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The Impact of Cultivated Land Fragmentation on Farmers' Ecological Efficiency of Cultivated Land Use Based on the Moderating and Mediating Effects of the Cultivated Land Management Scale

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Abstract: To date, scholars have increasingly focused on the reduction in crop yields caused by cultivated land fragmentation, yet its effects on the ecological efficiency of cultivated land use are often overlooked. This oversight leads to land resource waste and environmental pollution. It is essential to explore this problem to achieve moderate-scale farming operations and promote the green transformation of agricultural land. This study theoretically analyzed the mechanisms by which cultivated land fragmentation and management scales influence the ecological efficiency of cultivated land use. Based on 2023 household data from Changde and Shaoyang, China, empirical tests were conducted using the stochastic frontier analysis method, Tobit model, and structural equation model. The research results indicate that: (1) The mean ecological efficiency of cultivated land use among the total sample households was 0.822, and the eco-efficiency in the plains was slightly lower than that in the hilly areas. (2) The scale of cultivated land management played a moderating role in the impact of cultivated land fragmentation on ecological efficiency, with differences observed between topographical types. The scale of management can offset part of the negative impact of cultivated land fragmentation on the ecological efficiency of cultivated land use. (3) Regarding the impact of cultivated land fragmentation on the ecological efficiency of cultivated land use, cultivated land management scale changes play a complete mediating role. These findings help provide policy implications to improve the ecological efficiency of cultivated land use. Policy support should be strengthened by promoting moderate-scale cultivated land operations, enhancing the comprehensive remediation of cultivated land fragmentation, and developing skilled farmers for long-term environmental sustainability.

Keywords: cultivated land fragmentation; cultivated land management scale; ecological efficiency of cultivated land use; farmers; topographical types

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1. Introduction

Cultivated land fragmentation (CLF) is a phenomenon in which land is divided into discrete parcels scattered over a wide area [1–3] and usually with uneven sizes. For agricultural purposes, most farms in many developing countries are small (1–2.5 ha) [4] and are frequently fragmented into many plots, particularly in China [5]. Since the 1980s, the reform of China's land system has promoted sustained and rapid growth in agricultural production, with grain output increasing from 3.05 × 108 t in 1978 to 6.87 × 108 t in 2022. However, CLF primarily resulted from the household contract responsibility system, which adjusted land holdings based on household size and soil fertility to ensure equal

distribution. Under the essential national condition of "more people and less land", this policy has led to the small and scattered fragmentation of cultivated land operated by rural households [6–8]. Moreover, with rapid urbanization and industrialization, CLF in China has become increasingly severe, with the average area of cultivated land in China declining by more than 32% since the 90s [9]. Despite over two decades of efforts by the Chinese government to address CLF through policies such as land consolidation and transfer, the results remain inadequate, and the issue persists prominently [10]. Small-scale cultivation and fragmentation of cultivated land have become typical features of agricultural production in China, and they are dominated by small-scale farmer management.

The academic community has focused on the impact of CLF on cultivated land use efficiency. Farmers are the basic units of agricultural production and management and are the primary sources of cultivated land use. Changes in farmers' input and output behaviors, affected by the degree of CLF, have implications for cultivated land use efficiency. The spatial dispersion of plots can reduce production risks by improving the planting structure [6] and taking full advantage of intensive smallholder farming [4], which can positively affect cultivated land use efficiency [11–13]. However, many scholars believe that CLF has a significant negative impact, mainly because it increases the cost of agricultural production [14], hinders the large-scale adoption of agricultural machinery [15], and reduces the efficiency of cultivated land use [16–18]. Liu et al. noted that CLF is becoming a key obstacle to improving the productivity and sustainability of land resources [19]. From the perspective of cultivated land use practices, most scholars focus on the economic benefits of cultivated land use and ignore the ecological issues behind the high food yields. Cultivated land use ecological efficiency (CLUEE) relates to obtaining the wealthiest possible socioeconomic outputs with the lowest possible inputs in the cultivated land use process while minimizing negative environmental impacts [20]. As pointed out by Feng et al., China's ecological efficiency of cultivated land use showed a significant downward trend from 1993 to 2013, based on a comprehensive consideration of economic output, non-point-source pollution, and carbon emissions [21]. Weighing economic and ecological benefits is critical to sustainable cultivated land resource use [22]. Many studies have discussed CLUEE and its influencing factors. They found that the resource endowment of cultivated land leads to regional differences in CLUEE, with topography and CLF having significant effects on CLUEE [23,24]. Still, surprisingly, few studies have explored the mechanism by which CLF affects CLUEE.

In a market-oriented and mechanized agrarian society, CLF significantly threatens agricultural production and food quantity [11]. To ensure food security, the Chinese Government aims to increase the scale of cultivated land to reduce fragmentation, as has been done in countries with smaller farms, such as Japan and Bangladesh [25]. Apart from CLF, the cultivated land management scale (CLS) can also potentially affect efficiency [6,26,27]. In Bangladesh, the scale–productivity relationship varies across regions, depending on technological development and environmental opportunities. This relationship is positive in technologically advanced areas, whereas underdeveloped regions still have a classic reverse relationship [26]. CLF also affects CLS and hinders the centralized management of cultivated land. The harmful effects of fragmentation increase dramatically as the size of the farm increases. According to Kawasaki, the emphasis should be switched from increasing size to alleviating fragmentation to ensure efficient gain [25]. Unfortunately, the direction of the impact of CLS on efficiency remains unclear, and few scholars have explored the effects of combining CLF and CLS on farmers' CLUEE.

Agricultural modernization requires the large-scale management of cultivated land. The relationship between CLF and CLUEE is expected to become increasingly significant. Therefore, this study aims to clarify the effect of CLF on CLUEE and the role of CLS on this effect. From a micro perspective, this study considers two typical agricultural areas in Hunan Province; uses questionnaire research data from farmers; empirically tests the stochastic frontier analysis method, Tobit regression model, and mediation effect model; analyzes the effects of CLF and CLS on CLUEE; and conducts a heterogeneity analysis and

robustness test of the research results to provide new ideas for realizing appropriate scale management of cultivated land and promoting its green transformation.

