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The Influence of Livelihood Capital on the Continuous Adoption Willingness of Climate Smart Agricultural Technology by New Agricultural Operators —— Taking Traditional Agricultural Areas in Southern China as an Example

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Abstract: Climate-smart agriculture (CSA) technology holds tremendous potential in minimizing climate risks, carbon sequestration, ensuring food security, and achieving sustainable intensification goals. Adopting CSA technology has become essential for realizing sustainable agricultural systems. This study employs the Heckman two-stage model to analyze how livelihood capital influences the sustained adoption of CSA technology, utilizing micro-level survey data from 221 new agricultural business entities in Wuhu City, Anhui Province. The results demonstrate significant positive correlations between human capital, physical capital, social capital, financial capital, natural capital, and digital capital among these entities and their willingness to adopt CSA technologies. Therefore, it is crucial to enhance public education, technical training, and incentive policies, leverage digital technologies to empower agricultural development, and stimulate the vitality of new agricultural business entities. These measures will facilitate the continuous diffusion of CSA technology, driving China's green agricultural transformation and high-quality development.

1. Introduction

In recent years, global climate issues have intensified significantly, with agricultural production facing growing instability and vulnerability [1]. The relationship between agriculture and climate change has garnered substantial academic attention. As one of the most climate-sensitive industries, agriculture is severely impacted by extreme weather events like droughts and floods caused by climate change [2]. Moreover, agricultural activities themselves are major contributors to climate change, with greenhouse gas emissions from farming continuing to rise across nations.

To address climate change, nations and organizations have made relentless efforts. In 2014, the Food and Agriculture Organization of the United Nations (FAO) introduced the Guiding Principles for Climate-Smart Agriculture (CSA). As a foundational and driving force for both adaptation and mitigation strategies against climate change's adverse impacts, CSA serves as a cornerstone for achieving sustainable intensification (SI) goals [3]. This agricultural approach significantly enhances crop yields and quality while optimizing resource efficiency, reducing waste and losses [4]. The widespread adoption of CSA technologies holds crucial significance for agricultural modernization, compensating for traditional farming limitations and boosting productivity. Extensive research by domestic and international scholars has identified key factors influencing CSA adoption willingness, including farmers' personal characteristics such as gender [5], education level, and non-agricultural employment status [6]. Additionally, household endowments like labor and economic capital can facilitate CSA implementation [7-8]. Political, social, and environmental factors also impact adoption decisions [9-11]. Although CSA contributes to sustainable development goals, previous studies indicate slow and limited farmer adoption rates—critical prerequisites for successful CSA implementation and agricultural system sustainability [12]. In the context of long-term climate adaptation, sustained CSA use proves more vital than initial adoption.

As primary demanders of agricultural technologies, farmers' adoption behaviors are shaped by both their inherent conditions and external environmental factors [13]. Compared to traditional farmers, new agricultural business entities—those actively supported and cultivated by the state—operate on a larger scale with stronger resource endowments, serving as the core driving force for sustainable adoption of CSA (Conservation and Sustainable Agriculture). Therefore, investigating the factors influencing the continuous adoption of CSA technologies among these new agricultural business entities holds significant practical importance. The cultivation of "new-quality productive forces" has become pivotal for China's agricultural transformation. Digital technologies have inevitably permeated all sectors of the economy and society, making their application in agricultural development crucial. The sustainable livelihood framework has been extensively applied in farmer behavior studies [14]. Incorporating various forms of capital from farming households into this framework helps reveal objective patterns of their sustained adoption of CSA technologies. However, existing research on sustainable livelihood frameworks predominantly focuses on five categories—human capital, physical capital, social capital, natural capital, and financial capital—while neglecting digital capital analysis [15].

This study employs a sustainable livelihood analysis framework and continuous use model, utilizing 221 household micro-research data from Wuhu City, Anhui Province. Through the Heckman two-stage model, we analyze how livelihood capital influences farmers 'willingness to sustainably adopt CSA technologies. The research aims to enhance farmers' commitment to adopting CSA technologies, provide policy recommendations for their sustained promotion, and support China's national carbon peaking and carbon neutrality goals while advancing agricultural green development and high-quality growth.

2. Theoretical Analysis and Research Hypothesis

2.1 Theoretical Analysis

The Sustainable Livelihood Analysis Framework, developed by the UK's Department for International Development (DFID), serves as a tool to evaluate and promote sustainable development. It integrates multiple factors including social, economic, and environmental dimensions to comprehensively understand and assess sustainability [16]. Under this framework, development actors consider their livelihood capital conditions when selecting livelihood strategies, aiming to maximize the benefits of their livelihood capital. Existing research categorizes farmers' livelihood capital into five types: human capital, natural capital, social capital, physical capital, and financial capital. With the advancement of digital information technology, the role of digital capital has become increasingly significant [17-21]. This paper proposes adding digital capital to the framework.

