Digitalization for Loss Reduction and Quality Improvement: The Mitigation Effect of Agricultural Product Supply Chain Digitalization on Farmers' Poverty Vulnerability Under Natural Disasters

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ABSTRACT

Focusing on the core issue of how digital transformation of agricultural product supply chains mitigates farmers' poverty vulnerability under natural disasters, this study establishes an integrated analytical framework of "digital economy–supply chain transformation–disaster shock–poverty vulnerability mitigation" against the background of China's agricultural transition from yield-oriented to quality-oriented development. Using cross-level integrated data consisting of CFPS micro-farmer panel data and county-level macro digitalization data from 2010 to 2018, this paper employs econometric methods including FGLS, Probit, and Bootstrap mediation effect tests to systematically explore the risk-resistant value of supply chain digitalization across the full chain: pre-disaster early warning, mid-disaster response, and post-disaster recovery. The results show that agricultural product supply chain digitalization (three dimensions: production, circulation, and supervision) significantly mitigates farmers' poverty vulnerability under natural disasters, with circulation digitalization having the strongest poverty-reduction effect. Income optimization, transportation improvement, and health security constitute the three core mediating channels with significant multi-path linkage effects. The mitigation effect exhibits significant heterogeneity across eastern, central, and western regions and among farmers with different operation types. This study enriches the interdisciplinary research of digital economy and rural poverty, and provides empirical support and practical pathways for the government to implement targeted disaster-resistance and poverty-reduction policies, enterprises to optimize supply chain digitalization, and farmers to improve risk coping capacity.

Keywords: Agricultural Product Supply Chain Digitalization; Poverty Vulnerability; Natural Disasters; Mediation Effect; Rural Revitalization.

1. INTRODUCTION

1.1 Research Background

The agricultural product supply chain is a core carrier of the basic livelihood industry. Its efficiency and resilience directly determine agricultural efficiency, farmers' income growth potential, and consumer experience. China's agriculture is at a critical transitional stage: rising consumer demand for quality, safety, freshness, and traceability forces the supply chain to upgrade toward standardization and digitalization. Meanwhile, China suffers from frequent natural disasters, which cause unsalable products, production capacity damage, and income fluctuation—major risks pushing farmers back into poverty [4]. Traditional agricultural supply chains suffer from weak logistics, information asymmetry, and insufficient risk resilience. High post-harvest losses and mismatched production and marketing have long persisted, making it difficult to hedge disaster-induced poverty vulnerability [3][8].

In this context, digitalization has become a core tool to connect supply chain segments, improve coordination efficiency, and strengthen resilience. [1] It is critical for achieving both quality upgrading and efficiency improvement of agricultural products. From intelligent planting and breeding at the production end, smart cold chain and online sales at the circulation end, to blockchain traceability at the supervision end, digital technologies are reshaping the agricultural supply chain system [2]. However, its mechanism and actual effect in disaster resistance and poverty reduction remain under-explored, requiring systematic investigation into its internal relationship and action boundaries [11] [12].

1.2 Research Significance

1.2.1 Theoretical Significance

First, it fills a research gap by linking agricultural supply chain digitalization with disaster and poverty reduction for the first time in an integrated framework, enriching interdisciplinary research on digital economy and rural poverty. Second, it refines core concepts by decomposing supply chain digitalization into production, circulation, and supervision dimensions, systematically analyzing their differentiated functions and improving the theoretical system. Third, it innovates methodology by using cross-level integrated micro-farmer and macro-county data combined with multi-dimensional econometric models, overcoming limitations of single-dimensional data and providing a reference for similar studies.

1.2.2 Practical Significance

First, it supports precise disaster and poverty-reduction policies by identifying key pathways and boundaries of digitalization, helping the government design region-differentiated measures. Second, it empowers supply chain actors with practical digital transformation directions for enterprises and accessible guidelines for farmers. Third, it advances rural revitalization by promoting government-enterprise-farmer coordination, consolidating poverty alleviation achievements, and integrating digital rural construction with agricultural modernization.

1.3 Literature Review

Existing studies focus on three streams. First, agricultural supply chain digitalization: foreign research started early, emphasizing blockchain, IoT, and supply chain coordination, but insufficiently addresses disaster scenarios [11][12][13]. Domestic research aligns with digital rural strategies, studying transformation paths, efficiency, and supervision, but often treats digitalization as a single dimension and neglects poverty-reduction linkages.

Second, natural disasters and farmers' poverty vulnerability: foreign studies form a complete system of measurement, mechanisms, and strategies [8][9][10]. Domestic research focuses on vulnerability identification and return-to-poverty risks under poverty alleviation and rural revitalization, but mostly from policy or individual behavioral perspectives, ignoring supply chain transformation and limiting mediation channels to income [1][2][3][4][5].

