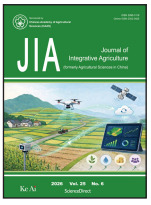
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RESEARCH ARTICLE

Does digital literacy promote climate disaster-adaptive production behaviors among grain-producing smallholders in China?

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Highlights

- The adoption rate of climate disaster-adaptive production behaviors remains low among grain-producing smallholders in Sichuan Province, China.
- Digital literacy contributes to climate disaster-adaptive production behaviors by enhancing farmers' climate disaster risk awareness.
- The positive impact of digital literacy on climate disaster-adaptive production behaviors is heterogeneous across different levels of government support.

Abstract

Climate disasters lead to substantial economic losses and grain yield losses, emphasizing the need for adaptation to ensure food security. As digital technologies advance, it is imperative to investigate how digital literacy among grain farmers affects their adaptive production behaviors in the face of climate disasters. Drawing on survey data from 505 grain-producing smallholders in Sichuan Province, China, this study constructs a theoretical framework linking digital literacy, climate disaster risk perception, and adaptive production behaviors. Empirical analysis shows that digital literacy positively impacts the adaptive production behaviors of grain-producing smallholders. Our results are robust across various models and tests. An analysis of the mediation mechanism reveals that digital literacy contributes to climate disaster-adaptive production behaviors by improving the awareness of climate disaster risks. Heterogeneity analysis shows that the positive impact of digital literacy is more pronounced for smallholders that receive internet skills training and climate information services, and this impact intensifies as the level of agricultural infrastructure improves. The findings suggest that digital literacy plays a key role in reducing production risks, thereby contributing to increased sustainable agricultural development among smallholders.

Keywords: digital literacy, climate disaster-adaptive production behaviors, grain-producing smallholders, China

1. Introduction

The current trend of global warming has led to a rise in the frequency of severe and unpredictable climatic disasters such as droughts, floods, and typhoons (IPCC 2022), which pose a significant threat to global food security (FAO 2021). In China, there has been a significant increase in the occurrence of climate-related disasters between 1961 and 2022, and in 2022, China's average surface temperature was 0.92°C above the long-term average, making 2022 one of the three warmest years since the beginning of the 20th century, with a total of 3,501 extreme high-temperature events recorded nationwide (National Climate Centre 2023). The cumulative area affected by crop disasters in China in 2023 reached 10.54 million ha, and direct economic losses caused by climate disasters, such as low temperatures, droughts, and floods, exceeded 26.5 billion CNY (NBSC 2024). Affected by climate change, rice, wheat, and maize yields in China are projected to decline by 36.25, 18.26, and 45.1%, respectively, by the end of the 21st century (Zhang *et al.* 2017).

Agriculture is the foundation of China's economic development, and mitigating climate disasters is crucial for ensuring food security and stabilizing economic growth (Gao and Qin 2024). In China, over 210 million smallholders rely on agriculture as their primary source of livelihood (Huang

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et al. 2024). Smallholders, being the essential production unit within the agricultural sector, are more susceptible to the adverse effects of climate change. Hence, implementing adaptive behaviors is a crucial strategy for them to effectively respond to climate disasters (Hu *et al.* 2022). However, the overall education level among Chinese farmers is relatively low, and they face challenges such as information asymmetry (Zheng *et al*. 2022), high transaction costs, and credit restrictions (Abdul-Rahaman and Abdulai 2018). These challenges hinder their adoption of adaptive production behaviors needed to cope with climate disasters (Mao *et al.* 2022).

Meanwhile, the advancements in digital technologies, including big data, cloud computing, and artificial intelligence, have made digital knowledge and information integral to individuals' daily lives and production (Gao *et al.* 2023; Li J J *et al.* 2024). This progress has also created significant opportunities for smallholders by facilitating the dissemination of agricultural information among farmers. Being better informed allows farmers to adopt advanced farming techniques, access superior markets, and improve their livelihoods (Liu *et al.* 2022). In this sense, it is essential to emphasize the importance of digital literacy for individuals. It is not only a core component of human capital but also a crucial factor in optimizing production behavior. It is reasonable to posit that digital literacy plays an important role in helping smallholders adopt climate disaster-adaptive production behaviors. Nevertheless, the relationship between digital literacy and such adaptive behaviors has been insufficiently explored in the existing literature.

The concept of digital literacy was initially put forward by Gilster (1997) in his book *Digital Literacy*. He described it as the ability to access, understand, organize, and critically evaluate digital information. The ongoing progress of the internet and information technology has broadened both the scope and meaning of digital literacy. Current research on the concept of digital literacy mainly involves two distinct levels of understanding. Some researchers view digital literacy as a collection of capabilities characterized as the ability to access, assess, process, share, and utilize digital information (Martin and Grudziecki 2006; Tohara 2021; Nurcahyani *et al.* 2022; Li P *et al.* 2024). Others view digital literacy as a cognitive framework, representing a multifaceted value system that integrates abilities, knowledge, motivation, attitudes, and ethics (Eshet 2012; Havrilova and Topolnik 2017; Greene *et al.* 2018). For the purpose of measuring digital literacy, scholars commonly develop comprehensive indicator systems for evaluation. Nedungadi *et al*. (2018) put forward an analytical framework that covers aspects such as information literacy, online health-services, financial literacy, e-government literacy, cybersecurity literacy, and online education literacy. Chen *et al.* (2024) evaluated digital literacy across five aspects, such as information literacy, occupational competency literacy, and digital social literacy. Similarly, Pangrazio *et al.* (2020) focused on aspects such as digital generalization, social interaction, creativity, and security. These studies offer diverse perspectives for assessing digital literacy.

As research progresses, a growing number of scholars are beginning to investigate climate disaster-adaptive production behaviors from a digital perspective. Balogun *et al.* (2020) have demonstrated that digitalization can enhance food security, promote public involvement in adaptation efforts, and alleviate the impact of climate disasters. Zhang L Y *et al.* (2024) pointed out that digital transformation offers novel concepts for agriculture to safeguard against climate disasters, with digital agriculture being a prime example. Digital agriculture can comprehensively enable agriculture to adapt to climate change through means such as risk warning, intelligent detection, and precision agriculture. The projects on the digitization of climate data play a crucial role in supporting climate analysis and forecasting. These projects offer early-warning information for climate adaptation, thereby bringing about numerous social and economic benefits for regional livelihoods (Munang *et al.* 2013). Digital finance, as a tool for risk-sharing, can enhance farmers' capacity to undertake risks and reduce the vulnerability of agricultural production to adverse conditions (Wu *et al.* 2021). Digital financial services are not limited by time or space, and can lower the cost for farmers to access financial services. This effectively reduces the financial strain that farmers encounter when adopting climate-adaptive technologies (Li H *et al.* 2024). Some scholars have found that digital promotion can inspire apple growers to adopt climate-adaptation technologies. This is achieved by alleviating credit constraints and enhancing their awareness of the ecological and economic advantages (Mao *et al.* 2024). Additionally, Marshall *et al.* (2023) have demonstrated how digital capabilities can strengthen essential factors associated with resilience, such as social capital, community capacity, economic development, and communication.

This study analyzes survey data from 505 grain-producing smallholders in Sichuan, China. It employs an OLS model to explore the influence of digital literacy on adaptive production behaviors in response to climate-related disasters, as well as the underlying mechanisms. Compared to prior research, this study makes key contributions in the following areas:

First, this paper develops a theoretical framework to study the connection among "digital literacy", "climate disaster risk perception" and "climate disaster-adaptive production behaviors." This framework explains the intrinsic mechanism through which digital literacy influences climate disaster risk perception and, in turn, promotes adaptive production behaviors. It also provides a new perspective for research on adaptive production behaviors in response to climate-related disasters.