2. Literature Analysis and Theoretical Framework

2.1. The Direct Effect of Cultivated Land Fragmentation on the Ecological Efficiency of Cultivated Land Use

Most studies have concluded that CLF negatively affects cultivated land use efficiency. How should CLF affect farmers' CLUEE when ecological issues are considered? Following the path in which CLF affects the efficiency of farm households' cultivated land use through the inputs of production factors, we analyzed the impact of CLF on CLUEE.

When considering land use decisions, farmers always seek to maximize their return on land [28]. Although finer cultivated fields decrease farm machinery's efficiency [29], farm machinery is still chosen by farmers in pursuit of improved productivity, resulting in increased carbon emissions, thus hindering the improvement of CLUEE. Environmental conditions, including the degree of CLF, determine the outcomes of farmers' production decisions [30]. Owing to the increase in the price of farm machinery services in areas with finer cultivated land, rational farmers may reduce their farm machinery use behavior [31] and replace it with labor, which results in a reduction in carbon emissions and thus promotes CLUEE. In addition, CLF may weaken the effect of pesticides and fertilizers, forcing farmers to compensate for it by increasing the application amount, which in turn raises carbon emissions and surface pollution, thereby inhibiting the improvement of CLUEE (Figure 1). Therefore, the following hypothesis is proposed:

H1. *There is a relationship between cultivated land fragmentation (CLF) and the ecological efficiency of cultivated land use (CLUEE). The exact relationship is to be empirically tested.*

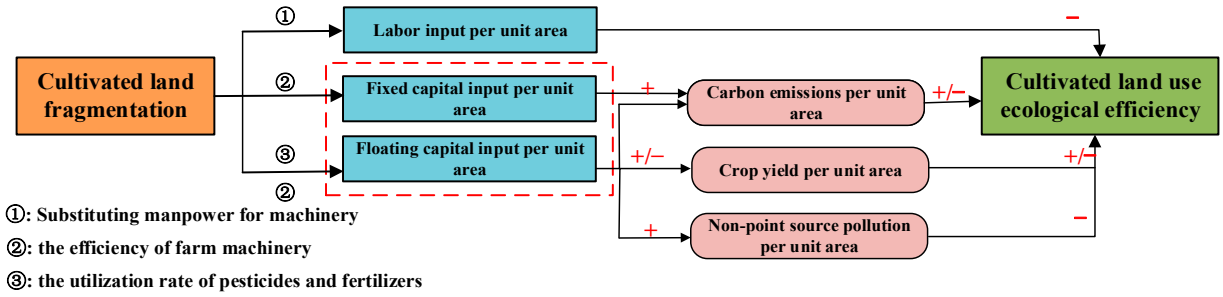

Figure 1. Effect path of cultivated land fragmentation on cultivated land use ecological efficiency.

2.2. The Direct Effect of Cultivated Land Management Scale on the Ecological Efficiency of Cultivated Land Use

In the theory of traditional economies of scale, the expansion of CLS is conducive to the farmers' rational allocation of factors of production, as well as to the adoption of capital-intensive technologies [32]. The indivisibility of fixed capital decreases the average cost of cultivated land use with an increase in yield, thereby improving the CLUEE. However, some scholars pointed out that the larger the available area of cultivated land, the more undesired the outputs generated in the process of land use [23,33], which leads to the aggravation of ecological and environmental problems in the process of cultivated land use [22]. In addition, the land market redistributes land to households with better farm management capabilities. Farmers with large areas of cultivated land are equipped with rich and diverse farming experience, which promotes a reduction in pesticides, fertilizers, and other agrochemicals per unit area of cultivated land. Nevertheless, Liu et al. pointed out that chemical fertilizer application by large-scale farmers may deviate from the optimal economic level, but the extent of this deviation is less than that of ordinary households, which is a rational choice to avoid risks under the condition of insufficient cognitive information on soil fertility [34] (Figure 2). Therefore, the following hypothesis is proposed:

H2. *There is a nonlinear relationship between cultivated land management scale (CLS) and ecological efficiency of cultivated land use (CLUEE). The exact relationship is to be empirically tested.*

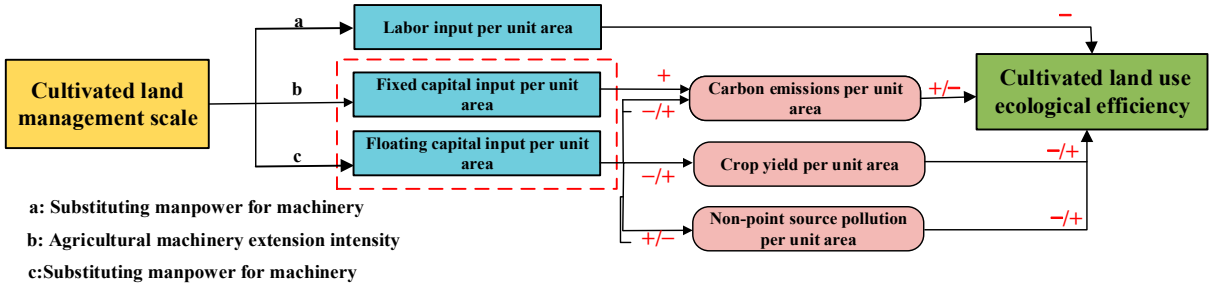

Figure 2. Effect path of cultivated land management scale on cultivated land use ecological efficiency.

2.3. The Moderating Effect of Cultivated Land Management Scale

Numerous studies have found that the impact of CLF on cultivated land use efficiency differs across various management scales. Tian and Feng found that farmers' participation in land transfers to expand CLS significantly enhanced the technical efficiency of rice production [35]. In other words, CLS significantly moderated the negative impact of land fragmentation on rice production's technical efficiency. After considering environmental pollution, CLS may change the direction of the effect of CLF on CLUEE.

