural expenditures should be adjusted to prioritize NRCE initiatives that demonstrate clear ecological benefits, ensuring that institutional support and market mechanisms work in tandem to foster sustainable agricultural development. In practical implementation, a dynamic project performance evaluation system can be established to screen high-value ecological NRCE projects. The potential risk of excessive policy dependence and inefficient fiscal investment exists; therefore, a scientific subsidy exit mechanism and regular supervision inspection should be constructed to reduce resource waste and policy distortion risks.

5.3. Limitations and Perspectives

This study still has two main limitations. First, the static SBM-DEA model adopted for CLUEE measurement cannot capture the intertemporal dynamic evolution of efficiency or distinguish gaps among frontier decision-making units, and the indicator system is restricted by data availability without incorporating more refined micro ecological dimensions. Second, the prefecture-level macro panel cannot reveal micro-level heterogeneity of village-level collective operations and farmer behaviors, and the sample limited to the YREB may restrict the generalizability of conclusions. Future research can adopt dynamic super-efficiency DEA models and combine multi-scale micro survey data to further verify and expand the findings.

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