Research on the Coordinated Development Mechanism and Policy Guarantee of Farmland Scale Management and Quality Improvement under the Background of Rural Revitalization

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ABSTRACT Coordinated optimization of farmland scale management and quality improvement requires quantitative analysis of nonlinear configuration effects, dynamic incentives, and spatial spillovers. This study constructs an integrated modeling framework combining fuzzy-set qualitative comparative analysis, dynamic game modeling, spatial difference-indifferences, and grouped comparative experiments. fsQCA is used to identify configuration paths under different resource endowments, the dynamic game model explains long-term maintenance-investment incentives, and the spatial econometric model evaluates infrastructure spillover effects. Counterfactual simulation and quasi-natural experiments are further conducted to test policy effectiveness. Results indicate that the appropriate scale range is 5–20 hectares, high-standard farmland construction generates a spatial spillover effect of 0.05, and the service-scale model outperforms the property-rights-scale model in coordinated quality improvement and operational efficiency. The study provides a quantitative decision-support framework for resource allocation, spatial interaction analysis, and regional system optimization.

INDEX TERMS spatial econometrics, dynamic game model, fsqca, resource allocation, spatial interaction

I. INTRODUCTION

QUOTING from the past: for a long time, farmland use policies have faced a persistent misalignment between "scale expansion" and "quality protection," particularly when reconciling land conservation with the landintensive infrastructure requirements of the industry. This research addresses the resulting conflict between agricultural output and the spatial demands of engineering zones to ensure a more cohesive policy framework. In terms of research and practice, these two have been neglected and treated separately, which has resulted in a dilemma of "emphasizing the land transferred but neglecting the improvement of soil fertility" in practice [1,2]. That is, agricultural subsidy policies are currently heavily biased towards land transfer operators with large scale, but have not effectively motivated large-scale maintenance investment behaviors, such as substitution of organic fertilizer and deep tillage; while quality improvement projects implemented by orders based on administration, due to the lack of any mechanism linking the benefits of large scale, have lacked motivation for farmers to participate and cannot be sustained in performance. This dilemma of "diseconomies of scale" and "quality deficit" has become the key bottleneck hindering the highquality development of agriculture during the process of rural revitalization, and it is necessary to explore the inherent coupling mechanism and solution path of the two from the perspective of system synergy. Existing research mainly focuses on the two major areas of farmland scale operation and quality improvement. Based on the survey data of farmers in Sichuan Province, Li et al. analyzed the impact of high-standard farm land construction on farmers' abandonment behavior and its mechanism from a micro perspective [3]. Kendall et al. found through interviews with Chinese farmers that the adoption of precision agriculture technology is influenced by multiple factors such as society, culture and economy, and proposed to improve its promotion and application by reducing costs and strengthening information and policy support [4]. Hao et al. used the difference-in-differences method to analyze provincial panel data in China and found that the construction of high-standard farmland significantly increased grain yield by increasing the multiple cropping index, mitigating the impact of disasters and transforming low-yield fields [5]. Liang et al. found through literature, statistics and spatial analysis that China's food security faces the problem of imbalance between demand growth and arable land resource constraints, and proposed to build a resilient arable land protection and strategic reserve system to promote sustainable use [6]. Wang et al. found through spatial analysis that the rational promotion of urban-rural integration and land reclamation can release agricultural land resources to a certain extent through urbanization, thereby alleviating the pressure on food security [7]. Yu et al. found that compared

