

Antecedent Configurations of Farmers' Climate Adaptation Behaviors in China: Based on Sustainable Livelihood Framework

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Research Article

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Abstract

The impact of climate change on agricultural production is becoming increasingly pronounced, making it imperative to promote farmers' climate adaptation to safeguard food security and livelihood stability. Grounded in the Sustainable Livelihoods Framework (SLF), this study employs a mixed-method approach integrating fuzzy-set Qualitative Comparative Analysis (fsQCA) and Propensity Score Matching (PSM) to investigate the configurations of livelihood capital that drive or hinder farmers' adoption of climate adaptation behaviors. The study further analyzes how these behavior-facilitating configurations affect farmers' income loss. The fsQCA results reveal that the combination of high information, financial, natural, and human capital promotes adaptation, with high social capital showing a substitutive effect. Conversely, configurations characterized by low social, human, and physical capital inhibit adaptation, demonstrating causal asymmetry. Moreover, all adaptation-promoting configurations reduce income loss, with the combination of high information, financial, and physical capital exhibiting superior mitigation effects. These findings provide a configurational perspective on farmer decision-making and offer targeted policy implications for enhancing climate resilience, particularly in resource-poor rural areas.

Introduction

Global climate change poses a severe threat to food security and imposes significant survival challenges on smallholder farmers, whose livelihoods are predominantly dependent on crop farming. For instance, extreme high temperatures have substantially reduced global wheat yields, inflicting considerable economic losses on farming communities (Asseng et al., 2015). Farmers' livelihood strategies are formulated based on a comprehensive assessment of their available livelihood capital. However, unlike the large-scale, resource-abundant agricultural systems in countries such as the United States, China's context of "*a large country with small-scale farmers*" means that the majority of its farmers operate with scarce livelihood capital. When considering climate adaptation strategies, these farmers often weigh the potential negative impacts, particularly the concern that high investments in adaptation technologies may not be recouped due to production risks (e.g., climate hazards), leading to a continuous depletion of their limited resource stocks. This apprehension, in turn, reinforces their reluctance to adopt adaptive behaviors, potentially creating a vicious cycle of climate-induced poverty (Hultgren et al., 2025) and farmland abandonment (You et al., 2025). Conversely, farmers endowed with sufficient livelihood capital are better positioned to access new resources and more likely to proactively engage in adaptation, thereby effectively mitigating climate-related losses (Hobfoll, Halbesleben, Neveu, & Westman, 2018). Therefore, optimizing the allocation of farmers' livelihood capital to enhance their adaptive capacity is an urgent priority.

Nevertheless, existing research on farmers' climate adaptation behaviors often adopts a reductionist approach, focusing on the net effects of individual livelihood capital elements while overlooking their synergistic configurations. This factor-isolated perspective struggles to explain why farmers with similar levels of aggregate capital may exhibit divergent adaptation decisions, and fails to identify the distinct, equifinal pathways that lead to adaptive outcomes. Moreover, it remains unclear whether different capital configurations that successfully promote adaptation yield uniform effects in mitigating economic losses. To address these gaps, this study employs a configurational perspective based on the Sustainable Livelihoods Framework (SLF). By integrating fuzzy-set Qualitative Comparative Analysis (fsQCA) and Propensity Score

Matching (PSM), we aim to: (1) identify the diverse configurations of livelihood capital that either facilitate or inhibit the adoption of climate adaptation behaviors, and (2) evaluate the differential impacts of these adaptation-driving configurations on reducing farmers' income loss. The findings are expected to provide a scientific basis and decision-making support for refining targeted climate adaptation policies.

Literature review

Climate adaptation refers to the process of reducing negative impacts and potential risks from climate change by leveraging favorable conditions and mitigating adverse factors. For smallholder farmers whose primary livelihood is crop cultivation, climate adaptation behaviors encompass a series of agricultural production adjustments taken to mitigate the negative impacts of climate change on their livelihoods. These measures primarily include crop variety substitution, adjustments to planting schedules and factor inputs, and the enhancement of protective infrastructure. The effectiveness of farmers' climate adaptation is primarily reflected in the ability of these adopted behaviors to significantly reduce income losses attributable to climate change, constituting the loss reduction effect. Existing research has yielded substantial findings concerning farmers' climate adaptation behaviors and their effectiveness, as summarized in Table 1.

Table 1
A review of farmers' climate adaptation behaviors and their effects

Research Domain	Perspective	Representative Theories	Conclusions	Variables	Methods
Farmers' Climate Adaptation Behaviors	Rational Behavior Perspective	Theory of Planned Behavior (Y. Zhang, Geng, Liang, Wang, & Xue, 2024)	This perspective emphasizes farmers' rational motivation, positing that they evaluate the consequences of climate adaptation behaviors based on their preferences and values to make optimal choices .	Intentions, behavioral attitudes, subjective norms, etc.	GLM(Mu, Li, Liu, & Wang, 2025)☐ SEM(Y. Zhang et al., 2024)☐ Experimental research (Cai & Song, 2017)☐ Meta(Huang et al., 2024)☐ Interview (Talanow, Topp, Loos, & Martín-López, 2021)
	Bounded Rationality Perspective	Construal Level Theory(Yazdanpanah et al., 2023) Protection Motivation Theory(Ghazali et al., 2021) Value-Belief-Norm Theory(L. Zhang, Ruiz-Menjivar, Luo, Liang, & Swisher, 2020)	When making climate adaptation decisions, farmers cannot achieve omniscience or perfect rationality; their choices are influenced by their perceptions and interpretations of the external environment.	Social norms, outcome awareness, protective motivation, psychological distance, etc.	
	Resource-Based Perspective	Resource Endowment(Huang et al., 2024) Sustainable Livelihoods Framework(Albore, Tesfay, Zenebe, & Abadi, 2025)	This perspective emphasizes a human-centered approach, focusing on establishing the mechanism of interaction between resources and livelihood strategies.	Resource, livelihood capital.	
Effectiveness of Farmers'			Emphasizes the income-	household income, crop	PSM(Kapoor & Pal, 2024)

Research Domain	Perspective	Representative Theories	Conclusions	Variables	Methods
Climate Adaptation Behaviors			increasing, yield-enhancing, and efficiency-improving effects of farmers' climate adaptation behaviors.	yield, and agricultural factor productivity.	ESR(Etwire, Koomson, & Martey, 2022) UQR(Yu et al., 2025)

However, the existing literature exhibits limitations that can be summarized into three key aspects, ultimately creating a compelling case for a configurational approach.

