"Silver-haired Farming" in the Digital Intelligence Era: Resilience, Determinants, and Functional Complementarity of Elderly Agriculture Under Scale Transition—A Logit Model-Based Empirical Analysis

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Abstract. The rapid advancement of digital technologies, including AI and IoT, is fundamentally reshaping global agricultural systems, yet the persistence of smallholder elderly farming in mountainous regions presents a paradox to conventional transition theories. This study investigates the determinants and systemic value of elderly agriculture under the dual pressures of digital transformation and large-scale farmland consolidation. Framing this inquiry within an analytical framework that integrates traditional econometric modeling with rigorous validation protocols, we construct an analytical framework encompassing natural endowments, digital access, household capital, and subjective preferences. A binary multivariate Logit model is employed for econometric analysis as a baseline benchmark within a broader hybrid computational framework that also incorporates bootstrap-based resampling and cross-validation protocols for robustness assurance, laying a reproducible foundation for subsequent deep learning extensions when richer spatiotemporal data become available, complemented by quantitative assessment of elderly agriculture's functional contributions. Results robustly support the "dual-constraint" hypothesis: limited digital skills (OR=0.68, $p<0.05$) and disadvantaged natural conditions (steep slopes, OR=1.32, $p<0.05$; small plots, OR=0.45, $p<0.01$) jointly "lock" elderly farmers into decentralized operations. The stay decision is simultaneously driven by livelihood necessities (low non-farm income, OR=0.21, $p<0.01$) and strong emotional land attachment (OR=2.14, $p<0.01$). Critically, we quantify a significant "functional complementarity" effect: elderly agriculture contributes 16.3% to regional grain output by cultivating marginal lands, while providing essential livelihood security and ecological services (18.7% higher soil organic matter). We conclude that elderly agriculture constitutes a source of systemic resilience, not a residual of transformation. Policy should pivot toward building a "digital inclusion" ecosystem—a core tenet of people-centric smart systems—bridging divides

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through adaptive technologies and socialized services to achieve coordinated development between smallholders and modern agriculture.

Keywords: elderly agriculture; digital divide; functional complementarity; digital inclusion; sustainable computing for agriculture; Logit modeling.

1 Introduction

The confluence of rapid urbanization and the digital technology revolution—centered on artificial intelligence (AI), the Internet of Things (IoT), and big data analytics—is profoundly reshaping rural socio-economic structures worldwide. In China, the urbanization rate reached 66.16% in 2023, while the aging rate of agricultural workers (aged 55+) exceeded 35%(National Bureau of Statistics, 2024). Concurrently, the government actively promotes "Digital Villages" and "Smart Agriculture," with AI applications such as drone-based crop protection, intelligent sensors, and big-data decision support systems becoming increasingly prevalent(Lee & Park, 2026). The conventional policy paradigm for addressing agricultural aging—"land transfer → scale operation → mechanization"—is being upgraded to a "smartification" narrative, aligning with the conference themes of intelligent systems and urban-rural digital transformation

However, a striking phenomenon challenges this linear evolution theory in complex terrains such as southern China's hilly regions. Despite high land transfer rates driven by local governments, small-scale, semi-subsistence farming dominated by elderly labor persists. Our field survey in southern Jiangxi reveals that in villages with a 74.3% land transfer rate, 25.7% of arable land is still cultivated by farmers aged 60 and above. Moreover, these elderly farmers have begun limited contact with basic digital tools (e.g., short-video platforms for agricultural information, mobile payments), indicating a partial but constrained digital engagement. This observation raises a fundamental question central to the conference's human-centric computing and sustainable development tracks: In the face of a pervasive digital revolution, how does so-called 'traditional' elderly farming endure? Is it merely a 'lagging residue' of technological diffusion, or does it form a functional complementarity and systemic equilibrium with large-scale smart agriculture under new techno-economic conditions?

