Research on World Agricultural Economy
https://journals.nasspublishing.com/index.php/rwae

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Climate Change and Agricultural Sustainability: Lessons from China

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ABSTRACT

Climate change poses a growing threat to global agricultural systems, with developing economies like China facing unique challenges in balancing food security, environmental protection, and economic growth. This study examines the interplay between climate risk, fiscal environmental protection expenditures, and agricultural sustainability across 31 Chinese provinces from 2012 to 2022. Utilizing panel data analysis and a moderating effect regression model, the research quantifies the heterogeneous impacts of climate risk on agricultural sustainability, revealing a significant negative correlation in provinces with lower baseline levels of sustainable development. Conversely, the effect diminishes in regions with higher sustainability performance. A critical counterintuitive finding is that fiscal environmental protection expenditures, intended to mitigate environmental degradation, inadvertently exacerbate the adverse effects of climate risk on agricultural sustainability, suggesting potential misalignment in policy implementation. These results underscore the necessity for regionally differentiated strategies that integrate both climate adaptation and mitigation measures with sustainable agricultural practices. The study contributes to the discourse on climate-agriculture policy by highlighting China's empirical lessons, which offer scalable insights for developing nations and analogous economies grappling with similar trade-offs between environmental governance and agricultural resilience. Ultimately, this research advocates for re-evaluating regional and fiscal policy to ensure synergistic outcomes under escalating climate challenges.

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ARTICLE INFO
Received: 19 March 2025 | Revised: 15 April 2025 | Accepted: 23 April 2025 | Published Online: 12 June 2025
DOI: https://doi.org/10.36956/rwae.v6i2.1874

CITATION
Fu, Y., Ali, D.H.A., Lan, L., 2025. Climate Change and Agricultural Sustainability: Lessons from China. Research on World Agricultural Economy. 6(2): 723–737. DOI: https://doi.org/10.36956/rwae.v6i2.1874

Keywords: Climate Change; Fiscal Environmental Protection Expenditures; Agricultural Sustainability; Quantile Regression; Moderating Effect

1. Introduction

In the 21st century, global agricultural systems confront significant challenges due to climate change. The Food and Agriculture Organisation of the United Nations (FAO) reports that climate-related disasters have resulted in an average annual decline of 1.8% in total factor productivity in the agricultural sector of developing countries [1]. China serves a dual function in climate governance and agricultural transformation; it is the largest food producer and carbon emitter globally. Following the establishment of the "dual-carbon" goal, China developed a "1+N" climate policy framework that integrates climate resilience into its agricultural modernisation strategy via the Rural Revitalisation Promotion Law, while also emphasising climate-smart agriculture through the National Climate Change Adaptation Strategy 2035 [2, 3]. The policy has yielded significant outcomes. Over the past decade, agricultural carbon intensity has significantly decreased, while high-standard farmland has enhanced food production capacity [4]. The implementation of straw return technology in the black soil region of Northeast China led to notable increases in soil organic matter and decreases in fertiliser usage [5], thereby illustrating the combined benefits of technological advancements and policy initiatives.

The strategic significance of sustainable agricultural development arises from its combined economic and ecological characteristics. The sector contributes significantly to GDP and employs a substantial workforce, while serving as a critical barrier to ecological security [6]. China is advancing agricultural transformation via a comprehensive governance framework, characterised by a notable rise in fiscal spending on environmental protection. In addition, the establishment of the largest agricultural insurance system globally, which achieved risk coverage surpassing CNY 4.7 trillion (approximately US$699 billion) by 2022, encompasses 83% of the three primary staple crops [7]. Regional policy innovations have achieved significant advancements, exemplified by the implementation of the 'water and soil co-management' model in the Yellow River Basin Ecological Protection Plan. Nonetheless, the systemic transformation of environmental policy encounters significant contradictions. Although the ecological protection red line system encompasses 25% of the national territory, local governments exhibit a structural bias in the allocation of environmental protection bonds, prioritising industrial emission reduction over agricultural adaptation. The institutional tension has resulted in notable practical consequences, evidenced by a decline in agricultural adaptation funding from 31% in 2015 to 19% in 2021 [8]. This occurred despite an average annual growth rate of 9.7% in central fiscal environmental protection expenditure. This led to a substantial decrease in rice production during the Yangtze River Basin mega-drought of 2022, when engineering measures were ineffective alongside ecological adaptation [9].