First, prevailing studies often examine the isolated influence of individual livelihood capitals. This approach overlooks the causal complexity inherent in farmers’ decision-making, where outcomes likely result from the interplay and configuration of multiple capitals rather than any single factor acting independently. For instance, while theories of rational behavior emphasize behavioral attitudes and perceived control(Y. Zhang et al., 2024), and perspectives of bounded rationality highlight the roles of risk perception and social norms(Yazdanpanah et al., 2023), both are more suited to explaining low-cost behaviors. They often fall short in accounting for high-cost climate adaptation, which hinges fundamentally on objective resource endowments(Lindenberg & Steg, 2007).

The Sustainable Livelihoods Framework (SLF) provides a comprehensive structure encompassing these endowments—financial, information, social, physical, human, and natural capital(Odero, 2006). While studies confirm the significance of these capitals, findings are often contentious(Ghazali et al., 2021). These contradictions likely arise from the single-factor analytical model, which fails to capture how different capitals complement or substitute for one another within specific configurations. Consequently, existing research cannot reveal the synergistic conditions of different capitals. This study employs a configurational perspective to investigate how specific combinations of livelihood capitals drive farmers’ climate adaptation behaviors.

Second, the link between configurations of livelihood capital and the mitigation of climate change-induced losses remains inadequately explored. First, the literature on the effectiveness of climate adaptation behaviors predominantly emphasizes positive outcomes like yield and income growth(Cheng, Zhang, Cheng, Ma, & Fan, 2024; Etwire et al., 2022). However, as extreme weather events intensify, the risk of agricultural losses is escalating, making loss mitigation a critical and increasingly prevalent concern. This focus is further warranted by farmers’ well-documented loss aversion(Lipion, 1968), a cognitive bias where the disutility of a loss is psychologically more impactful than the utility of an equivalent gain.

More fundamentally, existing studies often treat the antecedents of adaptation (e.g., livelihood capital) and their performance outcomes (e.g., loss reduction) as separate research streams (Table 1). This obscures a critical question: do all livelihood capital configurations that promote adaptation yield the same loss reduction effects? Variations in configuration likely lead to the adoption of different adaptation behavior

types and intensities, which in turn exhibit divergent cost-benefit ratios and efficacy in mitigating loss. Therefore, it is crucial to integrate this causal chain by examining the mechanistic pathway from “livelihood capital configurations, adaptation behaviors and loss reduction effects.” Clarifying this pathway is essential for identifying not just any configurations that drive action, but those most effective in safeguarding farmers’ livelihood stability and ensuring food security.

Third, the methodological approaches employed in existing studies have failed to effectively validate the synergistic effects among antecedent conditions influencing farmers’ climate adaptation behaviors. According to the Sustainable Livelihoods Framework, the key to enhancing farmers’ adaptation capacity lies in identifying: (1) which interdependent livelihood capitals contribute to high adoption rates of adaptation behaviors and effective loss reduction, and (2) whether multiple equivalent combinations of these capitals exist. However, conventional regression models that analyze net effects of isolated factors are inadequate for examining and revealing these complex relational patterns. Therefore, we adopt fuzzy-set Qualitative Comparative Analysis (fsQCA) – a configurational approach – to identify antecedent conditions that either enhance or inhibit farmers’ adoption of climate adaptation behaviors. Furthermore, building on prior research, we apply Propensity Score Matching (PSM) to antecedent configurations that lead to high-level adaptation behaviors, thereby identifying specific livelihood capital configurations that generate effective loss reduction effects. This analytical strategy provides valuable insights for designing policies to encourage more effective climate adaptation actions among farmers.

In summary, grounded in the Sustainable Livelihoods Framework, we construct an analytical framework (Fig. 1) to investigate farmers’ climate adaptation behaviors and their loss reduction effects, with a focus on the synergistic configurations of six livelihood capitals. Utilizing survey data from 526 farm households in Gansu, Ningxia, and other regions of China, we elucidate how these capitals interact to drive adaptation and evaluate the differential loss reduction effects resulting from different configurations.

This study makes three primary contributions. First, we provide a comprehensive lens for examining complex causal systems, moving beyond fragmented analyses of isolated factors. Second, we empirically reveal the equifinality and causal asymmetry inherent in how livelihood capital configurations influence adaptation behaviors, and offer a theoretical basis for reconciling controversies in prior literature. Third, by methodologically integrating fsQCA with PSM, we move beyond merely identifying drivers of farmers’ climate adaptation behaviors to pinpoint which specific configurations also yield the most effective loss reduction. This provides policymakers with differentiated and targeted insights for optimizing climate adaptation instruments, enabling a move away from one-size-fits-all approaches.

Research Methods

FsQCA approach

fsQCA is a set-theoretic method designed to model causal complexity. It infers conjunctural causality characterized by equifinality (multiple paths to the same outcome) and asymmetry (causes of an outcome’s presence may differ from causes of its absence) through set-subset relationships. A key advantage is that it is unaffected by multicollinearity and can identify conditions that are sufficient or necessary for the

outcome(Rihoux & Ragin, 2009). This method is therefore well-suited to demonstrating the multifaceted configurational effects of various livelihood capitals on farmers' climate adaptation behaviors.