Second, this study takes a climate information perspective to construct an indicator system covering four dimensions: "online climate information acquisition," "evaluation," "sharing," and "use of climate-related apps," aiming to assess the digital literacy of grain-producing smallholders. Compared to prior studies (Pangrazio *et al.* 2020; Chen *et al.* 2024), this research makes the first step to measure digital literacy within the context of online climate information, thereby complementing the existing literature on digital literacy evaluation frameworks. This contribution not only serves as a reference for the comprehensive measurement of digital literacy among farmers but also introduces a novel paradigm

for developing indicators in future research.

Third, this article empirically investigates the mechanism by which digital literacy influences the adaptive production behaviors of grain-producing smallholders in response to climate-related disasters. The previous studies have primarily focused on macro-level climate adaptation, such as digital agriculture (Zhang L Y *et al.* 2024), digital projects (Munang *et al.* 2013), big data analysis, and mobile ICT (Balogun *et al.* 2020). Although some studies have demonstrated the crucial role of digital capabilities in strengthening community resilience (Marshall *et al.* 2023), the specific mechanism underlying this relationship remains unclear. This article, from a micro perspective, elucidates the mediating role of climate disaster risk perception in the association between digital literacy and adaptive production behaviors in response to climate-related disasters. It provides micro-level evidence for the theoretical connection between digital literacy and adaptation to climate disaster in grain-producing smallholders. Moreover, it expands the scope and depth of existing literature on climate disaster-adaptive production behaviors.

The remainder of this article is organized as follows: Section 2 provides the theoretical analysis. Section 3 describes the study area and the data sources. Section 4 analyzes and discusses the empirical results. Finally, Section 5 summarizes the main conclusions and provides policy recommendations.

2. Theoretical analysis

Farmers' adaptive production behaviors in response to climate disaster is defined as the process of behavioral adjustments or technological applications undertaken to alleviate or prevent the negative impacts of climate disasters (IPCC 2014). Common adaptive behaviors include modifying planting and harvest dates (Zhang *et al.* 2021), adopting novel crop varieties (Yu *et al.* 2014), and implementing advanced technologies (Mao *et al.* 2024). The theory of reasoned action posits that an individual's decision-making is a rational evaluation based on available information (Fishbein and Ajzen 1977). Individuals possess varying levels of knowledge and information, which in turn affect their positions in market transactions. Those with greater access to information are typically in a more favorable position, whereas individuals with inadequate information often encounter disadvantages in transactions (Krawitz and Newhouse 1978). Digital literacy, as a critical skill set in the digital economy era, overcomes traditional temporal and spatial limitations (Bai *et al.* 2023). It significantly reduces information asymmetry and bridges information gaps among stakeholders. This transformation directly impacts farmers' production behaviors by enhancing their access to and utilization of reliable information. Specifically, digital literacy can promote farmers' adaptive production behaviors in response to climate disasters through the "information effect" and the "learning effect."

First, digital literacy generates "information effects" to promote adaptive production behaviors in response to climate disasters. On one hand, it expands individuals' social networks in both virtual and physical spaces, allowing them to leverage digital tools to access diverse information resources (Prior *et al.* 2016). This facilitates the proactive gathering of information pertaining to climate-related disasters and addresses the limitations of conventional information dissemination methods. On the other hand, digital literacy enhances individuals' ability to identify and filter out misinformation (Li P *et al.* 2024). This improves the reliability of climate information available to farmers and enables them to more effectively adapt their production behaviors in response to climate disasters.

Second, digital literacy generates "learning effects" to promote climate disaster-adaptive production behaviors. On one hand, farmers with advanced digital literacy can acquire effective adaptive production practices in response to climate disasters through the "Internet+Agriculture" model. This process not only increases their profit expectations as a result of the "learning effect," but also boosts their confidence in adopting adaptive production behaviors in the face of climate disasters. On the other hand, according to modern network economics theory and information economics theory (Akerlof 1970), the Internet integrates information, informational elements, and material elements into a cohesive entity. Farmers with digital literacy can engage with agricultural technicians, experts, and other stakeholders *via* the Internet. This connection enables them to use the "learning effect" to address challenges that arise during the implementation of adaptive production in response to climate disaster and promote such behaviors. Based on this, Hypothesis 1 is proposed:

H1: Digital literacy promotes the adaptive production behaviors of grain-producing smallholders in response to climate disasters.

According to cognitive behavioral theory, an individual's behavior is not random, but rather stems from a solid cognitive foundation. This foundation is then translated into personal preferences that influence decision-making (Cooke and Sheeran 2004). In climate change scenarios, awareness of climate-related risks is essential for the identification of adaptation strategies (Pennings and Leuthold 2000). When farmers recognize the potential for climate disasters to damage crops, they are more likely to adopt corresponding adaptive behaviors (Arbuckle *et al.* 2015; Mase *et al.* 2017). However, a lack of awareness of risks of climate disasters will lead a farmer not to take any adaptation actions (Sulewski and Kłoczko-Gajewska 2014). Furthermore, if farmers fail to accurately assess the severity of a disaster, adaptive behaviors will be compromised (Weber 2006). This attitude of ignorance and skepticism can lead to a lack of concern regarding climate disaster risks, or even a refusal to acknowledge their existence (Eggers *et al.* 2015).

Therefore, a higher level of farmers' awareness of climate disaster risks is positively correlated with a higher likelihood that they will adopt climate disaster-adaptive production behaviors. Digital literacy plays an important role in improving farmers' awareness of climate disaster risks. On one hand, digital literacy's improvement equips farmers with the ability to skillfully use digital media to form a thorough grasp of climate disaster-related information and shape farmers' cognitive norms about climate disasters. The

increased cognition optimizes their decision-making process and motivates them to adopt positive behaviors including climate adaptation technologies (Nakano *et al.* 2018). On the other hand, as digital literacy improves, farmers gain greater access to education and training opportunities, such as online courses. This improvement can help farmers better understand the scientific principles and potential impacts of climate change, accurately assess climate disaster risks, and enhance their awareness of these risks, thereby promoting their adoption of adaptive production behaviors. Hypothesis 2 is therefore proposed:

H2: Digital literacy promotes climate disaster adaptation behaviors among grain-producing smallholders by improving their perceptions of climate risks.

3. Data and methods

3.1. Data and samples

We selected Sichuan Province, China, as our research area. Sichuan Province, located between 26°03′–34°19′N and 97°21′–108°12′E, and is one of China's key regions for addressing climate change. On one hand, Sichuan functions as an ecological barrier and a critical water conservation area for the upper reaches of the Yangtze and Yellow Rivers (He *et al.* 2023). The province is characterized by a complex and diverse natural environment, suffering from frequent natural disasters (Pang *et al.* 2021). In 2022, Sichuan encountered a drought of a magnitude not seen in six decades (He and Qi 2025). On the other hand, Sichuan is recognized as one of China's 13 major grain-producing regions and is the only major grain-producing province in the western part of the country (Feng *et al.* 2023). Sichuan's annual rice production accounts for about 50% of the total rice output in Southwest China (Zhang *et al.* 2015), making a significant contribution to China's food security. According to the *China Statistical Yearbook*, Sichuan Province had 16.535 million rural broadband subscribers in 2024, and rural households owned 18.5 computers per 100 households on average. These developments have provided favorable conditions for enhancing the digital literacy of grain farmers.