Existing research predominantly examines this phenomenon from sociological perspectives (Jianqiu, Zhichao & Jialing,2023) or economic lenses focusing on land productivity (Otsuka, 2013), yet largely overlooks the critical context of uneven digital economy penetration and AI technology adoption. In particular, the absence of systematic empirical analysis that integrates digital variables into a unified econometric framework limits the capacity to identify the distinct roles of digital access, biophysical constraints, and behavioral responses in shaping farmers' operational decisions. This research gap is particularly salient given the conference's emphasis on digital inclusion, sustainable computing, and responsible.

This study integrates traditional agricultural economics with digital economy analysis to test the core hypothesis: under the constraints of mountainous natural conditions and digital technology limitations, elderly decentralized farming forms a

resilient symbiotic system with digital-scale agriculture through "functional complementarity." Our approach comprises four phases: (1) characterizing coexistence patterns using primary survey data; (2) constructing an econometric model incorporating digital variables to identify key factors influencing elderly farmers' stay decisions; (3) quantifying the complementary value of elderly agriculture across social, economic, and ecological dimensions; and (4) deriving policy implications that align with the conference's vision of people-centric smart systems and sustainable urban-rural development. Theoretical Framework and

2 Theoretical Framework and Research Hypotheses

2.1 Literature Review and Research Gap

Existing literature on the role of "elderly agriculture" in agricultural transition can be summarized in two competing schools. The neoclassical economics tradition argues that economies of scale and technological progress are fundamental to productivity improvement, viewing small-scale, aging operations as inefficient and transitional, ultimately to be replaced by capital- and technology-intensive large-scale entities(Deininger & Byerlee, 2012). This perspective has recently expanded to suggest that smart agriculture will eventually achieve complete labor replacement. In contrast, the agrarian political economy and livelihood framework emphasizes the resilience, multifunctionality, and socio-cultural value of smallholder economies, arguing that small farmers serve not merely as production units but as carriers for livelihood maintenance, risk mitigation, and cultural preservation (Fan & Zhu.,2025).

A critical gap in both schools is their treatment of technology as a neutral, seamlessly diffusing factor. They overlook the significant access, skill, and benefit divides inherent in digital technology applications—a central concern of human-centric computing and digital inclusion. There is a notable absence of systematic empirical analysis examining elderly agriculture under the dual context of digital transformation and large-scale transition, particularly quantitative research assessing how digital technology variables influence operational decisions and their interactions with large-scale agriculture. This study addresses this gap by constructing an integrated analytical framework that incorporates digital constraints as a key determinant.

2.2 Analytical Framework: The Dual-Track Symbiosis Model

This study develops an integrated analytical framework grounded in the concept of distributed intelligent systems and socio-technical resilience. The core logic posits that in mountainous regions, fragmented natural endowments (e.g., slope gradients, plot fragmentation) and differentiated digital endowments (e.g., network coverage, digital skills, service accessibility) collectively form a "constraint matrix." This matrix classifies agricultural operations into two relatively isolated yet interconnected trajectories:

Track One: Digital-Scale Agriculture. focuses on "core plots" characterized by flat terrain, contiguous parcels, and favorable conditions for digital infrastructure

deployment. Operating entities (family farms, cooperatives, enterprises) invest in intelligent machinery, precision irrigation, and big-data platforms to pursue capital- and technology-driven scale economies.

Track Two: Digitally-Constrained Elderly Agriculture. operates on "marginal plots" characterized by steep slopes, small size, scattered distribution, and poor economic viability for digital transformation. Limited digital access, high learning costs, and expensive smart equipment constrain elderly farmers, whose decision-making reflects a complex blend of livelihood security, risk mitigation, and emotional value. While they may adopt low-cost digital tools (e.g., mobile information access), their core production remains experience- and labor-dependent.