The application of fsQCA in this study followed these operational steps:

(1)Data Calibration

The raw data of antecedent conditions (livelihood capitals) and the outcome (adaptation behavior level) were transformed into fuzzy-set membership scores ranging from 0 (full non-membership) to 1 (full membership). This process defines the degree to which each case belongs to the sets of, for example, "high financial capital" or "high adaptation behavior."

(2)Analysis of Necessary Conditions

We tested whether any single livelihood capital was a necessary condition for high (or low) levels of adaptation behavior across all cases. Following established convention, a condition with a consistency score exceeding 0.9 was considered necessary.

(3)Analysis of Sufficient Configurations: Truth Table Construction: The calibrated data were used to construct a truth table encompassing all logically possible combinations of livelihood capital conditions and their corresponding outcomes. To refine the truth table and eliminate less plausible configurations, we applied the following three thresholds in the minimization process:

Frequency threshold

This specifies the minimum number of cases required for a configuration to be retained in the analysis. Considering our sample size, we set this threshold to 8 to ensure that each configuration was supported by a substantive number of observations.

Raw consistency threshold

This indicates the degree to which cases sharing a given configuration consistently lead to the outcome. Although a value above 0.75 is generally deemed acceptable, we adopted a more stringent threshold of 0.85 to enhance the robustness of sufficient conditions.

PRI consistency threshold

The Proportional Reduction in Inconsistency (PRI) measures the extent to which a configuration is a subset of the outcome, thereby helping to identify and resolve contradictory configurations. A threshold of 0.5 was applied to minimize such inconsistencies.

(4)Solution Generation: The software-generated three solutions: complex, parsimonious, and intermediate. We report the intermediate solution (which incorporates plausible counterfactuals) and use the parsimonious solution to identify core conditions (those appearing in both solutions) and peripheral conditions (those appearing only in the intermediate solution).

PSM approach

Grounded in the counterfactual inference framework, the Propensity Score Matching (PSM) method aims to mitigate selection bias by constructing a comparable control group for the treatment group, thereby facilitating a robust estimation of the Average Treatment Effect on the Treated (ATT). In this study, we employ PSM to quantitatively evaluate the differential impacts on climate-related loss reduction from the various antecedent configurations identified by the prior fsQCA as leading to high-level climate adaptation behaviors. This analytical step allows us to pinpoint which specific livelihood capital combinations are not only conducive to adaptation actions but are also most effective in mitigating economic losses.

Data sources

The data for this study were obtained through a field survey conducted in Gansu and Ningxia provinces, located in China's ecologically vulnerable Loess Plateau region. The selected areas are geographically proximate and share homogeneous agro-climatic conditions characterized by aridity and low rainfall. The survey targeted smallholder farmers engaged in wheat and maize cultivation, whose similar production modes render them particularly susceptible to climate-induced income losses, thereby ensuring a relevant and focused sample for our research.

To ensure representativeness, a stratified random sampling approach was employed. A total of 711 questionnaires were distributed and collected. After removing responses with missing values and samples from farmers who had not implemented any adaptation measures, 526 valid questionnaires were retained for analysis.

Measurement and calibration of variables

Variable measurement

The measurement of variables proceeded as follows. First, the outcome variable for the configurational analysis—the level of climate adaptation behavior—was measured by farmers' self-assessed degree of implementation across a range of common adaptation practices, rated on a Likert scale. This approach captures the intensity of behavioral response rather than merely the count of practices adopted.

Second, the outcome variable for the effect evaluation—climate loss—was operationalized as the monetary value of crop income loss that farmers directly attributed to climate-related disasters during the survey period. This provides a targeted measure to analyze the loss reduction effects of farming-related adaptation behaviors.

Finally, for each livelihood capital dimension, we constructed a multi-indicator measurement system based on established literature and field research. The scores for each capital type were then synthesized from these underlying indicators using the entropy method to determine objective weights. The detailed measurement indicators for all variables and their reference sources are presented in Table 2.

Table 2
Variable definitions and summary statistics.

Variables	Definitions	Mean	SD
Conditional Variables			
Human capital			
Household member	Number of household members	4.935	1.528
Agricultural laborers	Number of Agricultural laborers	1.797	0.780
Educational	Duration of schooling	6.466	4.484
Degree of physical health	1 = Healthy-3 = Unhealthy	2.525	0.729
Physical capital			
House type	1 = Thatched house; 2 = Earth-and-wood house; 3 = Brick-and-wood house; 4 = Concrete-structure house; 5 = Commercial housing	3.076	0.747
Value of agricultural production tools	The value of agricultural machinery such as tractors, and agricultural water pumps.	0.608	1.239
Value of household appliances	The value of durable consumer goods such as refrigerators and electric washing machines.	1.955	4.141
Natural capital			
Farmland quantity	mu, a unit of area (= 0.0667 ha)	16.701	41.142
Farmland Fertility	1 = Very poor; 2 = Poor; 3 = Fair; 4 = Good; 5 = Very good	3.304	0.900
Field Road Conditions	1 = Very inconvenient; 2 = Inconvenient; 3 = Fair; 4 = Well-developed; 5 = Very well-developed	3.631	1.020
Farmland Water Conservancy Infrastructure	1 = Very poor; 2 = Poor; 3 = Fair; 4 = Good; 5 = Very good	1.975	1.196
Financial capital			
Per Capita Disposable Income	otal Household Income / Number of Household Members	1.838	1.853
Agricultural income	Total annual agricultural income of all household members	3.107	5.096
Ease of Obtaining Bank Loans	1 = Very difficult; 2 = Difficult; 3 = Moderate; 4 = Easy; 5 = Very easy	3.068	1.133
Social capital			
Frequency of Social Interactions	1 = Never; 2 = Occasionally; 3 = Moderate; 4 = Frequent; 5 = Very frequent	3.222	1.032
Level of Trust in Others	1 = Complete distrust; 2 = Slight distrust; 3 = Moderate; 4 = Relatively high trust; 5 = Complete trust	3.932	0.804