In August 2024, our research team conducted field surveys of selected grain smallholder households in Sichuan Province. We selected 10 prefecture-level cities in Sichuan: Chengdu, Dazhou, Deyang, Guang'an, Luzhou, Mianyang, Nanchong, Neijiang, Yibin, and Ziyang. From these cities, we selected 1–3 districts or counties. Within each district or county, 1–3 towns were chosen, and 1–3 villages were randomly selected from each sample town. From each sample village, 10–20 households were randomly surveyed. This sampling strategy ensures the scientific rigor and representativeness of the data.

The questionnaire covered individual, household, and production characteristics, government support, village features, adoption of climate disaster-adaptive technologies, digital literacy of grain-producing smallholders, climate disaster risk perception, and other relevant factors. The survey was administered by trained graduate students through one-on-one interviews with grain-producing smallholders. A total of 530 questionnaires were distributed, and after excluding invalid or incomplete responses, 505 valid questionnaires were collected, resulting in a validity rate of 95%.

3.2. Econometric models

Baseline regression model The adoption intensity of production behaviors adapted to climate disasters is measured using the entropy method, which is not a typically truncated data. Therefore, OLS model is used for regression analysis. The specific model settings are as follows:

$$CAPB_i=\alpha_0+\alpha_1 DL_i+\alpha_2 X_i+\gamma_t+\varepsilon_i \quad (1)$$

Among them, i represents a farmer and t denotes a county. $CAPB_i$ stands for climate disaster-adaptive production behaviors, and DL_i stands for digital literacy. X_i represents control variables, including the following four: individual characteristics, family characteristics, production and operation characteristics, as well as village characteristics. α_0 is a constant term, α_1 is the core independent variable regression coefficient, α_2 is the control variable regression coefficient; γ_t is fixed in the county. The effect is utilized to regulate the influence of the intrinsic attributes of each county on the model's regression results; ε_i is the random error term.

Mechanism analysis model Drawing on the methods of Jiang (2022), Mao *et al.* (2024), and Zhang J *et al.* (2024) for testing mechanisms, and drawing on previous theoretical and literature support, this study selects variables that reflect the channels through which the core explanatory variable affects the explained variable. In other words, the effect of the selected mediating variable on the explained variable should be direct and clear. Building on eq. (1), this study establishes eq. (2) to identify the impact of digital literacy on climate disaster risk perception. Since climate disaster risk perception is an ordinal discrete variable, an Ordered Probit model is constructed as follows:

$$M_i=\alpha_0+\alpha_1 DL_i+\alpha_2 X_i+\gamma_t+\varepsilon_i \quad (2)$$

where M_i refers to the mechanism variable: climate disaster risk perception. The other variables' definitions are identical to those in eq. (1).

3.3. Main variables

Explained variable: Climate disaster-adaptive production behaviors Climate disaster-adaptive behaviors usually refers to the response behaviors taken by individuals to avoid climate-related disaster risks (Zhang *et al.* 2023). Among various adaptation behaviors, the adoption of climate adaptation technologies plays a critical role in mitigating risks related to climate disaster, maintaining food yields, and boosting farmers' income (Maia *et al.* 2018). Drawing on the research of Mao *et al.* (2024), Rodríguez-Barillas *et al.* (2024), this study utilizes a questionnaire item asking farmers, "Which of the following technologies have you adopted to mitigate the adverse effects of climate disasters on food production?" The listed climate adaptation technologies include water-saving irrigation, improved crop varieties, conservation farming, pest and disease control, and agricultural machinery for drainage. This study uses the entropy method to measure technology adoption intensity as a proxy for climate disaster-adaptive production behaviors. Table 1 presents the descriptive

statistics for the adoption of these technologies.

Core explanatory variable: digital literacy Evaluating digital literacy typically involves measuring an individual's ability to effectively manage and flexibly apply digital information (Greene *et al.* 2014). Specifically, it encompasses the ability to acquire, evaluate, process, share, and apply digital information (Li P *et al.* 2024). Given that information is a core element of digital literacy, this article concentrates specifically on climate information. The evaluation is conducted across four aspects: climate information acquisition, evaluation, communication, and the use of climate-related apps. First, access to climate information forms the foundation of digital literacy. It involves a person's ability to seek, retrieve, and collect climate data in a digital environment using specific skills. Second, the evaluation of climate information involves the ability to systematically analyze and assess climate data, which includes evaluating its relevance, accuracy, and effectiveness. This skill is essential for informed decision-making and the optimization of production processes in the digital era. Third, the communication of climate information pertains to the ability to share information and resources, thereby facilitating the exchange of information among individuals. This process enhances grain-producing smallholders' ability to comprehend and apply new technologies and knowledge. Finally, the use of climate digital platforms is also a key factor influencing grain-producing smallholders' decisions on farming practices, resource management, and livelihood strategies.

This study selects 12 measurement questions to assess digital literacy using factor analysis. The specific measurement questions are detailed in Table 2. Factor analysis was used to assess digital literacy. The specific assessment questions are shown in Table 2. Before performing the factor analysis, the Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy and Bartlett's test of sphericity were conducted to assess the suitability of the variables for factor analysis. The results of these tests are presented in Table 3. The KMO coefficient is 0.836, indicating a strong correlation among the measurement questions. The significant *P*-value of Bartlett's test (P=0) confirms that the factor analysis results are valid. Four main factors were identified, based on the criterion that the eigenvalue exceeds 1, with the cumulative variance contribution of these factors accounting for 78.29%. The variance contribution of each factor relative to the total variance determines the weight of each factor score, which ultimately provides the digital literacy

Table 1 Descriptive statistical analysis of indicators for the adoption intensity of climate-adaptive production behaviors

Measurement question	Adopted	Not adopted	Mean	SD	Indicator properties	Weight
Adoption of water-saving irrigation technology (Yes=1, No=0)	55	450	0.1089	0.3118	+	0.2863
Adoption of new varieties such as drought-resistant, waterlogging-resistant, and stress-tolerant varieties (Yes=1, No=0)	277	228	0.5485	0.4981	+	0.1782
Adoption of conservation tillage practices (Yes=1, No=0)	127	378	0.2515	0.4343	+	0.0777
Adoption of pest and disease control technologies (Yes=1, No=0)	147	358	0.2911	0.4547	+	0.1593
Adoption of agricultural machinery for drainage (Yes=1, No=0)	50	455	0.0990	0.2990	+	0.2985

Table 2 Digital literacy assessment questions

Indicator layer	Specific assessment questions	Mean	SD
Digital acquisition literacy	How frequently do you access weather transition information through digital tools? (5-point Likert scale: 1=never to 5=always)	2.9525	1.1691
	How frequently do you access agricultural climate disaster information through digital tools? (5-point Likert scale: 1=never to 5=always)	3.0218	1.0881
	How frequently do you access agricultural climate warning information through digital tools? (5-point Likert scale: 1=never to 5=always)	3.0020	1.0625
	How frequently do you access agricultural climate policy information through digital tools? (5-point Likert scale: 1=never to 5=always)	2.5287	1.0670
Digital judgment literacy	Are you able to assess the authenticity and reliability of online climate information? (5-point Likert scale: 1=completely unable to fully capable)	3.3030	0.8938
	Are you able to extract the main ideas from a large amount of online climate information? (5-point Likert scale: 1=completely unable to 5=fully capable)	3.1901	0.9017
	Are you able to identify valid information from a large amount of online climate information? (5-point Likert scale: 1=completely unable to 5=fully capable)	3.1525	0.9121
Digital communication literacy	How frequently do you share and discuss climate-related information with others online prior to agricultural production? (5-point Likert scale: 1=never to 5=always)	2.8059	1.1118
	How frequently do you share and discuss climate-related information with others online during agricultural production? (5-point Likert scale: 1=never to 5=always)	2.7802	1.1327
Digital APP usage literacy	Number of WeChat public accounts focused on climate	0.5505	1.0303
	Number of agricultural climate-related apps downloaded	0.1624	0.4425
	How proficient are you in using agricultural climate-related apps? (5-point Likert scale: 1=completely unskilled to 5=completely proficient)	1.9683	1.1577

score.