As previously mentioned, CLF affects machinery inputs and marginal returns, and it can reduce the efficiency of agricultural machinery utilization [36]. However, Lu et al. indicate that the adverse effects of irregular plot shapes are weakened by increasing the plot size of agricultural land [37]. Some studies show that improvements in mechanical operation efficiency and technological progress will increase production, but this will be constrained by the economies of scale of the plot. This is because when an economic unit holds multiple plots of land in different locations, management and production efficiency are hindered [17]. Diseconomies of scale lead to an unreasonable proportioning of production factors, emphasizing the negative impact of CLF and inhibiting the improvements in CLUEE (Figure 3). Therefore, the following hypothesis is proposed:

H3. *The cultivated land management scale (CLS) is a moderator between cultivated land fragmentation (CLF) and the ecological efficiency of cultivated land use (CLUEE).*

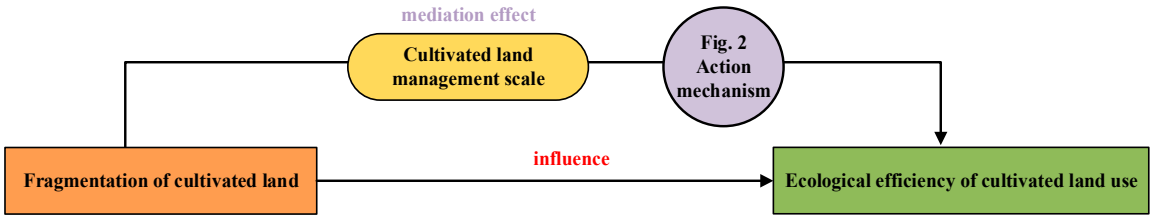

Figure 3. Theoretical path of the moderation effect of cultivated land management scale.

2.4. The Mediating Effect of Cultivated Land Management Scale

The transfer of cultivated land is the primary way for altering the scale of cultivated land management [38]. Su et al. indicated that trading cultivated land use rights enables farmers to manage large-scale cultivated lands, improves the level of cultivated land consolidation, and addresses cultivated land fragmentation to some extent [39]. However, high levels of CLF can endanger agricultural production if transferred farmers are unable to consolidate and level the land. Inappropriate farm sizes and plot distributions increase production costs because farmers lack access to large machinery and lose time between scattered plots [4]. Meanwhile, Pavel Ciaian et al. found that, in many developing economies, scarcity of cultivated land and limited land markets reduce farmers' willingness to transfer cultivated land and hinder their ability to expand their CLS [40]. In conjunction with the

theoretical analysis in Section 2.2, CLF affects CLS, which in turn affects farmers' CLUEE (Figure 4). Therefore, the following hypothesis is proposed:

H4. *The cultivated land management scale (CLS) is a mediator between cultivated land fragmentation (CLF) and the ecological efficiency of cultivated land use (CLUEE).*

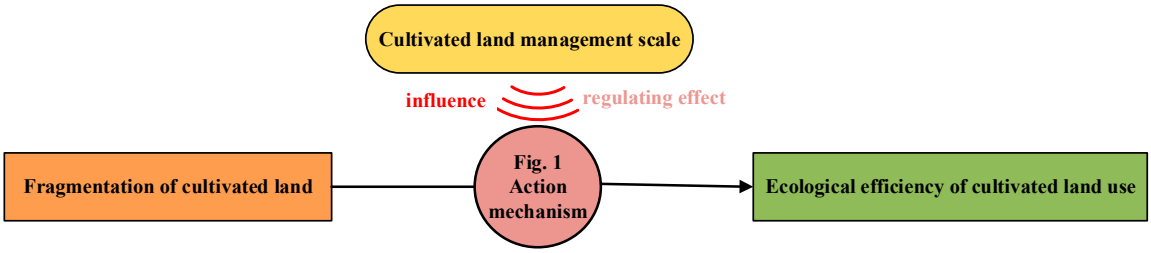

Figure 4. Theoretical path of the mediation effect of cultivated land management scale.

3. Materials and Methods

3.1. Study Area

Hunan Province is a large agricultural province with a substantial grain production base in China. With superior agricultural production conditions, Hunan's total grain output reached 30.68 million t in 2023, an increase of 1.7% over 2022, and the sown area of grain reached 4,763,500 hm^2, of which the rice planting area and output ranked first in the country. Changde City and Shaoyang City are representative of the plain and hill topography in this study. Changde City is a flat lake agricultural area around Dongting Lake, and Shaoyang City is a water-saving rural area in the central and southern Hunan Hills. The two areas have favorable conditions for agricultural production and similar climates, with rainfall concentrated in the summer and insignificant cooling in the winter, which play a crucial role in guaranteeing national food security and the development of green agriculture. A map of the study area is shown in Figure 5.

