frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 16 April 2025
DOI 10.3389/fenvs.2025.1551030

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OPEN ACCESS

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RECEIVED 24 December 2024
ACCEPTED 03 April 2025
PUBLISHED 16 April 2025

CITATION
Zeng X, Lu H, Qi H and Ji L (2025) Does extreme weather affect the resilience of agricultural economies? Analysis based on agricultural insurance.
Front. Environ. Sci. 13:1551030.
doi: 10.3389/fenvs.2025.1551030

Does extreme weather affect the resilience of agricultural economies? Analysis based on agricultural insurance

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Introduction: Against the backdrop of global warming and the frequent occurrence of extreme weather events, effectively bringing into play the effectiveness of agricultural insurance in supporting agriculture and enhancing the resilience of the agricultural economy is of universal significance for countries around the world. This study aims to explore the impact of extreme weather on the resilience of the agricultural economy, as well as whether agricultural insurance plays a role in the relationship between the two.

Methods: Based on the panel data of 31 provinces (autonomous regions and municipalities directly under the Central Government) in China from 2011 to 2022, this paper selects 15 indicators from three dimensions, namely the pressure layer, the state layer, and the response layer, and measures the resilience of the agricultural economy by using the entropy method. Furthermore, through the fixed effects model and the moderating effects model, this paper empirically analyzes the impacts of extreme weather changes such as extreme high temperatures, extreme low temperatures, and extreme precipitation on the resilience of the agricultural economy, and examines the moderating role of agricultural insurance in this context. Finally, this paper explores whether the impacts of extreme weather on the agricultural economy in different regions are consistent, and the effectiveness of the role of agricultural insurance in different regions.

Results: The study has revealed that extreme weather changes, predominantly characterized by extreme high temperatures, are detrimental to the enhancement of agricultural economic resilience. Conversely, agricultural insurance can effectively alleviate the negative impacts of extreme weather on the resilience of the agricultural economy. Meanwhile, the results of the heterogeneity test further validate the adverse effects of extreme weather on agricultural economic resilience and the negative moderating role of agricultural insurance therein. Overall, the adverse impacts of extreme weather are more pronounced in the central and eastern regions compared to the western region. Similarly, the moderating effects of agricultural insurance are more evident in the eastern and central regions than in the western region.

Discussion: Based on the heterogeneity analysis, this study explores the reasons for the inconsistent impacts of extreme weather and agricultural insurance in different regions. By comparing the agricultural insurance systems of China with those of other countries, and further from an international perspective, a policy framework is constructed, which takes promoting the high-quality development of agricultural insurance and enhancing the resilience of the agricultural economy as its core. Based on this framework, this paper puts forward some suggestions that may help mitigate the adverse impacts of extreme weather changes on agricultural production and further steadily strengthen the resilience of the agricultural economy.

KEYWORDS

agricultural economic resilience, extreme weather, agricultural insurance, entropy method, evidence from China

1 Introduction

The United Kingdom Meteorological Office (UKMO) reported that England recorded 1,695.9 mm of rainfall between October 2022 and March 2024, establishing an 18-month record high that caused severe inundation of arable lands and crop damage across most regions. This meteorological anomaly inflicted substantial negative impacts on the UK agricultural economy. Meanwhile, Brazil—the world's leading orange juice exporter—experienced a dramatic 40% reduction in orange juice inventories to approximately 85,000 metric tons in 2023, as documented by the Citrus Juice Exporters Association. This decline was primarily attributed to extreme heatwaves and associated drought conditions that severely compromised citrus yields. In Southeast Asia, Thailand faced unprecedented agricultural challenges during the 2024 summer season when maximum temperatures persistently hovered around 40°C. Concomitant drought conditions led to significant reductions in durian production and escalating cultivation costs, directly impacting farmer incomes and causing estimated economic losses exceeding. These regional crises exemplify broader global trends: the FAO reports a 30% increase in extreme weather-related agricultural disruptions over the past decade, with heatwaves, cold snaps, and precipitation extremes collectively reducing global crop yields by an average of 12% annually. Such climate-induced shocks are particularly perilous for subsistence farmers and low-income countries, where adaptive capacities remain limited. The compounding effects of temperature extremes, hydrological variability, and pest proliferation under climate change are increasingly undermining agricultural system resilience. This not only threatens short-term food security but also exacerbates long-term sustainability challenges, necessitating urgent investment in climate-smart agriculture and risk management frameworks.

Temperature and precipitation are crucial natural factors influencing agricultural production. The characteristic of having a high correlation with weather makes the output of the agricultural economy vulnerable to extreme weather events. Extreme weather is mainly characterized by extreme high temperatures, extreme low temperatures, extreme rainfall, and drought (Kimsanova et al., 2024), which, to a certain extent, encompass environmental factors such as light, heat, water, and soil that are essential for agricultural production. Therefore, compared with climate change (Malik and Ford, 2024), which is a comprehensive result of multiple factors including sea-level rise, global warming, and ecosystems (Kim and Park, 2024), extreme weather, as an extreme form of climate change, has a more significant impact on agricultural production when focusing on extreme weather changes. It is more in line with the needs of agricultural productivity development and food security maintenance in the context of global warming and the frequent occurrence of extreme weather. In recent years, the global agricultural development has been severely affected by extreme weather changes, and the factors of extreme weather changes have gradually become a major concern for scholars, farmers, and other groups. According to statistics from relevant departments, between 1993 and 2023, approximately $3.8 trillion worth of crops and livestock production were lost due to natural disaster events, which is equivalent to an average annual loss of $123 billion, accounting for 5% of the global annual agricultural GDP. In 2023, the global average surface temperature was approximately 1.45°C higher than the average level between 1850 and 1900. Global warming has further exacerbated the impacts and losses caused by natural disasters. Moreover, there are complex interactions among extreme high temperatures, extreme low temperatures, and extreme precipitation. These interactions are not only manifested among extreme weather events but also in their impacts on the disaster resistance capacity of crops and the agricultural system. In the case of extreme high temperatures, the evaporation of water vapor in the atmosphere accelerates. When the water vapor reaches a certain degree of saturation, precipitation is likely to form. However, if the precipitation is insufficient to alleviate the drought caused by the high temperature, it may instead exacerbate the severity of the drought, as the high temperature will accelerate the evaporation of soil moisture. On the other hand, extreme precipitation may bring about a brief period of cool weather, but subsequently, due to the rapid evaporation of water, the temperature may rise rapidly again, creating "hot and humid" weather conditions that are unfavorable for crop growth. In winter, the combined effect of extreme low temperatures and precipitation may lead to severe freezing disasters, causing direct damage to crops and agricultural facilities. Cold and rainy weather in spring may lead to delayed crop growth or hindered physiological activities, resulting in a reduction in agricultural production. The alternating occurrence of extreme high temperatures and extreme low temperatures may pose a great challenge to the growth cycle of crops. High temperatures may cause heat damage to crops, while low temperatures may cause cold damage. Such significant fluctuations in temperature may also affect the activity of soil microorganisms, thereby influencing soil fertility and the nutrient absorption of crops. The combined effects of extreme weather will seriously affect the disaster resistance capacity of crops. On the one hand, the combined effects of extreme high temperatures, low temperatures, and precipitation may make agricultural disasters more complex, and the severity and scope of the disasters may be further expanded. For example, high temperature and drought may lead to the withering and death of crops, and subsequent heavy rains may exacerbate soil erosion and the outbreak of crop diseases and pests. On the other hand, it reduces the stress resistance and yield of crops: Extreme weather conditions may lead to the hindered growth and development of crops, reducing their abilities to resist drought, cold, and diseases, as well as their yields. High temperatures may cause damage or death to crop leaves, affecting photosynthesis and nutrient absorption; low temperatures may lead to slow crop growth, reduced yields, and even freezing damage.

The impact of extreme weather on the development of the agricultural economy has drawn significant attention from scholars. Pulighe et al. (2024) conducted a study on the impacts of climate change on the yields and revenues of three Italian agricultural and food value chains (viticulture, fruits and vegetables, and dairy cows). The study demonstrated that climate change has already affected crop productivity and income levels, and rising temperatures, changes in precipitation patterns, and extreme weather events have been identified as the main driving factors. Furtak and Walinska (2022) research, starting from environmental factors, shows that extreme weather such as floods and droughts has a certain impact on soil microorganisms, and changes in soil moisture are important factors affecting crop growth and yields, which in turn will have an impact on the agricultural economy. Schmitt et al. (2022) and others conducted a comprehensive assessment of the impacts of various extreme weather events on multiple crops. Specifically, they compared the impacts of frost, high temperatures, droughts, and waterlogging on the yields of winter wheat, winter barley, winter rapeseed, and grain corn in Germany, and monetized the historical yield losses caused by extreme weather events at the spatial classification level. Gouveia et al. (2023) mainly studied the impacts of extreme climates on the spatiotemporal distribution within the agricultural economic system, with a focus on considering the impacts on crops in South American countries under different climate scenarios. Jatuporn and Takeuchi (2023) and others used a panel data set of 76 provinces in Thailand from 1995 to 2019 to analyze the impacts of climate change on the economic growth of the agricultural sector and its variability. The research results show that extreme weather events have a negative impact on the agricultural economy, but an increase in total rainfall is positively correlated with the agricultural economy. An increase in extreme temperatures will reduce the variability of agricultural growth. Do et al. (2021) and others used a panel data set from 2000 to 2018 to analyze the impacts of extreme weather events and climate change on the outputs of agricultural and fishery enterprises in the central and central highland regions of Vietnam. The research results indicate that extreme weather events and climate change have had a negative impact on the agricultural and fishery enterprises in this region.

The resilience of the agricultural economy refers to the ability of the agricultural economic system to maintain its own operation when facing external shocks (Popescu et al., 2023). Based on the evaluation of relevant indicators, some scholars have started to explore the influencing factors of agricultural economic resilience. For instance, Yao et al. (2024) argued that the agglomeration of the agricultural industry can enhance socialized services and improve agricultural production efficiency, thereby significantly enhancing the resilience of the agricultural economy. Some scholars have also pointed out that crop diversity (Mattas et al., 2024) can similarly promote the enhancement of rural economic resilience. As one of the effective means of risk compensation (Zhichkin et al., 2023), agricultural insurance is widely used to mitigate the impacts of natural disasters and compensate for losses, which is crucial for stabilizing agricultural production and development. Many existing studies have shown that agricultural insurance is conducive to poverty alleviation in rural areas, increasing farmers' income, withstanding risks in agricultural production (Seamon et al., 2023), and promoting the stable development of the agricultural economy. In 2022, the central and southern regions of Italy were severely affected by extreme weather, resulting in agricultural losses of over six billion euros, and the crop yields in some areas even decreased by 80%. In the face of such catastrophic losses, agricultural insurance played an important role. Theoretically, as a professional financial tool for managing risks in agricultural production, agricultural insurance can effectively disperse the risks in agricultural production and operation, and improve the ability of agriculture to withstand risks. It has an inherent consistency with the ability of agricultural economic resilience to resist shocks and damages. However, there is still a lack of further empirical analysis on whether agricultural insurance can truly mitigate the impact of extreme weather on agricultural economic resilience.