Mechanism variable: climate disaster risk perception Risk perception refers to an individual's assessment of the probability of occurrence of a particular event and its consequences (Sjöberg *et al.* 2004), or a subjective evaluation of a threat and its intensity (Sjöberg 1998). Based on the findings of Xin *et al.* (2024), the questionnaire item "How do you perceive the impact of climate disasters on food production? (5-point Likert scale: 1=Not large to 5=Very large)" was selected as the indicator for climate disaster risk perception. Additionally, in order to test the robustness of the mediating effect, the item "How likely do you think climate disasters will occur within 1 year? (5-point Likert scale: 1=Completely impossible to 5=Completely possible)" was used as a substitute variable for the perception of climate disaster risk in the robustness check.

Instrumental variable: 5G infrastructure construction This study employs the presence of a 5G base station in a community as an instrumental variable for digital literacy. The detailed description and verification of the instrumental variable are provided in Section 4.2 below.

The control variables According to the research conducted by Zhang *et al.* (2023), the control variables in this study mainly cover the following four aspects. The first aspect pertains to individual characteristics, including gender, age, education level, and health status of producers and operators. The second aspect relates to family characteristics, including household savings, total household population, number of party members, and the number of household cadres. The third aspect relates to production characteristics, including cultivated land area, number of cultivated plots, and the convenience of access to agricultural machinery. The fourth aspect focuses on village characteristics, which include climate disaster conditions and the status of high-standard farmland development. Table 4 presents the definitions, assignments, and descriptive statistics for each variable.

3.4. Analysis of the characteristics of climate disaster-adaptive production behaviors adoption

Climate disaster-adaptive production behaviors are classified into five levels based on scores measured by the entropy method. The classification intervals are as follows: [0, 0.2) for Level I, [0.2, 0.4) for Level II, [0.4, 0.6) for Level III, [0.6, 0.8) for Level IV, and [0.8, 1] for Level V. The distribution of adoption levels is illustrated in Fig. 1. Among the various levels, Level I has 296 households, accounting for 58.62%, which is the highest proportion across all intervals. Level II includes 132 households, accounting for 26.14%, while Level III has 38 households, accounting for 7.52%. The number of grain farmers in Levels IV and V is relatively small, with 28 and 11 households, respectively. Overall, grain-producing smallholders in Sichuan Province have a relatively low adoption levels of climate disaster-adaptive production behaviors. The low adoption rate of climate disaster-adaptive production behaviors may be attributed to certain adoption barriers. First, inadequate access to relevant information poses a significant challenge (Abdul-Rahaman and Abdulai 2018). Many grain-producing smallholders lack effective information channels, making it difficult for them to obtain timely warnings and response strategies for climate disasters. Second, high implementation costs serve as another major constraint (Abid *et al.* 2016). The adoption of climate disaster-adaptive production technologies often requires substantial financial investment, which can be a heavy burden for farmers with limited economic resources. Third, the complexity of technology use is also a critical factor. Some climate disaster-adaptive production technologies demand advanced expertise and skills, which many smallholder farmers lack. Adopters typically need to possess greater agricultural experience and technical proficiency (Abid *et al.* 2015).

Table 3 Kaiser-Meyer-Olkin (KMO) and Bartlett's test results

Test	Value
KMO test	0.836
Bartlett's test of sphericity	
Chi-square	134.524
Degrees of freedom	66
Significance (Sig)	0.000

4. Results and discussion

4.1. Baseline results

To confirm the regression model accuracy and mitigate multicollinearity issues among variables prior to the empirical analysis, multicollinearity tests are performed in this section, with findings presented in Table 5. The findings indicate that the maximum variance inflation factor (VIF) value among all explanatory variables is 5, and the maximum 1/VIF value is 0.913, suggesting the absence of significant multicollinearity among the chosen explanatory variables.

Table 6 presents the baseline regression results on the impact of digital literacy on adaptive production behaviors in response to climate disasters. Personal characteristics, family characteristics, production characteristics, village characteristics, and county dummy variables are gradually added in columns (1) to (6). In all estimates, the digital literacy coefficient is significantly positive. The regression results in column (6) are used as the baseline for analysis. These findings indicate that the regression coefficient for digital literacy is 0.0718, statistically significant at the 1% level. This suggests that, on average, a 1-unit increase in digital literacy leads to a 0.0718-unit increase in climate disaster-adaptive production behaviors, confirming Hypothesis 1. Individuals inevitably use digital devices and digital information actively or passively in production and daily life (Lyons *et al.* 2021). Digital literacy is an important form of human capital (Wang *et al.* 2025), enabling individuals to proficiently use digital devices and digital information. Our research argues that digital literacy fundamentally facilitates the accessibility and usability of climate information among agricultural production and management entities, addressing climate information asymmetry and thereby promoting adaptive production behaviors in response to climate disasters. This is also consistent with the conclusion that digital literacy can alleviate information asymmetry (Chen *et al.* 2024).

Table 4 Descriptive statistics of main variables

Variables	Code	Definitions	Mean	SD	Min	Max
Climate disaster adaptation behaviors	Adaptation behaviors	Entropy method calculation	0.1945	0.2205	0.0000	1.0000
Digital literacy	Digital literacy	Factor analysis calculation	–0.0000	0.5040	–1.2016	1.5204
Gender	Gender	Gender of the respondent: 1=male; 2=female	1.3149	0.4649	1.0000	2.0000
Age	Age	Logarithm of the respondent's age	4.0134	0.2728	2.9957	4.4543
Education degree	Education	Educational level of respondent: 1=never studied; 2=elementary school; 3=junior high school; 4=high school; 5=technical secondary school/vocational high school; 6=college/higher vocational school; 7=undergraduate degree; 8=postgraduate degree	2.9168	1.3877	1.0000	8.0000
Health level	Health	Subjective health assessment of the respondent: 1=loss of labor; 2=frequently ill; 3=occasionally ill; 4=general; 5=healthy	4.2871	0.8767	2.0000	5.0000
Family savings	Family savings	Logarithm of family savings amount	7.3070	4.7273	0.0000	13.0170
Total family population	Population	Total number of household members (persons)	4.3307	1.6558	1.0000	12.0000
Family Party members	Party members	Number of family Party members (persons)	0.2475	0.4961	0.0000	4.0000
Family cadres	Cadres	Number of family cadres (persons)	0.0891	0.2921	0.0000	2.0000
Farmland area	Farmland area	Logarithm of the farmland area	1.8411	1.0848	0.2624	7.2449
Farmland fragmentation	Fragmentation	Logarithm of the number of farmland plots	2.1025	0.7912	0.6931	8.0067
Agricultural machinery accessibility	Machinery	Evaluation of the accessibility of agricultural machinery in household grain production: (5-point Likert scale: 1=very inconvenient to 5=very convenient)	2.9960	1.1269	1.0000	5.0000
Climate disaster	Climate disaster	Has the village experienced a drought in the past year? (1=yes, 0=no)	0.5366	0.4992	0.0000	1.0000
High-standard farmland construction	High-standard farmland	The logarithm of the area of high-standard farmland construction in the village	4.2430	3.2114	0.0000	8.4340
Climate disaster risk cognition	Risk cognition	How much impact will climate disasters have on food production? (5-point Likert scale: 1=not large to 5=very large)	3.3683	1.0346	1.0000	5.0000
5G base station	5G base station	Whether to build 5G base stations in villages, (1=yes, 0=no)	0.3307	0.4709	0.0000	1.0000