with small-scale farming, new agricultural models significantly improve resource utilization efficiency and reduce environmental pollution by increasing resource input and specialization, thereby promoting green and sustainable agricultural development [8]. Ge and Lu constructed a theoretical analysis framework for rural spatial governance and explored its implementation path in national land spatial planning in order to improve the unified urban-rural governance system [9]. However, the aforementioned studies have two shortcomings: first, they treat large-scale operation and quality improvement as independent policy objectives, lacking in-depth analysis of their synergistic evolution mechanism; second, their research methods are mostly linear, making it difficult to capture the nonlinear relationship and spatial interaction effects between the two. Therefore, to overcome these aforementioned limitations, this paper employs the following strategies: First, configurational qualitative comparative analysis is applied to explore the synergistic conditions of large-scale operation and quality improvement in different resource endowment scenarios, which extendarily overcome the limitation of regression methods in dealing with multiple causal relationships occurring simultaneously. Second, a dynamic game theory model is constructed to theoretically explore the roots of failure in synergistic mechanism for explaining the long-term investment incentive, which makes up for the limitation of static analysis method in explaining the long-term investment incentive. Third, a spatial difference-in-differences model is introduced to explore the spatial spillover effect of infrastructure, such as high-standard farmland construction, which reduce endogeneity bias caused by traditional assessment method ignoring spatial interaction effect. Finally, through the integration of these methods, the study systematically explores how large-scale farming and soil fertility protection can improve together over time. By moving beyond linear analysis, we can better understand how policy incentives in one county influence farming practices in the next, ultimately creating a practical cycle of sustainable land use and industrial growth.

II. CONFIGURATION IDENTIFICATION OF SYNERGISTIC CONDITIONS

To find out the combinations of conditions for synergistic development between large-scale farmland management and quality improvement under different resource endowment, this paper uses qualitative comparative analysis and does configuration analysis based on micro-level survey data of 22 big grain-producing counties. The strength of qualitative comparative analysis over traditional regression method is that it can find out the different combinations of multiple causal conditions that equivalently lead to the same outcome simultaneously. As for the selection of conditional variables, based on analytical framework of "operating entity—factor allocation—technology adoption", this paper establishes three kinds of conditions as follows: first, condition about operating entity, including operating scale (area transferred) and type of operating entity (family farm, cooperative and leading enterprise); second, condition about factor allocation, including development level of land transfer market (transfer rent and standardization of transfer contract) and credit; and third, condition about technology adoption, including coverage rate of agricultural machinery socialized service and level of high-standard farmland construction. The outcome variable is set as total factor productivity of farmland, and Solow residual method is used to calculate it. In the data calibration stage, direct calibration method is used to convert raw data into fuzzy set membership scores. For continuous variable of scale of operation and coverage rate of agricultural machinery socialized services, the membership score was set according to three anchor points of complete membership, intersection and no membership, and the 95th, 50th and 5th percentile of sample data were used as the standard of three anchor points respectively. For variable of type of subject and high-standard farmland construction, the membership score of corresponding level was set according to theoretical expectation. Based on this, truth table was established and Boolean minimization was used. Firstly, the samples were grouped according to the combination of condition variables and the mean of outcome variable of each group was calculated. The threshold of consistency was set as no less than 0.8, and the threshold of coverage was set as no less than 3 cases. Necessity analysis was used to verify whether a single condition was a necessary condition for the outcome. The necessity consistency of three conditions of operation scale, agricultural machinery socialized services and high-standard farmland construction were all below 0.9. It means that there was no single necessary condition, and the synergistic outcome of large-scale operation was realized under the condition of multiple conditions.

Then, a sufficiency analysis was carried out to obtain three solutions based on standard analysis procedures: complex solution, simple solution and intermediate solution. According to theoretical expectations, interme diate solution was selected as the main basis for analysis. Analysis results indicate that there are three "appropriate scale + service coverage", "organized entity + supporting elements" and "infrastructure + tech nology application" paths to a high level of synergy between large-scale operation and quality improvement: overall consistency of the three paths was 0.86 and overall coverage was 0.52, which revealed that the configuration analysis has a good explanatory capacity.

These configurational paths serve as the empirical foundation for the subsequent models. Specifically, the 'organized entity' path informs the parameters of the dynamic game in Section 3, while the 'infrastructure' path is tested for regional externalities in the spatial model in Section 4. All analyses are based on a nested dataset: the 22 counties analyzed in the fsQCA provide the geographic boundaries for the spatial panel data (2015–2025), and the survey data for the grouped experiments in Section 5 were sampled from the core households within these same 22 counties, ensuring cross-methodological consistency.