In summary, against the backdrop of the frequent occurrence of extreme weather conditions, it is of utmost urgency to scientifically assess the impact of extreme weather on the resilience of the agricultural economy, further actively exert the regulatory role of agricultural insurance, enhance the resilience of the agricultural economy, and mitigate agricultural climate risks. Existing studies have conducted extensive research on the impact of climate change on agricultural production. However, they have not fully revealed the impact effects of extreme weather, such as extreme high temperatures, extreme low temperatures, and extreme precipitation, on the agricultural economy. There is a lack of research on the theoretical framework of agricultural economic resilience, as well as an in-depth examination of the potential role of agricultural insurance in alleviating the impacts of extreme weather. Unlike most existing studies that analyze from the perspectives of the impact of climate change on the agricultural economy and the impact of agricultural insurance on the agricultural economy, this paper focuses on extreme weather and agricultural economic resilience. By using the entropy method, it scientifically constructs the concept of agricultural economic resilience, providing new insights for the theoretical development of agricultural economic resilience. Moreover, this paper introduces agricultural insurance as a moderating variable to explore the effectiveness of agricultural insurance in enhancing agricultural economic resilience under extreme weather conditions. This study effectively expands the existing research framework and offers a new perspective for understanding the adaptability of the agricultural economic system when confronted with uncertain factors.

In view of this, based on the analysis of the theoretical mechanism by which extreme weather affects the resilience of the agricultural economy, this paper conducts an empirical analysis of the impact of extreme weather on the resilience of the agricultural economy and tests the mitigating effect of agricultural insurance therein, with the aim of providing policy references for agriculture to adapt to climate change and enhance the resilience of the agricultural economy. The marginal contributions of this paper mainly lie in the following aspects: 1) From the perspective of agricultural economic resilience, it examines the impacts of extreme high temperatures, extreme low temperatures, and extreme precipitation on the agricultural economy, providing new theoretical insights for the high-quality development of the agricultural economy and making up for the deficiency in the existing literature regarding the research on agricultural economic resilience. 2) It scientifically constructs an indicator system for agricultural economic resilience and conducts reasonable measurements thereof. Using the entropy method, it measures agricultural economic resilience through a total of 15 indicators from three dimensions (the pressure layer, the state layer, and the response layer). The measurement of extreme weather is represented by the number of days when the daily maximum temperature (daily minimum temperature) is greater than (less than) the 90th percentile value, and extreme precipitation is represented by the number of days when the daily heavy precipitation is greater than the 90th percentile value. At the same time, the moderating role of agricultural insurance is introduced to reveal the positive role of agricultural insurance in mitigating the impacts brought about by extreme weather and enhancing the resilience of the agricultural economy. 3) Despite the fact that this research was executed within a circumscribed geographical scope, the ramifications of extreme weather events on the agricultural economy exhibit a remarkable degree of universality on a global scale. Consequently, the findings and policy proposals derived from this study possess broad applicability to other nations. In particular, it is advisable to propel the high-quality development of agricultural insurance and enhance the resilience of the agricultural economy in a robust manner. This can be achieved by focusing on several key aspects: elevating the safeguarding standards of agricultural insurance, fortifying policy support and institutional safeguards, and nurturing the growth of new types of agricultural business entities.

The specific structure of this paper is as follows: Section 2 presents the theoretical analysis and research hypotheses. Section 3 conducts the research design, encompassing variable selection, data sources, descriptive statistics of variables, as well as model specification. Section 4 focuses on the regression results of the empirical analysis, which mainly include the benchmark regression and the moderating role of agricultural insurance. Section 5 is dedicated to the discussion, and Section 6 concludes the paper.

2 Theoretical analysis and research hypothesis

2.1 Theoretical connotation and research methods of agricultural economic resilience

The term “resilience” was first proposed by the ecologist Holling (1973), which denoted the ability of a natural system to recover or bounce back to its pre-shock state or trajectory. Subsequently, it has been widely applied in fields such as sociology and economics, and its connotation has been continuously expanded within these domains. Economic resilience (Svoboda et al., 2024) generally refers to the ability of an economic system to quickly return to its pre-shock condition when confronted with external shocks. Agricultural economic resilience follows its fundamental connotation. Agricultural economic resilience (Garreau et al., 2024) is the ability of the agricultural economy to maintain the normal operation of its own system even when facing risk shocks such as natural disasters, policy changes, and market fluctuations. Davis et al. (2024) proposed that the growth of agricultural productivity is a driving factor for economic growth and development, and enhancing agricultural productivity is also regarded as the foundation of the inclusive rural transformation process. With the continuous advancement of the modernization process, there is still an urgent need to boost the productivity of agriculture and the agricultural food system to achieve resilient and inclusive rural development. Morkunas et al. (2022) argued that the concept of agricultural economic resilience is interdisciplinary. In the research on agriculture, climate change, sustainability, and food security, agricultural economic resilience is mainly regarded as an endogenous phenomenon, which thus makes the research on agricultural economic resilience somewhat challenging. Currently, the main method for measuring agricultural economic resilience is to construct a multidimensional indicator framework (Favas et al., 2024). Most scholars conduct a restorative assessment of agricultural economic resilience through a predefined framework. Meuwissen et al. (2019) developed a framework for analyzing the attributes of the agricultural economic system, challenges (shocks, long-term pressures), indicators for measuring the functional performance of the agricultural economic system, resilience capabilities, and resilience-enhancing attributes. The novelty of this framework lies in that the focus of the analysis is mainly placed at the agricultural system level, taking into account the accumulating challenges and various agricultural processes, as well as the consideration of the multiple functions that the agricultural system can provide and which may change over time. Based on the previous research by other scholars, Roy et al. (2019) defined the framework of agricultural economic resilience as including three capabilities (i.e., absorptive, adaptive, and transformative) and five dimensions, namely, social, economic, ecological, physical, and institutional. Then, by applying a combination of top-down and bottom-up methods, 15 indicators were formulated, and the number of resilient farmers (households) after being shocked was determined according to the percentile values of the comprehensive resilience index. Volkov et al. (2021) paid more attention to the practical aspects of agricultural economic resilience and defined its core functions within a broader national economic development framework. He selected the agricultural sector of Lithuania for analysis. By choosing an index to measure the economic resilience of the agricultural sector, which was composed of variables reflecting the core functions of the agricultural sector, and the core functions of the agricultural sector included producing affordable food, ensuring the viability of farms, and providing decent-income employment opportunities for agricultural workers. Through the measurement of the agricultural economic resilience index, an important conclusion was drawn that the key factor for maintaining the resilience of the agricultural economy is the economic viability of farms. The multidimensional indicator framework of agricultural economic resilience illustrates the resistance, recovery, and transformation of agricultural production when facing external shocks from multiple dimensions, and it can reflect the core essence of agricultural economic resilience (Ginigaddara and Kodithuwakku, 2024). Therefore, this paper follows the multidimensional indicator framework, selects 15 indicators from three levels (pressure layer, state layer, and response layer), and uses the entropy method to measure agricultural economic resilience.

2.2 Impact of extreme weather on the resilience of agricultural economy

Extreme weather generally refers to extreme high temperatures, extreme low temperatures, extreme precipitation, and extreme drought. Against the backdrop of accelerating global warming, the incidence of such climatic anomalies has demonstrated a statistically significant upward trend. Agricultural production, as a biophysical process inherently reliant on solar radiation, thermal conditions, hydrological cycles, and soil fertility, exhibits inherent vulnerability due to its close coupling with environmental systems. This sector's developmental trajectory is intimately intertwined with natural resource endowments and climatic regimes (Alilla et al., 2024). Consequently, the high degree of meteorological dependency renders agriculture disproportionately vulnerable to extreme weather events compared to other economic sectors. Extreme weather events caused by significant deviations of temperature and precipitation from the average state will lead to substantial changes in the external environment of agricultural production. This will result in a decrease in agricultural production capacity levels and an increase in agricultural production costs, causing relatively large losses to agricultural economic production (Marmai et al., 2022). At the same time, the likelihood of the agricultural economy recovering in a short period of time decreases, and the resilience of the agricultural economy is reduced. Specifically, the impact of extreme weather on the resilience of the agricultural economy can be divided into the following three aspects.

Extreme weather phenomena are likely to increase the uncertainty of agricultural productivity. The occurrence of extreme weather events such as heavy rainfall, floods, and high temperatures has, to a certain extent, altered the production factors required for agricultural production. This has led to the advancement of the growth and development period of crops and the change of the growth cycle of crops (Aragón et al., 2021), thus resulting in a decrease in the yield and quality of crops and causing a reduction in crop production. The change in the meteorological pattern has greatly enhanced the volatility of crop yields. The risk of crops being damaged during the production process has increased, exacerbating the uncertainty of agricultural production, and thus affecting the resilience of the agricultural economy.

Extreme weather phenomena are likely to increase the production costs of crops (dos Santos et al., 2024). For the agricultural economic system to maintain its own stable agricultural economic resilience, it is necessary to invest corresponding production costs. The production costs of crops include two aspects: adaptive costs and restorative costs. Adaptive costs refer to the costs incurred by agricultural producers for taking corresponding preventive measures in response to changes in the external environment such as climate change, such as improving the irrigation system and cultivating stress-resistant varieties. Restoration costs refer to the costs that agricultural production workers need to bear to restore the agricultural production system to its normal operation state after natural disasters or other extreme events occur. Extreme weather events lead to the destruction of the stability of the agricultural system. In order to cope with the shortage of irrigation water sources caused by extreme high temperatures, the cold resistance requirements of crops due to extreme low temperatures, the demand for the construction of farmland water conservancy facilities caused by extreme precipitation, and the risk of diseases and pests brought about by extreme weather, the agricultural sector has to increase expenditures on pesticides and fertilizers to ensure yields. At the same time, more human and financial resources are invested in agricultural infrastructure (Tang et al., 2024), which will lead to a continuous increase in the adaptive and restorative costs of agricultural production and further increase the costs of agricultural economic resilience.

Extreme weather phenomena affect the agricultural production environment. Extreme weather events will damage the natural environment in which crops grow. When the agricultural production environment is disturbed by a series of climatic factors, the growth cycle of crops, their ability to resist diseases and pests, and the quality and yield of agricultural products will all be damaged to varying degrees. The destruction of the ecological environment will exacerbate the uncertainty of agricultural production. This uncertainty involves crop output and the maintenance costs of crops, which will have a huge impact on the entire industrial chain of the agricultural system, thus exacerbating the uncertainty of agricultural economic resilience.

In conclusion, the frequent occurrence of extreme weather will damage agricultural productivity by affecting agricultural productivity, increasing agricultural production costs, and impacting the agricultural production environment, and further affect the development level of agricultural economic resilience. Based on the analysis of the theoretical connotations related to agricultural economic resilience, the following research hypotheses can be derived.

H1: Extreme weather will have an adverse impact on agricultural economic resilience.