This study aims to elucidate the mechanisms through which climate change impacts the sustainable development of agriculture by analysing the interactive effects of climate risk and policy interventions. Additionally, it is important to consider the effects of significant temporary anomalies on agricultural sustainability. Recent pandemics, particularly COVID-19, have significantly influenced economic activity and policy responses, potentially complicating the relationship between climate risk and agricultural sustainability. Consequently, research must consider that the estimated impacts of climate risk are not influenced by temporary anomalies to ensure result accuracy. The study's findings provide a theoretical framework for developing countries to address the "green transition trap". This phenomenon occurs when environmental policy design overlooks the unique characteristics of the agricultural sector, potentially leading to a crowding-out effect where adaptive investment displaces productive investment. The development of a climate-policy-agriculture sustainability analytical framework elucidates the contradictory phenomena observed in China's provincial panel data. It offers dual insights for countries in the global South. First, the imperative to establish a climate-smart agricultural technology system at the technological level. Second, creating a mechanism that prioritises funding for agricultural adaptation at the institutional level. This theoretical refinement, grounded in the practices of large countries, holds universal methodological importance for developing nations in achieving a balance between food security and the low-carbon transition.

2. Literature Review and Research Hypotheses

2.1. The Relationship between Climate Factors and Sustainable Agricultural Development

The connection between climate change and agricultural production has consistently been a fundamental research focus in agricultural economics. Neoclassical growth theory was the first to systematically elucidate how climate factors(as exogenous variables) impact the agricultural production function. Specifically, these factors directly affect land productivity and labour allocation efficiency through the transmission pathways of temperature and precipitation [10]. The prevalence of global climate risks has shifted research paradigms from the earlier unidirectional correlation of "climate yield" to a more complex systems analysis of "climate risk-system resilience". Recent studies utilising the vulnerability framework indicate that climate risk jeopardises agricultural sustainability via a threefold transmission pathway [11]. First, extreme weather events induce abrupt alterations in production factors [12]; second, droughts and floods hasten the deterioration of arable land quality [13]; third, inadequate investment in adaptation results in intergenerational inequities [14]. Evidence from the Chinese context supports this theory: climate change, primarily characterised by warming, does not enhance the agricultural economy's resilience, thereby confirming the detrimental impact of the "climate trap" on sustainable development [15].

The resilience of agricultural systems demonstrates considerable regional variability [16]. The pressure release theory posits that areas with low sustainable development are often trapped in a "cumulative cycle of vulnerability" [17], where inadequate infrastructure heightens exposure to climate risks, and limited adoption of green technologies diminishes system resilience.

These establish the primary hypothesis of the study:

Hypothesis 1. *Climate risk adversely impacts agricultural sustainability, with a more pronounced effect in regions exhibiting lower sustainability levels.*

2.2. The Relationship between Climate and Environmental Policies and Sustainable Agricultural Development

2.2.1. Regulatory Mechanisms of Environmental Policy Instruments

Porter's hypothesis provides an essential perspective for understanding the economic effects of environmental policies, and the "compensation effect of innovation" advocated by Porter has been partially verified in the field of agriculture [18]. The practice of China's ecological compensation policy shows that the targeted subsidy mechanism has resulted in an expansion of organic farming areas, and the fertiliser reduction policy has significantly increased the organic matter content of soils in fallow regions [19]. However, a significant threshold effect arises. The "green paradox" proposed by Van der Ploeg reveals that when environmental standards exceed farmers' capacity to adopt new technologies, crowding-out of production factors may be triggered [20]. This reflects a significant policy crowding-out effect.

2.2.2. The Double-Edged Sword Effect of Fiscal Environmental Protection Expenditure

Analysing local government behaviours from the public choice theory perspective shows a significant policy implementation bias in climate governance [21]. The policy crowding-out effect of fiscal environmental protection expenditures in agriculture refers to the phenomenon that increased government fiscal inputs for environmental protection goals produce a substitutionary squeeze on resource inputs in other key areas of agriculture under budget constraints, thereby weakening its ability for sustainable development [22]. Wang and Zhou found that when environmental protection expenditures account for a significant portion of the fiscal budget, the procurement of environmental protection equipment may crowd out investment in farmland water conservancy [23]. Furthermore, the transfer of environmental tax burden leads to an increase in production costs for small farmers [24]. This paradox suggests that fiscal instruments may act on agroecosystems through complex transmission mechanisms, as revealed by Du and Zhou in their study of the environmental Kuznets curve as a "governance efficiency trap". When policy implementation deviates from regional resource endowments, interventions may produce unintended negative effects [25]. This structural paradox is further amplified by climate shocks. A tracking study of the 2020 floods in the Yangtze River Basin found that agricultural recovery was slower in regions with high environmental spending than in regions with low expenditure [26]. Resource mismatch theory provides an explanatory framework, suggesting that the inefficient allocation of financial resources between climate adaptation and environmental protection creates a "policy adjustment trap".

These lead to the core hypothesis of this study:

Hypothesis 2. *Fiscal environmental protection expenditure exacerbates the negative effects of climate risk on agricultural sustainability.*

2.3. Research Gaps and Contributions

Despite the breadth of literature on climate risk and sustainable development, existing studies exhibit three significant limitations:

First, limited focus on the agricultural sector. Most research on environmental and climate issues has predominantly centered on the industrial sector. Additionally, studies on government expenditure for environmental protection have mainly focused on end-of-pipe solutions for industrial pollution management, often overlooking efforts to bolster agro-ecological resilience. As a result, critical assessments of the agricultural sector, vital for sustainability, remain largely unexplored.