Variables	Definitions	Mean	SD
Frequency of Participation in Group Activities	1 = Never; 2 = Occasionally; 3 = Moderate; 4 = Frequent; 5 = Very frequent	3.350	1.088
Information capita			
Whether Received Climate Warning Information	1 = Yes; 0 = No	0.829	0.446
Source of Early Warning Information	Number of Climate Warning Information Channels	1.719	0.849
Outcome Variables			
Climate cdaptation behaviors	Number of Climate Adaptation Behaviors Adopted	2.445	1.500
Climate loss	Agricultural Income Loss Attributable to Climate Change	0.329	1.086

Variable calibration

Calibration is the process of transforming raw data into set membership scores ranging from 0 (full non-membership) to 1 (full membership). We employed the direct calibration method, which is a standard procedure in fsQCA. The calibration anchors—the thresholds for full membership, the crossover point, and full non-membership—were set based on the sample distribution and established practice. Specifically, the 95th, 50th, and 5th percentiles of each variable’s distribution were used as these anchors, with specific values detailed in Table 3.

During calibration, a limited number of cases obtained a membership score of exactly 0.5. To resolve this ambiguity in set membership, we applied a constant adjustment of 0.001 to these scores, following established methodological recommendations (Fiss, 2011). For simplicity of interpretation in the results discussion, we refer to membership in the sets of “high” livelihood capital and “high” climate adaptation behavior simply as “high,” and their negations as “low.”

Table 3
Calibration anchors for each condition

Human capital	Full-Membership Threshold (90%)	Crossover Point (50%)	Non-Membership Threshold (10%)	Mean	SD
	0.500	0.398	0.190	0.369	0.115
Physical capital	0.102	0.036	0.020	0.051	0.054
Social capital	0.856	0.642	0.322	0.595	0.195
Natural capital	0.445	0.115	0.057	0.197	0.151
Financial capital	0.208	0.125	0.054	0.132	0.082
Information capital	0.350	0.157	0.036	0.143	0.134
Adaptive behavior	4.000	2.000	1.000	2.445	1.500

Empirical analysis

Analysis of necessary conditions

Following standard fsQCA procedure, we first performed necessity analysis to test whether any single livelihood capital constituted a necessary condition for a high level of climate adaptation behavior. A condition is deemed necessary if its consistency score exceeds the threshold of 0.9, indicating that it is present in almost all instances of the outcome (Fiss, 2011). As presented in Table 4, the consistency scores for all individual antecedent conditions fall below this critical threshold. Therefore, we conclude that no single type of livelihood capital is necessary for achieving a high level of adaptation, reinforcing the premise that the outcome is likely driven by combinations of conditions.

Table 4
Necessity analysis of single antecedent conditions

Antecedent Conditions	High-Level Climate Adaptation Behaviors		Low-Level Climate Adaptation Behaviors	
	Consistency	Coverage	Consistency	Coverage
Natural capital	0.548	0.582	0.644	0.635
~ Natural capital	0.656	0.665	0.576	0.542
Human capital	0.634	0.645	0.628	0.593
~ Human capital	0.599	0.635	0.623	0.612
Physical capital	0.564	0.656	0.681	0.591
~ Physical capital	0.674	0.631	0.575	0.621
Financial capital	0.579	0.625	0.609	0.609
~ Financial capital	0.638	0.637	0.625	0.579
Social capital	0.586	0.661	0.584	0.611
~ Social capital	0.655	0.629	0.676	0.602
Information capital	0.494	0.649	0.489	0.595
~ Information capital	0.692	0.593	0.712	0.566

Configuration analysis

The configurational analysis reveals that no single livelihood capital is necessary for high-level climate adaptation; instead, multiple distinct combinations of capitals. The solutions for both high and low levels of adaptation behavior are presented in Table 5.

Table 5
Farmers' Climate Adaptation Behaviors Configurations

	High-Level Climate Adaptation Behaviors				Low-Level Climate Adaptation Behaviors				
	S1	S2a	S2b	S3	N1a	N1b	N2	N3a	N3b
Natural capital	☒	●	☒	☒	●	●	●	●	●
Human capital		☒	●	☒	●		☒		●
Physical capital	●	☒	☒	☒		●	☒	☒	
Financial capital	●	☒	☒	☒	☒	☒	●	●	●
Social capital	☒	☒	☒	●	☒	☒	☒	●	●
Information capital	●	●	●	☒	☒	☒	☒	●	●
Consistency	0.838	0.872	0.859	0.864	0.825	0.867	0.878	0.853	0.854
Raw coverage	0.172	0.148	0.144	0.163	0.227	0.203	0.185	0.177	0.189
Unique coverage	0.071	0.041	0.028	0.066	0.043	0.026	0.039	0.017	0.033
Solution coverage	0.336				0.421				
Solution consistency	0.822				0.823				
Note:●=core causal condition (present); ●= peripheral condition (present);☒ = core causal condition (absent);☒ = peripheral condition (absent); Blank spaces indicate “do not care”.									

Configuration Analysis of Farmers' High-Level Climate Adaptation Behaviors

As shown in Table 5, the fsQCA identified four distinct configurations of livelihood capital that constitute sufficient conditions for high-level climate adaptation behaviors. The overall solution demonstrates high consistency (0.822) and a coverage of 0.336. This indicates a robust set of relationships, with the configurations explaining approximately 33.6% of the cases exhibiting high adaptation. Following standard fsQCA practice and focusing on the core conditions, these four configurations can be summarized into three models, as detailed below.