2.3 The regulating role of agricultural insurance

Agricultural insurance is a type of indemnity insurance specifically designed to provide coverage for agricultural producers. It offers protection against economic losses incurred during the production processes of planting, forestry, animal husbandry, and fishery, which are caused by natural disasters, accidental incidents, and other such events. As a fundamental tool for modern agricultural risk management, agricultural insurance exerts a significant influence on the shaping of agricultural economic resilience. It is capable of diversifying the risks of natural disasters in agricultural production and

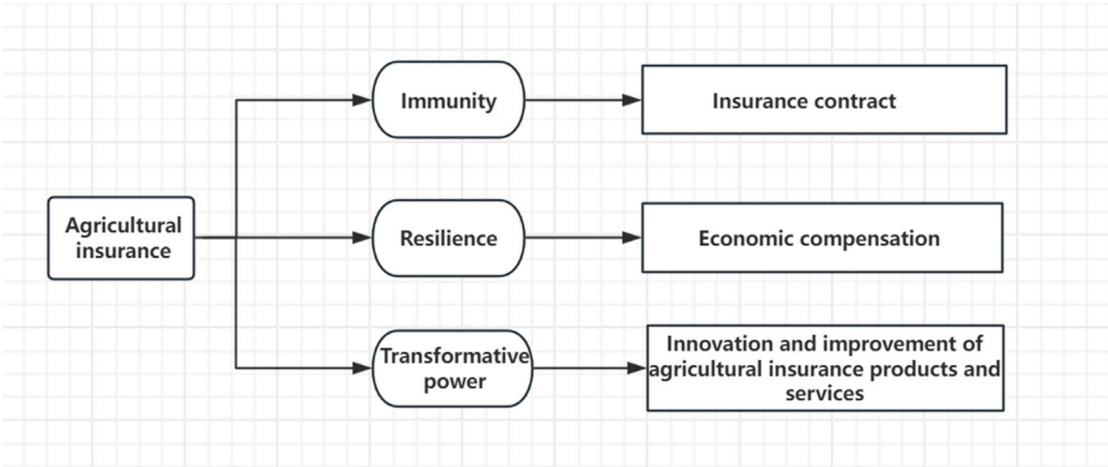

FIGURE 1
The diagram of the mechanism of action of agricultural insurance.

compensating for the losses caused by extreme weather phenomena (Santeramo et al., 2024), and it possesses the advantages of pre-event risk management and post-event loss compensation. The internal mechanism of interaction between agricultural insurance and agricultural economic resilience can be understood from three dimensions: resistance, recoverability, and transformative capacity (see Figure 1 The Diagram of the Mechanism of Action of Agricultural Insurance).

Agricultural insurance contributes to enhancing the resistance of the agricultural economic system. Resistance refers to the ability of the agricultural economic system to maintain its normal operation even after being impacted by risks from uncertain factors such as natural disasters. Agricultural insurance provides relevant risk guarantees. Through insurance contracts, it encourages agricultural production workers to adopt effective risk management strategies. By implementing a series of preventive measures, such as selecting crop varieties with strong stress resistance, it aims to reduce the losses caused by the uncertainties of climate change. By encouraging agricultural producers to adopt proactive risk management strategies, it reduces the uncertainty of agricultural production losses and improves the resilience of the agricultural economy.

Agricultural insurance helps to strengthen the recoverability of the agricultural economic system. Recoverability is the ability of the agricultural economic system to repair itself after suffering from disasters. Agricultural insurance can provide a financial buffer mechanism for agricultural producers. When the prices of crops fluctuate due to the impact of extreme weather, agricultural insurance, to a certain extent, provides economic compensation for agricultural production workers, directly influencing the resilience of the agricultural economy through the realization of its risk loss compensation function. The compensation provided by agricultural insurance can be quickly credited to the account shortly after a disaster. After receiving the post-disaster insurance compensation, agricultural producers can promptly purchase production raw materials, production tools, and repair damaged farmland, etc., thus quickly resuming normal production and operation activities, shortening the recovery period of the agricultural ecosystem, achieving the rapid recovery of the agricultural economy, and strengthening the resilience of the agricultural economy.

Agricultural insurance contributes to enhancing the transformative capacity of the agricultural economic system. Transformative capacity refers to the ability of the agricultural economic system to achieve self-renewal after being impacted by risk factors such as natural disasters. With the frequent occurrence of extreme weather phenomena and the continuous emergence of new agricultural risks, agricultural insurance, as a policy tool and means for risk prevention, continuously innovates and improves its risk resistance capabilities. The popularization of agricultural insurance has enhanced the risk awareness of a large number of agricultural producers, prompting them to adopt a series of measures to reduce risk losses. For instance, it can guide farmers to engage in large-scale operations, adjust the planting structure, improve production technologies, and so on, thereby optimizing the conditions for agricultural production. This not only provides a relatively solid foundation for the agricultural economic system to withstand risk shocks but also offers hardware support for the recovery and development of the agricultural economic system. Therefore, agricultural insurance can serve as an effective barometer for measuring the impact of extreme weather on agriculture (Seamon et al., 2023). Based on the above analysis, the following research hypothesis can be derived.

H2: Agricultural insurance will be able to mitigate the adverse impact of extreme weather on the resilience of the agricultural economy.

3 Materials and methods

3.1 Variable selection

3.1.1 Explained variables

In this paper, the Pressure-State-Response model (PSR model) is adopted for constructing the indicator system of agricultural

TABLE 1 Agricultural economic resilience index evaluation system.

Evaluation level	Index level	unit	Direction of action
Bed of pressure	Crop affected area	(hectares)	negative
	Crop disaster area	(hectares)	negative
	Population affected by natural disasters	(ten thousand)	negative
State layer	Growth rate of value added of primary industry	(%)	positive
	Total output value of agriculture, forestry, animal husbandry and fishery	(Hundred million)	positive
	Gross output value of primary industry/GDP	(%)	positive
	Per capital grain output	(kilogram)	positive
	Grain production/planted area	(%)	positive
	Total sown area of crops	(Ten thousand hectares)	positive
	Multiple cropping index	(%)	positive
	Cultivated area	(hectares)	positive
Response layer	Local government expenditure on science and technology	(Hundred million)	positive
	Government expenditure on agriculture, forestry and water conservancy	(Hundred million)	positive
	Effective irrigation rate	(%)	positive
	Total power of agricultural machinery	(megawatt)	positive

economic resilience. Meanwhile, based on the principles of data availability, rationality, and scientificity, 15 indicators are selected to measure the agricultural economic resilience (RES) from these three aspects respectively (see Table 1. Agricultural economic resilience index evaluation system).

In the PSR model, "Pressure (P)" refers to the external forces exerted on the environmental system by natural or human activities, focusing on the causes of system changes. "State (S)" refers to the condition of the environmental system when it is under pressure, reflecting the characteristics of changes in environmental elements. "Response (R)" represents the self-adjustment made by the system to cope with changes, which are the measures taken by the system to mitigate, prevent, or restore the changes. From this, it can be seen that the PSR model can systematically present the dynamic process of the agricultural economic system being impacted by risks and its subsequent recovery. Therefore, corresponding to the three processes of pressure, state, and response in the PSR model respectively, this paper divides the agricultural economic resilience into three stages: before, during, and after the risk disturbance, and divides the operation mechanism of agricultural economic resilience into the following three aspects.

(1) The pressure layer: During the development process of the agricultural economic system, both internal and external disasters exert pressure on agricultural production. Disasters such as floods and droughts that threaten the normal operation of the system have a negative impact. Three indicators, namely, the affected area of crops, the area of crops suffering serious damage, and the number of people affected by natural disasters, are selected for measurement. These indicators reflect the efforts in ecological protection and restoration of agricultural production in the region.
(2) The state layer: During the operation of the agricultural economy, the changes in the state of the system under pressure reflect its ability to resist pressure. Production conditions and the economic foundation are important elements for ensuring the resilience of the agricultural economy. Indicators such as the growth rate of added value of the primary industry, the total output value of agriculture, forestry, animal husbandry, and fishery, the ratio of the total output value of the primary industry to GDP, *per capita* grain output, the ratio of grain output to sown area, the sown area of crops, the multiple cropping index, and the cultivated land area are selected. These indicators reflect the endowment of basic resources for agricultural production, the ability to withstand agricultural risks, the degree of loss retention when impacted, and the potential for rapid handling in the face of impacts.
(3) The response layer: It refers to the active intervention and regulation of the agricultural economic system by human forces to restore it to a balanced state. Indicators such as local fiscal expenditure on science and technology, expenditure on agriculture, forestry, and water affairs, the effective irrigation rate, and the total power of agricultural machinery are selected. These indicators reflect the infrastructure and scientific and technological level of agricultural production in the region.

The entropy method (Satı, 2024), as an objective weighting method, reflects the degree of data dispersion by calculating the information entropy, and then determines the weights of each indicator. This method avoids the interference of subjective factors, making the evaluation results more objective and scientific. In comparison with the core variable method, when dealing with the problem of comprehensive evaluation of multiple indicators, the entropy method has certain advantages in terms of objectivity, precision, and flexibility.

Therefore, this paper uses the panel data of 31 provinces (autonomous regions and municipalities directly under the Central Government) in China excluding Hong Kong, Macao and Taiwan regions from 2011 to 2022 to measure the agricultural economic resilience. Since the indicators may have positive or negative impacts on the system, the data are first standardized. Here, y_{ij} represents the standardized result of the *jth* indicator x_{ij} in the *ith* province, and min (x_{ij}) and max (x_{ij}) represent the minimum and maximum values of this indicator respectively. The specific process is as follows, Formulas 1-6 therein represent the calculation process of the entropy method, and the Score value in Formula 6 represents the final result of the measurement of agricultural economic resilience.

Forward indicator processing:

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{1}$$

Negative indicator processing:

$$y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{2}$$

Calculate the weight of the JTH indicator:

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} \mathrm{y_{ij}}} \tag{3}$$

Calculate the entropy of the JTH index:

$$\mathrm{e}_j = -K^* \sum_{\mathrm{i}=1}^{\mathrm{n}} \left(\mathrm{y}_{ij}{}^* \ln(\mathrm{y}_{ij})\right) \tag{4}$$

among: $K = \frac{1}{\ln(n)}$.

The weight of the calculated index is:

$$w_j = \frac{1 - e_j}{\sum_{j=1} (1 - e_j)} \tag{5}$$

The comprehensive score of each sample is calculated as follows:

$$\mathrm{Score_i} = \sum_{\mathrm{j}} \mathrm{w_j} \times \mathrm{y_{ij}} \tag{6}$$

3.1.2 Core explanatory variables

Extreme weather is the core explanatory variable in this paper. In this study, extreme high temperature (EHT), extreme low temperature (ELT), and extreme precipitation (EP) are employed to measure extreme weather. According to the core indices of extreme climate recommended by the World Meteorological Organization (WMO) (Alexander et al., 2006), and the definitions of extreme climate indices by the Expert Team on Climate Change Detection and Indices, the number of days with the daily maximum temperature exceeding the 90th percentile value is selected to represent extreme high temperature. The number of days with the daily minimum temperature below the 90th percentile value is used to represent extreme low temperature (Brunner and Voigt, 2024). The heavy precipitation amount in the extreme precipitation index is chosen to represent extreme precipitation, that is, the number of days with the daily precipitation exceeding the 90th percentile value (Duan et al., 2024).

3.1.3 Adjusting variables

The moderating variable in this paper is agricultural insurance (AIS), and in this study, the premium income of agricultural insurance in each province is selected to measure agricultural insurance. The provincial premium income of agricultural insurance can examine the coverage and development status of agricultural insurance as a whole, and to a certain extent, it reflects the connection between the agricultural industry and the insurance industry.