Second, overemphasis on direct climate risk effects. Most prior research focuses solely on the direct impacts of climate risks using effect models, thereby overlooking how policy instruments can moderate these effects. This narrow approach fails to capture the complex interactions between climate dynamics and governmental interventions.

Third, unresolved challenges in fiscal policy implementation. There is a noticeable gap in explaining the paradoxes related to national policy implementation in the context of decentralised fiscal responsibilities. This encompasses the challenge of aligning local government finance 'racing governance' with national climate governance goals.

In response to these limitations, this study makes the following contributions.

First, this study develops a three-dimensional analytical framework of 'climate-policy-agricultural sustainability' to elucidate the regulatory mechanism of fiscal expenditure. It offers deeper insights into how integrated policy measures can influence agricultural sustainability outcomes.

Second, this study quantifies regional heterogeneity in agricultural sustainable development. By measuring and analyzing the differences in sustainable development levels across regions, this study sheds light on how diverse policy responses lead to varying outcomes, thereby emphasizing the importance of tailored regional strategies. This may yield additional insights into the advancement of sustainable agricultural development in countries facing analogous circumstances worldwide.

3. Methods and Variables

3.1. Data Sources

This study analyses the impact of climate risk on the agricultural sustainable development of 31 provinces in China, using provincial panel data from 2012 to 2022. By constructing specific indicators and analysing the moderating effect, the study aims to create a replicable and scalable case study to provide empirical evidence and policy reference for the high-quality development of China's agricultural economy under the 'dual-carbon' goal. The data used in this study are drawn from the Environmental Statistical Yearbook, China Blue Book on Climate Change, and provincial statistical yearbooks. First, based on the three-dimensional analytical framework in Section 2.3, a set of indicators representing agricultural sustainability, climate risk, policy variable, and related control variables is constructed. Second, after identifying the relevant variables, this study extracted the data for each province from the respective yearbooks and the China Blue Book on Climate Change. Third, the data were cross-checked for consistency. Moreover, to reduce data volatility and enhance data stability and comparability, all data were logarithmic and standardised.

3.2. Model Setting

3.2.1. Benchmark Regression Model

This study uses the fixed effects model for the benchmark regression utilising Stata 17.0 software. Building on Mendelsohn's research technique on the climate-agriculture nexus[10], the model's structure follows established practice in environmental economics and agricultural studies where climate risk is assumed to affect agricultural production processes and sustainability. This model builds on the links between climate volatility and agricultural outcomes. By capturing both direct effects and controlling for external determinants, this model is more commonly utilised in research examining climate-agriculture connections[27, 28]. This study further evaluates the connection between climate risk and sustainable agricultural development. The following regression model is set up:

$$AS_{itn} = \alpha_0 + \beta_1 CR_{it} + \sum \beta_i Z_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (1)$$

In Equation (1), i represents province and t represents year. AS is the dependent variable and represents the level of agricultural sustainability. CR is the independent variable and represents climate risk. α_0 is the constant term, β is the variable regression coefficient, and Z_{jit} is the control variable. μ_i is the individual fixed effect. λ_t is the time-fixed effect. ε_{it} is the random disturbance term.

3.2.2. Moderating Effects Model

From the literature review, environmental policies affect the agricultural sustainability of climate change. Therefore, this study considers the fiscal expenditure on environmental protection as a moderating variable, constructs the interaction term between climate risk and environmental protection expenditure, and analyses its impact on agricultural sustainable development. This study establishes a moderating effect model based on the benchmark model:

$$\begin{gathered} AS_{itn} = \alpha_0 + \beta_2 CR_{it} + \beta_3 FEE_{it} + \\ \beta_4 CR_{it} * FEE_{it} + \sum \beta_i Z_{it} + \mu_i + \lambda_t + \epsilon_{it} \end{gathered} \quad (2)$$

In Equation (2), FEE_{it} represents the moderating variable fiscal environmental protection expenditure. $CR_{it}*FEE_{it}$ represents the interaction term of climate risk and environmental protection expenditure. If the regression coefficient β_4 of the interaction term is significantly positive, it represents that environmental protection expenditure can strengthen the impact of climate risk on the sustainable development of agriculture; otherwise, it is weakened. If it is not significant, there is no moderating effect. The meanings of other variables are the same as those of the benchmark model.