(1) The Finance-and-Information-Intensive Model (S1)

Configuration S1 demonstrates that high information capital and high financial capital are the core conditions sufficient to drive high-level adaptation, even in the absence of social capital. Physical capital appears as a peripheral condition, likely enhancing adaptive capacity.

(2) The Information-and-Natural(Human) Capital- Intensive Model (S2a, S2b): These configurations reveal the core role of high information capital combined with either high natural capital (S2a) or high human capital (S2b). The absence of social capital across both sub-paths further underscores the substitutive relationship between information capital and social capital. Farmers on this path leverage their inherent productive endowments (land or skills) alongside critical information to facilitate adaptation.

(3) The Social Capital-Centric Model (S3)

Configuration S3 establishes high social capital as a single core condition capable of driving high-level adaptation, even when other capital types are deficient. This finding underscores the potent role of social networks, which can provide the necessary resources, knowledge, and normative pressure to initiate action, effectively compensating for shortcomings in other capital domains.

Configuration Analysis of Farmers' Low-Level Climate Adaptation Behaviors

The analysis also identified five configurations sufficient for a low level of climate adaptation behavior, which were categorized into three types based on their core causal conditions. The overall solution for this outcome demonstrates high consistency (0.823) and a coverage of 0.421, indicating a robust set of relationships that account for approximately 42% of the cases with low adaptation. The three types are detailed below.

(1) Social capitaldeficiency model (N1a, N1b)

The core condition across these configurations is the absence of social capital, which fundamentally inhibits the adoption of high-level adaptation behaviors. This is compounded by the peripheral conditions of low information and low financial capital, which further restrict access to critical knowledge and funds, making the implementation of adaptation measures particularly challenging.

(2) Human-Physical capital deficiency model (N2)

In this configuration, the joint absence of human and physical capital forms the core condition that prevents adaptation. The peripheral absence of social and information capital suggests a broader isolation from knowledge networks and technical support. Consequently, even the presence of financial capital is insufficient, as farmers lack the necessary skills, tools, and guidance to invest it effectively in adaptive measures.

(3) The inaction despite adequacy model (N3a, N3b)

These configurations are critical as they exemplify causal asymmetry. They reveal that the presence of information, social, and financial capital—and often human and natural capital—is not automatically sufficient to drive high-level adaptation. This counterintuitive finding suggests that non-capital factors, such as strong loss aversion, status quo bias, or a perception that adaptation costs outweigh the benefits, may paralyze decision-making even when objective resources are available.

Robustness test

To rule out the possibility that the configurational results were generated randomly, we conducted robustness tests by increasing the frequency threshold and PRI consistency threshold, following prior research (Fiss, 2011). As shown in Table 6, after adjusting the frequency threshold (8 to 10) and PRI threshold (0.5 to 0.55), the resulting configurations were all subsets of the original solutions, demonstrating the robustness of our findings.

Table 6
Robustness test

	Model1			Model2		
	D1	D2	D3	E1	E2	E3
Natural capital	☐	●	☐	☐	☐	●
Human capital		☐	●	●	☐	☐
Physical capital	●	☐	☐	☐	☐	☐
Financial capital	●	☐	☐	☐	☐	☐
Social capital	☐	☐	☐	☐	●	☐
Information capital	●	●	●	●	☐	●
Consistency	0.838	0.872	0.859	0.859	0.864	0.872
Raw coverage	0.172	0.148	0.144	0.144	0.163	0.148
Unique coverage	0.073	0.044	0.039	0.032	0.068	0.044
Solution coverage	0.271			0.265		
Solution consistency	0.830			0.835		
Note: Model1: Increase the frequency threshold from 8 to 10; Model2: Increase the PRI consistency threshold from 0.5 to 0.55.						

Analysis of the effect of different configurations on climate losses

Research steps

This study further examines the effects of different pathways leading to high-level climate adaptation behaviors on farmers' climate-related losses. Based on the counterfactual inference framework, farmers who implemented high-level adaptation behaviors were treated as the treatment group, while those who did not were considered as the control group. The specific steps are as follows:

(1) A series of Logit models were estimated. This study uses the implementation of climate adaptation behaviors through the four configuration pathways as the dependent variable. Independent variables include: (a) demographic characteristics: number of household laborers; (b) accessibility of government services—distance to township government; (c) accessibility of financial services—distance to the nearest bank branch; (d) technical demonstration—whether the government provides agricultural technology demonstrations; and (e) land improvement—whether land consolidation has been implemented. Climate

factors were not included as independent variables since temperature and precipitation levels were relatively uniform across the surveyed region. The logit regression results are presented in Table 7.

Table 7
Regression results of the logit model

	High-Level Climate Adaptation Behaviors			
	S1	S2a	S2b	S3
Demographic characteristics	0.214	-0.275	-0.286	0.543***
Accessibility of financial services	0.089***	0.040	-0.032	-0.077
Accessibility of government services	-0.078**	-0.043	-0.107	0.017
Technical demonstration	0.528	-1.999*	0.399	-0.473
land improvement	1.649***	0.311	0.469	0.110
CONS	-5.521***	-2.955***	-2.181***	-5.285***
N	526	526	526	526
Note:*** p < 0.01** p < 0.05* p < 0.1.				

(2) This study reports the matching effectiveness of the nearest neighbor matching method with a 1:2 ratio, using pathway S1 as an example. As shown in Fig. 4, notable differences are observed in the kernel density functions between the treatment group (S1) and the control group (non-S1) before and after matching. After matching, the kernel density curves of the treatment and control groups show substantial overlap, and the bias of control variables is reduced, indicating satisfactory matching quality.

Note

Solid lines represent the treatment group; dashed lines represent the control group.