These two tracks are not merely a dichotomy of advanced versus backward; rather, they are functionally complementary. The large-scale track pursues efficiency through capital- and technology-intensity, while elderly agriculture provides "gap-filling services" that the former cannot offer cost-effectively—including social security provision, complex marginal land utilization, agrobiodiversity preservation, and community relationship maintenance. Together, they form a more resilient local agro-ecosystem capable of mitigating environmental and social risks—a manifestation of sustainable computing principles applied to real-world socio-ecological systems. This conceptualization directly motivates our analytical pipeline, which employs Logit-based causal inference as the primary analytical engine, complemented by cross-validation protocols to ensure interpretability and robustness.

2.3 Research Hypotheses

Based on this framework, we propose three testable hypotheses:

H1 (Dual-Constraint Hypothesis): Unfavorable natural conditions (steep slopes, small plots) and limited digital access/skills significantly increase the probability of elderly farmers choosing decentralized operations.

H2 (Dual-Motivation Hypothesis): Household economic vulnerability (low non-farm income) and strong subjective land attachment independently and positively influence the stay decision.

H3 (Functional Gap-Filling Hypothesis): Elderly agriculture on marginal land makes a significant and quantifiable contribution to regional grain output, ecosystem services, and social welfare.

3 Study Design, Data, And Methodology

3.1 Study Area and Data

This study selected Zhongguan Town in Duchang County, Jiujiang City; Paibu Town in Tonggu County, Yichun City; and Longxiang Township in Quannan County, Ganzhou City as representative cases. These three counties respectively represent the three distinct landforms of Jiangxi: the lakeside plain, mountainous areas, and hilly regions. Digital village initiatives have been launched in all three areas, yet 4G/5G network coverage remains unstable in remote regions, while the application of smart

agricultural machinery is limited to flat terrain. This uneven distribution of digital infrastructure makes these areas ideal for examining the interaction between the digital divide and agricultural practices—a theme directly relevant to this conference's focus on digital inclusion and sustainable development of information and communication technologies in urban and rural areas.

Sampling Procedure: The data were collected through field surveys conducted in July–August 2024.

Using a stratified random sampling method, we first stratified the three selected counties by landform type—lakeside plain, mountainous, and hilly—and then, within each stratum, randomly selected one administrative village from each of the first two counties and two administrative villages from the third county, yielding a total of four sample villages. Within each village, we obtained a complete roster of households with members aged 60 and above engaged in agricultural production, and then drew a random sample proportional to village size.Questionnaires were distributed to 398 elderly farmers aged 60 and above who were still engaged in agricultural production, accompanied by semi-structured interviews. The effective response rate was 94.8%. Additionally, data on village-level land transfer practices, digital infrastructure coverage, and soil testing results were also collected.

Variable Measurement: The variables are defined as follows:

Dependent Variable: Farming operation model choice (Y = 1 if the farmer maintains decentralized operation, i.e., does not fully transfer land; Y = 0 if they choose full land transfer/exit from farming). This binary outcome was measured through direct questionnaire responses cross-verified with village land registration records.

Core Explanatory Variables

(1) Natural Land Endowments: Average slope (degrees)—measured via GPS field mapping at three representative points per plot and averaged; average parcel size (mu)—calculated from farmers' land contract certificates; average distance from main road (100 meters)—measured by GIS distance analysis.

(2) Digital Constraint: Digital skills—household head's self-assessment of proficiency in using common mobile applications (WeChat, mobile payments, short videos) on a 1-5 scale, validated through an interviewer-observed demonstration task; Digital service accessibility—accessibility of digital agricultural services (smart machinery, drone plant protection) at village level (dummy, 1 = available), confirmed with village committee records.

(3) Household Capital: Age (years)—self-reported and verified with ID cards; health status—1-5 self-rated scale; non-farm income ratio (%)—calculated from detailed household income itemization.

(4) Subjective Cognition: Land attachment—1-5 Likert scale; agricultural identity—1-5 Likert scale, both adapted from validated scales in prior Chinese rural studies.

Control Variable: Village-wide land transfer rate (%), measured from village collective records and verified through household-level data aggregation.

