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# Heterogeneous mitigation effects of adaptation initiatives on grain yield losses from extreme temperatures in China: implications for grain resilience and food security

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**Introduction:** The increasing frequency of extreme weather events has posed significant challenges to global food security. While it is well established that such events can reduce food production, the specific effects of different types of extreme weather on food security, as well as the heterogeneous mitigation strategies available, remain inadequately understood.

**Methods:** This paper systematically analyzes the impacts of extreme high and low temperature events on maize yields using panel data from major maize-producing regions in China from 2000 to 2023, highlighting the potential threats climate extremes pose to food security.

**Results and discussion:** The findings reveal that: (1) extreme high temperatures significantly suppress maize yields, with the number of extreme heat days showing a consistent negative effect nationwide and across regional and growth-stage subsamples, particularly pronounced in northern summer maize-producing areas, indicating heat stress as a key constraint on stable grain production and supply; (2) the effects of extreme low temperatures exhibit clear regional heterogeneity, with southern spring-sown maize more vulnerable to late frosts during seedling and nodulation stages, resulting in greater yield losses, whereas in northern regions, low temperatures mostly occur before sowing and have a limited impact; (3) the adverse effects of extreme temperatures have intensified over time, with extreme heat impacts worsening in recent years—reflecting cumulative climate risks and agricultural system vulnerability—while the negative impacts of low temperatures have somewhat diminished since 2010, indicating improved farmer adaptation; (4) agricultural insurance and protected agriculture have significantly mitigated the impacts of extreme low temperatures on maize yields, demonstrating their effectiveness in cold climates, but have yet to provide significant buffering against yield losses from extreme heat, suggesting opportunities to optimize existing insurance mechanisms and protective agricultural technologies. These findings contribute to a deeper understanding of climate adaptation strategies and support the achievement of SDGs 2 (Zero Hunger) and 13 (Climate Action) through enhancing resilience in the agri-food system.

## KEYWORDS

extreme temperatures, maize yield, food security, agricultural insurance, protected agriculture

# 1 Introduction

In recent years, with the intensification of global climate change, the frequency and intensity of extreme weather events have increased significantly, posing a serious threat to the stability of agricultural production systems and global food security (Lesk et al., 2016; Zhao et al., 2017; Liu et al., 2021). Numerous studies have shown that extreme climatic events, especially droughts and temperature anomalies, have had a significant impact on crop yields. Developing countries, due to their higher vulnerability and limited adaptive capacity, have borne the brunt of these impacts (Wheeler and von Braun, 2013; Sinore and Wang, 2024). Against this backdrop, ensuring stable food production under increasingly unstable climatic conditions has become one of the core challenges for global sustainable development (Hasegawa et al., 2021; Johansson et al., 2024). The United Nations' Sustainable Development Goal 2 (SDG 2) in the 2030 Agenda explicitly articulates the vision of "zero hunger," emphasizing the stabilization of staple food supplies, enhancing the resilience of agricultural systems, and strengthening adaptive capacity to climate change. These objectives have become key drivers for national agricultural policy formulation (IPCC, 2001; Biswas et al., 2021).

Among various extreme climate phenomena, extreme temperatures—especially extremely high and low temperature events—pose a uniquely severe risk to food security due to their immediate and often irreversible physiological effects on crops and their yield formation (Barlow et al., 2015; Schlenker and Roberts, 2009). As one of the world's three major staple crops, maize is particularly sensitive to temperature fluctuations (Dong et al., 2023). Exposure to extreme heat or cold during key growth phases such as tasseling, pollination, and grain filling can result in substantial yield losses or even complete crop failure (Zhang et al., 2020). Hence, accurately identifying and quantifying the impacts of extreme temperature variations on maize yields in China is of urgent practical significance for formulating effective adaptation strategies and enhancing the resilience of the national food system (Tao and Zhang, 2013).

The existing literature has revealed substantial spatial heterogeneity in how different types of extreme climate events—such as heatwaves, droughts, and floods—impact crop yields (Lobell et al., 2011; Lesk et al., 2021; Wei et al., 2017; Chriest and Niles, 2018). For instance, in Europe, heatwaves and droughts have reduced average grain yields by 9% and 7.3%, respectively (Brás et al., 2021). In China, floods and droughts have reduced cotton yields by 6.22% and 2.48%, respectively (Qian et al., 2020), while severe drought in Russia has led to wheat production losses exceeding 70% (Hunt et al., 2021; Deng et al., 2022). Although previous studies have employed multivariate regressions, geographically weighted models, and machine learning methods to assess the yield impact of extreme climate events (Powell and Reinhard, 2016; Chen et al., 2020; Gregory et al., 2005), most have focused on average temperature levels or isolated extreme weather episodes, often overlooking the effects of temperature frequency, especially the frequency of extremely high and low temperature days, on crop yields (Wang et al., 2014).