Figure 4 Matching Effect

Table 8 presents the balance test results for the matching covariates between the treatment and control groups. After matching, the standardized bias across all covariates was substantially reduced, and the differences between the groups became statistically insignificant at conventional levels. The likelihood-ratio test (LR- χ^2) for the joint significance of all covariates decreased sharply from 19.71 to 2.32, while the corresponding p-value increased from 0.001 to 0.804. These indicators collectively demonstrate that the matching procedure successfully eliminated systematic differences in observed pre-treatment characteristics between the two groups, thus establishing a solid foundation for a reliable estimation of the treatment effect (ATT).

Table 8
Balance Tests

Variable Matching	Treatment Group	Control Group	Bias	Absolute Bias	t	p > t	V(T)/V(C)
Demographic characteristics(U)	3.364	3.026	27.300		1.200	0.230	0.820
Demographic characteristics(M)	3.333	2.976	28.900	-5.700	1.010	0.317	1.220
Accessibility of financial services(U)	11.136	8.324	30.300		1.910	0.057	3.070*
Accessibility of financial services(M)	11.333	10.524	8.700	71.200	0.270	0.791	2.320
Accessibility of government services(U)	9.500	9.646	-2.000		-0.100	0.924	1.120
Accessibility of government services(M)	9.667	9.412	3.500	-74.100	0.110	0.910	1.200
Technical demonstration(U)	0.636	0.492	29.000		1.310	0.189	0.950
Technical demonstration(M)	0.667	0.619	9.600	67.000	0.310	0.755	0.940
land improvement(U)	0.955	0.591	67.400		3.310	0.001	1.320
land improvement(M)	0.857	0.952	-17.700	73.800	-1.040	0.305	2.700*
Note: U = Before matching; M = After matching							

(3) The Average Treatment Effect on the Treated (ATT) was estimated using nearest neighbor matching (1:2). Results from radius matching (caliper = 0.01) and kernel matching are also reported in Table 9 to demonstrate the robustness of the findings.

The results indicate that farmers following configuration S1 experienced a significant reduction in climate-related losses compared to the matched control group (ATT = -2203.37, $p < 0.001$), and this effect was consistent across all three matching methods.

In contrast, while the point estimates for configurations S2a, S2b, and S3 were also negative under nearest neighbor matching, these effects were not statistically significant under the more stringent radius and kernel matching methods. This pattern of results suggests that the loss reduction effects for these pathways are less robust. This performance disparity can be logically traced back to their capital configurations identified in the fsQCA: the absence of financial and physical capital as core conditions in S2a, S2b, and S3 likely constrains the effectiveness and reliability of the adaptation actions they enable, making their economic benefits more variable and sensitive to unobserved factors.

Table 9
Loss Reduction Effects of Different Configurational Pathways Leading to High-Level Climate Adaptation Behaviors

	Matching method	Treatment Group	Control Group	ATT	T
S1	nearest neighbor matching	421.429	3997.349	-3575.921	-3.490^{***}
	radius matching	421.429	3132.310	-2710.881	-2.890^{***}
	kernel matching	421.429	3446.897	-3025.469	-4.130^{***}
S2a	nearest neighbor matching	1156.250	2029.643	-873.393	-0.860
	radius matching	1156.250	3558.115	-2401.865	-2.310^{**}
	kernel matching	1156.250	3781.704	-2625.454	-3.140^{***}
S2b	nearest neighbor matching	1428.000	3576.356	-2148.356	-1.550
	radius matching	1428.000	2881.122	-1453.122	-1.910^{**}
	kernel matching	1428.000	3278.618	-1850.618	-3.050^{***}
S3	nearest neighbor matching	1420.000	2684.000	-1264.000	-1.120
	radius matching	1420.000	4015.862	-2595.862	-2.690^{***}
	kernel matching	1420.000	3486.975	-2048.975	-2.760^{***}

Discussion

(1) The configurational effects of livelihood capitals on farmers' adaptation behaviors underscore the value and necessity of constructing a farmer-centered analytical framework. This approach facilitates a more systematic understanding of the complex decision-making logic behind farmers' adaptation and the core tenets of the Sustainable Livelihoods Framework. Contrary to studies emphasizing single factors, our fsQCA reveals that no single capital is necessary. Both high and low adaptation levels can be achieved through multiple, functionally equivalent configurations (Table 5), demonstrating equifinality. Furthermore, the paths to low adaptation are not mere opposites of those leading to high adaptation, confirming causal asymmetry. These findings align with the complex systems perspective (Arthur, 2021) and demonstrate that promoting adaptation requires synergistic capital combinations rather than focusing on isolated factors (Rihoux & Ragin, 2009).

(2) The combination of high information capital with other key capitals leads to high-level adaptation, elucidating the synergistic conditions required for information to exert positive effects. Unlike studies concluding that information alone is sufficient (Mulwa, Marenja, Rahut, & Kassie, 2017), we find it must cooperate with capitals like financial or natural capital to enhance adoption. Furthermore, while reducing the psychological distance of climate change through information is common (Yazdanpanah et al., 2023), it does not invariably lead to action (Brügger, Dessai, Devine-Wright, Morton, & Pidgeon, 2015); an excessively close

distance may trigger defensive reactions or a state of fatalism. Our findings explain this: disengagement likely occurs when increased information capital reduces psychological distance without parallel enhancements in other synergistic capitals. This provides a configurational perspective on why interventions focused solely on making climate information more proximal can be ineffective or counterproductive.

(3) Configurations containing high information capital and those with high social capital exhibit a clear substitutability in driving high-level adaptation. In S3, high social capital alone sufficed, as it facilitates access to external resources and reduces costs (Guo, Wei, Zhong, & Wang, 2022). Conversely, configurations S2a and S2b show that for farmers lacking high social capital, combinations of high information with financial, natural, or human capital can effectively substitute for the driving role of social capital. The failure of configurations lacking high information capital (N1a, N1b, N2) to counter low social capital further corroborates this substitutability. A comparison of S2a and S2b also reveals substitutability between natural and human capital. These findings indicate that both social capital and “information capital+” configurations are crucial drivers, providing flexible leverage points for policy.