3.3. Variable Selection

3.3.1. Explained Variable

Agricultural sustainable development (AS) is used as the model's explained variable, representing the degree of sustainable development within the agricultural sector and capturing aspects such as long-term viability, environmental efficiency, and resource utilization[29]. Based on the analysis of agricultural sustainability and combining the research results of Bailey et al.[27], this article first evaluated agricultural sustainable development by selecting indicators from three aspects: agricultural workers, agricultural labour objects, and agricultural labour materials. Then, this study uses the entropy method to measure agricultural sustainability, as shown in **Table 1**. The entropy value technique mitigates subjective bias and objectively and accurately represents the contribution of assessment indicators to the system.

Table 1. Indicators for evaluating agricultural sustainability.

Explained Variable	First-Level Indicators	Second-Level Indicators	Attitude
Agricultural sustainable development (AS)	Agricultural workers	Years of schooling per rural labour force	+
		Number of labourers working outside the countryside/rural employees	–
		Output value of primary industry/number of employees in primary industry	+
		Number of students graduating from rural adult cultural and technical training schools/rural population	+
		Disposable income of rural residents per capita	+
	Agricultural labour objects	Number of farmers' specialised cooperative societies/employees in Primary Industry	+
		Number of state key leading enterprises specialising in agriculture	+
		Value added of agriculture, forestry, animal husbandry and fishery services	+
		Ratio of agricultural ammonia nitrogen emission /primary industry production value	–
		Ratio of chemical oxygen demand emission in agriculture/primary industry output value	–
		Ratio of forest cover	+
	Agricultural labour materials	Energy consumption in agriculture, forestry, animal husbandry and fishery/total output value of agriculture, forestry, animal husbandry and fishery	–
		Rural electricity consumption per capita	+
		Miles of rural roads/population of villages	+
		Number of rural broadband access users/rural households	+
		Number of employees in agricultural science and technology	+
		Agricultural research and development input stock	+

Note: + represents a positive impact and – represents a negative impact.

3.3.2. Explanatory Variable

Climate risk (CR) is used as an explanatory variable, quantifying the severity and frequency of adverse climate events that may potentially impact agricultural production and sustainability [15]. In this study, following the China Blue Book on Climate Change, the degree of climate risk faced by different regions is represented by summarising each province's extreme climate event data during the sample years [30]. The extreme climate event data include occurrences of extreme low temperatures, extreme high temperatures, extreme rainfall and extreme drought days. The climate risk is obtained by calculating the average of these four metrics.

3.3.3. Control Variables

This paper selects a series of control variables that may affect the sustainable development of agriculture, including rural population (POP), fiscal agricultural expenditure (FAE), rural per capita disposable income (RI), gross agricultural product (GAP), sown area of crops (SAC), and total power of agricultural machinery (AM). The variables collectively influence sustainable agricultural development across several dimensions, including demographic, economic, resource, and technological factors. POP constitutes the foundation of the agricultural labour force, and a moderate rural population supports the sustainability of agricultural practices and the stability of rural communities. FAE indicates the government's endorsement of the agricultural sector. RI serves as an indicator of farmers' living standards. Increased income levels enhance the intrinsic dynamics of agricultural development. GAP serves as a significant measure of agricultural economic development. SAC indicates the intensity of land utilisation, and excessive exploitation can result in soil degradation and ecological harm. Increased AM enhances production efficiency and reduces labour requirements, thereby facilitating the modernisation and sustainable development of agriculture.

3.3.4. Moderating Variable

In this study, the fiscal environmental protection expenditure Index (FEE) is a moderating variable, which represents the government expenditure on environmental protection. FEE denotes the financial resources allocated by the government for safeguarding the environment, which are used in various fields such as natural ecology protection, pollution prevention and control, environmental monitoring and regulation, etc., aiming at improving environmental quality, preventing environmental risks as well as promoting sustainable development [31]. For environmental governance in China, FEE is the most direct and efficient special expenditure made by local governments [8]. The FEE can be obtained by calculating the proportion of environmental protection expenditure to public budget expenditure. **Table 2** displays the statistical description of the study variables.

Table 2. Statistical description.

Variable	Sample Size	Mean	Median	Standard Deviation	Min	Max
AS	341	0.1789	0.1560	0.0923	0.0570	0.4742
CR	341	3.8034	3.8255	0.1865	3.2854	4.2400
POP	341	7.1553	7.3284	0.9357	5.3799	8.5448
FAE	341	6.2394	6.3108	0.5641	4.8172	7.1785
RI	341	1.4381	1.2951	0.6113	0.5594	3.5247
GAP	341	7.1507	7.4786	1.1429	4.1473	8.7334
SAC	341	8.0925	8.5866	1.2417	4.7694	9.6093
AM	341	7.6491	7.8457	1.1369	4.6261	9.4271
FEE	341	2.8891	2.7000	0.9432	1.1000	6.8000

4. Results

4.1. Model Selection

The study employs a panel data model for analysis, necessitating the initial use of the Hausman test to determine the appropriate selection between the fixed effect model and the random effect model. The Hausman test posits that the null hypothesis (H_0) favours the random effects model. The test results indicate chi2 = 109.92, p = 0.0000, signifying the rejection of the null hypothesis at the 1% significance level. This suggests that individual effects are associated with the explanatory factors, and the fixed effect model is preferred.