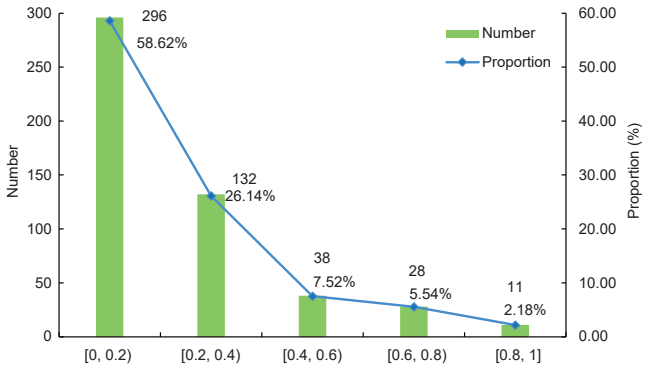


Fig. 1 Adoption intensity of climate disaster-adaptive production behaviors among grain-producing smallholders in Sichuan Province, China.

Table 5 Multicollinearity test results

Variable	VIF	1/VIF
Core independent variables		
Digital literacy	2.230	0.447
Individual characteristics		
Gender	1.099	0.913
Age	2.800	0.357
Education	2.570	0.389
Health	1.640	0.610
Family characteristics		
Family savings	1.650	0.605
Population	1.290	0.773
Party Members	1.330	0.752
Cadres	1.330	0.750
Production characteristics		
Farmland area	2.910	0.343
Farmland fragmentation	2.670	0.375
Machinery	1.650	0.605
Village characteristics		
Climate disasters	3.940	0.254
High-standard farmland	5.000	0.200

Based on the regression results of other control variables, we found that health status, family savings, farmland area, and agricultural machinery convenience significantly enhance adaptive production behaviors in response to climate disasters. The number of party members and high-standard farms' construction adversely affect climate disaster-adaptive production behaviors. Health status is directly related to farmers' working ability. Grain-producing smallholders with better health have more energy to carry out agricultural production activities, including implementing climate adaptation measures, such as building water conservancy facilities. As the economic capital of grain-producing

Table 6 Baseline regression results

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Digital literacy	0.1722***	0.1779***	0.1680***	0.1310***	0.1037***	0.0718***
	(0.0181)	(0.0183)	(0.0190)	(0.0187)	(0.0184)	(0.0242)
Gender		–0.0066	–0.0071	–0.0025	0.0037	0.0068
		(0.0186)	(0.0184)	(0.0178)	(0.0168)	(0.0164)
Age		0.1596***	0.1565***	0.1399***	0.1320***	0.0676
		(0.0509)	(0.0519)	(0.0508)	(0.0468)	(0.0516)
Education		0.0066	0.0063	0.0046	0.0075	0.0023
		(0.0088)	(0.0092)	(0.0090)	(0.0085)	(0.0085)
Health		0.0518***	0.0512***	0.0452***	0.0424***	0.0273***
		(0.0102)	(0.0102)	(0.0097)	(0.0091)	(0.0093)
Family savings			0.0037*	0.0041**	0.0058***	0.0056**
			(0.0020)	(0.0019)	(0.0019)	(0.0024)
Population			–0.0024	–0.0089*	–0.0049	–0.0042
			(0.0052)	(0.0049)	(0.0048)	(0.0047)
Party member			–0.0314	–0.0372*	–0.0394**	–0.0339*
			(0.0193)	(0.0195)	(0.0185)	(0.0175)
Cadres			0.0870**	0.0763**	0.0515	0.0394
			(0.0399)	(0.0381)	(0.0347)	(0.0353)
Farmland area				0.0422***	0.0496***	0.0612***
				(0.0162)	(0.0167)	(0.0210)
Farmland fragmentation				–0.0041	–0.0101	–0.0197
				(0.0163)	(0.0171)	(0.0219)
Machinery				0.0128	0.0305***	0.0341***
				(0.0095)	(0.0099)	(0.0103)
Climate disasters					0.1203***	0.0551
					(0.0193)	(0.0421)
High-standard farmland					0.0066**	–0.0258***
					(0.0027)	(0.0075)
County fixed effects	No	No	No	No	No	Yes
Constant	0.1945***	–0.6789***	–0.6786***	–0.6674***	–0.8139***	–0.1963
	(0.0090)	(0.2407)	(0.2472)	(0.2418)	(0.2310)	(0.2628)
Pseudo R^2	0.155	0.203	0.220	0.258	0.325	0.414
Observations	505	505	505	505	505	505

*, **, and *** denote significance at the 10, 5, and 1% levels, respectively, with robust standard errors shown in parentheses.

smallholders, family savings can serve as a financial resource to support climate adaptation behaviors such as adopting technology and adjusting irrigation. A higher number of family party members reduces the likelihood of participation in agricultural production, thus reducing the likelihood of adopting adaptive production behaviors in agricultural production. Grain-producing smallholders with larger cultivated land are more dependent on stable agricultural production. Climate disasters exert a greater impact on them, thereby creating more motivation to implement adaptive behaviors. Well-designed farm machinery access roads facilitate the integration with climate-adaptive technologies, thereby more effectively mitigating the impacts of climatic disasters on agricultural production. The construction of high-standard farmland is characterized by leveled land, contiguous plots, well-developed facilities, fertile soil, and a healthy ecosystem. These features make it more resistant to climate disasters and may also reduce the likelihood of grain-producing smallholders adopting climate disaster-adaptive production behaviors.

4.2. Endogeneity analysis

2SLS regression analysis The baseline regression may suffer from endogeneity issues, which are primarily reflected in the following two aspects: First, there may be a bidirectional causal relationship between digital literacy and farmers' adaptive production behaviors in response to climate disasters. That is, digital literacy may not only influence farmers' adoption of adaptive production behaviors, but farmers may also improve their digital literacy through practice as they adapt to climate disasters. Second, there may be the influence of omitted variables. Some unobservable factors, such as rural clan power structures, may affect farmers' climate disaster-adaptive production behaviors, leading to estimation bias. To mitigate the endogeneity problem, this study selects "the construction of 5G base stations in villages" as an instrumental variable for digital literacy. The rationale for choosing this instrumental variable is as follows: on one hand, the construction of 5G base stations significantly improves the speed and stability of network connectivity in rural areas, providing farmers with more opportunities to learn and apply digital technologies, thus enhancing their digital literacy. This conforms to the relevance assumption of instrumental variables. On the other hand, as part of rural infrastructure, 5G base station construction is mainly determined by macro factors such

as government planning and market layout, and does not directly affect individual production decisions. Additionally, existing literature has not found that the construction of 5G base stations directly impacts farmers' climate disaster-adaptive production behaviors, which indicates that this instrumental variable satisfies the exogeneity assumption. Therefore, the estimation results based on the instrumental variable approach in this study can, to some extent, alleviate the estimation bias caused by endogeneity, providing more persuasive empirical support for the research findings. This study uses two-stage least squares regression (2SLS). The regression results are shown in Table 7. Column (1) shows that the minimum eigenvalue statistic is 19.8343, which is greater than the 10% critical value of 16.38, and the instrumental variable is significant at the 1% level. This confirms the relevance condition, indicating that there is no weak instrument problem. The estimation results in column (2) of Table 7 indicate that after addressing endogeneity, digital literacy continues to have a significant positive effect on climate disaster-adaptive production behaviors at the 1% significance level.