3.1.4 Control variables

It is taken into account that the agricultural economic system itself will be influenced by various aspects, such as the construction of agricultural infrastructure, the intensity of agricultural support policies, the regional market scale, the input of agricultural factors, and the level of economic development. Following the principles of scientificity and operability of the data, this paper selects the electricity consumption in rural areas (ECR), the intensity of financial support for agriculture (FISC), the total retail sales of consumer goods (CSP), the investment in fixed assets of agriculture, forestry, animal husbandry and fishery (IFA), and the urban-rural income ratio (INC) as control variables to control the impacts of other factors on the resilience of the agricultural economy.

① Construction of agricultural infrastructure. Regions with a higher level of agricultural infrastructure construction have well-developed rural electricity and farmland water conservancy facilities, which significantly enhance the agricultural production capacity and the ability to prevent and mitigate disasters, and improve the resilience of the agricultural economy. In this paper, the electricity consumption in rural areas (ECR) is selected to represent the construction of agricultural infrastructure.

② Intensity of agricultural support policies. The healthy development of the agricultural economy cannot be separated from the government's support in economic, policy and other aspects. Regions with more financial support for agriculture can introduce advanced agricultural machinery and excellent varieties. This can not only improve agricultural production efficiency but also enhance the ability of regional agriculture to resist risks. In this paper, the proportion of financial expenditure on agriculture, forestry and fishery in the total financial expenditure (FISC) is selected to represent the intensity of government support.

③ Regional market scale. The vigorous development of the agricultural economy requires not only a solid agricultural foundation but also a good market environment. A larger market scale can invigorate the regional economy, increase consumption and investment demands, and has an important impact on the improvement of the resilience of the agricultural economy. In this paper, the total retail sales of consumer goods (CSP) is selected to represent the regional market scale.

TABLE 2 Descriptive statistics of variables.

Variables	Index level	Observations	Mean	S.D.	Min	Max
Dependent	RES	372	0.3531	0.1403	0.1079	0.6656
Core explanatory variable	EHT	372	59.35	14.86	24	105
	ELT	372	30.46	12.41	4	59
	EP	372	10.78	4.59	2	23
Control variable	ECR	372	274.60	390.7	1.2	1888
	FISC	372	0.1150	0.0339	0.0412	0.1879
	CSP	372	10454.84	9,139.084	270.42	44882.92
	IFA	372	805.35	810.63	3.52	4,214.31
	INC	372	2.5608	0.3812	1.8485	3.6069
Regulating variable	AIS	372	1750.57	1,669.5	18.93	8,200.65

Note:"RES" measures the resilience of the agricultural economy. "EHT" refers to the proportion of extreme weather caused by heat. "ELT" refers to the proportion of extreme weather caused by low temperatures. "EP" refers to the proportion of extreme weather caused by rainfall.
"ECR" refers to rural electricity consumption, "FISC" refers to the proportion of agricultural fiscal expenditure in total fiscal expenditure, "CSP" refers to the total amount of consumer goods supplied by various industries such as residents and society, and "IFA" refers to the investment in fixed assets in agriculture, forestry, animal husbandry and fisheries. "INC" refers to the ratio of the per capital disposable income of urban residents to the per capital disposable income of rural residents, and "AIS" refers to the agricultural insurance premium income.

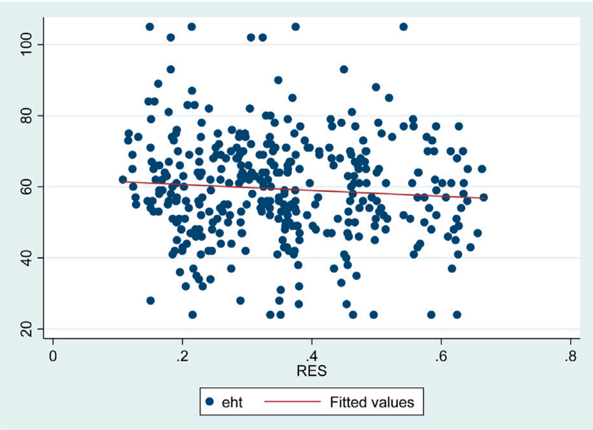

FIGURE 2
Scatter plot of agricultural economic resilience and extreme heat.

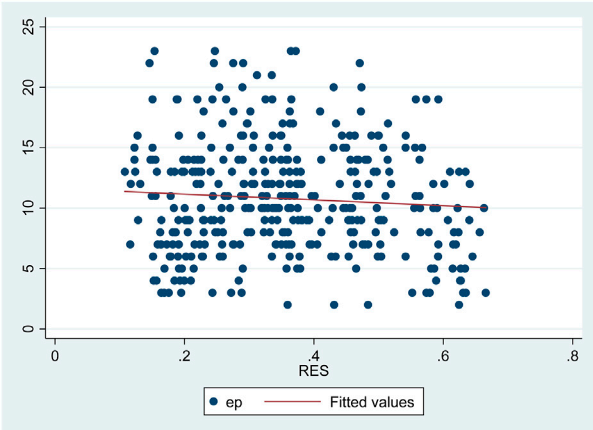

FIGURE 3
Scatter plot of agricultural economic resilience and extreme precipitation.

④ Input of agricultural factors. The agricultural production process is inseparable from the input of production factors such as human and material resources. In regions with more input of agricultural production factors, it is easier to form large-scale agricultural production, and the resilience of the agricultural economy is higher. In this paper, the investment in fixed assets of agriculture, forestry, animal husbandry and fishery is selected to represent the level of input of agricultural factors.

⑤ Level of economic development. Regions with a higher level of economic development have a solid economic foundation, superior agricultural production conditions, and a relatively high level of agricultural modernization, so they have stronger resilience of the agricultural economy. In this paper, the urban-rural income ratio (INC, the ratio of the *per capita* income in urban areas to that in rural areas) is selected to represent the level of economic development.

3.2 Data sources and descriptive statistics of variables

Based on the availability of data and ensuring the rationality of samples, this paper uses the balanced panel data of 31 provinces in China from 2011 to 2022 as research samples for empirical analysis. The data mainly come from China Statistical Yearbook (https://www.stats.gov.cn/sj/ndsj/), China Rural Statistical Yearbook (https://www.stats.gov.cn/zs/tjwh/), provincial statistical Yearbook (https://gdzd.stats.gov.cn/dcsj/gdsnjsj/), National Bureau of Statistics of China (https://www.stats.gov.cn/sj/ndsj/), National

TABLE 3 The results of the Variance Inflation Factor (VIF) test.

Variable	VIF	Variable	VIF
EHT	1.14	FISC	1.79
ELT	1.13	CSP	3.34
EP	1.10	IFA	1.47
ECR	2.33	INC	1.39

Meteorological science data Sharing Service Platform (https://www.geodata.cn/data/), *etc.* We do encounter some difficulties in terms of data acquisition. To maintain the sample size, we use the interpolation method to complete some of the missing data. Taking agricultural insurance (AIS) as an example, for the situation where AISt-1 and AISt+1 are known but AISt is missing, the linear interpolation value of AISt with respect to time is $\hat{X}_t = \frac{X_{t-1}+X_{t+1}}{2}$. If more accurate data can be obtained, we will continue to advance our research. Table 2. Descriptive statistics of variables presents the descriptive statistics of the main variables in this paper. Among them, the mean value of agricultural economic resilience is 0.3531, the minimum value is 0.1079, and the maximum value is 0.6656. This indicates that there are significant differences in agricultural economic resilience among different provinces. Meanwhile, there are also substantial disparities in extreme high temperature, extreme low temperature, and extreme precipitation among different provinces. Figure 2. Scatter plot of agricultural economic resilience and extreme heat and Figure 3. Scatter plot of agricultural economic resilience and extreme precipitation present the scatter plots of agricultural economic resilience (RES) against extreme heat (EHT) and extreme precipitation (EP) respectively. From these scatter plots, it can be roughly observed that there exists an obvious negative correlation between agricultural economic resilience and extreme weather changes.

3.3 Model setting

3.3.1 Benchmark regression model

This study verifies that extreme weather will have an adverse impact on the resilience of the agricultural economy based on the random effects model and the fixed effects model. Through the Hausman test, it is found that the p-value is 0.0000. Therefore, it is more reasonable to use the fixed effects model (van der Veer et al., 2024) for parameter estimation.

$$RES_{i,t} = \beta WEAT_{i,t} + \gamma X_{i,t} + \theta_i + \delta_t + \varepsilon_{i,t} + \alpha \tag{7}$$

In the above model, $RES_{i,t}$ represents the agricultural economic resilience of the i province in the t year, and $WEAT_{i,t}$ represents the extreme weather of the i province in the t year, including extreme high temperature, extreme low temperature and extreme precipitation. X_i and t represent a series of control variables, including rural electricity consumption, fiscal support for agriculture, rural-urban income ratio, total retail sales of social consumer goods, and fixed asset investment in agriculture, forestry, animal husbandry and fishery. θ_i and δ_t represent the region fixed effect and year fixed effect, $\varepsilon_{i,t}$ represent the random error term, β and γ represent the parameters to be estimated, α is the constant term.

3.3.2 Adjustment effect model

In order to test the regulatory role of agricultural insurance in the impact of extreme weather on the resilience of agricultural economy, this paper constructs the following regulatory model:

$$RES_{i,t} = \beta WEAT_{i,t} + \phi_1 AIS_{i,t} + \phi_2 WEAT_{i,t} \times AIS_{i,t} + \gamma X_{i,t} + \theta_i + \delta_t + \varepsilon_{i,t} \tag{8}$$

In the above model, $AIS_{i,t}$ represents the agricultural insurance premium income in the year t of the i province, $WEAT_{i,t} \times AIS_{i,t}$ represents the interaction term between extreme weather and agricultural insurance premium income, and the estimated coefficient φ_2 reflects the regulating effect of agricultural insurance premium income on the impact of extreme weather on the resilience of agricultural economy. If φ_2 and β are the same symbols, It indicates that agricultural insurance strengthens the impact of climate change on the resilience of agricultural economy, and *vice versa* indicates that agricultural insurance plays a mitigating role.

3.4 Testing and revision of the model

3.4.1 Multicollinearity test

This paper employs the Variance Inflation Factor method (VIF test) to examine multicollinearity. The Stata software is utilized to calculate the Variance Inflation Factor (VIF) for each explanatory variable (see Table 3. The results of the Variance Inflation Factor (VIF) test), if 0 < VIF <10, there is no multicollinearity; if 10 < VIF <100, there exists a relatively strong multicollinearity. It is found that the VIF values of all explanatory variables are less than 10. Therefore, there is no multicollinearity in this model.

3.4.2 Heteroscedasticity test

This paper adopts the White test to examine heteroscedasticity. The White test is conducted at a significance level of $\alpha = 0.05$. The test results show that the p-value (Prob > chi2) is equal to 0.0000. Therefore, the null hypothesis of homoscedasticity is strongly rejected, and it is concluded that heteroscedasticity exists. To address the issue of heteroscedasticity, in the subsequent empirical analysis of this study, Robust Standard Errors are employed to estimate the regression model.