4.2. Benchmark Regression

This study employed a benchmark regression utilising a two-way fixed effects model. Column (1) of **Table 3** omits control variables and fixed effects; column (2) includes control variables but neglects to account for double fixation of time and province; column (3) includes control variables while accounting for double fixation of time and province, resulting in the optimal goodness-of-fit and significance of the model. To exclude the effect of multicollinearity on coefficient estimation, the study conducted a VIF (Variance Inflation Factor) test and found that there was multicollinearity among some control variables. After removing SAC, the variable with the highest VIF value (VIF = 17.75 > 10), the study performed the VIF test again and found that all the control and core explanatory variables had VIF values less than 10 and there was no multicollinearity. Therefore, the regression was conducted again after excluding SAC, which can be seen in column (4). Column (4) is the precise result of the benchmark regression, which indicates a strongly negative regression coefficient for climate risk, suggesting that climate risk hinders sustainable agricultural development.

Table 3. Benchmark regression results.

VARIABLES	(1) AS	(2) AS	(3) AS	(4) AS
CR	−0.1344***	−0.0498**	−0.0373**	−0.03638**
	(0.0259)	(0.0206)	(0.0168)	(0.015)
POP		0.0751***	−0.3155*	−0.3178*
		(0.0106)	(0.1606)	(0.1577)
FAE		0.0050	0.0190	0.0183
		(0.0125)	(0.0333)	(0.0353)
RI		0.0609***	0.2046***	0.2033***
		(0.0091)	(0.0483)	(0.0448)
GAP		0.0263**	0.1081*	0 .1104**
		(0.0116)	(0.0537)	(0.0483)
SAC		−0.0266**	0.0103	
		(0.0123)	(0.0587)	
AM		−0.0386***	−0.0120	−0.0109
		(0.0105)	(0.0215)	(0.0187)
Constant	0.6902***	0.0342	1.4015	1.4785*
	(0.0986)	(0.0936)	(0.9450)	(0.8677)

Table 3. *Cont.*

VARIABLES	(1) AS	(2) AS	(3) AS	(4) AS
Observations	341	341	341	341
Adjusted R-squared	0.071	0.477	0.814	0.814
Year fixed	No	No	Yes	Yes
Province fixed	No	No	Yes	Yes

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.3. Endogeneity Test

Fixed effects models are susceptible to endogeneity, resulting in biased regression outcomes. In this study, endogeneity primarily arises from reverse causality and omitted variables. Initially, it is essential to consider reverse causality: the objective of sustainable development prompts governments to develop policies and implement actions aimed at environmental protection, which subsequently influences climate change in turn. Second, it is vital to consider omitted variables; certain unobservable micro variables related to climate change may influence sustainable agricultural development. The instrumental variables method effectively mitigates endogeneity issues. This study utilises the degree of topographic relief as an instrumental variable (IV) for climate risk, beginning from the micro dimension and referencing research by Park and Zhang [32]. Topographical variation influences the distribution of rivers and mountains, subsequently impacting soil erosion, pollutant transport, vegetation growth, and ecosystem restoration. Regions characterised by varying topographies exhibit distinct sensitivities to climate change. Regions with greater topographic relief tend to be more vulnerable to extreme climatic events such as floods and mudslides, amplifying climate risk. Thus, the correlation of instrumental variables is satisfied. The degree of topographic relief is a natural geographic feature resulting from long-term geological processes. It is not directly influenced by human activities or agricultural policies in the short term and does not directly impact the level of sustainable agricultural development. Therefore, the exogeneity condition for instrumental variables is fulfilled.

After adding IV to the model, the VIF test was conducted again to rule out multicollinearity. The VIF for IV is 2.14(<10), indicating that the risk of covariance for IV is ruled out. The VIF of control variables is also less than 10, so there is no multicollinearity.

Table 4 displays the outcomes of a two-stage ordinary least squares re-estimation of the benchmark model employing instrumental variables. The first stage of regression results indicates that the coefficient for the impact of topographic relief on climate risk is 0.4549825, with a standard error of 0.0284389 and a p-value of 0.0000. This finding is significantly positive at the 1% level, suggesting a robust correlation between the instrumental and explanatory variables. The F-statistic evaluates the null hypothesis that the IV lacks explanatory power for the potential endogenous variable. The standard guideline indicates that an F-statistic exceeding 10 suggests the IV is sufficiently robust, rendering weak instrumental bias improbable in influencing the results we obtained. In this study, the F-statistic is 12.35, exceeding 10, indicating the absence of weak instrumental variables and suggesting the validity of the selected instrumental variables. The second stage estimation results indicate that the coefficient for the impact of climate risk on agricultural sustainability is −0.0459872, with a standard error of 0.0232717 and a p-value of 0.048. This suggests climate risk adversely impacts agricultural sustainability, aligning with the benchmark regression. This demonstrates alignment with prior research following the resolution of endogeneity issues.