III. CONSTRUCTION OF MICRO-ENTITY INCENTIVE COMPATIBILITY MECHANISM

In the model, the assumption is that there is a representative transferee of land, who manages the farmland transferred in the model through a series of distinct periods. The decision of the transferee in each period consists of two parts: the decision of the scale of operation, i.e. determination of the area of transferred land; the decision of the level of maintenance investment, i.e. how many resources to invest in the improvement of the land fertility, i.e. do I use organic fertilizer or use conservation tillage etc. The state transition equation of soil quality is expressed as: current soil quality = the former soil quality less natural decay, and the improvement effect due to current maintenance investment. This context echoes the cumulative and lagging attributes of quality improvement.

The land transferor is interested in land rental revenues and the long-term preservation of land soils. The transfer of land between both parties creates an agreement. The incentive to invest by the transferee is influenced by the contract term and the risk of renewing the contract. In cases of short contract term or high levels of uncertainty in the renewal contract, the transferee will aim at lowering long term investment and maximise short term output. However, this behavioral logic is heterogeneous across regions; in areas with strong informal social capital and stable local norms, these 'soft constraints' often act as a substitute for formal tenure security, encouraging long-term maintenance even under short-term legal agreements. This nuance explains why the simultaneous presence of 'diseconomies of scale' and 'quality deficit' varies significantly depending on the local institutional environment.

In terms of policy intervention, the model adds two subsidy mechanisms: a transfer subsidy dependent on the size of the transfer, which seeks to incentivize the growth of scale; and a maintenance subsidy dependent on maintenance investment, which seeks to incentivize quality improvement. These two categories of subsidies may be applied singly or as combination. The purpose of the model is to identify the subgame perfect Nash equilibrium, i.e., how the optimal scale choice and optimal level of investment of the transferee are selected given various combinations of policy.

A backward induction solution to the model gives the following important conclusions: First, when there are only transfer subsidies, then the transferee would over-expand the scale, but the amount of maintenance investment is inadequate, leading to diseconomies of scale and overexploitation of land fertility. Second, when there are only maintenance subsidies the transferee has no incentive to invest in volume, but the incentive to expand the scale is not sufficient and the economies of scale will not be easily attained. Third, in the coordinated transfer and maintenance subsidies case, at an optimal level of the operating scale, the two subsidy types work in a complementary interaction: transfer subsidies ensure the establishment of economies of scale, and the maintenance subsidies channel part of the gains accrued at scale expansion to long-term investment, hence a coordinated scale and quality growth. Fourth, at some point, with the kind of coordinated subsidy policies that have been implemented, the investment incentives will decrease as there will be a decreasing marginal returns to scale, so there will be an optimal range of scales.

IV. EMPIRICAL TEST OF SPATIAL SPILLOVER EFFECT

To examine the spatial interaction effects of infrastructure such as high-standard farmland construction and agricultural machinery socialization services on the scale operation and quality improvement of cultivated land, this study uses a spatial econometric model for empirical testing. In terms of model selection, this paper constructs a spatial Durbin model as the benchmark model. The advantage of this model is that it can simultaneously capture the spatial lag effect of the explained variable, the spatial spillover effect of the explanatory variable, and the spatial correlation of the error term. The model is set as follows:

$$Y_{it} = \rho W Y_{it} + \beta X_{it} + \theta W X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Where, Y_{it} is the total factor productivity of cultivated land in county i in year t, which serves as a comprehensive measure of the coordinated development of scale operation and quality improvement. W is the spatial weight matrix. This paper uses a geographical adjacency matrix. If two counties are adjacent, the weight is 1; otherwise, it is 0. The matrix is then row-standardized. WY_{it} is the spatial lag term of the explained variable. The coefficient ρ reflects the impact of the total factor productivity of cultivated land in neighboring counties on the county, i.e., the spatial interaction effect. X_{it} is the core explanatory variable vector, including three key variables: the area of high-standard farmland construction, the degree of land fragmentation (as a proxy for structural barriers rather than raw scale), and the coverage rate of agricultural machinery socialized services. To avoid the risk of mathematical tautology where 'scale' explains a TFP variable already containing land inputs, we utilize the land transfer rate as a measure of market fluidity rather than a

direct input quantity, ensuring the model captures the efficiency gains of resource reallocation. WX_{it} is the spatial lag term of the explanatory variables, with coefficient θ reflecting the spatial spillover effect of core variables from neighboring counties on the current county. μ_i and λ_t control for county-level and year-level fixed effects, respectively, and ε_{it} is the random error term.