4 Results

4.1 Temporal evolution of provincial agricultural economic resilience

The trends of the resilience of the agricultural economy and the volatility rate of the resilience of the agricultural economy in 31 provinces (autonomous regions and municipalities directly under the Central Government) from 2011 to 2021 are shown in Figure 4. Trend chart of agricultural economic resilience in various

FIGURE 4
Trend chart of agricultural economic resilience in various provinces from 2011 to 2022.

TABLE 4 The volatility rate of the resilience of the agricultural economy in each province from 2011 to 2022.

Province (autonomous regions and municipalities)	Volatility	Province (autonomous regions and municipalities)	Volatility	Province (autonomous regions and municipalities)	Volatility
Beijing	0.046	Anhui	0.023	Sichuan	0.025
Tianjin	0.020	Fujian	0.017	Guizhou	0.039
Hebei	0.018	Jiangxi	0.015	Yunnan	0.017
Shanxi	0.018	Shandong	0.025	Xizang	0.016
Inner Mongolia	0.014	Henan	0.020	Shaanxi	0.010
Liaoning	0.040	Hubei	0.024	Gansu	0.016
Jilin	0.015	Hunan	0.025	Qinghai	0.016
Heilongjiang	0.033	Guangdong	0.035	Ningxia	0.013
Shanghai	0.043	Guangxi	0.015	Xinjiang	0.020
Jiangsu	0.025	Hainan	0.023		
Zhejiang	0.026	Chongqing	0.012		

TABLE 5 Baseline regression results.

Variables	Model 1	Model 2	Model 3	Model 4
	RES	RES	RES	RES
EHT	−0.000**	−0.000***	−0.000**	−0.000***
	(-2.19)	(-2.71)	(-2.13)	(-2.64)
ELT	−0.000	−0.000	−0.000	−0.000
	(-0.43)	(-0.40)	(-0.48)	(-0.45)
EP	−0.000	−0.000	——	——
	(-0.94)	(-0.92)	——	——
ECR	——	0.000	——	0.000
	——	(0.87)	——	(0.82)
IFA	——	0.000***	——	0.000***
	——	(3.34)	——	(3.38)
FISC	——	0.39***	——	0.389***
	——	(3.49)	——	(3.49)
CSP	——	0.000**	——	0.000**
	——	(2.22)	——	(2.21)
INC	——	−0.075***	——	−0.075***
	——	(-2.96)	——	(-2.98)
Constant	0.377***	0.499***	−0.370***	0.494***
	(30.44)	(7.08)	(41.91)	(7.11)
Observations	372	372	372	372
R^2	0.976	0.979	0.976	0.979
id Fe	Yes	Yes	Yes	Yes
year Fe	Yes	Yes	Yes	Yes

Note:T-statistics in parentheses,*、 ** and *** represent the significance levels of 10%, 5% and 1%, respectively.

provinces from 2011 to 2022 and Table 4. The volatility rate of the resilience of the agricultural economy in each province from 2011 to 2022 As can be seen from the figure, the resilience of the agricultural economy in most provinces in China shows an upward trend. The volatility rates of the resilience of the agricultural economy in regions such as Beijing, Shanghai and Liaoning are relatively large. The results indicate that, from the provincial-level analysis, the ability of agricultural production in most provinces to cope with risks has gradually improved, which can provide a certain degree of safety guarantee for agricultural economic production to some extent. Although the economic levels in places like Shanghai and Beijing are relatively developed, they are restricted by the small area of cultivated land and the small number of laborers willing to engage in agriculture. Therefore, the development level of the resilience of the agricultural economy in these areas fails to keep pace with the economic development level. Inner Mongolia, Qinghai and other places are restricted by the geographical environment. These places are located on the plateau, with high altitude and low temperature. Moreover, restricted by the level of economic development, agriculture cannot achieve modern operation well, so the development level of the resilience of the agricultural economy is low. Regions such as Heilongjiang and Liaoning are major grain-producing areas in China. They have a vast territory and are suitable for vigorously developing agriculture. With the strong support of government policies, the process of agricultural modernization has been continuously promoted, which is conducive to the improvement of the resilience of the agricultural economy to a certain extent. However, the relatively large volatility rate of the resilience of the agricultural economy in Liaoning is mainly due to the frequent occurrence of natural disasters.

4.2 Baseline regression

In order to test the hypothesis proposed above, this paper conducted an empirical test on the benchmark relationship between extreme weather and agricultural economic resilience. The results of the fixed effect regression model are shown in Table 5. Baseline regression results. Considering that extreme high temperature, extreme low temperature and extreme precipitation are the most important characteristics of extreme weather changes, Therefore, this paper only considers the models with the simultaneous changes of extreme high temperature, extreme low temperature and extreme rainfall for regression analysis.

Model one is a fixed effects model without adding control variables. The research findings show that extreme high temperature is significant at the 5% level, indicating that extreme high temperature has a significant inhibitory effect on the resilience of the agricultural economy. Meanwhile, the estimated coefficients of extreme low temperature and extreme precipitation are −0.43 and −0.94 respectively. Model two is a fixed effects model of extreme high temperature, extreme low temperature, and extreme precipitation after adding control variables. After adding the control variables, extreme high temperature remains significantly negative, and the significance level is stronger. The statistical significance has increased from 5% to 1%. Compared with Model 1, after adding the control variables, the regression coefficients of extreme low temperature and extreme precipitation fluctuate slightly, but they are still negative in a statistical sense. This implies that both extreme low temperature and extreme precipitation will affect the resilience of the agricultural economy to a certain extent, but there may be differences in the degree of influence. Model three and Model four respectively illustrate the fixed effects with and without adding control variables when extreme precipitation is not considered. Similar to the results of Model one and Model 2, after further adding control variables, the regression coefficient of extreme high temperature is also significantly negative, and the regression coefficient shows the characteristics of "a decrease in the coefficient value and an increase in significance". Combining with Model two that takes into account the factor of extreme precipitation, this result indicates that regardless of whether extreme precipitation is considered or not, the inhibitory effect of extreme high temperature on the resilience of the agricultural economy holds. At the same time, the regression coefficients of extreme precipitation are all negative, which shows that extreme precipitation will also have an adverse impact on the resilience of the agricultural economy. However, its regression coefficients are all smaller than those of extreme high temperature, indicating that compared with the impact of changes in extreme high temperature on the resilience of the agricultural economy, the impact of extreme precipitation on the resilience of the agricultural economy is relatively smaller. The benchmark regression results of this paper indicate that extreme high temperature, extreme low temperature, and extreme precipitation all have a certain inhibitory effect on the resilience of the agricultural economy. However, compared with the latter two, the adverse impact of extreme high temperature on the resilience of the agricultural economy is more significant.

The possible reasons for the above results are as follows: On the one hand, crops are highly sensitive to extreme high temperatures. The occurrence of extreme high temperature phenomena is usually accompanied by the occurrence of phenomena such as drought, which further exacerbates the impact on the agricultural economy. Extreme high temperatures lead to the rapid evaporation of soil moisture and the intensification of crop transpiration, thus increasing the consumption of water. The moisture in the soil cannot meet the needs of the crops, and the soil quality deteriorates, resulting in limited crop growth, decreased yields, and further damage to the resilience of the agricultural economy. High temperatures accelerate the growth rate of crops, shorten the normal growth cycle of agricultural economic crops, reduce the efficiency of photosynthesis and the ability to absorb nutrients, and affect farmland productivity. High temperatures exacerbate the breeding and spread of pests and diseases, promote the reproduction and growth of insects, are conducive to the reproduction and spread of pathogens, and increase the risk of crops being attacked by pests and diseases, thus damaging the resilience of the agricultural economy. On the other hand, with the continuous trend of climate warming, the number of extremely low temperature days in China has decreased significantly, and the number of extremely high temperature days has increased significantly, further making the negative impact of extreme high temperatures on the resilience of the agricultural economy relatively more prominent (Bottino et al., 2024). Therefore, it is necessary to strengthen the prevention of extreme high temperatures. To deal with the adverse impact of extreme high temperatures on the agricultural economy, it can be started from multiple aspects. In hot and dry weather, methods such as sprinkler irrigation and daytime irrigation with nighttime drainage can be adopted to reduce the field temperature; shading nets or plastic mulch can be used to reduce soil evaporation, maintain soil moisture, promote crop growth, improve the microclimate in the field, and achieve the goal of enhancing the agricultural economy; to deal with pests and diseases, the detection of pests and diseases in the field can be strengthened, and crops with strong resistance to pests and diseases can be selected for planting.

In contrast, although extreme low temperatures and extreme precipitation will also have an adverse impact on the resilience of the agricultural economy, the adverse impacts brought by both can usually be mitigated by taking corresponding measures. Extreme low temperatures may cause frost damage to crops or stagnation of crop growth, and heavy rain may lead to waterlogging in farmland, etc. However, the harm caused by low temperatures can be alleviated by taking cold protection measures. For example, by adjusting the sowing time of crops, using greenhouses, applying fertilizers, and other methods, the cold resistance of crops and the heat preservation performance of the soil can be improved. The problem of excessive precipitation in extreme precipitation can be improved by measures such as drainage and soil improvement, and the problem of insufficient precipitation can also be alleviated by artificial rainfall, irrigation, and other methods.

Among the control variables, the investment in fixed assets of agriculture, forestry, animal husbandry, and fishery, as well as the intensity of financial support for agriculture, have significant positive impacts on the resilience of the agricultural economy. An increase in the investment in fixed assets of agriculture, forestry, animal husbandry, and fishery (Czubak and Zmyślona, 2024) is often used to upgrade agricultural infrastructure and introduce advanced agricultural technologies and equipment, such as the construction of farmland water conservancy facilities and the introduction of intelligent agricultural equipment. This promotes agricultural modernization, increases the added value of agricultural products, and further enhances the resilience of the agricultural economy. The government continuously provides financial support for agricultural development. Financial funds

TABLE 6 Results of endogeneity problem handling and robustness test.

Variables	Endogeneity test	Robustness test				
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	RES	RES	RES	RES	RES	RES
EHT	−0.009***	−0.000**	−0.000***	−0.000***	−0.000***	−0.002**
	(-3.04)	(-2.37)	(-2.80)	(-2.81)	(-2.12)	(-2.73)
ELT	−2.660***	−0.000	−0.000	−0.000	−0.000	−0.003
	(-5.16)	(-0.43)	(-0.41)	(-0.41)	(-0.56)	(-0.79)
EP	−0.061	−0.000	−0.000	−0.000	−0.000	−0.003
	(-1.35)	(-0.93)	(-0.91)	(-0.92)	(-0.27)	(-0.12)
Control variable	Controlled	Uncontrolled	Controlled	Controlled	Controlled	Controlled
Constant	——	31.65***	5.98***	5.94***	6.19***	−0.43
	——	(0.377)	(0.428)	(0.428)	(0.57)	(-0.232)
Observations	324	324	324	324	341	324
R^2	0.613	0.980	0.983	0.983	0.983	0.972
id Fe	Yes	Yes	Yes	Yes	Yes	Yes
year Fe	Yes	Yes	Yes	Yes	Yes	Yes
F - test	20.4***	——	——	——	——	——
Anderson LM test	8.75**	——	——	——	——	——
C-D Wald F test	20.77	——	——	——	——	——
Sargan test P-value	0.82	——	——	——	——	——

Note:T-statistics in parentheses,*、 ** and *** represent the significance levels of 10%, 5% and 1%, respectively.