As one of the largest maize-producing countries in the world, China's maize-growing regions span diverse climatic zones

across the north and south, making them highly susceptible to temperature variability (Chen et al., 2011; Zhang and Yang, 2019; Wu et al., 2021). Several studies have documented the negative effects of rising temperatures on China's maize yields, with clear regional disparities (Huang et al., 2021; Song et al., 2020). Moreover, excessive precipitation is projected to cause a decline in maize yields by approximately 9.1% by the end of the century (Fu et al., 2025; Ren et al., 2008; Li et al., 2011). Although some studies have investigated the impacts of extreme weather on maize production in China, empirical research explicitly incorporating frequency-based extreme temperature metrics—such as the number of extreme high- or low-temperature days—remains scarce. Existing studies have also paid limited attention to the heterogeneous moderating effects of adaptation measures, such as agricultural insurance and protected agriculture. Furthermore, most prior work has insufficiently examined the differential responses of maize production between northern and southern regions in conjunction with adaptation strategies. Only through in-depth analyses that integrate regional and temporal heterogeneity with systematic assessments of adaptation initiatives can differentiated policies be formulated according to local conditions to effectively mitigate the negative impacts of extreme weather on maize yields.

In China, agricultural insurance for maize production is primarily structured as yield insurance, which compensates farmers for losses when actual yields fall below insured levels due to major natural disasters such as droughts, floods, hail, strong winds, and frost. Insurance is not directly written against "high" or "low" temperatures; instead, its role in moderating temperature shocks should be understood as the indirect buffering effect of existing yield-based schemes on climate-related risks. In recent years, pilot programs have also introduced innovative products such as weather index insurance, where temperature or precipitation thresholds trigger payouts, as well as quality insurance and income insurance (often under the "insurance plus futures" model). However, these products remain in the early stages of experimentation and are not yet widely adopted nationwide. Accordingly, this study focuses primarily on yield-based agricultural insurance, while acknowledging the emerging diversification of insurance options for maize production in China.

The overall objective of this study is to analyze the heterogeneous impacts of extreme high and low temperatures on maize yields and to evaluate the effectiveness of differentiated intervention strategies tailored to different types of extreme weather. Utilizing panel data from twenty major maize-producing provinces in China spanning 2000 to 2023, this paper systematically examines how the frequency of extreme temperature events affects maize yields, with a particular focus on the distinct roles of agricultural insurance and facility-based agriculture in mitigating yield losses caused by these temperature extremes. Additionally, the study explores the regional heterogeneity and temporal evolution of these impacts, aiming to provide a scientific foundation for formulating locally adapted climate risk response policies.

Compared to existing literature, this study offers several key contributions. First, while prior research primarily emphasizes the effects of average temperatures or discrete extreme weather events on agricultural outputs, it pays limited attention to the systematic relationship between changes in the frequency of

extreme temperatures—a critical climate variable—and crop yields. By focusing on frequency as a dimension, this paper complements quantitative identification methods for extreme temperature shocks and broadens the perspective on how climate extremes impact agriculture. Second, through the use of long-term provincial panel data from 2000 to 2023, the study identifies differential effects of extreme heat and cold on maize yields and further conducts empirical analyses across spatial heterogeneity between northern and southern regions, as well as temporal evolution trends, thereby enriching empirical evidence on the dual heterogeneity of space and time. Third, based on these empirical findings, the paper proposes targeted climate adaptation policy recommendations, highlighting the importance of establishing regional and phased response systems to extreme climate risks, which also contributes valuable evidence supporting the SDGs.

## 2 Development of maize production and extreme weather in China

As one of the world's three major staple crops, maize plays a crucial role in the global food security system (Neupane et al., 2022; Ye et al., 2024; Li et al., 2022). According to data from the Food and Agriculture Organization of the United Nations (FAO), global maize production exceeded 1.2 billion tons in 2022, with China ranking as the second-largest producer after the United States. China's annual output reached approximately 270 million tons, accounting for over 20% of global production. The maize cultivation area in China has long remained around 400 million mu (approximately 26.7 million hectares), representing nearly a quarter of the nation's total arable land. Maize is one of the country's most important food and feed crops. Although China's average maize yield (around 6.3 tons per hectare) still lags behind that of developed agricultural countries like the United States (exceeding 10 tons per hectare), the country's overall output ranks among the world's highest, playing a vital role in ensuring food security, supporting animal husbandry, and maintaining global competitiveness in agricultural products.