(4) This study finds that some farmers with abundant capital do not adopt high-level behaviors (N3a, N3b), which appears to contradict the “resource gain spiral” of Conservation of Resources theory. Potential reasons include: (1) Status quo bias (Zaca, Wale, & Chipfupa, 2025), where resource-endowed farmers are less impacted by climate shocks and thus prefer inertia. (2) The “dark side” of high social capital, where homophilous networks create an information cocoon (Paul, Weinthal, Bellemare, & Jeuland, 2016), constraining exposure to diverse adaptation strategies and reducing diversification intention. Future research should investigate this phenomenon. Furthermore, the contrast between S3 and N3b, where high social capital is present in both yet outcomes differ, further confirms the asymmetric, synergistic effects of livelihood capitals, suggesting policy should leverage key conditional configurations rather than universally enhancing all capitals.

(5) The different high-adaptation configurations demonstrate varying effects in reducing losses. Compared to S1, which shows significant and stable effects, the patterns in S2a, S2b, and S3 promote adaptation but their loss reduction is constrained by the absence of core financial and peripheral physical capital, limiting the scope of feasible actions. This corroborates that financial capital is a prerequisite for other capitals to function effectively (Lax & Krug, 2013) and underscores the necessity to investigate how antecedent configurations influence behavioral performance. For the surveyed region, governments should thus prioritize promoting the S1 configuration to achieve optimal loss reduction.

Conclusions and policy recommendations

Conclusions and policy recommendations

Conclusions

This study demonstrates that farmers’ climate adaptation behaviors and their economic outcomes are more understood through the lens of livelihood capital configurations. By integrating the Sustainable Livelihoods

Framework with fsQCA and PSM methods, we reveal how synergistic, equifinal, and asymmetric combinations of capitals drive decision-making and performance. The key findings are as follows:

(1) Farmers' Climate Adaptation Behaviors are driven by the conjunctural causation of livelihood capitals. The absence of any single necessary condition underscores that adaptive action emerges from synergistic interactions among multiple resources, not from the isolated abundance of any one.

(2) The configurations to adaptation exhibit causal complexity, characterized by equifinality (multiple pathways to high Farmers' Climate Adaptation Behaviors) and causal asymmetry (the drivers of high adaptation are not simply the inverse of those leading to low adaptation). We identified three sufficient configurations for high-level adaptation and three distinct pathways that inhibit it.

(3) A critical contribution of this study is revealing the heterogeneous performance of different adaptation-driving configurations. While all identified pathways reduce losses, the configuration combining high information, financial, and physical capital demonstrates a superior and more robust mitigation effect. This provides actionable evidence for targeting policy support towards the most effective and resilient capital combinations.

Policy recommendations

Building on the empirical findings, we propose the following policy recommendations aimed at helping farmers construct resilient livelihood capital configurations to enhance climate adaptation and reduce losses.

(1) Promote Targeted Capital Configurations Based on Synergistic and Substitutable Pathways. Policymakers should move beyond one-size-fits-all support and tailor interventions to facilitate the formation of the specific high-performance configurations identified in this study. For the Information-Finance-Physical Intensive Model (S1): synergize investments in rural information infrastructure (e.g., climate service platforms), inclusive financial products (e.g., green credits, adaptation loans), and support for agricultural mechanization services. For the Information-and-Endowment-Driven Model (S2a/S2b): offer substitutable packages. Farmers can be supported either through investments in land improvement (e.g., irrigation, soil conservation) to enhance natural capital, or through targeted skills training to build human capital—both combined with robust climate information services. For the Social Capital-Centric Model (S3): identify and empower local “champion” farmers. Leverage their social networks to disseminate knowledge, provide peer-to-peer support, and build community-level adaptive capacity.

(2) Mitigate Behavioral Barriers to Prevent Inaction Despite Capital Adequacy. Policies must address the non-capital factors that can paralyze action, even when resources are available. To counter status quo bias: when providing climate information, ensure it is localized and concretely illustrates the impacts on specific local crops and farm economics to heighten perceived urgency and relevance. To counter the “dark side” of social capital: deliberately foster diverse social networks. Create platforms that connect farmers with heterogeneous groups, including agricultural experts, successful adopters from different communities, and service providers, to break down information cocoons and expose farmers to a wider range of strategies and perspectives.

Limitations and future research directions

This study has several limitations that point to fruitful avenues for future research:

- (1) The climatic characteristics of the study region are relatively homogeneous. Future research could expand to more diverse regions to test the validity of our findings across different climate zones, thereby enhancing the generalizability of the conclusions.
- (2) While this study focused on the extent of adaptation behavior adoption and its aggregate loss reduction effect, future work could investigate the configurational antecedents and differential effectiveness of specific types of adaptation behaviors to yield more precise and granular findings.
- (3) Although we explored potential reasons for the lack of proactive adaptation among farmers with adequate livelihood capital, future research is needed to delve deeper and elucidate the complex underlying causes of this phenomenon to develop more effective strategies for addressing it.

Declarations

Funding Statement

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Ethics statements

The protocol of this study underwent review and received official approval from Northwest A&F University, China. Prior to taking part in the survey, all participants were requested to provide signed informed consent. Measures were implemented to ensure the anonymity of participants and maintain the strict confidentiality of their information throughout the research process.

Author Contribution

C.Z.Y: Data curation, Conceptualization, Writing – original draft.

Data Availability

Data will be made available on request.