(Okafor et al., 2024) may be used for the introduction and promotion of agricultural technologies and the improvement of agricultural infrastructure, achieving the goal of effectively resisting natural disasters, and thus promoting the improvement of the resilience of the agricultural economy. However, the urban-rural income ratio (Vallury et al., 2024) has a significant negative impact on the resilience of the agricultural economy. The reason may be that a higher urban-rural income ratio implies a large income gap between urban and rural areas, which reflects the imbalance in urban and rural economic development. This imbalance affects the stability of agricultural economic development. Most of the rural labor force floods into cities, and at the same time, it affects the distribution of resources between urban and rural areas, leading to the outflow of talents and resources in rural areas, and further weakening the resilience of the agricultural economy. In conclusion, the research hypothesis H1 of this paper has been verified.

4.3 Handling of endogeneity problem

Although this paper has taken into account various control variables that affect the resilience of the agricultural economy and has tried to avoid the estimation bias caused by omitted variables as much as possible, there may still be endogeneity estimation bias due to other omitted variables. To this end, this paper uses the instrumental variable method to measure the possibility of bias brought about by unobserved variables. The one-period lag of extreme high temperature and the climate risk index are introduced as instrumental variables to further eliminate the possible endogeneity problems caused by omitted variables. Model one in Table 6. Results of Endogeneity Problem Handling and Robustness Test reports the estimation results of the second stage of the IV-2SLS method. The Anderson LM statistic passes the test at the 5% significance level. The C-D Wald F statistic is greater than the critical empirical value of 10%, and the p-value of the Sargan test is greater than 0.1. It can be considered that there are no problems of unidentifiable instrumental variables and weak instrumental variables, and the selection of instrumental variables is reasonable and exogenous. In addition, extreme high temperature and extreme low temperature are significantly negative at the 1% test level, and the regression coefficient of extreme precipitation is also negative, indicating that the adverse impact of extreme climate on the resilience of the agricultural economy still holds, and the research conclusion is reliable.

4.4 Robustness test

In order to further test the robustness of the baseline regression, this paper adopts the following methods to continue the regression.

TABLE 7 Results of adjustment effects.

Variables	Model 1	Model 2	Model 3	Model 4
	RES	RES	RES	RES
EHT	−0.001**	−0.006***	−0.001**	−0.008**
	(-2.39)	(-1.95)	(-2.32)	(-2.57)
ELT	−0.000	−0.001	0.000	−0.001
	(-0.43)	(-0.33)	(-0.57-)	(-0.53)
EP	−0.000	−0.000	−0.000	−0.020
	(-0.94)	(-0.92)	(-0.45)	(-2.63**)
AIS	−0.040**	0.038**	0.040**	0.032**
	(2.32)	(2.33)	(2.31)	(2.03)
AIS × EHT	——	0.001*	——	0.001**
	——	(1.76)	——	(2.38)
AIS × ELT	——	0.000	——	0.000
	——	(0.14)	——	(0.35)
AIS × EP	——	——	——	0.003***
	——	——	——	(2.66)
ECR	0.000	0.000	0.000	0.000
	(1.35)	(1.34)	(1.38)	(1.35)
IFA	0.000***	0.000***	0.000***	0.000***
	(3.64)	(3.58)	(3.62)	(3.31)
FISC	0.834**	0.660*	0.836*	0.556
	(2.23)	(1.70)	(2.23)	(1.45)
CSP	0.000***	0.000**	0.000***	0.000*
	(2.72)	(2.05)	(2.72)	(1.80)
INC	−0.198**	−0.190**	−0.198**	−0.185**
	(-2.32)	(-2.23)	(-2.31)	(-2.14)
Constant	−1.020***	−0.690**	−1.012***	−0.291
	(-4.07)	(-2.23)	(-4.05)	(-0.83)
Observations	372	372	372	372
R^2	0.976	0.976	0.976	0.977
id Fe	Yes	Yes	Yes	Yes
year Fe	Yes	Yes	Yes	Yes

Note:T-statistics in parentheses,*、 ** and *** represent the significance levels of 10%, 5% and 1%, respectively.

4.4.1 Exclude samples of municipalities directly under the central government

Considering that the agricultural economic mode and agricultural production activities of municipalities directly under the central Government are obviously different from those of other provinces and regions, the sample data of Beijing, Tianjin, Shanghai and Chongqing were excluded in this paper, and the remaining sample data were used for regression processing. The results are shown in Model two and Model three in Table 6. Results of Endogeneity Problem Handling and Robustness Test. Extreme high temperature is significantly negative at 5% level and 1% level before and after adding control variables, and the regression coefficients of extreme low temperature and extreme precipitation are still negative. The fixed effect regression coefficients after excluding the samples of municipalities are basically consistent with the basic regression results. The above regression results show that eliminating the sample of municipalities does not affect the conclusion obtained by the baseline regression.

4.4.2 Adding control variables

With the development of industry, modern agricultural technology has been widely developed and applied, which further promotes agricultural modernization. Therefore, Industrial added value (IAV) is selected as the control variable to increase, and Model four takes the added industrial added value as the control variable to conduct robustness test. The results show that the estimated coefficient of extreme high temperature is still significant at 1% level and the sign is still negative, which is basically the same as the basic regression result.

4.4.3 The control variables are lagged by one period

In order to eliminate the estimation bias resulting from reverse causality, this paper includes all control variables with a one-period lag into the regression model. According to the results of Model five in Table 6. Results of Endogeneity Problem Handling and Robustness Test, the regression coefficient of extreme high temperature is significantly negative at the 5% significance level. The regression coefficients of extreme low temperature and extreme precipitation remain negative, which is basically consistent with the results of the basic regression. Therefore, the conclusions of this paper still demonstrate robustness.

4.4.4 Replace the evaluation method of the resilience of the agricultural economy

This paper further employs the principal component analysis method to re-evaluate the resilience of the agricultural economy and conducts regression estimation again, aiming to eliminate the impact brought about by the differences in the evaluation methods of the resilience of the agricultural economy. The regression results after replacing the evaluation method of the resilience of the agricultural economy are shown in Model six of Table 6. Results of Endogeneity Problem Handling and Robustness Test: The regression coefficient of extreme high temperature is −0.002, which is very close to the result of the benchmark regression. Although the significance level has decreased, it is still significantly negative at the 5% level. The regression coefficients of extreme low temperature and extreme precipitation, though fluctuating, remain negative, indicating that extreme high temperature, extreme low temperature, and extreme precipitation all have negative impacts on the resilience of the agricultural economy to varying degrees.

The above robustness tests indicate that excluding samples from municipalities directly under the central government, adding control variables, lagging the control variables by one period, and replacing the evaluation method of the resilience of the agricultural economy have little impact on the coefficients to be estimated and their significance in the benchmark regression. This shows that the benchmark regression results of this paper are robust, and the obtained research conclusions are reliable, further verifying the research hypothesis H1 of this paper.

4.5 The regulating role of agricultural insurance

To further examine whether agricultural insurance can mitigate the impact of extreme weather and further achieve the effect of promoting the improvement of agricultural economic resilience, this paper conducts a test on the above-mentioned impact based on Formula 8. The results of the moderating effect are shown in Table 7. Results of adjustment effects. Similar to the idea of the benchmark regression analysis, this paper analyzes the situations of considering extreme high temperature, extreme low temperature, and extreme precipitation separately, as well as the situation of considering all three of them simultaneously. As can be seen from Table 7. Results of adjustment effects, the regression coefficients of extreme high temperature in the four model situations are all negative and significant at the 5% level, which further verifies the conclusion of the benchmark regression in this paper. In Model 4, the regression coefficients of the interaction terms between agricultural insurance and extreme high temperature, as well as between agricultural insurance and extreme precipitation, are both positive at the 5% level and have the opposite sign to the main effect. This indicates that, as a moderating variable, agricultural insurance significantly weakens the adverse impacts of extreme high temperature and extreme precipitation on agricultural economic resilience. At the same time, after considering the factor of agricultural insurance, the significance level of the regression coefficient of extreme high temperature decreases from the 1% level in the benchmark regression result to the 5% level, and the absolute value of the regression coefficient decreases to some extent. This, to a certain degree, shows that agricultural insurance plays a positive role in mitigating the adverse impacts of extreme weather on agricultural economic resilience.

In conclusion, the results of the moderating effect indicate that the negative impact of extreme weather on the resilience of China's agricultural economy weakens with the development of agricultural insurance. That is, agricultural insurance negatively moderates the weakening effect of extreme weather on the resilience of China's agricultural economy. Therefore, continuously promoting the development of agricultural insurance and improving the protection level of agricultural insurance are effective ways to cope with extreme weather changes and enhance agricultural economic resilience. The research hypothesis H2 of this paper has been verified.

4.6 Heterogeneity test

Based on the geographical division of China into the eastern, central, and western regions, this paper conducts grouped regression analysis on the research samples, and the benchmark regression results are shown in Table 8. Heterogeneity of Benchmark Regression Based on a Regional Perspective. The regression coefficients of extreme high temperature are negative in the eastern, central, and western regions, indicating that extreme high temperature has certain adverse effects on the resilience of the agricultural economy in different regions. However, this effect is only significant in the eastern and western regions of China. Moreover, judging from the coefficient values, the coefficient value in the central region is significantly larger than those in the eastern and western regions, suggesting that the impact of extreme high temperature on the resilience of the agricultural economy in the central region is greater than that in the eastern and western regions. The regression coefficients of extreme low temperature and extreme

TABLE 8 Heterogeneity of benchmark regression based on a regional perspective.

Variables	Eastern region	Central region	Western region
	RES	RES	RES
EHT	−0.059*	−0.001**	−0.000
	(-1.80)	(-2.58)	(-1.11)
ELT	−0.011	−0.000	−0.000
	(-0.45)	(-0.02)	(-1.65)
EP	−0.003	−0.001	−0.000
	(-1.25)	(-0.92)	(-0.53)
Control variable	Controlled	Controlled	Controlled
Constant	−1.783**	0.421***	−0.489
	(-2.09)	(4.38)	(-1.57)
R^2Observations	144	108	120
	0.972	0.982	0.982
year Feid Fe	Yes	Yes	Yes
	Yes	Yes	Yes

Note:T-statistics in parentheses,*、 ** and *** represent the significance levels of 10%, 5% and 1%, respectively.

precipitation are also negative, indicating that extreme low temperature and extreme precipitation will also have adverse effects on the resilience of the agricultural economy in different regions. Therefore, the impact of extreme climate on the resilience of the agricultural economy exhibits regional heterogeneity, among which the adverse impacts on the central and eastern regions are more obvious than those on the western region.