From 2000 to 2023, China's maize cultivation area and output exhibited a clear upward trend. The sown area expanded from 23.1 million hectares in 2000 to 44.2 million hectares in 2023, nearly doubling over the period. Between 2000 and 2015, the area increased significantly from 23 million to over 38 million hectares. After peaking at 44.2 million hectares in 2016, it stabilized in the 42–44 million range, remaining high since 2020. Maize production has grown even more markedly, rising from 106 million tons in 2000 to 288.8 million tons in 2023—an increase of over 170%. Before 2015, production rose steadily from 106 million to 224.6 million tons. After 2016, production entered a plateau phase, remaining above 250 million tons. Since 2021, production has accelerated again, reaching a record high in 2023 (see Figure 1).

From the perspective of regional distribution, China's main corn-producing areas are primarily concentrated in the Northeast Plain, the North China Plain, and the Huang-Huai-Hai region. Among them, Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Shandong, and Henan are recognized as the dominant maize-producing provinces in China. From 2018 to 2022, the

combined maize planting area in these seven provinces accounted for approximately 66% of the national total (Figure 2), while their aggregate maize output exceeded 70% of the country's total production (Figure 3). These regions benefit from favorable natural resource endowments and a high degree of agricultural mechanization, making them a vital component of China's core grain production functional zones (Ye et al., 2023).

However, in recent years, maize production in China has encountered a series of structural challenges (Ely et al., 2016; Meng et al., 2013). On the one hand, influenced by the higher profitability of cash crops and the continuous outflow of rural labor, certain major maize-producing areas have exhibited a trend of “non-grainization”, resulting in increased fluctuations in planting area (Jia et al., 2022). On the other hand, the frequency of extreme climate events has risen sharply, with extreme high-temperature occurrences intensifying notably in North China and Northeast China, thereby increasing the vulnerability of maize yields to thermal stress (Pickson et al., 2022). Additionally, since the maize planting season in southern China often coincides with periods of extreme low temperatures, there is also a heightened risk of cold damage during early spring sowing and the seedling stage, which further exacerbates the uncertainty in grain production outcomes (Deng et al., 2025).

We also compiled the changes in extreme high and low temperatures in China's main maize-producing provinces from 2000 to 2023. As shown in Figure 4, the annual average number of extreme high-temperature days exhibited a statistically significant upward trend during this period, with a slope of 0.779 days per year ( $p < 0.01$ ). Since 2017, extreme high-temperature days have increased markedly and reached a peak of 73.949 days in 2023, which is more than 20 days higher than the level observed in 2000. This result indicates that extreme heat events have become increasingly frequent and intense. In contrast, the number of extreme low-temperature days showed a downward but statistically insignificant trend, with a slope of  $-0.448$  ( $p > 0.1$ ). Although intermittent peaks occurred in certain years such as 2012 and 2013, extreme low-temperature days have generally declined since 2015 and stabilized at around 30 days between 2020 and 2023.

Historical data indicate that the inter annual variability of maize production in China has gradually increased, with yield fluctuations in certain years closely associated with extreme temperature events. For instance, persistent heatwaves in North China during 2013 and localized cold spells in Northeast China in 2020 significantly impacted maize yields. Although national policies—such as the implementation of the “market-based purchase plus subsidy” mechanism and the promotion of high-yield and stress-resistant varieties—have been introduced, the overall resilience of maize production under climate stress remains insufficient.

Extreme temperature events have increasingly surpassed the average trends of climate change in their impact on maize production, posing rising threats and uncertainties. As a temperate crop, maize is highly sensitive to temperature during key growth stages such as flowering, pollination, and grain filling. When exposed to extreme high temperatures, often accompanied by prolonged drought and soil moisture deficits, maize suffers reduced photosynthetic efficiency and impaired nutrient transport, leading to decreased pollen viability, incomplete pollination, and