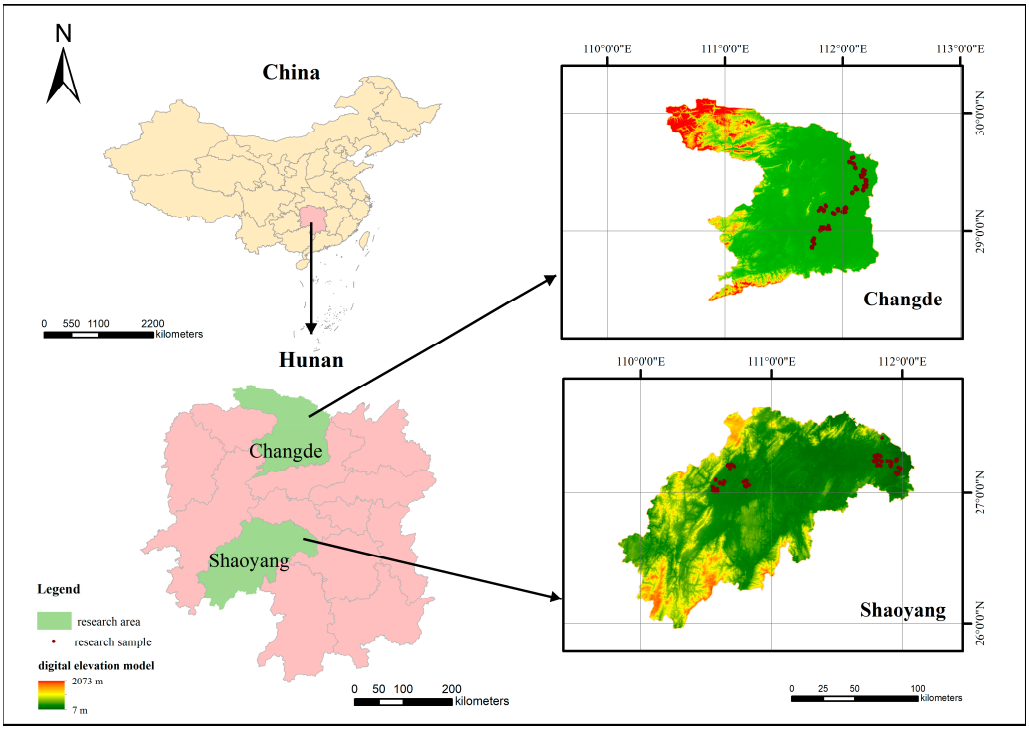

Figure 5. The map of the study area. Note: This map is based on the standard map with review number GS (2022) 4632 downloaded from the website of Standard Map Service of the State Administration of Surveying, Mapping, and Geoinformation, and the base map is not modified.

3.2. Data Source

The research data come from the rural household survey conducted by the research group in July–August 2023 in Hunan Province. The sampling method adopts a combination of stratified and random sampling, and the survey form is a household interview and questionnaire survey. The specifics of data collection are as follows. First, according to the differences in economic development level and topographical types, the study randomly selected Dingcheng District and Anxiang County in Changde City, Shaodong City, and Dongkou County in Shaoyang City as the sample counties. Second, four townships were randomly selected from each sample county based on the differences in rural development levels and distance from the county government. Third, the study selected four villages from each township based on the distance between the village committees and crop planting structure. Finally, a sample of 10–15 farmers was randomly selected from each village to obtain the target data. The respondents are household heads or other agricultural laborers with rich pastoral experience. The survey mainly included information on the essential personal characteristics of the farmers, the household's socioeconomic factors, and the cultivated land's utilization. It effectively covers the relevant information to be analyzed in the paper. A total of 896 questionnaires were collected, and after excluding invalid questionnaires and individual questionnaires with extremely abnormal data, 885 valid questionnaires were obtained, with an effective rate of 98.77%. We only studied rice farmers and finally used 824 farmer questionnaires as survey data.

3.3. Variable Selection

a. The explained variable was cultivated land use eco-efficiency (CLUEE). This study determined the evaluation indices of the CLUEE using inputs and outputs, as shown in Table 1. The input indicators include labor (L), working capital (W), and fixed capital (F) inputs. Output indicators consist of desired (Y) and non-desired (UO) outputs, and the measurements of carbon emissions and surface source pollution in non-desired outputs are based on Hu et al. [41].

Table 1. Evaluation index of ecological efficiency of cultivated land use.

Type	Variable Selection			Connotation
Input	Labor input (L)	Labor time		Labor time per unit sown area during rice production (d·hm^{-2})
	Capital input (K)	Floating capital input (W)	Pesticide input	Cost of purchasing pesticides per unit sown area during rice production (¥·hm^{-2})
			Fertilizer input	Costs of purchasing nitrogen fertilizers, phosphate fertilizers, potassium fertilizers, compound fertilizers, and other fertilizers per unit sown area during rice production (¥·hm^{-2})
			Seed input	Cost of purchasing seed per unit sown area during rice production(¥·hm^{-2})
			Irrigation input	Costs of irrigating per unit sown area during rice production(¥·hm^{-2})
		Fixed capital input (F)	Agricultural machinery input	Costs of personal or rental farm transporters, transplanters, cultivators, harvesters, and other agricultural machinery per unit sown area during rice production(¥·hm^{-2})
Output	Desirable output (Y)	Production		Rice production per unit sown area(kg·hm^{-2})
	Undesirable output (UO)	Carbon emissions, non-point-source pollution		Carbon emissions per unit sown area(kg/hm^2) + non-point-source pollution per unit sown area(kg/hm^2)

b. The core explanatory variable was cultivated land fragmentation (CLF). This study adopts the composite index method based on Wen et al. [42] to measure the degree of CLF. This method integrates three critical indicators from a micro-level perspective, considering the natural and human-induced factors that influence cultivated land management. Precisely, the method captures the average plot area ($\bar{a}$), number of plots (n), and the average distance between plots ($\bar{d}$). This composite index allows for a more nuanced and

accurate measurement of cultivated land fragmentation. The calculation formula is given by Equation (1).

$$CLF_i = t\overline{a}_i + tn_i + td_i \quad (1)$$

where CLF_i is the degree of CLF of the ith farmer, whose value ranges from 0 to 1. The closer the value is to 1, the higher the degree of CLF. The weight of the three evaluation indices, t, was consistently determined to be 1/3.

c. Cultivated land management scale (CLS) was a moderating and mediating variable. Based on different research objectives, the academic community mainly adopts three methods to define cultivated land management scales: actual cultivated land area operated by households, actual sown area of households, and average contracted cultivated land area per household. This research adopts households' actual sown area of crops as the indicator of CLS, as it objectively reflects the land area and resources that households invest in rice production, which directly affects their production output. Therefore, it is more accurate to choose this indicator to explore the role that CLS plays in how CLF affects CLUEE.

d. Control variables. Based on the literature [20,29], we selected the education level (edu), the share of agricultural income (agr-inc), the dependency ratio (dep), distance to market towns (mar), and topographical type (top) as the control variables. The variable settings and descriptive statistics are presented in Table 2.

Table 2. Variable declaration.