Regarding the measurement of variable, we use the Solow residual method to calculate the total factor productivity of cultivated land based on the county-level agricultural output, labor input, cultivated land area and the agricultural capital stock. The high-standard farmland construction area is measured by the proportion of cumulative high-standard farmland area to the total cultivated land area in county. The rate of farmland transfer is measured by the proportion of transferred cultivated land area to the area of household-contracted cultivated land. The rate of agricultural machinery socialized service is measured by the number of agricultural machinery professional cooperatives and the comprehensive index of total agricultural machinery power in county, which reflects socialized service supply capacity in this region.

To accurately estimate the spatial effects, this paper uses the quasi-maximum likelihood method for parameter estimation, which can effectively handle estimation bias caused by spatial autocorrelation. The estimation results primarily focus on three types of effects: direct effects, i.e., the impact of changes in explanatory variables within the county on the explained variable within the county; indirect effects (spatial spillover effects), i.e., the impact of changes in explanatory variables within the county on the explained variables of neighboring counties; and the total effect, i.e., the sum of direct and indirect effects.

Regarding model specification testing, firstly, the Moran index is used to test the spatial autocorrelation of the explained variable. If significant spatial clustering characteristics exist, it indicates the necessity of introducing a spatial model. Secondly, the LM test, LR test, and Wald test are used to select between the spatial lag model, the spatial error model, and the spatial Durbin model to determine the optimal model specification. If the test results support the spatial Durbin model, further testing is needed to determine whether the model can be simplified to a spatial lag model or a spatial error model.

V. POLICY EFFECTIVENESS EVALUATION OF COORDINATED DEVELOPMENT

A. EXPERIMENTAL SETUP

To systematically examine the effectiveness of the coordinated mechanism between farmland scale management and quality improvement, this study designed a progressive experimental framework. First, a counterfactual simulation experiment was conducted, setting the management scale to continuously vary between 1 and 50 hectares. The long-term investment levels and soil fertility changes were compared under three policy scenarios: "only land transfer subsidies," "only maintenance subsidies," and "coordinated development of both," identifying the "appropriate scale threshold" for achieving a positive mutual promotion between scale management and quality improvement. Second, the phased implementation of high-standard farmland construction was used as a quasi-natural experiment. A spatial difference-in-differences method was employed to compare the changes in total factor productivity of farmland before and after the project's initiation between the experimental group and the control group, identifying the direct effects of infrastructure improvement and its spatial spillover effects on neighboring areas. Finally, based on the technical service models of new agricultural business entities, a comparative study was conducted, dividing the sample into four groups: "ownership scale + self-purchased agricultural machinery," "ownership scale + managed services," "service scale + full-process managed services," and traditional smallholders. Propensity score matching was used to control initial conditions, and differences in soil organic matter content, output per unit area, and cost-return ratio were calculated among the groups. This examined the differentiated promoting effect of "service scale-driven" on quality improvement under different collaborative paths.

B. COUNTERFACTUAL SIMULATION OF APPROPRIATE SCALE RANGE AND SYNERGISTIC EFFECTS

Based on the subgame perfect Nash equilibrium obtained from the dynamic game model, this paper designed a counterfactual simulation experiment. The operating scale was set as a continuous variable from 1 hectare to 50 hectares, simulating three policy scenarios: "only transfer subsidies," "only maintenance subsidies," and "coordination of transfer and maintenance subsidies." By comparing the changes in the long-term investment level of the transferee within different scale ranges, an appropriate scale range in which scale operation and quality improvement mutually promote each other was identified.