Table 4. Endogeneity test results.

	The First Stage of Regression Results CR	The Second Stage Estimation Results AS
Topographic relief (IV)	0.4549825***	
CR		−0.0459872**

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$.

4.4. Robustness Test

This section aims to evaluate the robustness of the benchmark regression results. Four types of robustness tests are conducted, with the results presented in **Table 5**. Column (1) presents the findings from substituting the research model with an individual fixed effects model. Column (2) shows the findings from a random effect model. Column (3) presents the outcomes of substituting the explanatory variables with their one-period lagged counterparts. Column (4) presents the result after excluding the year affected by COVID-19, to control for potential interference from major external events. The results from the four robustness tests indicate that climate risk has a consistently negative impact on agricultural sustainability. These align with the results drawn from the benchmark regression, reinforcing the notion that climate risk adversely affects agricultural sustainability.

Table 5. Robustness test results.

VARIABLES	**(1)** **fix_olsg** **AS**	**(2)** **ran_gls** **AS**	**(3)** **lag_dfix** **AS**	**(4)** **Covid-19** **AS**
CR	−0.0442***	−0.0472***		−0.0380**
	(0.0141)	(0.0148)		(0.0139)
POP	−0.0662	0.0757***	−0.3871*	−0.2230*
	(0.0882)	(0.0192)	(0.2192)	(0.1200)
FAE	0.0387	0.0285	0.0083	−0.0006
	(0.0335)	(0.0263)	(0.0353)	(0.0335)
RI	0.0013	0.0264	0.2370***	0.1809***
	(0.0351)	(0.0254)	(0.0558)	(0.0362)
GAP	−0.0292	0.0000	0.1230*	0.1004***
	(0.0309)	(0.0179)	(0.0687)	(0.0323)
AM	−0.0485	−0.0559***	−0.0198	−0.0065
	(0.0290)	(0.0215)	(0.0241)	(0.0177)
Lag.CR			−0.0254*	
			(0.0144)	
Constant	1.1602	0.0559	1.9042*	1.0148
	(0.7591)	(0.1410)	(1.0893)	(0.7677)
Observations	341	341	310	310
R-squared	0.738	0.567	0.812	0.835
Year fixed	No	No	Yes	Yes
Province fixed	Yes	No	Yes	Yes

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.5. Quantile Regression

As China's agricultural development is extremely unbalanced, a panel quantile regression model is built based on the above to investigate further the impacts of climate risk on economic development under different levels of sustainable agricultural development. The results are presented in **Table 6**, where columns (1) to (5) show the panel regression models at different quantile levels. Examining the coefficient values for the explanatory variable CR reveals that the influence of climate risk varies across regions with differing levels of sustainable agricultural development at each quantile. As the quantile levels increase, its regression coefficient changes from significant to non-significant. Specifically, climate risk has a significant negative impact on agricultural sustainability in areas with a low to medium level of agricultural sustainability (10th to 50th quantile). As the level of sustainability continues to increase (75th to 90th quantile), the negative effect becomes insignificant.

Table 6. Panel quantile regression results.

VARIABLES	(1) AS q10	(2) AS q25	(3) AS q50	(4) AS q75	(5) AS q90
CR	−0.0336*	−0.0445**	−0.0457*	−0.0119	−0.0090
	(0.0176)	(0.0188)	(0.0247)	(0.0305)	(0.0276)
POP	0.0381***	0.0392***	0.0624***	0.0993***	0.1198***
	(0.0104)	(0.0126)	(0.0111)	(0.0113)	(0.0135)
FAE	0.0097	0.0116	−0.0086	0.0051	−0.0130
	(0.0118)	(0.0145)	(0.0135)	(0.0175)	(0.0176)
RI	0.0171	0.0324**	0.0620***	0.1046***	0.1238***
	(0.0104)	(0.0156)	(0.0105)	(0.0132)	(0.0197)
GAP	0.0040	0.0145	0.0254***	−0.0005	−0.0069
	(0.0090)	(0.0105)	(0.0090)	(0.0099)	(0.0082)
AM	−0.0237***	−0.0270**	−0.0540***	−0.0618***	−0.0553***
	(0.0084)	(0.0124)	(0.0094)	(0.0104)	(0.0112)
Constant	0.0290	0.0010	0.0953	−0.1455	−0.1916
	(0.0894)	(0.0859)	(0.1035)	(0.1346)	(0.1322)
Observations	341	341	341	341	341
R-squared	0.1822	0.2182	0.2735	0.3769	0.4495
Year fixed	Yes	Yes	Yes	Yes	Yes
Province fixed	Yes	Yes	Yes	Yes	Yes

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.6. Moderating Effect Analysis