Type	Variable	Symbol	Definitions
Explained variable	Cultivated land use eco-efficiency	CLUEE	The farmers' cultivated land use eco-efficiency value
Core explanatory variable	cultivated land fragmentation	CLF	The cultivated land fragmentation composite index
The moderating variable and the mediating variable	cultivated land operation scale	CLS	Rice planting area (hm^2)
Control variable	Education level	edu	Primary school or below = 1, junior middle school = 2, high school or special (or technical) secondary school = 3, junior college or above = 4
	Share of agricultural income	agr-inc	Agricultural income/gross household income
	Dependency ratio	dep	Number of non-agricultural labor force/number of the labor force
	Distance to the market town	mar	Distance from the farmer's address to the central town or market town (km)
	Topographical Types	top	Plain area = 1; hilly area = 0

3.4. Research Methods

3.4.1. The Stochastic Frontier Model

This study used the stochastic frontier model, which is often used for data with multiple inputs and single outputs, to measure CLUEE. It combines an efficiency measurement and analysis of influencing factors, which considers the influence of stochastic factors and particular values that are not easily disturbed [43] and is suitable for dealing with survey data. The model treats undesired outputs as input factors based on Korhonen and Luptacik's treatment of negative outputs [44]. The model is expressed in Equation (2).

$$Y_i = f(L_i, K_i, UO_i, \beta_1, \beta_2, \beta_3)\exp(V_i - U_i) \quad (2)$$

where Y_i represents the farmer's grain production per unit of sown area, and L_i, K_i, and UO_i represent the farmer's labor input per unit area, capital inputs, and non-expected outputs, respectively. V_i is the random error term. U_i is the random vector obeying $\mathrm{N} = (\mathrm{m_i}, \sigma_u^2)$. β_1, β_2 and β_3 are coefficients to be estimated.

3.4.2. The Moderation Effect Model

In this study, we used the stochastic frontier and Tobit models to test whether CLF and CLS have a nonlinear impact on CLUEE and analyzed how CLF affects CLUEE under the moderating effect of CLS.

a. The model of the stochastic frontier non-efficiency influencing factors is shown in Equation (3).

$$m_i = \omega_0 + \sum_{i=1}^{\theta} \omega_\theta Z_{\theta i} + \varepsilon_i \quad (3)$$

where ω_0 is the constant term, θ represents the number of key explanatory variables and control variables, ω_θ represents the coefficients to be estimated for the key explanatory variables and control variables, $Z_{\theta i}$ represents the indicators for the key explanatory variables and control variables, and ε_i represents the random disturbance term. By measuring how each factor affects the degree of ecological inefficiency in cultivated land use, we can determine how it affects CLUEE.

b. Tobit model

The Tobit model is commonly used to address situations where the dependent variable is censored or limited in its range. Taking into account that the explanatory variable CLUEE in this study is a left-truncated variable with a range greater than 0 and less than 1, and in the case where the SFA model is not applicable, the Tobit model is chosen to explore how CLF affects CLUEE and the moderating role of CLS in this process. Drawing on the framework for analyzing mediating effects, we constructed a hierarchical regression model combined with the research hypothesis of this paper.

3.4.3. The Mediation Effect Model

Structural equation modeling (SEM) is mainly used to analyze the complex relationship between multiple explanatory variables and the explanatory variables themselves, taking into account the measurement errors of the explanatory variables to improve accuracy. To further analyze the mechanism of CLF on CLUEE, we established a mediation effect model of CLF-CLS-CLUEE and introduced mediator variables to observe the explanatory and explained variables. The model is expressed by Equation (4).

$$\eta = B\eta + \Gamma\xi + \varphi \quad (4)$$

where η represents the observed explanatory variable, ξ represents the observed explained variable, B and Γ are the path coefficient matrices for the observed explanatory variable and the observed explained variable, respectively, and φ represents the portion of the observed explained variable that is not explained by the observed explanatory variable.

4. Empirical Results

4.1. Estimated Results of Farmers' Ecological Efficiency of Cultivated Land Use

After the applicability test of the model, it is appropriate to use the C-D production function stochastic frontier model to estimate CLUEE. According to the distribution of ecological efficiency of cultivated land use (Figure 6), the farm households with CLUEE values in the 0.9–1 range are the most common, with 310 households accounting for 37.62% of the total sample. The average CLUEE value for the sampled farmers is 0.822.

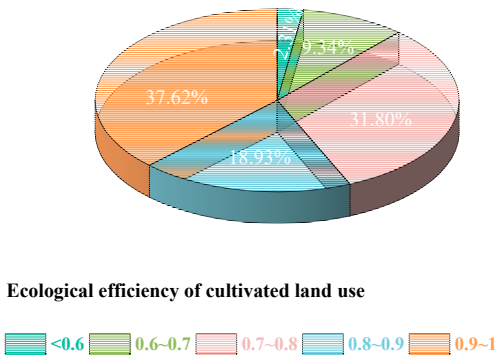

Figure 6. The distribution of farmers' ecological efficiency of cultivated land use.

4.2. Moderating Effect Analysis Based on Cultivated Land Management Scale

4.2.1. Estimated Results

Based on the above theoretical analysis and indicator selection, we chose the C-D production function stochastic frontier model to analyze the influence mechanism of CLF and CLS on CLUEE. The estimation results are presented in Table 3. Model M1 contains the core explanatory variable; Model M2 contains the moderating variable and its square term; Model M3 contains the core explanatory variable, the moderating variable, and its square term; and Model M4 includes the interaction term of the core explanatory variable and the moderating variable.

Table 3. Estimation results of the moderation effect of the overall sample.

Variable	Model M1		Model M2		Model M3		Model M4	
	Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Error
Constant	0.152 *	0.070	0.149 **	0.068	0.148 **	0.069	0.116	0.073
CLF	0.098	0.099			0.048	0.102	0.520 **	0.243
CLS			0.065	0.073	0.059	0.073	0.045	0.075
CLS^2			0.004	0.023	0.004	0.023	0.025	0.024
CLF × CLS							−0.360 *	0.189
edu	−0.020	0.016	−0.021	0.016	−0.021	0.016	−0.017	0.015
agr-inc	−0.220 ***	0.089	−0.226 ***	0.086	−0.232 **	0.090	−0.221 ***	0.085
dep	−0.037	0.030	−0.038	0.029	−0.038	0.029	−0.035	0.027
mar	0.004	0.006	0.004	0.006	0.004	0.006	0.004	0.005
top	0.009	0.030	0.012	0.029	0.009	0.030	0.020	0.032
gamma	0.878 ***	0.030	0.887 ***	0.029	0.887 ***	0.027	0.881 ***	0.029
log-likelihood function	343.837		344.605		344.719		347.706	
LR test	61.689		60.152		61.917		67.891	

Note: If the estimation coefficient of an influencing factor variable is negative, the impact of the variable on technical non-efficiency is negative, while the impact on the ecological efficiency of cultivated land use is positive. *, **, and *** represent $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively.