The regression results in Table 9. Heterogeneity of the Moderating Effect Based on a Regional Perspective verify the moderating effect of agricultural insurance on the adverse impacts of extreme climate in different regions of China. Similar to the benchmark regression results, the regression coefficients of the main effects (extreme high temperature, extreme low temperature, and extreme precipitation) are all negative. The regression coefficient of the moderating effect (the interaction term between agricultural insurance and extreme high temperature) is significantly positive in the central region, and it has the opposite sign to the main effect, indicating that agricultural insurance plays a negative moderating role in the impact of extreme high temperature on the resilience of the agricultural economy in the central region, and can effectively weaken the adverse impact of extreme high temperature on the resilience of the agricultural economy in the central region. However, the moderating effects of agricultural insurance on extreme low temperature and extreme precipitation in the central region are not significant. The reasons may be as follows: 1) In the central region of China, since the historical occurrence frequency and loss degree of extreme weather events such as extreme low temperature and extreme precipitation may not be as significant as those of extreme high temperature, insurance companies in the central region may invest less in the research and development of products related to extreme low temperature and extreme precipitation. 2) There are more high-temperature days in summer in the central region, and high temperature has a greater impact on crops. Therefore, farmers have a greater demand for compensation for extreme high temperature, and insurance companies have correspondingly increased their efforts in the research and development of insurance products in this regard. Although the central region is also affected by extreme low temperature and extreme precipitation, these extreme weather events are greatly influenced by regional factors. In some areas, extreme low temperature and extreme precipitation may not be common, which further affects farmers' willingness to purchase insurance and insurance companies' supply of these products. At the same time, the regression coefficient of the interaction term between agricultural insurance and extreme precipitation is significantly positive in the eastern region, and it has the opposite sign to the main effect, indicating that agricultural insurance plays a negative moderating role in the impact of extreme precipitation on the resilience of the agricultural economy in the eastern region, and can effectively weaken the adverse impact of extreme precipitation on the resilience of the agricultural economy in the eastern region. However, the moderating effects of agricultural insurance on extreme high temperature and extreme low temperature in the eastern region of China are not significant. The reasons may be as follows: 1) In terms of geographical location, the eastern region of China is located on the eastern coast of China, adjacent to the Pacific Ocean, and is greatly influenced by the marine climate. It is more vulnerable to extreme precipitation compared with the central and western regions. Extreme precipitation events often have the characteristics of wide range and large losses, and are likely to cause serious impacts on the non-grain crop industries in the eastern region. 2) The eastern region has a developed economy, and farmers have relatively high income levels and risk awareness. However, for risks such as extreme high temperature and extreme low temperature, agricultural insurance has certain limitations in terms of the coverage of insurance types. Farmers may be more

TABLE 9 Heterogeneity of the moderating effect based on a regional perspective.

Variables	Eastern region	Central region	Western region
	RES	RES	RES
EHT	−0.016	−0.001	−0.027
	(-1.63)	(-1.61)	(-0.62)
ELT	−0.009	−0.001	−0.009
	(-1.26)	(-0.70)	(-0.37)
EP	−0.001	−0.000	−0.002
	(-1.23)	(-0.01)	(-0.09)
AIS	0.033***	0.000	0.000
	(4.26)	(0.07)	(0.00)
AIS × EHT	0.000	0.000**	0.001
	(0.88)	(2.17)	(1.15)
AIS × ELT	0.000	−0.000	0.000
	(1.06)	(-0.11)	(0.90)
AIS × EP	0.002**	0.000	0.001
	(2.35)	(0.93)	(0.63)
Control variable	Controlled	Controlled	Controlled
Constant	−0.261	−1.707**	−1.735**
	(-0.93)	(-2.41)	(-2.33)
Observations	144	108	120
R^2	0.983	0.983	0.976
id Fe	Yes	Yes	Yes
year Fe	Yes	Yes	Yes

Note:T-statistics in parentheses,*、 ** and *** represent the significance levels of 10%, 5% and 1%, respectively.

inclined to adjust the planting structure, strengthen field management, and other methods for agricultural risk management. 3) The occurrence frequency of extreme low temperature events in the eastern region is relatively low, and the impact on agricultural production varies depending on the crop type and growth stage. This may lead to the problems of low claim settlement rates and high operating costs for agricultural insurance in the eastern region when dealing with extreme low temperature events. The moderating effect coefficient is not significant in the western region, indicating that the moderating effect of agricultural insurance does not hold in the western region. This paper believes that compared with the eastern and central regions, the reason why the moderating effect of agricultural insurance is not significant in extreme weather conditions in the western region may be the result of the combined effects of various factors, such as the weak economic foundation, harsh agricultural production conditions, and weak insurance awareness of farmers in the western region. This further leads to the relatively lagging development of agricultural insurance in the western region, with a low penetration rate and claim settlement rate of agricultural insurance. Therefore, when natural disasters such as extreme high temperature occur, agricultural insurance in the western region is difficult to play an effective role in risk protection.

5 Discussion

The agricultural economic sector is one of the sectors that are extremely sensitive to weather changes. When extreme weather events occur, the agricultural economic sector often suffers substantial losses. Therefore, this study mainly investigates the impact of extreme weather on the resilience of the agricultural economy, and whether agricultural insurance plays a moderating role between extreme weather and the resilience of the agricultural economy, rather than merely exploring the impact of changes in temperature and precipitation on the agricultural economy. Many studies on the impact of climate on the agricultural economy have mostly focused on climate change. However, as an extreme form of climate change, extreme weather has a more significant impact on agricultural production. By using the relevant data of extreme high temperature, extreme low temperature, and extreme rainfall, this paper has successfully demonstrated that extreme weather poses great risks to the resilience of the agricultural economy and the moderating role played by agricultural insurance in this context. However, based on the panel data of 31 provincial administrative regions (provinces, autonomous regions, and municipalities directly under the Central Government) in China from 2011 to 2022, this study has obtained findings on how agricultural insurance moderates the impacts of extreme weather in different regions. The reasons for the different effects in each region, as well as whether the moderating role of agricultural insurance is applicable to other countries, still await further discussion.

According to the geographical division of China into the eastern, central, and western regions, agricultural insurance in these regions has its own characteristics in the ways of moderating the adverse impacts brought about by extreme weather. The eastern region focuses on the innovation of agricultural insurance products and services; the central region emphasizes the compensation for risk management losses; while the western region places importance on policy support and system construction, as well as disaster prevention, mitigation, and risk management.

The eastern region of China has a developed economy. With the continuous development of industrialization and urbanization, the demand for agricultural insurance has also increased accordingly. However, due to the limitations of land resources and the reduction in the sown area of crops, the development of agricultural insurance is somewhat restricted. Therefore, the eastern region mainly enhances the ability of agricultural insurance to withstand extreme risks by increasing the coverage rate of agricultural insurance in the existing sown areas. The possible reasons for the significant moderating effect of agricultural insurance in the eastern region are as follows: 1) Level of economic development. The eastern region has a relatively rapid economic development and possesses strong financial strength, providing a solid economic foundation for the development of agricultural insurance. Local governments in the eastern region are able to invest more funds in the subsidy and promotion of agricultural insurance, thereby increasing the coverage rate and protection level of agricultural insurance. 2) The diversified agricultural industrial structure gives rise to a strong demand for insurance. The agricultural development in the eastern region of China is characterized by non-grain crop industries such as vegetables and aquatic products. These agricultural industries are affected by natural disasters, which further influence market prices. Therefore, farmers have a more urgent demand for agricultural insurance. 3) Farmers' awareness level. With the upgrading of the agricultural industrial structure and the continuous advancement of agricultural modernization in the eastern region, farmers are increasingly aware of the importance of agricultural insurance in diversifying risks, withstanding irresistible factors such as natural disasters, and safeguarding their incomes. Their recognition and acceptance of agricultural insurance are constantly increasing, and their willingness to participate in insurance is also rising. 4) The development level of the insurance market. The agricultural insurance market in the eastern region has developed relatively early and has a high level of market maturity. There are several powerful insurance companies in this region. These insurance companies possess rich experience and technical advantages in aspects such as the design of agricultural insurance products and claim settlement. At the same time, the intense competition among insurance companies has prompted continuous innovation of insurance products, continuous optimization of insurance services, and continuous improvement of claim settlement efficiency.

The central region of China is an important grain-producing area, and the popularity of agricultural insurance is relatively high. However, due to the complex terrain and diverse and complex climate, extreme weather has a relatively serious impact on agricultural production. In response to the severe impacts brought by extreme weather, the central region of China has enhanced farmers' ability to withstand extreme weather risks by expanding the coverage of agricultural insurance. Insurance companies in the central region, in terms of risk management and loss compensation, provide timely loss compensation to farmers affected by disasters through scientific loss assessment and claim settlement mechanisms. In addition, the eastern region (it should be the central region here, probably a slip of the pen) has also explored the integration of agricultural insurance with financial services such as credit and guarantee, providing more financial support and services to farmers. The possible reasons for the relatively significant moderating effect of agricultural insurance in the central region are as follows: 1) Demand for agricultural insurance. The agricultural production conditions in the central region of China are relatively complex, and natural disasters occur frequently. Therefore, agricultural production faces relatively high risks. Given the high risks of agricultural production in the central region, farmers show a strong demand for agricultural insurance in order to maintain the stability and sustainability of agricultural production. 2) Level of the insurance market and services. As an important area for agricultural production, the central region has a large production scale, and the agricultural insurance market has huge potential, providing broad development space for insurance companies. This further encourages insurance companies to continuously optimize the innovation of agricultural insurance products and service levels, improving farmers' experience and satisfaction in purchasing insurance.

The western region of China is one of the regions where natural disasters occur frequently, and extreme weather has a great impact on agricultural production. Therefore, the demand for agricultural insurance in the western region is relatively high. However, due to the relatively low level of economic development in the western region, farmers have limited ability to pay for agricultural insurance, and the development of agricultural insurance is somewhat restricted. Therefore, the government in the western region mainly encourages insurance companies to carry out agricultural insurance business by providing policy support and financial subsidies, increasing the coverage and protection level of agricultural insurance, and strengthening the construction of the agricultural insurance system at the same time. The possible reasons for the insignificant moderating effect of agricultural insurance in the western region are as follows: 1) Relatively lagging economic development level. The economic development level in the western region is relatively low, and farmers' income levels are also low. After deducting expenses for daily life, agricultural seeds, fertilizers, pesticides, etc., farmers have less disposable income and it is difficult for them to afford high insurance premiums. In addition, the agricultural insurance premium rates in the western region are relatively high, which is a heavy burden for farmers in the western region and suppresses their demand for insurance. 2) Single variety of insurance products and relatively low service level.

Agricultural insurance products in the western region mainly focus on traditional planting and breeding industries, which is difficult to meet farmers' diversified insurance needs. Moreover, the service level of agricultural insurance in some areas is low, with cumbersome claim settlement procedures, insufficient service outlets, and a low level of informatization. This affects farmers' information about purchasing insurance and reduces their willingness to participate in insurance. 3) Inadequate competition in the agricultural insurance market. The agricultural insurance products in the western region have little heterogeneity, and the prices are too high. The service awareness of insurance companies needs to be improved, and there is a lack of motivation and vitality for innovation. This further leads to the relatively slow development of agricultural insurance in the western region, making it difficult to form an effective market competition pattern and affecting the role and effectiveness of agricultural insurance. 4) Climate and geographical conditions. The geographical and natural environment in the western region is complex, and agricultural production faces relatively high risks. However, due to the lack of pertinence and adaptability of agricultural insurance products, it is difficult to effectively deal with these risks, resulting in certain limitations on the role of agricultural insurance in the western region and preventing it from fully playing its role in withstanding natural disasters.