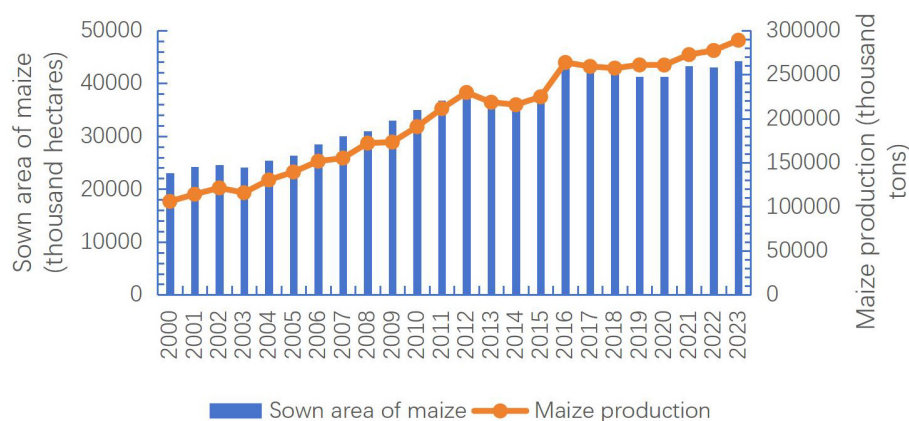


FIGURE 1  
Trends of Maize Sown Area and Production in China from 2000 to 2023.

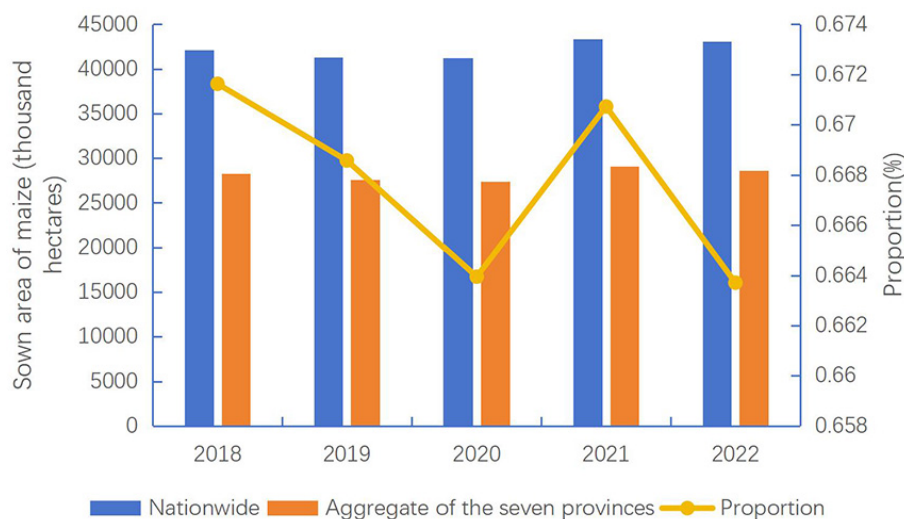


FIGURE 2  
Share of Sown Maize Area in Seven Dominant Producing Regions.

insufficient grain filling—ultimately resulting in significant yield losses. In contrast, extreme low temperatures mainly threaten spring-sown maize in southern regions, where cold snaps or late frosts during the seedling or jointing stages suppress growth, prolong the growing period, or even cause reproductive damage or plant death. Moreover, extreme temperatures frequently overlap with abnormal precipitation or severe convective weather, triggering compound disasters such as floods and droughts, which further destabilize maize production systems and threaten food security. As global warming intensifies, the frequency and severity of extreme temperature events are increasing, exacerbating the climatic vulnerability of maize yields. Therefore, identifying and quantifying the specific impacts of extreme temperatures on maize production is of vital importance for enhancing the adaptability and resilience of agricultural systems. Therefore, under the current policy framework, it is essential to identify and quantify the effects of extreme temperature events on maize output. Doing so will not

only enhance the capacity for risk early warning and regulation of staple crop production, but also provide a scientific basis for optimizing regional cropping structures and formulating climate adaptation policies for the agricultural sector.

## 3 Materials and methods

### 3.1 Data sources and sample description

This study selects twenty major maize-producing provinces in China from 2000 to 2023 as the research sample and constructs a provincial-level panel dataset for empirical analysis. Data on maize yield, planting area, and total output are obtained from authoritative statistical sources, including the China Rural Statistical Yearbook, China Statistical Yearbook,