The estimation results of Model M1 show that the estimated coefficient of the CLF variable is positive. As the degree of land fragmentation increases, the value of the ecological efficiency of cultivated land use decreases. There is a negative relationship between CLF and CLUEE, which supports H1 but fails to pass the significance test. In Models M2, M3, and M4, the CLS variable and its quadratic coefficients are always positive. With the change in the degree of land fragmentation, the value of ecological efficiency of cultivated land use showed an "inverted U" trend that first increased and then decreased. The test indicates a nonlinear relationship between CLS and CLUEE, and H2 has been validated. In other words, when cultivated land is operated on a larger scale, the ratio between various production factors will gradually become reasonable, and the scale effect will effectively improve CLUEE; however, once the scale exceeds the management capacity, diseconomies of scale will occur and cause the opposite effect.

Combined with models M1, M3, and M4, it can be seen that, after adding the interaction term between CLF and CLS, the intensity of the effect of CLF on CLUEE changes. The estimated coefficient of the CLF variable changes from 0.098 to 0.520, and the level of significance changes from insignificant to significant. The estimated coefficient of the interaction term is negative and passes the significance test at the 10% level. CLF significantly and negatively affects CLUEE, whereas the interaction term has a significant positive effect. This indicates a substantial difference in the impact of CLF on farmers' CLUEE among different CLS, and hypothesis H3 of this paper is verified. Among the control variables, the estimated coefficient of agr-inc is negative and passes the significance test at the 1% level. This means that the farmers' CLUEE is significantly and positively affected by the share of agricultural income.

4.2.2. Robustness Test of the Moderating Effect Model

To test the reliability of the empirical results, the robustness of the model was examined by replacing the indices that portray the core explanatory variables. By replacing the CLF composite index with a single indicator, the estimated coefficient of the effect of the number of plots on farmers' CLUEE was positive, and the interaction term between CLS and the number of plots also positively affected farmers' CLUEE. After replacing the core explanatory variable indicators, the sign of the estimated coefficients did not change, but the size of the coefficients and the level of significance changed slightly, verifying the moderating effect of CLS on CLF, affecting the efficiency of farm households' cultivated land use. A possible explanation for this is that compared with the comprehensive index of CLF, a single indicator of the number of land parcels cannot comprehensively portray CLF. This leads to the conclusion that the empirical results are robust.

4.3. Mediating Effect Analysis Based on Cultivated Land Management Scale

4.3.1. Fitness Test

The results of applying Amos 26.0 to test the goodness-of-fit of the sample-mediated effects model are presented in Table 4. All the indicators in the model passed the fitness test, and the overall fit and fitness of the model met the requirements.

Table 4. Fitness testing index of structural equation model.

Fit Index	χ^2/df	RMSEA	GFI	AGFI	NFI	IFI	CFI
Model Estimate	1.158	0.014	0.925	0.860	0.925	0.989	0.989
Suggested Value	$1 < \chi^2/df < 3$	<0.08	>0.9	>0.8	>0.9	>0.9	>0.9
Evaluation	Ideal	Ideal	Ideal	acceptable	Ideal	Ideal	Ideal

4.3.2. Estimated Results of Direct and Indirect Effects

The estimated results of the direct effects are shown in Table 5(a). It shows that the degree of CLF not only negatively affects CLUEE but also affects CLS. The impact of CLF on CLUEE is insignificant, which indicates that CLF may indirectly affect CLUEE by affecting CLS, and this indirect effect of CLF needs to be further tested. Edu, dep, and agr-inc significantly impact farmers' CLUEE; mar and top do not have significant effects.

Table 5. Estimation results of the overall sample.

(a) Direct Effect Estimation Results.

Pathway	Unstandardized Estimate			Standardized Path Coefficient
	Unstandardized Path Coefficient	Standard Error	Critical Ratio	
CLS ← CLF	−0.602 ***	0.193	−3.116	−0.108
CLUEE ← CLS	0.022 **	0.008	2.695	0.093
CLUEE ← CLF	−0.038	0.046	−0.839	−0.029
CLUEE ← edu	0.008 *	0.004	1.763	0.060
CLUEE ← dep	0.013 *	0.007	1.850	0.063
CLUEE ← agr-inc	0.075 ***	0.018	4.245	0.145
CLUEE ← mar	−0.001	0.002	−0.844	−0.029
CLUEE ← top	−0.005	0.007	−0.700	−0.024

(b) Indirect Effect Estimation Results.

Pathway	Indirect Effect			Direct Effect		Mediation Effect
	Indirect Effect Coefficient	95% Confidence Interval		95% Confidence Interval		
		Lower Bound	Upper Bound	Lower Bound	Upper Bound	
CLUEE←CLS←CLF	−0.010 **	−0.028	−0.004	−0.042	0.113	supported, complete mediation

Note: *, **, and *** represent $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively.

Based on the bootstrapping proposed by Preacher and Hayes, sampling was repeated 5000 times [45] to test the mediating effect of CLS in the path of CLF affecting the CLUEE. The test results are shown in Table 5(b). (1) the indirect effect coefficient of CLF was −0.010 and was significant at the 5% level, indicating that the indirect effect of CLF exists. (2) The lower and upper bounds of the indirect effect of CLF were −0.028 and −0.004, respectively, which are harmful in the 95% confidence interval, verifying that the indirect effect of CLF was significant. (3) The lower and upper bounds of the direct effect of CLF were −0.042 and 0.113, respectively, and the interval range included 0. CLS, therefore, played a fully mediating role in the process of CLF affecting CLUEE. This finding suggests CLS has a complete mediating effect on CLUEE, which verifies H4. A path diagram of the mediating effect of the overall sample is shown in Figure 7.