TABLE 1. Simulation Results of Appropriate Scale Ranges under Different Policy Scenarios

Operation scale interval (ha)	Transfer subsidy only	Conservation subsidy only	Transfer & conservation synergy
1–5	Low	Medium	Medium
5–10	Medium	Medium	High
10–20	Low	High	High+
20–50	Low	Low	Medium

Simulation results analysis shows that when the scale is 5-20 hectares, the total investment level in the long term is relatively high. When the "synergistic transfer and maintenance subsidy" scenario is adopted, the investment level of 5–10 hectares increases from "medium" of single scenario to "high", and the investment level of 10–20 hectares increased from "high" of single maintenance subsidy to "high+", which represents the accumulation effect of synergistic policy. When the scale exceeds 20 hectares, the investment level presents a decreasing trend, and the synergistic policy can still keep the investment level at "medium", which is better than the single policy scenario. Therefore, while the simulation identifies an appropriate scale range of 5–20 hectares for typical grain-producing scenarios, this threshold is not a rigid 'one-size-fits-all' requirement. In line with the fsQCA findings, this range represents a 'configuration-sensitive' benchmark; different resource endowments—such as high service coverage or organized entity support—can shift this optimal window. It is recommended to implement coordinated subsidy policies that remain flexible to these regional configurations rather than strictly adhering to a fixed hectare limit.

C. NATURAL EXPERIMENT ON THE SPILLOVER EFFECTS OF HIGH-STANDARD FARMLAND CONSTRUCTION

To explore the spatial spillover effects of high-standard farmland construction, this paper takes the phased implementation of the project as a quasi-natural experiment and constructs a spatial difference-in-differences model. The counties implementing contiguous improvement earlier constitute the experimental group, and the counties that did not implement the project constitute the control group. The direct effect of infrastructure improvement on total factor productivity of cultivated land is the difference before and after the implementa tion of the project, and the spatial spillover effect on neighboring counties is the difference of the differences.

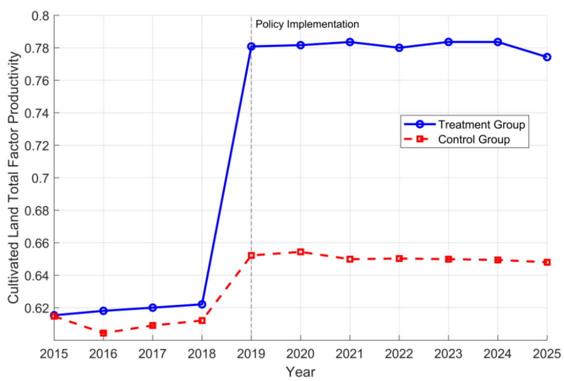

FIGURE 1. Natural Comparison of Spillover Effects of High-Standard Farmland Construction

As shown in Figure 1, high-standard farmland construction has a significant positive impact on total factor productivity of cultivated land. After the policy was implemented in 2019, the average total factor productivity (TFP) of the experimental group counties increased from 0.62 to 0.78, an increase of 0.16; while the control group counties only saw an increase from 0.61 to 0.65 during the same period, an increase of 0.04. Spatial difference-in-differences estimation results showed that the direct effect of the policy was 0.12, and the spatial spillover effect was 0.05, with a combined contribution of 0.17. This means that the construction of high-standard farmland not only directly improved the farmland use efficiency of the county, but also generated a spillover gain of approximately 0.05 in neighboring counties through spatial diffusion. This result indicates that infrastructure improvement has significant positive externalities at the regional scale, providing a quantitative basis for formulating land consolidation policies for regional coordinated development.