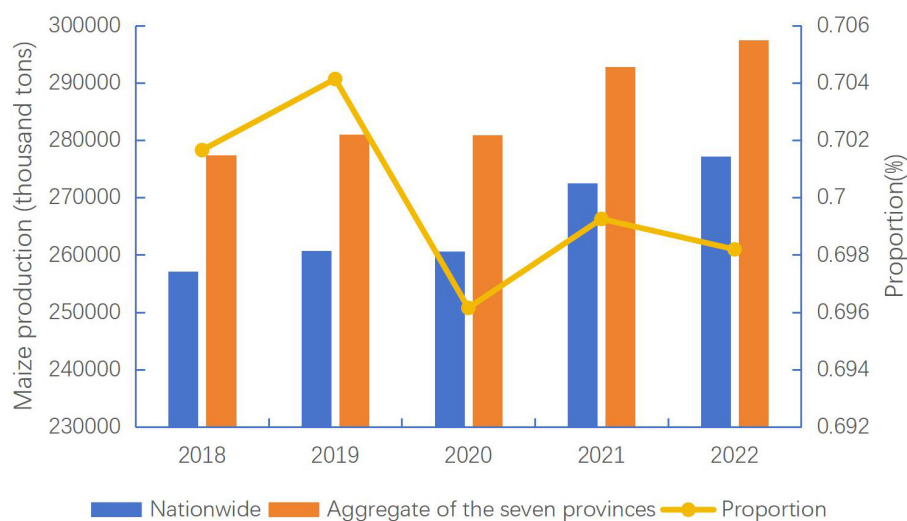


FIGURE 3  
Share of National Maize Production by Seven Leading Producing Provinces.

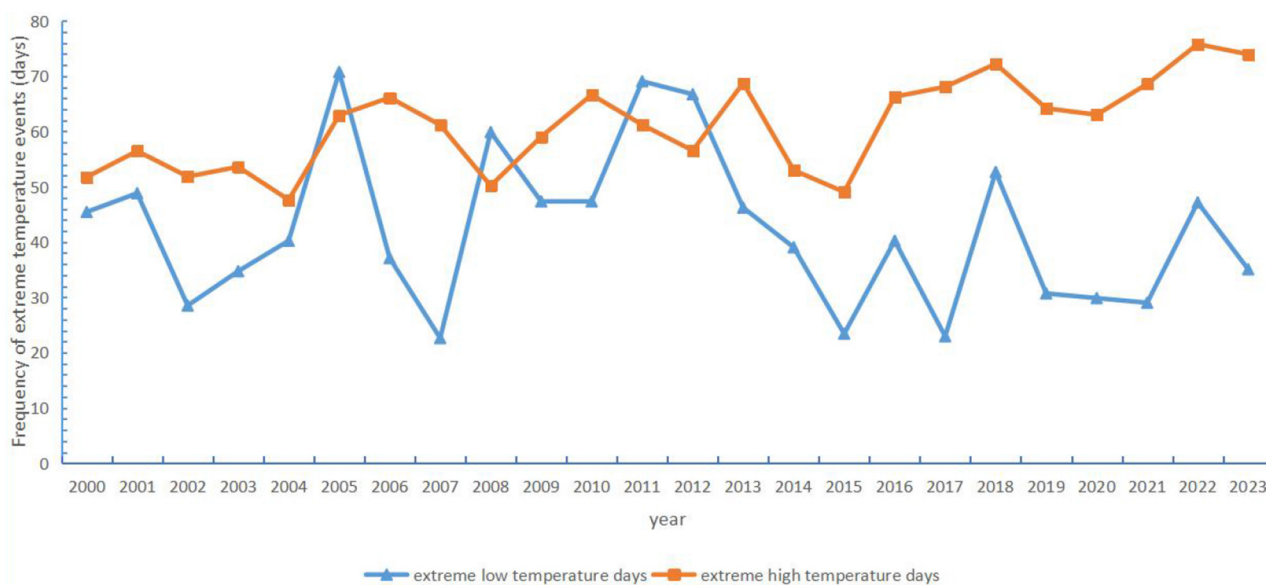


FIGURE 4  
Trends in the Frequency of Extreme High and Low Temperature Days in Major Maize-Producing Provinces of China (2000–2023).

and the Compilation of National Agricultural Product Cost and Benefit Data.

Extreme temperature indicators are derived from daily meteorological observations provided by the National Meteorological Science Data Center of the China Meteorological Administration. By compiling a provincial-level daily average temperature dataset, we calculate the annual frequency of extreme high and low temperature days, which are then matched to the maize growth cycle.

To ensure comparability and data integrity, the analysis focuses on twenty provinces with consistently large-scale maize cultivation and continuous data availability. These provinces

include Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Shandong, Henan, Shanxi, Shaanxi, Anhui, Jiangsu, Sichuan, Chongqing, Hunan, Hubei, Jiangxi, Guangxi, Yunnan, Guizhou, and Ningxia.

### 3.2 Model specification and variable selection

To systematically evaluate the impact mechanism of extreme temperature variations on maize production, we construct an

econometric model based on panel data analysis. Previous research has demonstrated substantial regional heterogeneity in crop yield responses to climate change (Thornton et al., 2009; Maestrini and Basso, 2018; Malikov et al., 2020).

To accurately capture the effects of extreme high and low temperatures, a fixed-effects panel model is employed, which controls for unobserved heterogeneity across regions and time. Additionally, a set of control variables is included to account for other potential factors influencing maize yields.