Recent studies by Dorkenoo et al. (2024), Mahdavimanshadi and Fan (2024), and their colleagues have respectively confirmed that extreme weather events pose significant risks to the agricultural economies of Ratanakiri Province in northeastern Cambodia and the semi-arid regions of the southwestern United States. The research by Manganyi et al. (2024) and others also points out that agricultural insurance can provide economic compensation for agricultural producers when they suffer from natural disasters. This is consistent with the research conclusion of this study in terms of the research direction. Therefore, the research conclusion of this study still has reference significance and practical significance for other countries. From the perspective of policy formulation and implementation, this illustrates that a reasonable and forward-looking agricultural insurance policy can provide a stable expectation and clear guidance for the agricultural economy, which is helpful for insurance institutions to operate in a reasonable and standardized manner and improve the effectiveness of agricultural insurance. At the same time, the policy execution ability of local governments and their collaborative ability with other departments will also affect the effectiveness of agricultural insurance. If there is insufficient policy execution ability or deviations exist, it may lead to problems such as insufficient protection level of agricultural insurance and low quality and efficiency of services.

At the same time, there are certain differences in aspects such as service quality between China's agricultural insurance and that of other countries. Although Chinese insurance companies have achieved accurate underwriting and efficient claim settlement through advanced technologies such as remote sensing and GPS, there are still problems such as difficulties in loss assessment and uneven quality of claim settlement services in some underdeveloped regions and links. Other countries such as India and Thailand are also actively exploring ways to improve the service quality and efficiency of agricultural insurance. This indirectly reflects that both the service capabilities of insurance companies and the level of economic development will affect the effectiveness of agricultural insurance. In terms of service capabilities, first of all, professional agricultural insurance companies have a higher proportion of agricultural insurance business than comprehensive companies. They usually possess more accurate risk assessment capabilities and more professional teams, which to a certain extent helps to improve the effectiveness of agricultural insurance. Although comprehensive companies also provide agricultural insurance business, due to the dispersion of their business, the limited investment of resources may occur, and the effectiveness of their agricultural insurance may be inferior to that of professional agricultural insurance companies. Secondly, whether the service system of insurance companies is convenient and whether the insurance clauses are easy to understand and standardized are important factors affecting the effectiveness of agricultural insurance. If insurance companies can provide services close to farmers and establish a sound grass-roots service system, it will help to improve farmers' satisfaction and enthusiasm for participating in insurance, thereby enhancing the effectiveness of agricultural insurance. Conversely, if the insurance clauses of insurance companies are difficult to understand, it may deepen farmers' misunderstandings of insurance products and reduce farmers' trust in insurance companies and insurance products, thus reducing the effectiveness of insurance. In relatively economically developed regions, the demand for the agricultural insurance market may be stronger, and the competition among agricultural insurance institutions may be more intense, which in turn helps to promote insurance institutions to continuously improve service quality, provide personalized insurance products, and enhance the level of insurance risk protection. In regions with a relatively low level of economic development, farmers are restricted by factors such as low income levels and limited insurance awareness, which to a certain extent limits the positive effect of agricultural insurance on the agricultural economy. Compared with China's continuous expansion of the coverage of agricultural insurance in various fields of agriculture, forestry, animal husbandry, and fishery, the types of agricultural insurance in other countries pay more attention to protection in specific fields. For example, the agricultural insurance in the United States mainly focuses on the fields of grain crops and animal husbandry; while Japan's agricultural insurance covers multiple varieties such as rice, wheat, and livestock. Whether it is to expand the coverage of agricultural insurance or to pay more attention to protection in specific fields, it means that the refinement and specialization of insurance products and services can better meet the diversified needs of farmers and effectively play the role of agricultural insurance in resisting risks. Therefore, countries should formulate and improve the agricultural insurance system according to their own national conditions and the needs of agricultural development, so as to better provide risk protection and support for agricultural production.

6 Conclusion

Based on the panel data of 31 provinces (autonomous regions and municipalities directly under the Central Government) in China from 2011 to 2022, this paper empirically analyzed the impact of extreme weather on agricultural economic resilience, and tested the regulatory role of agricultural insurance in the impact of extreme weather on agricultural economic resilience. The findings of this study are as follows: First, extreme weather has a significant negative impact on the resilience of agricultural economy, in which the adverse impact of extreme high temperature on the resilience of agricultural economy is higher than that of extreme low temperature and extreme precipitation, and this conclusion is still established after a series of robustness tests. Second, agricultural insurance plays a negative regulating role in the impact of extreme weather on the resilience of agricultural economy, which can alleviate the adverse impact of extreme weather on the resilience of agricultural economy.

The above conclusions are of great significance for coping with extreme weather changes and ensuring agricultural production safety. In view of the fact that climate warming and frequent extreme weather are common in the world, this paper proposes an evolutionary approach to promote the high-quality development of agricultural insurance and improve the resilience of agricultural economy based on the above conclusions, which is of universal significance not only for China, but also for all countries in the world. The following suggestions may help the high-quality development of agricultural insurance and steadily improve the resilience of agricultural economy.

First, promote the improvement of the protection level of agricultural insurance within an appropriate range, and strengthen the support of agricultural insurance for climate adaptation and mitigation measures. The main purpose of agricultural insurance is to provide risk protection for agricultural production. When the premium income of agricultural insurance is high, it means that more funds are available for compensating the losses of agricultural production caused by force majeure factors, which can better ensure the stability of agricultural production. At the same time, with the increase in the premium income of agricultural insurance, it also indicates that the business scale of agricultural insurance is constantly expanding, the protection level of agricultural insurance is continuously improving, and agricultural insurance can cover more production areas, providing risk protection for more agricultural producers. Agricultural insurance can effectively mitigate the inhibitory effect of extreme weather on the resilience of the agricultural economy. Therefore, it is necessary to continuously promote the development of agricultural insurance, establish a dynamic adjustment mechanism for the protection level of agricultural insurance according to local conditions, combined with the situation of the agricultural industrial structure and agricultural production costs, etc., improve the effectiveness of agricultural insurance in supporting agriculture, and generally reduce the degree of risk exposure of agricultural production in the face of extreme weather, so as to empower the steady improvement of the resilience of the agricultural economy with agricultural insurance.

However, at the same time, it is necessary to consider the occurrence of potential accidents and the issue of moral hazard. The enthusiasm of farmers is an important prerequisite for the effectiveness of agricultural insurance. In some regions, farmers have insufficient awareness of agricultural insurance, and the income of some farmers is not high. Excessively high premiums make it difficult for them to afford, affecting their enthusiasm for participating in insurance. In terms of insurance products and services, the underwriting coverage rate of some local characteristic and advantageous agricultural products is relatively low, and many cash crops are difficult to be protected by agricultural insurance. Therefore, insurance products need to be continuously innovated to meet the actual needs of farmers. With the frequent occurrence of extreme weather phenomena caused by climate warming, if agricultural insurance can promptly include these risks and provide corresponding protection, the effectiveness of agricultural insurance will be greatly improved. The potential moral hazard of farmers themselves and insurance companies may also affect the effectiveness of agricultural insurance operations. Farmers themselves may falsely report the disaster situation and exaggerate the extent of damage after an insurance accident occurs, or deliberately create an insurance accident to defraud insurance compensation; insurance companies may also mislead farmers to purchase insurance or conduct false underwriting, and may deliberately delay the compensation time during the claim settlement process, harming the interests of farmers. Insurance companies can improve farmers' insurance awareness by strengthening the publicity of agricultural insurance knowledge, such as the principle of utmost good faith and the obligation of truthful disclosure, *etc.*, and at the same time, strengthen the professional quality education of business personnel to ensure that business personnel perform their duties conscientiously during the underwriting and claim settlement processes. Local governments play an important role in the implementation of agricultural insurance policies. If local governments have strong financial capabilities, their policy implementation capabilities are often stronger, and the effectiveness of agricultural insurance will also be greatly enhanced. However, in actual operations, the policy strength of insurance for local characteristic and advantageous agricultural products may be insufficient, and the subsidy methods for agricultural insurance are limited, which greatly affects the effectiveness of agricultural insurance.

Second, Pay attention to the risk protection needs of new agricultural business entities. Construct an information sharing platform involving multiple entities to achieve the efficient integration and transformation of information such as disaster warnings, market prices, and agricultural technologies. This will build a bridge for the improvement of the risk awareness of new agricultural business entities and the optimization of their insurance strategies. At the same time, it can serve as a demand feedback channel to form a direct communication mechanism between new agricultural business entities and insurance institutions, establish a fast claim settlement channel, simplify the claim settlement procedures, and improve the efficiency of claim settlement. Utilize scientific and technological means, such as satellite remote sensing, UAV aerial photography, big data analysis, etc., to enhance the accuracy and timeliness of loss assessment. Meanwhile, provide personalized insurance products to meet the needs of new agricultural business entities. In addition to the common crop planting insurance and livestock and poultry breeding insurance, develop insurance products for the characteristic industries of new agricultural business entities, such as facility agriculture insurance and agricultural product price index insurance, etc. In response to the credit needs of new agricultural business entities, introduce agricultural credit guarantee insurance to provide risk protection for their financing. In this way, it can provide effective support for the construction of a more stress-resistant and resilient agricultural production system.

Third, Improve the policies for agricultural production to cope with extreme weather changes, and actively implement measures to enhance the resilience of the agricultural economy. A scientific assessment of the impact of extreme weather changes on the resilience of agricultural economic development requires not only taking into account the impact of extreme weather changes on agricultural economic growth, but also considering their influence on the stability of agricultural development and the resilience of the agricultural economy. To address the challenges posed by extreme weather, on the one hand, it is necessary to formulate risk response plans, strengthen the monitoring, early warning, and emergency management of extreme weather phenomena, clarify the responsibilities and tasks of various departments in disaster response, and enhance cooperation among departments such as agriculture, meteorology, and water resources. By utilizing technologies such as satellite remote sensing, real-time monitoring of multiple elements including meteorology, soil, and hydrology should be carried out to improve the accuracy and timeliness of monitoring. On the other hand, relevant departments need to step up infrastructure construction, increase investment in farmland water conservancy facilities, improve the irrigation and drainage systems, enhance the flood control, waterlogging drainage, and drought resistance capabilities of farmland, reduce the dependence of agricultural production on climate resources, and mitigate agricultural climate risks. Farmers should be encouraged and supported to actively adopt climate adaptation and mitigation measures, such as building high-standard agricultural facilities like greenhouses, and enhancing the wind resistance, snow resistance, and seismic resistance of agricultural facilities. In areas vulnerable to disasters such as typhoons and heavy rains, protective facilities such as windbreaks and flood control dikes should be constructed. All these efforts aim to promote the stable development of the agricultural economy.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XZ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. HL: Writing – review and editing. HQ: Conceptualization, Methodology, Writing – original draft. LJ: Conceptualization, Methodology, Visualization, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by the National Social Science Foundation Project, grant number 21BJY164, supported by "Research on Target Integration, Space Spillover and Agricultural Policy Financial Support".

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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