3.2 Model Specification and Core Computational Algorithm

To systematically examine the determinants of elderly farmers' operational decisions, this study employs a binary Logit regression model. The model is specified as follows:

$$P(Y_i=1)=\Lambda(\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\beta_5X_5+\beta_6X_6+\beta_7X_7+\beta_8X_8+\beta_9X_9+\beta_{10}X_{10}+\beta_{11}X_{11}+\varepsilon_i) \quad (1)$$

where $Y_i = 1$ if farmer i chooses decentralized operation; $\Lambda(\cdot)$ is the logistic cumulative distribution function; and parameters are estimated via Maximum Likelihood Estimation (MLE), implemented using Stata/BE 17.0. The algorithm iterates until the change in parameter estimates falls below 10^{-6}, yielding MLE estimates that report Odds Ratios (OR=exp(β)) and robust standard errors for each explanatory variable.

Model Diagnostics and Validation: To ensure model reliability and transparency, we conducted the following diagnostic procedures: (1) Multicollinearity assessment using Variance Inflation Factor (VIF), with VIF > 10 indicating potential collinearity; (2) Goodness-of-fit evaluation using the Likelihood Ratio Chi-square test, McFadden Pseudo R^2, and Percent Correctly Predicted (PCP); (3) Robust standard errors estimated via the Huber-White sandwich estimator to address potential heteroskedasticity; (4) Bootstrap-based resampling with 1,000 iterations to obtain bias-corrected confidence intervals; (5) Leave-one-out cross-validation (LOOCV) to evaluate out-of-sample predictive accuracy and detect potential overfitting. These procedures, routinely employed in both econometric and machine learning practices, collectively assess model stability and generalizability.

Regarding Computational Extensions: While our current sample size (N = 398) is optimally suited to the parsimonious Logit specification—which prevents overfitting and preserves statistical efficiency for causal interpretation—the analytical framework is designed to accommodate more advanced computational models when data conditions permit. Specifically, the same feature set could serve as input vectors for tree-based ensemble algorithms (e.g., Random Forest, XGBoost) or neural network architectures when panel or remotely sensed data become available. We explicitly position our Logit-MLE results as the core empirical findings, with bootstrap and LOOCV procedures serving as robustness checks rather than alternative models. This hybrid strategy ensures that our inferences remain economically interpretable for policy audiences while incorporating computational rigor for validation.

4 Empirical Results and Analysis

4.1 Descriptive Statistics

Of the 1,668 mu (approx. 104 hectares) of cultivated land in the sample area, 74.3% is under large-scale operations and 25.7% is managed by elderly farmers in fragmented plots. These scattered plots exhibit distinct marginal characteristics: 63.7% have slopes exceeding 15°, while 57.3% are smaller than 0.5 mu (0.033 ha). Notably, only 41.2% of elderly farmers are proficient in using smartphones for agricultural information

access, compared to over 90% for large-scale operators. While drone-based crop protection services are accessible at the village level, they are primarily deployed on contiguous farmland, making coverage of elderly farmers' scattered plots prohibitively expensive. This uneven distribution of digital services underscores the digital divide as a key structural constraint.

4.2 Logit Model Regression Results and Algorithm Validation

Goodness-of-Fit and Diagnostic Tests: We first conduct overall goodness-of-fit tests for the binary Logit model using three complementary criteria: the Likelihood Ratio Chi-square(LR chi2(10) = 92.18, p<0.001). McFadden Pseudo R^2 (0.302), and Percent Correctly Predicted (82.4%), all indicating satisfactory model fit for cross-sectional micro-data. All VIF values are below 2.5, confirming no severe multicollinearity. The bootstrap-based standard errors (1,000 iterations) were consistent with the robust standard errors reported below, and the LOOCV accuracy of 81.7% closely aligns with the in-sample PCP of 82.4%, indicating that the model is not overfitted and exhibits satisfactory out-of-sample generalizability.) These diagnostic metrics collectively confirm that the model provides a reliable statistical foundation for the parameter estimates and result interpretations presented below.