Conditional mixed process method To address potential endogeneity issues arising from omitted variables and measurement errors in regression, we further used the instrumental variable conditional mixed process estimation method (CMP) introduced by Roodman (2011). The regression results are presented in Table 8. The initial estimation shows that the instrumental variable for 5G base station construction is significant at the 1% level. Additionally, lnsig_1, lnsig_2, and atanhrho_12 are all statistically significant at the 1% level, confirming the validity of the selected instrumental variable. The second-stage estimation results indicate that digital literacy exerts a significant positive effect on climate disaster-adaptive production behaviors at the 1% level. This reinforces the robustness of our conclusion that digital literacy promotes climate disaster-adaptive production behaviors.

Table 7 2SLS regression

Variable	First stage regression: Digital literacy	Second stage regression: Climate disaster-adaptive production behaviors
5G base station (IV)	0.2109***	
	(0.0474)	
Digital literacy		0.9713***
		(0.2334)
First stage *F* value	19.8343***	
Individual characteristic variables	Yes	Yes
Family characteristics variables	Yes	Yes
Production characteristic variables	Yes	Yes
Village characteristic variables	Yes	Yes
County fixed effects	Yes	Yes
Observations	505	505

*** denotes significance at 1% level with robust standard errors shown in parentheses.

Table 8 Endogeneity discussion results based on instrumental variable conditional mixture estimation

Variable	First stage regression: Digital literacy	Second stage regression: Climate disaster-adaptive production behaviors
5G base station (IV)	0.2109***	
	(0.0460)	
Digital literacy		0. 9712***
		(0.2337)
Individual characteristic variables	Yes	Yes
Family characteristics variables	Yes	Yes
Production characteristic variables	Yes	Yes
Village characteristic variables	Yes	Yes
County fixed effects	Yes	Yes
lnsig_1		–1.0592***
		(0.2010)
lnsig_2		1.1101***
		(0.0331)
atanhrho_12		–1.4369***
		(0.2374)
Observations		505

*** denotes significance at 1% level with robust standard errors shown in parentheses.

4.3. Robustness tests

Propensity Score Matching (PSM) method estimation results Since grain-producing smallholders' adoption of climate disaster-adaptive production behaviors is a self-selected action influenced by how much resources they have and government support, rather than random occurrences, we may have biased model estimations. PSM method is considered effective in addressing samples with self-selection bias. PSM seeks to establish treatment and control groups by emulating natural experiments, ensuring that covariates are distributed as uniformly as possible between these groups, thus reducing bias and mitigating endogeneity. In this study, the sample was initially categorized into two groups: a high digital literacy group (treatment group) and a low digital literacy group (control group). This classification was based on the median of the digital literacy variable. Individual, family, production, and village characteristics were included as control variables, and the Logit model was used for regression analysis. The treatment group's data were then matched with the control group using 1:3 nearest neighbor matching and kernel matching methods. As shown in Figs. 2 and 3, matching reduced the differences between the two groups, confirming the balance of the data and that the common support assumption was met. Table 9 presents the re-regression results after excluding samples that did not satisfy the common support assumption. The regression coefficient values remain stable, with digital literacy having a positive impact at the 1% significance level. These results are consistent with the baseline regression, further confirming that digital literacy promotes climate disaster-adaptive production behaviors.

Changing the measurement method of climate disaster-

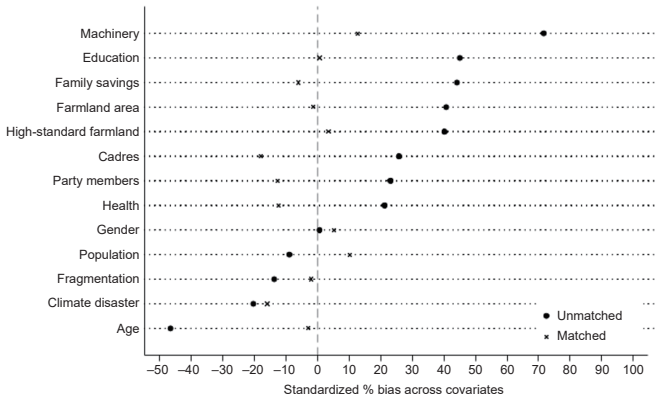


Fig. 2 Standardized deviation of control variables (1:3 nearest neighbor matching).

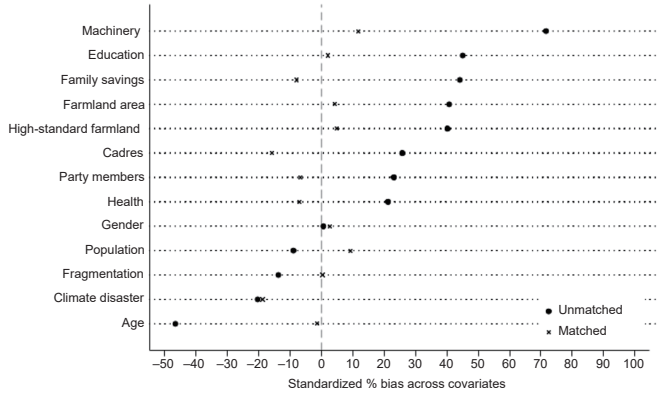


Fig. 3 Standardized deviation of control variables (kernel matching).

adaptive production behaviors The number of adaptive production behaviors adopted was used as the measurement standard. These behaviors were coded as a discrete variable, with values ranging from 0 to 5, corresponding to the number of behaviors adopted. Given the ordinal nature of the variable, an Ordered Probit model was employed for regression analysis. As shown in column (1) of Table 10, the coefficient for digital literacy is 0.5944, indicating a positive impact on climate disaster-adaptive production behaviors at the 1% significance level. These results are consistent with the baseline regression.

Changing the measurement method of digital ability Digital literacy is measured using the entropy method in this section. By directly utilizing the information from the decision matrix to compute weights, the entropy method minimizes the influence of subjective factors, thereby improving the scientific rigor and precision of the evaluation outcomes. As shown in column (2) of Table 10, the coefficient for digital literacy is 0.3125, indicating a positive impact on grain-producing smallholders' climate disaster-adaptive production behaviors at the 1% significance level.

Relaxing the digital literacy indicator system In order to improve the quantitative measures of digital literacy, five supplementary questions were added to the initial questionnaire. These questions pertain to the frequency of obtaining about agricultural product market information online, agricultural input market information online, rural financial information online, as well as the frequency of online transactions involving the sale of agricultural products and the purchase of agricultural inputs. This brought the total number of questions to 17. Factor analysis was then rerun to measure digital literacy. As shown in column (3) of Table 10, the coefficient for digital literacy is 0.1165, indicating a positive impact on farmers' climate disaster-adaptive production behaviors at the 1% significance level. These results are consistent with the baseline regression.