China's environmental protection expenditures have historically favoured industrial pollution control, with relatively limited funding allocated to agroclimatic governance. Due to the pressure from local governments' environmental protection assessments, fiscal resources are disproportionately allocated to industrial environmental protection projects that readily demonstrate political success, thereby diminishing the budget for agricultural disaster preventive infrastructure. Consequently, a structural deviation in environmental protection expenditures and a crowding-out impact from policy implementation are expected. This study examines fiscal environmental protection expenditure as a moderating variable. It evaluates the regression coefficients of the interaction term with climate risk to investigate its influence on sustainable agricultural development. **Table 7** presents the regression results on the moderating effect. Inter 1 is the interaction term between fiscal expenditures on environmental protection and climate risk. The results indicate that the regression coefficient for climate risk is significantly negative, indicating that climate risk adversely impacts agricultural sustainable development. The coefficient of Inter 1 is significantly positive, indicating that expenditures on environmental protection intensify the adverse impact of climate risk on sustainable agricultural production.

Table 7. The results of moderating effect analysis.

VARIABLES	(1) AS
CR	−0.0371**
	(0.0155)
FEE	−0.0047
	(0.0086)
Inter 1	0.0213*
	(0.0113)
POP	−0.3196**
	(0.1549)
FAE	0.0221
	(0.0319)
RI	0.2051***
	(0.0466)
GAP	0.1140**
	(0.0471)
AM	−0.0129
	(0.0227)
Constant	1.3172
	(0.8339)
Observations	341
Adjusted R-squared	0.815
Year fixed	YES
Province fixed	YES

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5. Discussion

The study's results validate two hypotheses. This study demonstrated that climate risk adversely affects sustainable agricultural development in China, hence supporting Hypothesis 1. This finding illustrates the multifaceted effects of climate change on agricultural production systems. Climate risk mainly manifests through extreme weather events, temperature anomalies, and irregular precipitation, which directly disturb the agricultural production environment and ecological equilibrium [33, 34]. Extreme weather events exert a "double-lock effect" on agricultural productivity by directly altering crop physiology (e.g., elevated temperatures impede photosynthesis, flooding causes root hypoxia) and indirectly triggering resource degradation (e.g., soil erosion, water scarcity) [34]. This mechanism is intensified in the Chinese context by the smallholder-centric business model: decentralised production systems diminish risk-tolerant investment capacity under economies of scale. Moreover, underdeveloped agricultural insurance markets exacerbate the financial impact of climate shocks [35]. Drought-induced declines in maize output in the Yellow River Basin provinces frequently result in increased debt among farmers, thus obstructing the implementation of sustainable technology (e.g., water-saving irrigation) and establishing a "climate poverty trap" [36]. According to resource dependence theory, China's agriculture sector has traditionally relied on natural resources, which have become progressively precarious due to escalating climatic risks [37]. The advancement of agricultural technology, infrastructure development, and policy support is crucial in alleviating the effects of climate risk; however, substantial disparities in these areas exist across various regions of China, exacerbating the negative consequences of climate risk [38].

Additionally, this study reveals that the negative effect of climate risk on sustainable agricultural development is more pronounced in provinces with lower to medium levels of sustainable development and less pronounced in provinces with higher levels of sustainable development. This observation can be explained by the adaptive capacity theory, which posits that regions with higher levels of sustainable development typically possess superior agricultural infrastructure, advanced scientific and technological support, and higher managerial and policy responsiveness, which increases their adaptive capacity to climate risks [39]. On the contrary, provinces with lower and medium levels of sustainable development lag behind in terms of technological, financial, and policy support, resulting in agricultural systems that lack adequate buffers and adjustment mechanisms in the face of climate risks [40]. These inter-regional differences in adaptive capacity reflect structural contradictions in the process of China's agricultural modernisation, pointing to an urgent need for the government to promote balanced regional development, optimise resource allocation, and enhance the risk-resistant capacity in disadvantaged regions.

Furthermore, the study finds that fiscal environmental protection expenditure (FEEI) has a significant positive moderating effect, which confirms Hypothesis 2. This finding challenges the common belief that "environmental expenditure inevitably contributes to sustainable development". This counterintuitive finding reveals a potential "efficiency-equity" trade-off between environmental policies and climate adaptation goals, which can be analysed in terms of distortions in policy implementation mechanisms. The structural bias and institutional mismatch of fiscal environmental spending are key drivers of the negative effects. First, local governments in China have traditionally prioritised end-of-pipe industrial pollution control (e.g., construction of wastewater treatment plants) over investments that enhance agro-ecological resilience (e.g., soil remediation, biodiversity conservation) [29]. Such expenditures have crowded out public resources that could have been used for climate-resilient agricultural technologies (e.g., water-saving irrigation, drought-tolerant seed research and development), resulting in the exposure of the agricultural sector to higher climate vulnerability [41]. Second, the short-term orientation of environmental performance assessments has led to "campaign-style" governance, such as mandatory straw-burning policies without accompanying subsidies for comprehensive straw utilisation, forcing farmers to bear additional production costs (e.g., switching to fossil fuels to increase heat) and weakening their financial buffers against climate shocks [42]. This phenomenon confirms the "temporal inconsistency trap" of environmental policies, where failure to integrate farmers' long-term adaptation needs results in ecological gains being offset by economic losses [43]. This 'government failure' phenomenon suggests that over-intervention and inappropriate fiscal spending may weaken endogenous adaptation mechanisms in the agricultural sector [44].