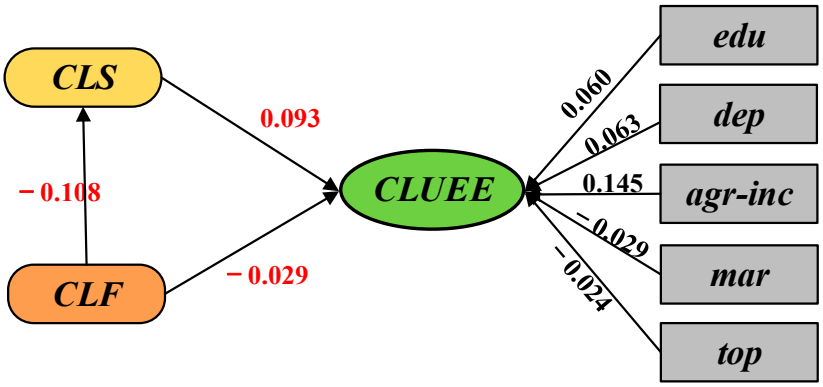

Figure 7. Path diagram of the mediating effect of the overall sample.

4.3.3. Robustness Test of the Mediating Effect Model

To test the reliability of the empirical results, we replaced the CLF composite index with a single indicator of the number of plots. We used structural equation modeling to test the mediating effect and whether the overall fit and fitness of the model met the requirements. The results show that the number of cultivated plots significantly and negatively affected CLS, and CLS significantly and positively affected CLUEE. In contrast, the number of cultivated plots did not significantly affect CLUEE. We found that CLS had a mediating complete impact on the number of cultivated plots affecting the CLUEE of farmers. The mediating effect of CLS remained after replacing the core explanatory variable, indicating that the mediating effect model is robust.

5. Discussion

5.1. Discussion of the Results

The results confirmed H1, indicating that the CLUEE decreases with the increase in CLF. H2, H3, and H4 were all verified, confirming CLS's moderating and mediating effect. However, in the case of H1, the impact of CLF on CLUEE was not statistically significant. As mentioned above, the topographic feature is an essential factor influencing CLUEE. This prompted us to analyze further whether there was heterogeneity in the impact of CLF on CLUEE. It can be found that there are differences in the CLUEE among the different topographical types (Figure 8). The mean value of the CLUEE of farm households in the plain area was lower than that in the hilly area. This result is inconsistent with the findings of Xu et al. [46]. High ecological efficiency areas tend to be highly dispersed cultivated land with relatively complex topography. These characteristics reflect China's unique agricultural landscape, particularly in hilly areas with prevalent terraced farming. However, the complexity of these systems can also introduce management challenges, affecting overall ecological performance.

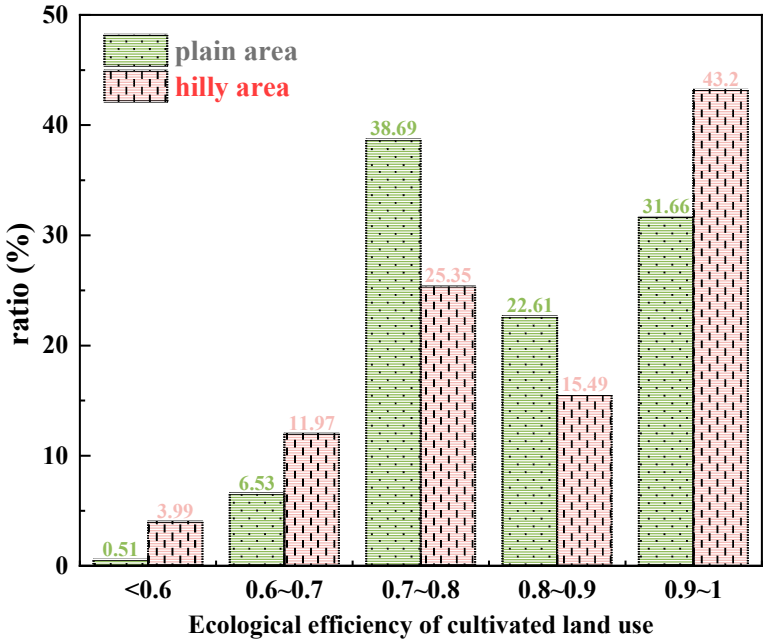

Figure 8. The ecological efficiency of cultivated land use in different topographical types.

From the perspective of landscape-type heterogeneity, the estimation results are shown in Table 6. The findings indicate that CLF significantly negatively impacts CLUEE in hilly areas, compared to relatively minor effects observed in plain areas. Specifically, CLF substantially adversely impacted farm households' CLUEE in hilly areas (Table 6(b)). In contrast, the effect was positive but did not pass the significance test for the plains (Table 6(a)). Subsequently, we found that the overall analysis demonstrated a moderating effect of CLS on CLUEE, but the heterogeneity analysis reveals that this effect is significantly more substantial in hilly areas. The results confirm that topography is essential in the relationship between CLF and CLUEE. As calculated before, the CLF degree in hilly areas is higher than in plain areas. The complex terrain in hilly areas limits the use of agricultural machinery, leading farmers to rely more heavily on chemical fertilizers, which causes non-point-source pollution and exacerbates the negative impact on CLUEE. Meanwhile, this condition increases the difficulty of agricultural management, significantly adversely affecting ecological performance. In contrast, land management interventions can alleviate land fragmentation in plain areas, such as expanding the scale of cultivated land operations [47]. Larger-scale cultivated land management enables more efficient resource allocation, better-mechanized farming conditions, and more effective management practices.

Table 6. Estimation results of moderation effect.