Changing the sample size for regression analysis (1) Samples with a cultivated land area of less than 2 acres were omitted from the analysis. Smaller land areas generally suggest a weaker dependence on food production for subsistence, leading to a more informal distribution of production resources by grain-producing smallholders. The estimation results are shown in column (4) of Table 10. The results demonstrate that, following the exclusion of these samples, digital literacy continues to exert a positive influence on adaptive production behaviors in response to climate-related disasters, reaching the 1% significance level. This outcome is consistent with the results obtained from baseline regression analysis. (2) Samples of elderly grain-producing smallholders over 75 years old were omitted as well. Elderly farmers, due to declining physical condition and lower receptivity to innovative technologies, may not accurately reflect the extent of adoption of adaptive production behaviors in response to climate disasters. The estimation results are shown in column (5) of Table 10. These results indicate that, after excluding elderly farmers, digital literacy continues to have a positive impact on climate disaster-adaptive production behaviors at the 1% significance level, which is consistent with the baseline regression results.

4.4. Mechanism analysis

In order to examine the existence of a mediating effect

Table 9 Propensity Score Matching (PSM) estimation regression results

Variable	PSM (1:3 nearest neighbor matching)	PSM (core matching)
	(1)	(2)
Digital literacy	0.0716***	0.0716***
	(0.0230)	(0.0230)
Individual characteristic variables	Yes	Yes
Family characteristics variables	Yes	Yes
Production characteristic variables	Yes	Yes
Village characteristic variables	Yes	Yes
County fixed effects	Yes	Yes
Constant	–0.2186	–0.2186
	(0.2668)	(0.2667)
Pseudo R^2	0.4183	0.4183
Observations	479	479

*** denotes significance at 1% level with robust standard errors shown in parentheses.

Table 10 Robustness test regression results

Variable	Adopted quantity	Changing the digital literacy measurement method	Relax the digital literacy indicator system	Delete samples with cultivated land area less than 2 acres	Delete samples of grain smallholders over 75 years old
	(1)	(2)	(3)	(4)	(5)
Digital literacy	0.5944***	0.3125***	0.1165***	0.0478*	0.0698***
	(0.1525)	(0.0828)	(0.0280)	(0.0260)	(0.0263)
Individual characteristic variables	Yes	Yes	Yes	Yes	Yes
Family characteristics variables	Yes	Yes	Yes	Yes	Yes
Production characteristic variables	Yes	Yes	Yes	Yes	Yes
Village characteristic variables	Yes	Yes	Yes	Yes	Yes
County fixed effects	Yes	Yes	Yes	Yes	Yes
Constant	–	–0.2988	–0.2013	–0.1265	–0.2226
	–	(0.2599)	(0.2611)	(0.2948)	(0.2666)
Pseudo R^2	0.185	0.428	0.426	0.445	0.409
Observations	505	505	505	451	473

* and *** denote significance at 10 and 1% levels with robust standard errors shown in parentheses.

related to climate disaster risk perception, this paper integrates variables pertaining to climate disaster risk perception into the regression equation and uses the Ordered Probit model for analysis. In column (1) of Table 11, digital literacy is found to have a positive impact on climate disaster risk perception at the 1% significance level. This suggests that the perception of climate disaster risk serves as a key channel through which digital literacy enhances adaptive production behaviors in response to climate disaster, thereby substantiating Hypothesis 2. For robustness testing, the question "How likely are climate disasters to occur within the next year? (5-point Likert scale: 1=Completely impossible to 5=Completely possibles)" was selected from the questionnaire. The results, shown in column (2) of Table 11, demonstrate that digital literacy still positively influences climate disaster risk perception, further verifying the robustness of the mediation effect. Individual cognition is a prerequisite for decision-making and action. In the context of climate change, the awareness of climate risks by the farmers, such as drought, extreme precipitation, and pests, significantly influences the adaptive production behaviors in response to climate-related disasters (Mase *et al.* 2017). In other words, when farmers are told that Climate disaster has negative impacts on their farm, they will take action to prevent or neutralize its impacts (Azadi *et al.* 2019). Grain-producing smallholders with more advanced digital literacy are more inclined to access and comprehend information related to climate disasters, which in turn influence s their perception of climate risk. Building on previous research (Arbuckle *et al.* 2015; Mase *et al.* 2017), we further explore the mediating role of climate disaster risk perception in the relationship between digital literacy and climate-adaptive production behaviors.

Table 11 Mechanism test results

Variable	Climate disaster risk awareness	
	(1)	(2)
Digital literacy	0.4851***	0.4994***
	(0.1520)	(0.1631)
Individual characteristic variables	Yes	Yes
Family characteristics variables	Yes	Yes
Production characteristic variables	Yes	Yes
Village characteristic variables	Yes	Yes
County fixed effects	Yes	Yes
Pseudo R^2	0.139	0.220
Observations	505	505

4.5. Heterogeneity analysis

As direct participants in agricultural production, farmers' production behavior is influenced by the value guidance of public organizations such as the government (Luo *et al.* 2019), which helps correct their cognitive and behavioral biases (Li and Zhou 2022). Government support plays a vital role in mitigating the impacts of climate disasters. In the absence of such support, the autonomous adaptive behaviors adopted by grain-producing smallholders in response to climate disasters may not be effective. The government can enhance the effectiveness of climate disaster responses by improving farmers' management practices (Keshavarz and Karami 2014) and providing training, thereby promoting the adoption of adaptive production behaviors in the face of climate disasters. This section will analyze heterogeneity from three perspectives: government-provided internet skills training, government climate information services, and the construction of agricultural facilities. Among these, internet skills training influences farmers' behaviors by enhancing their intrinsic capabilities, while climate information services and agricultural infrastructure development function by optimizing their external environments.

Heterogeneity of internet skills training provided by governments To investigate whether the impact of digital literacy on climate disaster-adaptive production behaviors is influenced by internet skills training, this article uses the question, "How often does a village or town organize Internet skills training?" (5-point Likert scale: 1=Never to 5=Often) as an indicator, collected by asking village officials. Samples that

selected "1" were assigned a value of 0, indicating that they had not received internet skills training. All other samples were assigned a value of 1, representing those who had participated in internet skills training. The estimation results in columns (1)–(2) of Table 12 show that digital literacy has a significant positive impact in the sample that received internet skills training. This is consistent with the conclusion of Tong *et al.* (2024) that the internet promotes farmers' adoption of climate adaptation behaviors. The internet, characterized by immediacy, sharing, and openness (Adamides *et al.* 2020), primarily influences individual economic behaviors by altering the relative costs of participating in various economic activities (Wang *et al.* 2024). Specifically, the internet enables more frequent communication among agricultural stakeholders, thereby reducing the cost of accessing climate adaptation-related information (Mtega and Msungu 2013). For farmers, their cultural and educational limitations affect their ability to learn how to use the internet. For the government, which possesses more comprehensive knowledge of internet use, organizing internet skills training programs for farmers helps transfer the latest internet-related knowledge and skills to them. This, in turn, enhances farmers' digital literacy and enables digital literacy to play a greater role in promoting climate disaster-adaptive production behaviors.