Logistic regression was performed using Stata 17.0. Table 1 reports the odds ratios (OR), marginal effects, and z-statistics.

Table 1. Logit model results for decentralized farming decisions (N=398).

variable classes	Variable name	Odds Ration (OR)	Z-Statistics	Marginal Effect (dy/dx)
natural talent	average slope (X_1)	1.32**	2.56	0.051**
	average parcel size(X_2)	0.45***	-3.89	-0.112***
	Distance from main road(X_3)	1.18*	1.96	0.038*
constrain numeric	Digital skills(X_4)	0.68**	-2.01	-0.069**
	digital service accessibility(X_5)	0.72*	-1.87	-0.065*
family endowment	Age(X_6)	1.05*	1.85	0.008*
	health condition(X_7)	0.77**	-2.45	-0.048**
	nonfarm income share(X_8)	0.21***	-5.12	-0.143***
subjective preference	land attachment(X_9)	2.14***	4.32	0.127***
	agricultural identity(X_{10})	1.67***	3.45	0.096***
controlled variable	village turnover rate(X_{11})	0.98	-0.35	-0.003
Model diagnosis	Pseudo R^2 = 0.302; LR chi2(10) = 92.18***; VIF < 2.5 for all variables			

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors are reported.

H1 is strongly supported: Natural constraints significantly influence stay decisions. A one-unit increase in slope raises the probability of staying by 5.1 percentage points, while a 0.1-mu increase in plot size reduces it by 11.2 percentage points. Digital

constraints are equally critical: a one-level increase in digital skills reduces the probability of staying by 6.9 percentage points, and service availability reduces it by 6.5 percentage points. This confirms that the digital divide and natural conditions jointly "lock" elderly farmers into decentralized farming practices—a finding directly relevant to the conference's focus on digital inclusion and people-centric system design.

H2 is fully supported: Household economic vulnerability (low non-farm income) serves as a strong push factor—a 10% increase in non-farm income share lowers the probability of staying by 14.3 percentage points—while subjective emotions (land attachment and farming identity) act as significant pull factors. Both effects are independent and statistically significant, highlighting the dual nature of the decision process.

Village transfer rate is not significant: This indicates that elderly farmers' decisions are not sensitive to the community-level transformation trend but depend more on household-specific constraints and preferences.

5 Quantitative Assessment of Functiongal Complementarity

Having identified the determinants of staying, we now quantify the systemic value of elderly agriculture—a critical step for validating H3 and demonstrating its relevance to sustainable development and resilient system design.

5.1 Social Gap-Filling: Livelihood Security and Governance Cost Savings

The food self-sufficiency rate among decentralized farming households reached 68.7%, generating an average annual cash expenditure saving of approximately 4,326 yuan—equivalent to 49.4% of their average annual agricultural cash income (8,764 yuan). Psychological well-being measurements revealed that elderly individuals engaged in regular farming exhibited significantly higher life satisfaction (4.12 vs. 3.47 on a 5-point scale, $p<0.01$).

Simulation analysis indicates that forced full transfer would cause livelihood difficulties for 21.6% of elderly farmers, requiring an estimated annual additional relief expenditure of ~178,000 yuan from the village collective. Elderly agriculture thus serves as a low-cost "land-based social stability" mechanism, directly contributing to sustainable community governance.

5.2 Economic-Ecological Gap-Filling: Output and Ecosystem Services

The average grain yield per mu on fragmented plots was 384 kg, lower than the 458 kg on large-scale farms. However, these plots—429 mu of marginal land that would otherwise be left fallow—contributed a substantial 16.3% to the region's total grain output. This represents a significant contribution to regional food security that would be lost under full consolidation.

Ecosystem service valuation reveals that 34.2% of decentralized households practice integrated crop-livestock systems. Soil testing showed their land had 18.7% higher

organic matter content than monoculture plots, indicating superior soil health. Crop species diversity reached 17 varieties, compared to just 3 (mainly rice and vegetables) in large-scale farming, enhancing agrobiodiversity and ecosystem resilience (Wang, 2022). These findings provide robust support for H3 and demonstrate the relevance of elderly agriculture to environmental monitoring and sustainable resource management—key concerns of the conference's green computing track.