Third, cross-research: few studies directly examine the three-way linkage. Relevant works are scattered in digital economy poverty reduction and supply chain resilience, mostly general macro-analyses without supply-chain focus or disaster scenario consideration [6][7].

Overall, existing research has three major limitations: isolated perspectives, single-dimensional definitions, and simplified methods with weak treatment of endogeneity and heterogeneity. This study addresses these gaps.

1.4 Research Innovations

First, perspective innovation: an integrated framework linking digital economy, supply chain transformation, disaster shock, and poverty vulnerability mitigation, bridging previously separated fields. Second, dimensional innovation: decomposing supply chain digitalization into three dimensions and identifying three interactive mediation channels. Third, methodological innovation: cross-level data and comprehensive econometric tools to handle endogeneity and heterogeneity, improving reliability.

1.5 Research Content and Structure

The paper comprises six parts: introduction; theoretical basis and hypotheses; research design; empirical results and analysis; conclusions and policy suggestions; limitations and prospects.

2. THEORETICAL BASIS AND HYPOTHESES

2.1 Core Theoretical Foundations

2.1.1 Supply Chain Coordination Theory

Supply chain coordination theory, which aims to integrate resources, share information, and align decisions across supply chain links to maximize overall benefits and address issues like the bullwhip effect caused by decentralized, self-interested decision-making, is especially critical in agricultural product supply chains—where perishability, seasonality, and volatile supply and demand make poor coordination lead to mismatched production and marketing, high losses, unstable prices,

and harm to both farmers and consumers—and its importance is amplified during natural disasters, where digitalization enables real-time information sharing and deep coordination across production, circulation, and supervision to facilitate pre-disaster early warning, in-disaster resource coordination, and post-disaster recovery, thereby alleviating farmers' poverty vulnerability, while disaster management theory provides a complementary framework covering the entire process of disaster prevention, emergency response, and recovery[13].

2.1.2 Disaster Management TheoryDisaster management

Disaster management theory is a comprehensive theoretical system based on full-cycle risk management to curb disasters and cut economic losses [8][10].It covers the full disaster cycle and splits response work into pre-disaster prevention, mid-disaster emergency response and post-disaster recovery with distinct tasks for each stage. Conventional disaster governance overemphasizes post-disaster rescue while ignoring proactive pre-disaster risk prevention. The absence of sound early warning mechanisms in developing countries thus results in severe economic losses for farmers hit by disasters [8].

Supply chain digitalization enables active full-cycle risk management, fundamentally reducing the risk of returning to poverty [1]. In the pre-disaster stage, digital technologies improve early warning accuracy and timeliness through big data analysis, allowing farmers to take preventive measures. In the during-disaster stage, digital platforms realize real-time disaster monitoring and resource coordination, and e-commerce platforms open green channels for agricultural products to reduce unsalable losses. In the post-disaster stage, digital platforms provide production support and digital financial services to help farmers resume production quickly [7][13]. Thus, disaster management theory provides an important theoretical basis for analyzing the role of supply chain digitalization in the entire disaster response process

2.1.3 Sustainable Livelihoods Theory

Farmers' livelihood capital (natural, physical, financial, human, social) determines risk resilience and poverty vulnerability [4]. Supply chain digitalization improves multiple forms of capital, strengthening farmers' ability to withstand natural disasters.

2.2 Research Hypotheses

2.2.1 Baseline Hypotheses

Supply chain digitalization enhances resilience through three dimensions, stabilizes income, and mitigates poverty vulnerability.

H1: Agricultural product supply chain digitalization significantly mitigates farmers' poverty vulnerability under natural disasters.

H1a: Production digitalization significantly mitigates poverty vulnerability.

H1b: Circulation digitalization significantly mitigates poverty vulnerability (most strongly).

H1c: Supervision digitalization significantly mitigates poverty vulnerability.

2.2.2 Mediation Hypotheses

H2: Income optimization mediates the relationship between supply chain digitalization and poverty vulnerability.

H3: Transportation improvement mediates the relationship.

H4: Health security mediates the relationship.

2.2.3 Heterogeneity Hypotheses

H5: The mitigation effect is regionally heterogeneous, stronger in central and western disaster-prone areas.

H6: The effect is heterogeneous across farmer types, stronger for diversified-operation farmers.

3. RESEARCH DESIGN

3.1 Data Sources

This study uses a cross-level matched dataset:

Microdata: China Family Panel Studies (CFPS) 2010, 2014, 2018; 12,786 valid rural household samples after screening.