D. GROUPED COMPARATIVE EXPERIMENT OF TECHNOLOGY SERVICE MODELS

To analyze the effects of different technology adoption models on farmland quality and efficiency, this paper classified and compared the new types of agricultural operators in the sample of the survey area according to their technology service models. The sample could be classified into the following four types: "large-scale operation with self-purchased agricultural machinery," "large-scale operation with managed services," "large-scale operation with managed services for the whole process," and traditional smallholder farmers who did not join in the large-scale operation and quality improvement project. To ensure the validity of the grouped comparison, propensity score matching (PSM) was implemented with a focus on matching quality. Post-matching tests confirmed that the standardized mean differences for all covariates were reduced to below 10%, and a density plot analysis verified that the majority of treated and control cases fell within the common support area. While PSM effectively controls for observed covariates such as plot quality and crop type, we further conducted a Rosenbaum bounds sensitivity analysis to address potential hidden bias from unobserved confounders like farmer motivation or credit access. The results (Gamma = 1.5) indicate that the findings are robust against moderate levels of unobserved heterogeneity. After ensuring these statistical foundations, we measured the differences in the following three indicators: the content of soil organic matter, yield per unit area, and cost-return ratio, for each group.

TABLE 2. Comparison of Farmland Quality and Management Efficiency under Different Technical Service Models

Technical service model	Soil organic matter content (g/kg)	Output per unit area (kg/mu)	Cost-benefit ratio (%)
Traditional smallholders (control group)	18.5	480	32.5
Property rights scale operation + self-purchased machinery	20.2	535	28.6
Property rights scale operation + trustee service	22.8	578	35.2
Service scale operation + full trustee service	25.6	612	41.8

Table 2 shows significant improvement in each treatment group as compared to the traditional smallholder control group in terms of the content of the soil organic matter, output per unit area and cost- rate return. The best result was the large-scale service + full-process managed services, with soil organic matter content of 25.6 g/kg, a 38.4% improvement over the control group; output per unit area of 612 kg/mu, a 27.5% improvement over the control group; and a cost-benefit ratio of 41.8, an increase of

9.3 percentage points over the control group. The scale operation of property rights + entrusted services model came second, and the three indicators increased by 23.2, 20.4, and 2.7 percentage points over the control group. The scale operation of property rights + self-purchased agricultural machinery model of operation performed better in output indicators than the control group, but its cost-return ratio decreased by 3.9 percentage points, and this model is more pressured by the cost of agricultural machinery purchase and maintenance. These findings confirm the importance of service-scale traction in enhancing the synergistic development of improvement in land quality and operational performance of arable land.

VI. CONCLUSION

This paper constructs a synergistic analysis framework of "operating entities—factor allocation—technology adoption" to systematically explore the collaborative development mechanism between arable land scale operation and the high-quality expansion of the industry. By aligning agricultural land productivity with the advanced technological requirements of engineering, the study reveals how optimized resource allocation drives both land efficiency and industrial modernization. The study found that an appropriate scale range is a fundamental condition for achieving synergistic development, and subsidy policies need to be precisely matched with the scale range; the construction of high-standard farmland has a significant spatial spillover effect, and infrastructure improvement can drive synergistic improvement in neighboring areas; the service-scale model has a greater advantage than the property rights-scale model in promoting the synergy between quality improvement and operational efficiency. This study has certain limitations. The survey sample mainly focuses on major grain-producing counties, and the applicability of the conclusions to non-major grain-producing areas needs to be verified. The assumptions about the agent behavior in the dynamic game model are somewhat idealized and fail to fully reflect the complexity of real-world decision-making. Future research could further expand the sample scope and introduce a behavioral economics perspective to deepen the discussion on the heterogeneous decision-making mechanisms of textile industry business entities. This would allow for a more comprehensive exploration of the collaborative mechanisms and pathways emerging within textile engineering clusters in the context of digital technology empowerment.

AUTHOR CONTRIBUTIONS

Mingfang Song designed, collected and analyzed the data, and drafted the manuscript. Mingfang Song conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Mingfang Song participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

FUNDING

Fund Project: General Project of Social Science Fund of Hunan Province (Project No.: 24YBA348). Project Title: Farmland Protection Mechanism and Empirical Study in the Context of Rural Land Confirmation.

ACKNOWLEDGEMENTS

Not applicable.

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