The continuous use model posits that farmers' sustained adoption of technology represents an extension and continuation of their initial adoption behaviour [22]. Farmers' adoption decisions regarding CSA technology involve two phases: The first phase determines whether farmers choose to adopt CSA technology, while the second phase examines whether adopted farmers decide to maintain their adoption commitment.

2.2 Research Hypotheses

Human capital encompasses farmers' health status, educational attainment, technical competencies, and other endowments that can be converted into income sources through productivity. Human capital proves particularly crucial in agricultural activities requiring higher labor resource endowments and specialized knowledge.

Physical capital primarily reflects the fixed physical assets that farmers rely on for production, serving as the material foundation for agricultural activities and adoption of new technologies. These assets enhance production efficiency and facilitate resource acquisition, thereby supporting technological adoption.

Natural capital represents the natural resource endowment of farmers' agricultural production over extended periods. Agricultural development largely depends on natural capital, particularly land – the primary material for farming and a crucial foundation for farmer livelihoods.

Financial capital refers to the financial assets that farmers possess in their production and daily life, including both accessible funds and disposable funds. For rural households, household income constitutes the most critical form of financial capital.

Social capital refers to the social norms and bond structures that tightly connect social entities, encompassing social relationships, cooperation, trust, norms, and institutional constraints. It primarily reflects farmers' ability to mobilize all social resources, including interpersonal networks, in achieving their objectives.

Digital capital refers to the digital technology-related resources and capabilities that farmers possess in agricultural production and management processes. These assets help farmers enhance efficiency, reduce costs, and increase profits. Through specialized agricultural apps, websites, or official accounts, farmers can access real-time information on agricultural policies, market trends, and weather forecasts, enabling them to make more informed decisions.

3. Data Sources and Research Design

3.1 Introduction of the Study Area

This study focuses on Wuhu City in Anhui Province, with three key dimensions examined: 1. Geographical Environment: Situated in the Yangtze River Delta Plain, Wuhu enjoys a subtropical monsoon climate with abundant rainfall ideal for agriculture. This unique geographical advantage has established it as one of China's major rice and oilseed production bases, earning the city the title "Top Rice Market in Southern Jiangnan". 2. Policy Framework: The city has pioneered digital management systems for "Wuhu Rice" cultivation through soil-climate modeling, implementing smart agriculture practices across the entire rice-growing process. Its flagship "Smart Wuhu Rice Demonstration Project (128)" features over 100 hundred-mu plots, 20 thousand-mu fields, and 8 ten-thousand-mu demonstration zones, covering 280,000 mu of smart rice cultivation. 3. CSA Practices: Through digital rural pilot projects and the Rice Industry Internet, Wuhu is advancing smart agriculture.

3.2 Data Sources

The data used in this study were collected through a research project conducted by our team between June and July 2023 across four districts of Wuhu City, Anhui Province: Yijiang District, Jinghu District, Jiujiang District, and Nanling County. The survey employed a two-stage sampling method. First, representative towns with homogeneous characteristics were selected from each district as study samples. Subsequently, 30-60 new agricultural business entities were chosen for investigation based on their town sizes. Researchers conducted one-on-one interviews with each selected entity and completed relevant questionnaires. A total of 236 questionnaires were distributed, with 221 valid responses obtained after excluding irrelevant and invalid submissions, achieving a 94% response rate.

3.3 Variable Settings

This study selects two dependent variables: adoption behavior and sustained adoption intention. Adoption behavior refers to whether farmers adopt integrated water-fertilizer irrigation measures (including ecological farming practices, IoT cloud computing technologies, and big data applications). Sustained adoption intention assesses farmers' willingness to continue using these technologies after initial adoption. The adoption behavior is measured through the question "Have you adopted integrated water-fertilizer irrigation measures (ecological farming practices, IoT cloud computing technologies, and big data applications) in 2023?" with a value of 1 for adoption and 0 otherwise. Sustained adoption intention is evaluated through the question "Are you willing to continue adopting integrated water-fertilizer irrigation measures (ecological farming practices, IoT cloud computing technologies, and big data applications)? If yes, assign a value of 1; otherwise, 0".

According to the research design, this study measures six aspects of livelihood capital. In terms of human capital, we measured farmers' educational level and labor force size. For physical capital, we evaluated whether households owned smart agricultural machinery and the accessibility of farmland roads. Regarding natural capital, we measured household contracted land area and cultivated land area. Financial capital was assessed through annual household income and agricultural investment. Social capital was evaluated by participation in large-scale agricultural organizations and family members' experience as village cadres, representing both breadth and depth of social capital. Digital capital was measured by frequent use of specialized agricultural apps, websites, or official accounts, along with knowledge and skills in e-commerce sales processes for agricultural products.