Macrodata: China County Statistical Yearbook, China Agricultural Statistical Yearbook, and Ministry of Agriculture digitalization monitoring data.

Data are matched by county code to form a farmer-county-year panel.

3.2 Variable Definition

3.2.1 Dependent Variable: Poverty Vulnerability (Vulner)

Measured by Vulnerability as Expected Poverty (VEP) [9]. Equal to 1 if the future poverty probability > 0.5; otherwise 0. Continuous values are used for robustness checks.

3.2.2 Core Independent Variable: Supply Chain Digitalization (Dig)

County-level composite index via entropy method, decomposed into:

Dig1 (production): intelligent facilities, agricultural IoT, water-fertilizer integration.

Dig2 (circulation): online retail share, rural logistics stations, smart cold chain.

Dig3 (supervision): blockchain traceability, digital quality monitoring.

3.2.3 Mediating Variables

Income: log of per capita household operating income.

Traffic: rural road density and logistics accessibility.

Health: healthcare expenditure ratio and self-rated health.

3.2.4 Control Variables

Individual: age, gender, education, health;

Household: size, labor ratio, operation type, assets, disaster status;

County: per capita GDP, primary industry share, fiscal agricultural support, infrastructure.

3.3 Model Specification

3.3.1 Baseline Regression Model

Probit model for binary dependent variable; FGLS for robustness.

$$Vulner_{it} = \alpha_0 + \alpha_1 Dig_{ct} + \sum \alpha_k Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

3.3.2 Mediation Effect Model

Following Wen et al. with Bootstrap:

$$M_{it} = \beta_0 + \beta_1 Dig_{ct} + \sum \beta_k Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$Vulner_{it} = \gamma_0 + \gamma_1 Dig_{ct} + \gamma_2 M_{it} + \sum \gamma_k Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

3.3.3 Heterogeneity Model

This study conducts heterogeneity analysis through group regression. The samples are grouped by the eastern, central and western regions, and farmer operation types (single operation / diversified operation), and baseline regression is carried out respectively to compare the differences in coefficients between groups.

The regional grouping is based on the division standard of the National Bureau of Statistics. The eastern region includes 11 provinces, municipalities, and autonomous regions: Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The central region includes 8 provinces: Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan. The western region includes 12 provinces, municipalities, and autonomous regions: Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

The farmer operation type grouping is based on the definition in the variable definition section. Single-operation farmers are those who engage in only one type of agricultural production and operation activity; diversified-operation farmers are those who engage in two or more types of agricultural production and operation activities.

3.4 Endogeneity

Instrumental variable: average digitalization level of other counties in the same province, satisfying relevance and exogeneity.

4. EMPIRICAL RESULTS AND ANALYSIS

4.1 Descriptive Statistics

Table 1 reports the descriptive statistics of the main variables.

Table 1. Descriptive Statistics of Main Variables.

Variable Name	Observations	Mean	Standard Deviation	Minimum	Maximum
Poverty Vulnerability (Vulner)	12786	0.312	0.463	0	1
Supply Chain Digitalization (Dig)	12786	0.247	0.158	0.032	0.876
Production Digitalization (Dig1)	12786	0.289	0.174	0.041	0.892
Circulation Digitalization (Dig2)	12786	0.198	0.162	0.025	0.854
Supervision Digitalization (Dig3)	12786	0.254	0.181	0.036	0.901
Income Optimization (Income)	12786	9.247	0.876	6.125	12.458
Transportation Improvement (Traffic)	12786	0.325	0.194	0.042	0.913
Health Protection (Health)	12786	0.412	0.207	0.051	0.924
Household Head’s Age (Age)	12786	52.34	12.56	18	92
Household Head’s Gender (Gender)	12786	0.587	0.492	0	1
Household Head’s Years of Education (Edu)	12786	7.23	3.45	0	16

Table 1. (continued) Descriptive Statistics of Main Variables.

Variable Name	Observations	Mean	Standard Deviation	Minimum	Maximum
Household Head's Health Status (Health_head)	12786	3.21	0.98	1	5
Household Population Size (Size)	12786	4.32	1.56	1	12
Labor Force Ratio (Labor)	12786	0.623	0.214	0	1
Operation Type (Type)	12786	0.425	0.494	0	1
Total Assets (Assets)	12786	10.56	1.23	6.34	15.78
Whether affected by disasters (Disaster)	12786	0.347	0.476	0	1
Per capita GDP (PGDP)	12786	10.23	0.78	8.12	13.45
Proportion of primary industry (Indus)	12786	0.234	0.125	0.056	0.678
Financial support for agriculture (Finance)	12786	0.125	0.067	0.023	0.345
Infrastructure level (Infra)	12786	0.678	0.213	0.123	0.987

From Table 1, we can see that:

First, the average value of farmers' poverty vulnerability in the sample is 0.312, that is, 31.2% of farmers are at risk of falling into poverty in the future. This shows that although China has achieved a comprehensive victory in poverty alleviation, the problem of poverty vulnerability still exists, and the task of consolidating the achievements of poverty alleviation is still arduous.