Building on this framework, we further explore the heterogeneous impacts of extreme temperatures across geographic regions and assess the temporal evolution of these effects. This provides empirical support for the formulation of region-specific and time-sensitive agricultural adaptation policies. The specific model specification is as follows:

$$\text{Yield}_{it} = \alpha + \beta_1 \text{EHT}_{it} + \beta_2 \text{ELT}_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Among them,  $i$  represents the province,  $t$  represents the year,  $\text{Yield}_{it}$  is the corn yield,  $\text{EHT}_{it}$  and  $\text{ELT}_{it}$  are the frequencies of extreme high and low temperatures, respectively.  $X_{it}$  is the control variable,  $\mu_i$  is the province fixed effect,  $\lambda_t$  is the year fixed effect, and  $\varepsilon_{it}$  is the random error term. In terms of model setting, this paper adopts a two-way fixed effect model for estimation, and introduces the province fixed effect  $\mu_i$  to control the characteristics of each region that do not change over time, such as soil type, planting tradition, and natural resource endowment. The year fixed effect  $\lambda_t$  is introduced to control annual shocks such as macroeconomic policies, market environment, and climate background to ensure the robustness of the model estimation results.

In the selection of control variables, we draw on insights from existing literature (Chandio et al., 2020; Chen and Gong, 2021; Lee et al., 2024) and incorporate key agricultural input factors that are known to influence maize yield. These include fertilizer application (Fertilizer), effective irrigation area (Irrigation), total power of agricultural machinery (Machinery), the number of employees in the primary industry (Labor), and maize planting area (Area), to control for regional differences in agricultural resources and technological conditions. To address potential issues related to variable dimensionality and heteroscedasticity, all continuous variables are logarithmically transformed.

To explore the buffering and moderating effects of agricultural insurance and protected agriculture on maize yields under extreme temperature shocks, this study constructs a fixed-effects panel regression model with interaction terms, while controlling for other key influencing factors. This model not only identifies the direct effects of the frequency of extreme high and low temperatures on maize yields, but also assesses whether the coverage of agricultural insurance and the development level of protected agriculture exert significant moderating effects. In doing so, it reveals the practical effectiveness of different adaptation strategies in the context of climate stress. The specific model specification is as follows:

$$\text{Yield}_{it} = \alpha + \beta_1 \text{HTD}_{it} + \beta_2 \text{LTD} + \beta_3 (\text{HTD}_{it} \times \text{Insurance}_{it}) + \beta_4 (\text{LTD}_{it} \times \text{Insurance}_{it}) + X'_{it} \gamma + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$\text{Yield}_{it} = \alpha + \beta_1 \text{HTD}_{it} + \beta_2 \text{LTD} + \beta_3 (\text{HTD}_{it} \times \text{Protected}_{it}) + \beta_4 (\text{LTD}_{it} \times \text{Protected}_{it}) + X'_{it} \gamma + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Here,  $\text{Insurance}_{it}$  represents agricultural insurance. Agricultural insurance mainly refers to a government-led risk protection system, whose core function is to provide financial compensation to reduce farmers' losses caused by natural disasters, thereby enhancing their disaster resilience and production stability. In this study, the per agricultural holding (farm) agricultural insurance premium is used as a proxy variable to reflect the coverage level and participation rate of agricultural insurance in each region.

$\text{Protected}_{it}$  represents protected agriculture. Protected agriculture refers to controlled-environment farming methods centered on facilities such as greenhouses, plastic tunnels, and hoop houses. Its purpose is to create a more stable growing environment by regulating key factors such as temperature and humidity, thus mitigating the adverse effects of extreme external climate conditions. This study uses the annual area of protected agriculture in each province as an indicator to reflect the level of development of protected agriculture in different regions. The meanings of other variables and the model specification are consistent with those in Equation 1.

### 3.3 Data descriptive statistics

To ensure the robustness and explanatory power of the empirical model, this study conducts a descriptive statistical analysis of the main variables, with the results presented in Table 1. During the sample period, the average maize yield (Yield) was 5,549.07 kg/hectare, with a standard deviation of 1,101.58. The maximum and minimum values were 9,432.14 and 302.05, respectively, reflecting substantial interprovincial disparities in maize yields across China and highlighting pronounced spatial heterogeneity in maize production.

Regarding extreme temperatures, the average number of annual extreme high temperature days was 60.58 days, with a standard deviation of 14.48 and a maximum of 119.6 days. The mean number of extreme low temperature days was 42.67 days, with a standard deviation of 17.12 and a maximum of 92.33 days. These figures suggest that both extreme high and low temperature events are frequent and may pose significant threats to maize yield stability (Du and Xiong, 2024).