Heterogeneity of climate information services delivered by governments To examine whether there is heterogeneity in the impact of digital literacy on adaptive production behaviors in response to climate disaster due to the provision of climate information services, this study includes a relevant survey question. The study employs the question, "How often does a village or town provide climate information services?" (5-point Likert scale: 1=Never to 5=Often) as an indicator, collected by asking village officials. Samples with a score of 1 were assigned a value of 0, representing areas that do not provide climate information services. The remaining samples were assigned a value of 1, representing areas that provide such services. The estimation results in column (4) of Table 12 which indicates that, in samples where climate information services are provided, digital literacy has significantly positively impacts on climate disaster-adaptive production behaviors. This also validates the conclusion of Owusu *et al.* (2021) that access to climate information significantly influences farmers' climate adaptation behaviors. Climate information services are valuable tools for the agricultural sector to identify and respond effectively to environmental changes (Born *et al.* 2021). These services can unleash the potential of agricultural production through weather forecasting and the rational utilization of meteorological resources (Bernardi 2011). Grain-producing smallholders with higher digital literacy tend to adopt adaptive production behaviors based on climate information provided by the government to mitigate adverse impacts. Moreover, the availability of climate information enhances smallholder farmers' awareness of climate change, thereby encouraging a more proactive adoption of adaptive production practices.

Heterogeneity of government agricultural infrastructure development To explore whether the impact of digital literacy on adaptive production behaviors in response to climate disasters varies with the level of agricultural infrastructure, this study includes a relevant survey question. Specifically, the level of agricultural infrastructure construction is represented by asking village officials, "How effective are the village agricultural water conservancy facilities in operation? (measured on a 5-point Likert scale: 1=Very poor to 5=Very good). Samples with a score of 2 were assigned a value of 0 (indicating low levels, as the minimum score is 2), while the remaining samples were assigned a value of 1 (indicating high levels). The estimation results presented in columns (5)–(6) of Table 12 demonstrate that digital literacy has a statistically significant positive impact at the 1% level in samples characterized by high levels of agricultural infrastructure construction. Conversely, its impact is not statistically significant in samples with low levels of agricultural infrastructure. This finding indicates that the positive influence of digital literacy on adaptive production behaviors in response to climate disaster is more significant in regions with better-developed agricultural infrastructure. Agricultural infrastructure constitutes the foundation for agricultural production. It is characterized by high investment costs and long payback cycles, which underscores the need of support and construction initiatives from the government (Li *et al.* 2018). Enhanced agricultural infrastructure mitigates regional disparities in natural conditions, fosters agricultural economic development (Yan 2019), motivating farmers to

Table 12 Government support heterogeneity test results

Variable	Heterogeneity in internet skills training		Heterogeneity in meteorological information service		Heterogeneity in agricultural infrastructure construction	
	Provide training (1)	No training (2)	Provide service (3)	No service (4)	High level (5)	Low level (6)
Digital literacy	0.0879***	–0.0190	0.0645**	0.0336	0.0697***	0.0641
	(0.0297)	(0.0344)	(0.0317)	(0.0303)	(0.0263)	(0.0501)
Individual characteristic variables	Yes	Yes	Yes	Yes	Yes	Yes
Family characteristics variables	Yes	Yes	Yes	Yes	Yes	Yes
Production characteristic variables	Yes	Yes	Yes	Yes	Yes	Yes
Village characteristic variables	Yes	Yes	Yes	Yes	Yes	Yes
County fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Constant	–0.2355	0.4073	–0.7082**	0.9921***	–0.1189	–0.3960
	(0.3395)	(0.5056)	(0.3577)	(0.3091)	(0.2963)	(0.3558)
Pseudo R^2	0.432	0.472	0.427	0.580	0.400	0.523
Observations	373	132	370	135	441	64

adopt adaptive behaviors in response to climate-related disasters, and strengthens the resilience of agricultural sector against adverse conditions. Furthermore, well-developed infrastructure equips farmers with a broader array of adaptive measures, such as adjusting crop structures and the adoption of advanced planting techniques.

5. Conclusion and policy implications

5.1. Conclusion

We surveyed 505 grain-producing smallholders in Sichuan Province, China, to explore their adoption of adaptive production behaviors in response to climate disasters. Additionally, we examined the impact of digital literacy on these behaviors. Our study drew the following conclusions: The adoption rate of climate disaster-adaptive production behaviors among grain-producing smallholders in Sichuan Province is relatively low. Digital literacy has a positive impact on adaptive production behaviors in response to climate disasters, where the perception of their risks serves as a key channel through which digital literacy promotes these behaviors. The positive impact of digital literacy on adaptive production behaviors in response to climate disasters varies significantly depending on government support. Specifically, among those who received internet skills training, had access to climate information services, and benefited from well-developed agricultural infrastructure, the positive impact of digital literacy on adaptive production behaviors in response to climate disasters is more pronounced.

5.2. Policy implications

First, we should enhance the infrastructure development in rural areas. On one hand, efforts should be made to advance the construction of digital infrastructure. This includes upgrading the "three networks" — rural telecommunications, broadband, and cable television networks — thereby establishing a more comprehensive rural information service system. On the other hand, the technological support for agricultural infrastructure construction should be reinforced. Investment in agricultural infrastructure should be increased, and the application of advanced engineering technologies and materials should be actively promoted. For example, in the construction of agricultural water conservancy facilities, the use of new pipeline materials and waterproof materials should be encouraged. Furthermore, a specialized agricultural facility maintenance team should be established to oversee routine inspections, repairs, and upkeep of agricultural infrastructure.

Second, we should enhance grain-producing smallholders training and improve digital literacy. The government and relevant departments should implement targeted training programs aimed at grain-producing smallholders to improve their skills to use digital tools and platforms. This initiative should include creation of user-friendly instructional manuals for digital communication tools and trading platforms. Furthermore, the government and relevant departments should organize expert-led initiatives including digital literacy workshops and knowledge-sharing competitions in rural areas. For grain-producing smallholders with diverse production and operational needs, it is essential that group training sessions should be tailored to their specific characteristics. Designated personnel can provide targeted guidance on using smartphones and other digital tools through simple and accessible formats, including instructional videos and visual aids.

Third, we should enhance the awareness of grain-producing smallholders regarding the risks associated with climate disasters. Establish a dedicated agricultural meteorological service WeChat official account to regularly release climate disaster warnings, disaster prevention and mitigation knowledge, and case studies on responding to climate disasters. Use short video platforms (e.g., Douyin and Kuaishou) to create educational videos explaining climate disaster characteristics and their impact on grain production. This will provide farmers with comprehensive climate disaster information and response guidance, enhancing their awareness of climate disaster risks. By integrating public guidance with targeted digital outreach, grain-producing smallholders can be better prepared to respond effectively to climate challenges.

Fourth, we should strengthen meteorological services to support grain production. To achieve this, county-level meteorological digital service platforms should be established to provide accurate and professional agricultural weather services. Optimizing the network of agricultural monitoring systems and observation stations will support farmers in adopting climate-resilient production practices. Completing climate zoning for major food crops and conducting climate disaster risk assessments will provide small-scale grain farmers with scientific guidance and risk evaluations, helping them better cope with the challenges posed by climate disasters and reduce production risks.

In terms of limitations and future perspectives. On one hand, this study selected Sichuan Province as the research area, and the findings may have certain regional limitations. In future research, we plan to expand the sample size to enhance the generalizability and reliability of the results. On the other hand, it is important to note that all data rely on the recollections and statements of farmers surveyed, and are therefore susceptible to biases such as recall bias and social expectation bias.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT 4.0 to assist in improving the clarity and readability of the language. All content generated was carefully reviewed and revised by the authors as necessary, and the authors take full responsibility for the final content of the article.

Data availability

The data used in this study were collected by the project team members and have been kept confidential.

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