Second, the average value of the comprehensive index of agricultural product supply chain digitalization is 0.247, with a standard deviation of 0.158. The minimum value is 0.032 and the maximum value is 0.876, indicating that there is a large difference in digitalization level among counties in China. Substantial inter-county heterogeneity exists in digitalization levels.", while that of some counties is still very low.

Third, among the three sub-dimensions, the average value of circulation digitalization is the lowest (0.198), which is lower than production digitalization (0.289) and supervision digitalization (0.254). This indicates that circulation digitalization is the short board of current supply chain transformation, and it is also the key link that needs to be strengthened in the future.

Fourth, the distribution of control variables is in line with the actual situation. For example, the average age of household heads is 52.34 years old, the average years of education is 7.23 years, and the average household population size is 4.32 people. 34.7% of the households have been affected by natural disasters in the past year, which indicates that natural disasters are a common risk faced by farmers.

In order to further understand the differences in poverty vulnerability and supply chain digitalization among different groups, this study also conducts descriptive statistics by region and farmer operation type. The results show that the average poverty vulnerability in the western region is 0.387, which is higher than that in the central region (0.305) and the eastern region (0.246). The average supply chain digitalization level in the eastern region is 0.325, which is higher than that in the central region (0.236) and the western region (0.178). The average poverty vulnerability of single-operation farmers is 0.356, which is higher than that of diversified-operation farmers (0.268). The average supply chain digitalization level of diversified-operation farmers is 0.273, which is higher than that of single-operation farmers (0.229). These results preliminarily indicate that there are significant differences in poverty vulnerability and supply chain digitalization among different regions and different types of farmers.

4.2 Baseline Regression Results

Supply chain digitalization is significantly negative at the 1% level (–0.113): one-unit increase reduces vulnerability probability by 11.3 percentage points. All three sub-dimensions are significant. Dig2 (–0.142) has the strongest effect, consistent with reality: circulation digitalization directly solves unsalable products and losses.

4.3 Mediation Effect Results

Bootstrap confirms all three mediators are significant. Income optimization accounts for 35.2% (largest), followed by transportation (28.7%) and health (21.4%), with significant joint effects.

4.4 Heterogeneity Analysis

4.4.1 Regional Heterogeneity

Coefficient absolute values: west (–0.174) > central (–0.105) > east (–0.068). Effect is stronger in less developed, disaster-prone central and western areas.

4.4.2 Farmer-Type Heterogeneity

Diversified farmers (–0.135) benefit more than single-operation farmers (–0.082), as diversified products better match online channels.

4.5 Robustness Checks

Four methods confirm robustness: replacing dependent variable, Logit instead of Probit, 1%–99% winsorization, and instrumental variable estimation. Core results hold.

5. CONCLUSIONS AND POLICY IMPLICATIONS

5.1 Main Conclusions

1. Supply chain digitalization significantly mitigates disaster-induced poverty vulnerability; circulation digitalization is most effective.
2. Income optimization, transportation improvement, and health security are key mediating channels.
3. Effects are stronger in central/western regions and for diversified-operation farmers.

5.2 Policy Suggestions

5.2.1 Government: Top-Level Design and Infrastructure Support

Implement differentiated policies: strengthen smart cold chain, logistics, and digital platforms in central/western regions; build full-chain digital models in eastern regions. Establish unified digital standards and county-level disaster-risk early warning systems.

5.2.2 Enterprises: Market Leadership and Technology Application

Circulation and logistics firms expand smart cold chain and online matching. Agri-tech firms provide low-cost intelligent equipment and training. Platforms improve digital supervision, branding, supply chain finance, and skill training.

5.2.3 Farmers: Capacity Building and Participation

Learn digital and e-commerce skills, adopt diversified management. Join cooperatives to access digital supply chains, share logistics and branding resources, and enhance bargaining power and resilience.

5.3 Limitations and Future Research

Limitations: data up to 2018; focus only on natural disasters; no analysis of synergy with agricultural insurance or relief. Future research can update data, expand risk scenarios, and explore multi-stakeholder coordination mechanisms.

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