In terms of agricultural inputs, the average fertilizer application (Fertilizer) was 2.074 million tons, with a maximum of 7.161 million tons and a standard deviation of 1.27 million tons, indicating substantial variation in fertilizer use across provinces. The average effective irrigation area (Irrigation) was 2,479 thousand hectares, with a maximum of 6,630 thousand hectares, reflecting notable disparities in water infrastructure development. The average total power of agricultural machinery (Machinery) was 34.1 million kilowatts, with a standard deviation of 24.7 million kilowatts, indicating differences in the level of mechanization.

In addition, the average number of workers employed in the primary industry (Labor) was 11.01 million, suggesting a still-large agricultural labor force, albeit with considerable regional variation. The average maize planting area (Area) was 1,507 thousand hectares, with a maximum of 65,240 thousand

TABLE 1 Descriptive statistics of variables.

| Variables  | Definition   | Unit                          | N   | Mean     | Std.     | Min      | Max      |
|------------|--|-------------------------------|-----|----------|----------|----------|----------|
| Yield      | Maize yield  | Kilograms per hectare (kg/ha) | 480 | 5549.073 | 1101.583 | 3002.046 | 9432.14  |
| HTD        | Extreme high temperature days                                  | Days                          | 480 | 60.58    | 14.48    | 22.69    | 119.6    |
| LTD        | Extreme low temperature days                                   | Days                          | 480 | 42.67    | 17.12    | 0        | 92.33    |
| Fertilizer | Fertilizer application   | 10,000 metric tons            | 480 | 207.40   | 127.00   | 23.58    | 716.10   |
| Irrigation | Effective irrigated area                                       | 1,000 hectares                | 480 | 2479.00  | 1480.00  | 398.80   | 6630.00  |
| Machinery  | Total agricultural machinery power                             | 10,000 kilowatts              | 480 | 3410.00  | 2470.00  | 380.60   | 11710.00 |
| Labor      | Number of employees in the primary industry                    | 10,000 persons                | 480 | 1101.00  | 683.40   | 81.00    | 3569.00  |
| Area       | Total maize sown area  | Hectares                      | 480 | 1507.00  | 1289.00  | 131.10   | 6524.00  |
| Protected  | Protected agriculture area(log)                                | Hectares                      | 480 | 9.595    | 2.077    | 3.456    | 13.137   |
| Insurance  | Per agricultural holding (farm) agricultural insurance premium | Yuan                          | 480 | 15.612   | 29.045   | 0        | 180.629  |

Yuan is China's currency, and in 2024, 1 Yuan was approximately equal to USD 0.14.

hectares, highlighting the large-scale maize cultivation in some key production regions.

## 4 Empirical results

### 4.1 Benchmark regression results

To systematically assess the impact of extreme temperature frequency on maize yield, this study constructs a two-way fixed effects model incorporating both province and year fixed effects. To determine the appropriate model specification, we compared fixed-effects and random-effects estimations. The Hausman test strongly rejected the null hypothesis that the random-effects model is consistent ( $\text{Prob} > \chi^2 = 0.0020$ ), thereby supporting the fixed-effects specification. We further compared model selection criteria. For the two-way fixed-effects model, the AIC and BIC were 6865.328 and 6980.758, respectively. For the random-effects model, the AIC and BIC were 6903.328 and 7097.085, respectively. Since the fixed-effects model provided lower AIC and BIC values, it demonstrated a better fit. These results indicate that unobserved heterogeneity is correlated with explanatory variables, justifying our choice of the two-way fixed-effects approach. The benchmark regression results are reported for two specifications: without control variables (Model 1) and with the inclusion of control variables (Model 2). The results are presented in Table 2. All models employ robust standard errors to account for heteroskedasticity and control for unobservable regional heterogeneity and annual macroeconomic shocks. The regression outputs demonstrate a satisfactory overall model fit, with  $R^2$  values of 0.532 and 0.584 for Models 1 and 2, respectively, indicating that the selected variables have strong explanatory power for variations in maize yield.