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Figures

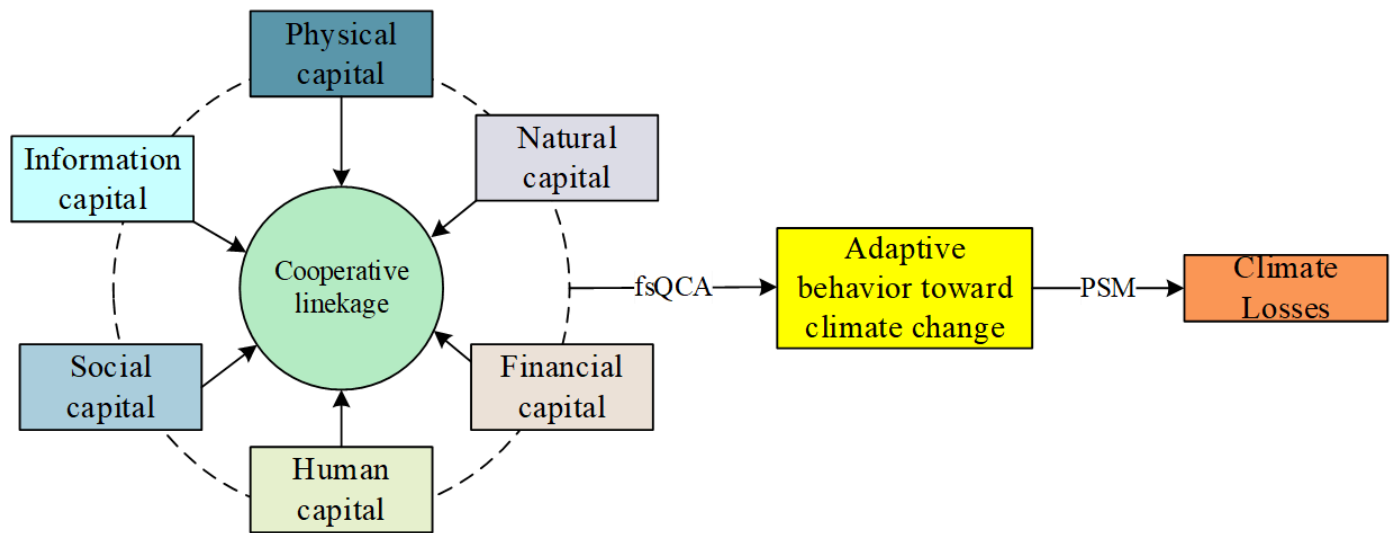


Figure 1

Theoretical framework

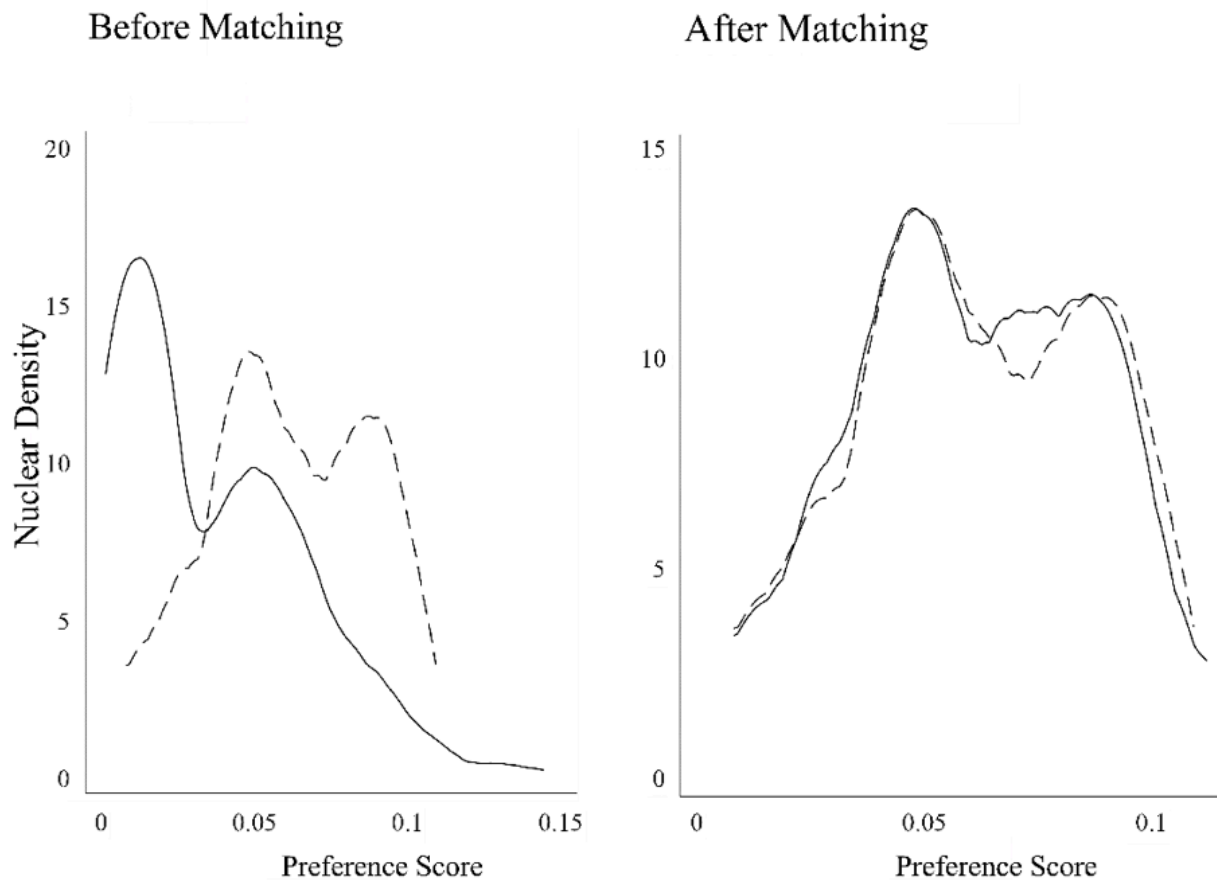


Figure 2

Figure 4 Matching Effect

Note: Solid lines represent the treatment group; dashed lines represent the control group.