6 Policy Implications and Conclusion

6.1 Potential Risks and Challenges

While the current equilibrium is stable, it remains dynamic and fragile, facing three major risks: (1) Intensified intergenerational digital divide—with current elderly operators averaging 68.7 years old, this trajectory may shrink if subsequent generations lack digital integration pathways; (2) Technological lock-in and exclusion—mainstream digital agriculture R&D focuses on large-scale scenarios, potentially marginalizing smallholder needs (a concern for responsible AI); (3) Policy incentive misalignment—one-sided subsidies for smart equipment and encouragement of large-scale transfers may disrupt existing complementarity and accelerate social exclusion.

6.2 Policy Implications: Building a Digital Inclusive Agricultural Service System

Policy should abandon the "substitution" mindset and pivot toward building an inclusive system that fosters symbiosis between the two tracks—a practical instantiation of people-centric smart systems and digital inclusion. Specific recommendations include:

(1) Implementation of "Digital Literacy" and Adapted Technology Programs: Provide targeted training for elderly farmers on basic smartphone and simple APP applications. Encourage the development of "light-intelligent," low-cost, easy-to-operate agricultural tools suitable for small plots (Shen et al, 2025)—an application of human-computer interaction principles for marginalized user groups.

(2) Innovate a "Digital + Socialized" Service Model: Develop village-level cooperative-based "digital trusteeship" services, where younger technicians operate smart devices to provide elderly farmers with on-demand, pay-as-you-go precision farming services, effectively bridging the digital divide.

(3) Design "Digital Inclusion" Subsidies and Insurance: Include digital service procurement for small farmers in subsidy scopes. Develop green digital insurance or ecological compensation products linked to marginal land use, aligning economic incentives with sustainable computing goals.

(4) Incorporate Multi-dimensional Values into Digital Village Evaluation: Shift the assessment framework from focusing solely on technology adoption rates and economic efficiency to include social inclusivity and ecological sustainability indicators—recognizing and supporting the multifunctional value of elderly agriculture as a component of resilient socio-technical systems

7 Conclusion

By introducing digital technology constraints as a key variable, this study expands the theoretical and empirical understanding of the coexistence of "elderly agriculture" during agricultural scale transition. The findings demonstrate that, within an unevenly developing digital economy—a context highly relevant to the conference's exploration of intelligent systems and digital transformation—the co-existence of elderly agriculture and large-scale smart agriculture represents a rational equilibrium rather than a transitional anomaly. Elderly agriculture, through its "functional complementarity" in social security, complex land management, and ecological resilience, constitutes a vital source of resilience for China's mountainous agricultural systems.

The study makes three major contributions: (1) empirically demonstrating that the digital divide is a key factor shaping contemporary agricultural management patterns; (2) quantifying the combined effects of natural, digital, household, and emotional factors on elderly farmers' decision-making through rigorous econometric methods; and (3) systematically evaluating the multifaceted value of elderly agriculture in the digital era, thereby challenging the dominant substitution narrative.

Future research should longitudinally track how digital technology diffusion dynamically alters this equilibrium(Zhang et al., 2024) and conduct in-depth evaluations of "digital inclusion policy" interventions. Computationally, subsequent work can employ recurrent neural networks (RNNs) or Transformer-based sequence models to capture temporal dependencies in farmer decision trajectories, and leverage reinforcement learning (RL) frameworks to simulate adaptive policy optimization under alternative intervention scenarios. The construction of digital twin models at the village level---integrating agent-based simulation with real-time sensor data streams---would further enable predictive and prescriptive analytics for equitable agricultural digitalization. These computational extensions, grounded in the conceptual and empirical framework developed here, align closely with the conference's vision of intelligent systems and sustainable computing for human-centric development.

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