(a) Estimation Results of Moderation Effect in the Plain Area.								
Variable	Model N1		Model N2		Model N3		Model N4	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Constant	0.758 ***	0.032	0.779 ***	0.021	0.752 ***	0.032	0.740 ***	0.044
CLF	−0.047	0.068			−0.076	0.070	−0.111	0.112
CLS			−0.017	0.022	−0.022	0.022	−0.004	0.051
CLS^2			−0.001	0.007	−0.002	0.007	−0.003	0.007
CLF × CLS							−0.052	0.128
edu	0.008	0.006	0.009	0.006	0.009	0.006	0.008	0.006
agr-inc	0.050 **	0.022	0.058 **	0.023	0.062 ***	0.023	0.062 ***	0.023
dep	0.011	0.010	0.012	0.010	0.012	0.010	0.012	0.010
mar	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.002

Table 6. *Cont.*

(b) Estimation Results of Moderation Effect in the Hilly Area.								
Variable	Model Q1		Model Q2		Model Q3		Model Q4	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Constant	−0.511 ***	0.108	−0.091	0.088	−0.430 ***	0.117	−0.571 ***	0.107
CLF	2.080 ***	0.691			1.614 *	0.750	1.012	0.684
CLS			−0.057	0.186	−0.275	0.207	−0.564 **	0.219
CLS²			0.109	0.078	0.242 ***	0.093	0.230 **	0.094
CLF × CLS							−2.902 ***	1.056
edu	−0.051 **	0.023	−0.035	0.022	−0.057 **	0.023	−0.067 ***	0.022
agr-inc	−0.928 ***	0.160	−0.490***	0.057	−0.970 ***	0.171	−1.196 ***	0.151
dep	−0.119 ***	0.040	−0.075*	0.038	−0.114 **	0.040	−0.137 ***	0.039
mar	0.042 ***	0.009	0.034***	0.009	0.040 ***	0.010	0.054 ***	0.010
gamma	0.998 ***	0.001	0.998***	0.006	0.997 ***	0.001	0.998 ***	0.001

Note: 1. If an influencing factor variable's estimation coefficient is negative, the variable's impact on technical non-efficiency is negative. In contrast, the effect on the ecological efficiency of cultivated land use is positive. *, **, and *** represent $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. 2. According to the test results, the Tobit model was selected for the plain area samples, and the beyond logarithmic stochastic frontier production function model was selected for the hilly areas.

In addition, the empirical evidence of H4 suggests that CLS has a significant, fully mediating effect on the link between CLF and CLUEE, further validating the findings of Cheng et al. [48] that CLF affects CLS and hinders improvements in CLUEE. This aligns with the goals of China's current high-standard farmland construction efforts [31]. By implementing the "One Household One Plot" governance model for cultivated land fragmentation, large-scale cultivated land operations can be realized, allowing for the gradual optimization of production factor allocation. Among the control variables, edu, agr-inc, and dep significantly affect the CLUEE of the sample farmers. Specifically, farmers with higher education levels can accept the concept of green agriculture development and have the ability to master related technologies. Share of agricultural income positively affects CLUEE. The reason for this may be that the higher the degree of dependence of farm households on agricultural income, the more they hope to obtain stable and long-lasting agricultural income, and the stronger the awareness of cultivated land quality protection. At the same time, farmers are more likely to operate large-scale cultivated land, have more experience in cultivation, and have more access to and mastery of advanced green agricultural technologies. The dependency ratio negatively affects CLUEE. This is because farmers will pay more attention to the sustainable utilization and long-term development of arable land to ensure the stable output of agriculture when they have higher pressure on family support.

5.2. Policy Implications

Based on the above conclusions, we obtain the following insights in this paper:

(a) Reducing the fragmentation of cultivated land according to local conditions and realizing appropriate scale operation. In the plains, policies should promote the consolidation of small, scattered plots of land into larger, more cohesive units. By subsidizing land transfers or leases, farmers can pool their resources, expand the scale of their operations, and promote large-scale mechanization. In hilly areas, land improvement should be combined with developing soil and water conservation infrastructure, such as constructing terraces and implementing erosion prevention techniques. Considering the challenges of integrating scattered small plots of land in hilly areas, the government can promote the cooperative farming model, thereby striking a balance between ecological benefits and economic viability and improving agricultural modernization.

(b) Developing skilled professional farmers for long-term environmental sustainability. Strengthen the farmer training system, led by the relevant agricultural and rural departments, in cooperation with experts from agricultural universities and local practitioners. Technical assistance should be provided with green farming practices. At the same time,

an expert-farmer online consultation platform should be developed to facilitate real-time communication on local agricultural pollution issues, guaranteeing increased farming incomes and farmers' yields and realizing sustainable agricultural development.

5.3. Limitations and Future Work

Compared with other studies, this study has the advantage of using primary microdata from farmers, and the study results are discussed in different topographic types, which are more relevant. However, there are some shortcomings. Due to data collection limitations, the number of farmers with large cultivated land operations is small. Increasing the sample of large-scale farmers could make the results more rigorous. In addition, due to time constraints, this paper did not analyze the dynamic effects of CLF and CLS on CLUEE in different historical periods. In future research, the survey data of rural households at fixed observation points can be used for further analysis.

6. Conclusions

Focusing on individual farm households, this study adopts a micro perspective to examine the effects of CLF on farm households' CLUEE and their intrinsic mechanisms. This study utilized representative household-level data collected in 2023 in two typical agricultural districts, Changde City and Shaoyang City, Hunan Province. This study empirically evaluated them using various statistical models, including SFA, moderating effect, and mediating effect models. The conclusions of this study are as follows:

(1) The average value of the farmers' CLUEE in the research area was 0.822, with 0.178 showing room for improvement. There were topographical differences in CLUEE, as follows: the average value of CLUEE in plain areas was 0.818, while that of hilly areas was 0.823.
(2) In the total sample, CLF did not significantly affect CLUEE. The effect of CLF on CLUEE differed according to the topographic type. CLF had a significant effect. CLF substantially negatively impacted farm households' CLUEE in hilly areas, while relatively minor effects were observed in plain areas.
(3) The moderating effect of CLS on the impact of CLUEE was significant, and there were also differences in topographic types. In the entire sample, the negative impact of CLF on CLUEE diminished with the expansion of CLS. The moderating effect of CLS still held after the robustness test with the single indicator instead of the composite index. The regulatory impact of CLF was not verified in the plains, which is consistent with the insignificant negative effect of CLF. In hilly areas, CLF negatively affected CLUEE, and CLS partially offset the negative impact of CLF on CLUEE.
(4) CLS played a significant mediating effect on the path through which CLF affects CLUEE. The mediating effect was manifested as follows: CLS significantly and positively affects CLUEE and plays a complete mediating role in CLF's effect on CLUEE.

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