4. Model Construction

The adoption decision of CSA technology among farmers involves two sequential stages: the first stage represents the initial adoption behavior, while the second stage examines farmers' continued willingness to adopt the technology after initial adoption. If farmers fail to adopt CSA technology in the first stage, their sustained adoption intention remains unobservable. Only when farmers have adopted CSA technology can their continued adoption intention be measured. Consequently, the sample selection bias issue arises regarding farmers' sustained adoption intention for CSA technology, necessitating analysis through the Heckman sample selection model. The Heckman sample selection model constructed in this paper is defined as:

$$y_{1i}^{*} = \alpha x_{1i} + \mu_{1i} \tag{1}$$

$$y_{1i} = \begin{cases} 1, & \text{if } y_{1i}^{*} > 0 \\ 0, & \text{if } y_{1i}^{*} \le 0 \end{cases}$$

$$y_{2i}^{*} = \beta x_{2i} + \mu_{2i} \tag{2}$$
$$y_{2i} = \begin{cases} c, & \text{if } y_{1i} = 1 \\ 0, & \text{if } y_{1i} = 0 \end{cases}$$

Equation (1) represents the selection equation, while Equation (2) denotes the outcome equation. Here, $y_{1i}$is the latent variable, and $y_{1i}$and y_{2i} represent two dependent variables: y_{1i} indicating farmers' adoption behavior and y_{2i} representing their sustained adoption intention. The observation of y_{2i} occurs when and only when y_{1i}= 1. c=0,1 denotes farmers' sustained adoption intention, with x_{1i} and x_{2i}representing independent variables influencing both adoption behavior and sustained adoption intention. α and β are the parameters to be estimated, while μ_{1i} and μ_{2i} denote residual terms. i represents the i-th sample farmer.

The conditional expectation of farmers' continuous adoption intention in Equation (2) is:

$$\begin{aligned} E(y_{2i}|y_{2i} = C) &= (y_{2i}|y_{1i}^{*} > 0) \\ &= E(\beta x_{2i} + \mu_{2i}|\alpha x_{1i} + \mu_{1i} > 0) \\ &= E(\beta x_{2i} + \mu_{2i}|\mu_{1i} > -\alpha x_{1i}) \\ &= \beta x_{2i} + E(\mu_{2i}|\mu_{1i} > -\alpha x_{1i}) \\ &= \beta x_{2i} + \rho\sigma\lambda(-\alpha x_{1i}) \end{aligned} \tag{3}$$

In Equation (3), $\lambda(.)$ represents the inverse Mills ratio; ρ denotes the correlation coefficient between y_{1i} and y_{2i} ; and σ stands for standard deviation. To ensure the identifiability of Equation (1) and avoid multicollinearity caused by identical variables in both stages, at least one identifiable variable must be introduced that affects stage one but not stage two. Specifically, the number of independent variables in Equation (1) must exceed that in Equation (2).

5. Results and Analysis

The results are shown in Table 1. Educational level has a significant positive impact on the willingness to continuously adopt water-fertilizer integration. People with higher education usually have advantages in knowledge reserve, risk awareness, innovation acceptance and sustainable development concept, which collectively promote their continuous adoption of water-fertilizer integration technology.

The actual cultivated land area significantly positively influences farmers' willingness to adopt IoT technologies. As the cultivated land expands, farmers gradually achieve economies of scale in agricultural production. New technologies like IoT typically require initial investments. Implementing these technologies on larger plots allows for more efficient allocation of fixed costs, reducing per-unit production expenses and boosting economic returns.

The annual household income over the past year significantly positively correlates with both the willingness to adopt integrated water-fertilizer management and ecological farming practices. Similarly, agricultural investment levels during this period demonstrate strong positive correlations with the adoption of these technologies. Households with higher annual incomes typically possess greater financial resources and capacity to experiment with new technologies.

Participation in large-scale agricultural organizations significantly enhances farmers' willingness to adopt integrated water-fertilizer management and IoT technologies. By joining such entities, farmers gain easier access to practical training and application experience in these technologies.

Regular engagement with specialized agricultural apps, websites, or official accounts significantly boosts farmers' willingness to adopt integrated water and fertilizer management. These platforms provide up-to-date technical insights, success stories, and policy updates, helping farmers better understand integrated water-fertilizer systems while strengthening their trust in new technologies.