Table 8 demonstrates whether the hypothesis is valid.

Table 8. Hypotheses overview and decision.

Hypothesis	Results	Decision
Hypothesis 1. *Climate risk adversely impacts agricultural sustainability, with a more pronounced effect in regions exhibiting lower sustainability levels.*	Empirical results indicate that climate risk significantly reduces agricultural sustainability. Additionally, its negative effect is more evident in provinces with low to medium sustainable development levels compared to those with high levels.	Accepted
Hypothesis 2. *Fiscal environmental protection expenditure exacerbates the negative effects of climate risk on agricultural sustainability.*	The analysis shows a significant positive moderating effect of fiscal environmental protection expenditure, suggesting that, contrary to common expectations, higher expenditure intensifies rather than mitigates the adverse impact of climate risk.	Accepted

6. Conclusions and Recommendations

The study analyses the impacts of climate risk and fiscal and environmental protection expenditures on the sustainable development of agriculture by constructing panel data for 31 provinces in China from 2012 to 2022.The empirical findings indicate that climate risk adversely impacts agricultural sustainable development in China, with a pronounced effect in provinces exhibiting lower levels of sustainable development, whereas the effect is insignificant in provinces with higher sustainable development levels. In addition, a moderated effects regression found that fiscal environmental protection expenditures exacerbated the negative effect of climate risk on agricultural sustainable development to a certain extent. These results suggest that climate change directly threatens agricultural production systems, while misallocation of environmental protection expenditures in fiscal policy may crowd out investments needed for effective climate adaptation and mitigation.

This study presents the following recommendations:

First, reprioritise environmental expenditures. Local governments should reorient environmental spending to better integrate agricultural adaptation goals. A fixed proportion of environmental funds should be allocated to climate-smart agricultural technologies—such as drought-resistant seeds, precision irrigation, and ecological infrastructure (e.g., terracing, soil stabilisation)—rather than inefficient end-of-pipe pollution controls. This shift enhances the agricultural sector's resilience and aligns environmental protection with adaptive capacity building.

Then, build differentiated regional policies. In provinces with lower sustainability levels, a bundled "climate resilience–poverty alleviation" approach is recommended. This includes participatory budgeting, localized adaptation initiatives, and community-based disaster insurance schemes. Conversely, more developed provinces should adopt a "climate responsibility sharing" framework, supporting less developed regions via horizontal fiscal transfers, such as eco-compensation based on carbon emissions.

Finally, strengthen risk governance and policy accountability. Establish a multi-level and cross-sectoral climate risk assessment and early warning system to provide timely and practical information support to the agricultural sector. Agricultural insurance and risk-sharing mechanisms should be expanded to mitigate climate-related losses. Additionally, fiscal and agricultural policy implementation must be underpinned by robust transparency and accountability frameworks, with continuous policy evaluation to avoid inefficiencies stemming from misaligned interventions.

This study provides a macro perspective on the relationship between climate risk and agricultural sustainability based on provincial-level data, but it may overlook micro-level and local heterogeneity. Therefore, future research should explore micro-level analysis using county-level or industrial enterprise data to provide more granular insights. Then, this study analysed the moderating effect of government fiscal policy, and future research could consider incorporating other moderating or mediating variables. This would help clarify the pathways and mechanisms through which climate risk impacts agricultural sustainability, offering a more comprehensive understanding of the underlying dynamics. Finally, the study's spatial analysis was insufficient. Incorporating spatial analysis could further enhance the understanding of regional interdependencies and spatial spillover effects. Future research should explore how spatial interactions affect the relationship between climate risk, fiscal policy, and agricultural sustainability.

Author Contributions

Conceptualization, Y.F. and L.L.; methodology, Y.F. and D.H.A.A.; software, Y.F.; validation, Y.F. and D.H.A.A.; formal analysis, Y.F.; resources, Y.F.; data curation, Y.F. and L.L.; writing—original draft preparation, Y.F.; writing—review and editing, Y.F. and D.H.A.A.; supervision, D.H.A.A.; funding acquisition, Y.F. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the Chongqing Social Science Planning Fund, grant number [2022NDQN27], and the Humanities and Social Sciences Research Project of Chongqing Municipal Education Commission, grant number [22SKGH464].

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used for the study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results

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