Table 1 Estimates of the impact of livelihood capital on farmers' willingness to continue adopting CSA technologies

livelihood capital	Variable	Integrated water and fertilizer irrigation		Ecological cultivation		Internet of Things, cloud computing and big data technologies	
		Adopt	Continued willingness to adopt	Adopt	Continued willingness to adopt	Adopt	Continued willingness to adopt
Explained variable	Degree of education	-0.005 (-0.045)	0.070** (2.865)	-0.006 (-0.058)	0.054 (1.173)	0.111 (0.943)	0.007 (0.261)
	The number of working people in a household with income	0.077 (0.836)	-0.029 (-1.148)	-0.113 (-1.290)	0.006 (0.106)	0.084 (0.873)	-0.048 (-1.746)
Physical capital	Whether it has intelligent agricultural machinery	0.198 (0.658)	0.177* (2.501)	0.165 (0.602)	0.310* (2.331)	0.604 (1.656)	0.156* (2.090)
	The convenience of roads on farmland	-0.131 (-1.482)	0.021 (0.854)	-0.026 (-0.305)	0.015 (0.327)	-0.033 (-0.351)	-0.010 (-0.382)
Natural capital	Family contracted land area	0.047 (1.316)	-0.012 (-1.341)	-0.006 (-0.159)	-0.003 (-0.150)	0.055 (1.377)	-0.004 (-0.416)
	Actual area of cultivated land under family ownership (For logarithms)	0.021 (0.169)	0.339 (1.944)	0.276* (2.323)	0.611 (1.549)	0.312* (2.112)	0.481* (2.408)
Financial capital	The annual income of the family in the past year (For logarithms)	-0.215 (-1.415)	-0.025 (-0.681)	-0.113 (-0.783)	0.166* (2.264)	-0.188 (-1.173)	-0.049 (-1.193)
	Agricultural inputs to the family in the past year (For logarithms)	0.136 (1.014)	0.234* (2.020)	0.356** (2.734)	0.450 (1.620)	0.377* (2.421)	0.280* (2.078)

Social capital	Whether to join a large-scale agricultural organization	-0.260 (-1.313)	0.130* (2.543)	0.143 (0.763)	0.109 (1.103)	-0.051 (-0.236)	0.109* (1.991)
	Whether family members hold positions as village officials go through	0.418 (1.497)	-0.051 (-0.756)	-0.129 (-0.517)	0.113 (0.823)	0.340 (1.154)	-0.109 (-1.552)
Digital capital	Do you often consult agricultural apps, websites or public accounts?	0.711** (3.099)	0.180* (2.431)	0.021 (0.107)	0.094 (0.900)	0.620* (2.528)	0.051 (0.795)
	Whether they have the knowledge and ability of various processes of agricultural products e-commerce sales	-0.382 (-0.698)	0.228 (1.856)	-0.138 (-0.271)	0.324 (1.367)	-0.411 (-0.559)	0.292* (2.318)

Note: *, ** and *** indicate significance at the 10%, 5% and 1% statistical levels, respectively.

6. Conclusions and Policy Recommendations

6.1 Conclusion

Human capital has a significant positive impact on farmers' willingness to continuously adopt CSA. Farmers with higher education levels usually have stronger learning ability and information access channels, which enables them to better understand and apply the long-term benefits brought by CSA model, thus enhancing their willingness to adopt this model.

Physical capital has a significant positive impact on the continuous adoption of CSA by farmers. As a modern agricultural technology tool, UAV can help farmers improve farming efficiency, monitor crop growth and optimize farmland management. This technological advantage makes farmers more willing to continue adopting CSA mode.

Natural capital has a significant positive correlation with farmers' willingness to continuously adopt CSA. Farmers with larger cultivated land area usually have stronger resource integration ability and advantages of large-scale production.

Financial capital has a significant positive impact on farmers' willingness to continuously adopt CSA. Higher household income and sufficient agricultural input not only improve farmers' risk tolerance, but also provide them with more funds to adopt advanced agricultural technologies and management methods, thus encouraging them to continue participating in CSA mode.

Social capital significantly promotes farmers' willingness to adopt CSA. By joining social organizations, farmers can access more resources, technical support and market information, thereby reducing risks and improving production efficiency. This collective collaboration model further enhances their confidence and enthusiasm in participating in CSA.

Digital capital has a significant positive impact on farmers' willingness to continuously adopt CSA. By providing technical support, optimizing information access and management, and improving market participation, digital capital significantly enhances farmers' willingness and ability to adopt climate-smart agricultural practices.

6.2 Policy Recommendations

Based on the above research conclusions, in order to better guide new agricultural business entities to improve their willingness to continuously adopt CSA technology, thereby promoting the diffusion of CSA technology, promoting the high-quality development of agriculture and rural areas, and adding new momentum for agricultural development, this paper puts forward the following policy suggestions: Strengthen publicity, education and technical training to improve the subject's awareness and acceptance.Policy guidance will be given to stimulate the vitality of new agricultural operators and encourage them to join large-scale agricultural organizations.Give full play to the advantages of new agricultural operators in scale operation, resource utilization and financial support.

Through multi-level policy support and resource integration, it can not only promote the continuous practice and innovation of new agricultural operators, but also inject strong impetus into the development of agriculture and rural areas, and finally achieve the goal of agricultural modernization.

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