From the perspective of core explanatory variables, the number of extreme high temperature days exhibits a significant negative effect on maize yield in both models, with results statistically significant at the 1% level. Specifically, the regression coefficient of extreme high temperature days in Model 1 is  $-7.798$ , indicating that each additional extreme high temperature day reduces maize yield by approximately 7.80 kg per hectare. After controlling for agricultural input factors in Model 2, the coefficient decreases in

TABLE 2 Effects of extreme temperatures on maize yield.

| Variables       | Model 1                  | Model 2                  |
|-----------------|--------------------------|--------------------------|
| HTD             | -7.798***<br>(1.990)     | -5.902***<br>(1.924)     |
| LTD             | -0.140 (2.335)           | -0.849<br>(2.246)        |
| Fertilizer      | —                        | 2.844***<br>(0.858)      |
| Irrigation      | —                        | 0.082<br>(0.069)         |
| Machinery       | —                        | -0.073*<br>(0.039)       |
| labor           | —                        | 0.040<br>(0.113)         |
| Area            | —                        | 0.218***<br>(0.070)      |
| Province effect | Yes                      | Yes                      |
| Time effect     | Yes                      | Yes                      |
| _cons           | 5066.129***<br>(181.486) | 4239.997***<br>(260.803) |
| N               | 480                      | 480                      |
| R2              | 0.532                    | 0.584                    |

Robust standard errors are in parentheses. \*and \*\*\* represent the statistical significance levels of 10% and 1%, respectively.

magnitude to  $-5.902$ , though it remains significantly negative. This robust inhibitory effect suggests that heat stress may severely constrain maize productivity by accelerating physiological processes during key growth stages and impairing pollination and grain filling.

In contrast, while the regression coefficients for extreme low temperature days are negative in both models, they do not reach conventional levels of statistical significance, indicating a relatively weaker influence on maize yield. In Model 2, which incorporates control variables, agricultural input factors display varying degrees of explanatory power. Notably, the coefficient for total agricultural

**TABLE 3** Regional heterogeneity effects of extreme temperatures on maize yield.

| Variables         | Model 1                  | Model 2                  |
|-------------------|--------------------------|--------------------------|
| HTD               | −1.255<br>(3.046)        | −9.027***<br>(3.070)     |
| LTD               | −6.546*<br>(3.876)       | 3.879<br>(2.901)         |
| Control variable  | Yes                      | Yes                      |
| Individual effect | Yes                      | Yes                      |
| Time effect       | Yes                      | Yes                      |
| _cons             | 5206.091***<br>(627.546) | 4509.857***<br>(325.706) |
| N                 | 216                      | 264                      |
| R2                | 0.470                    | 0.725                    |

Robust standard errors are in parentheses. \* and \*\*\* represent the statistical significance levels of 10% and 1%, respectively.

machinery power (Machinery) is  $-0.073$  and statistically significant at the 5% level, which may reflect the inadequate adaptation of mechanized operations to the spatial and temporal requirements of maize cultivation in certain regions, or inefficiencies in machinery usage—commonly referred to as “machinery mismatch.” The coefficient for maize planting area (Area) is significantly positive (0.218), suggesting that large-scale operations contribute to higher yields per hectare, possibly due to improved resource allocation associated with concentrated and contiguous farming practices. Although fertilizer input (Fertilizer), effective irrigation area (Irrigation), and primary industry employment (Labor) are positively associated with yield, these variables do not reach statistical significance.

## 4.2 Regional heterogeneity analysis

Given the substantial disparities between northern and southern China in terms of climate regimes, agricultural practices, cropping systems, and maize varieties, the effects of extreme high and low temperatures may manifest with distinct patterns and sensitivities. To assess the regional heterogeneity of these impacts, this study conducts group regressions for the northern and southern major maize-producing provinces. The regression results are reported in [Table 3](#), where Model 1 presents the estimates for southern provinces and Model 2 corresponds to northern provinces. Both models control for province and year fixed effects and include the same set of control variables to ensure comparability of the results.

As shown in [Table 3](#), the number of extreme high temperature days exerts a significant negative impact on maize yield in northern China. Specifically, the regression coefficient for extreme high temperature days in Model 2 is  $-9.027$  and is statistically significant at the 1% level, indicating that each additional day of extreme high temperature leads to an average yield reduction of approximately 9.03 kg per hectare. This result may reflect the fact that maize cultivation in northern regions is primarily concentrated in the summer cropping zone, where the grain filling stage coincides with

**TABLE 4** Temporal heterogeneity effects of extreme temperatures on maize yield.

| Variables         | Model 1                  | Model 2                  |
|-------------------|--------------------------|--------------------------|
| HTD               | −3.453<br>(2.980)        | −4.547**<br>(1.933)      |
| LTD               | −8.085***<br>(3.245)     | 1.923<br>(2.322)         |
| Control variable  | Yes                      | Yes                      |
| Individual effect | Yes                      | Yes                      |
| Time effect       | Yes                      | Yes                      |
| _cons             | 4216.426***<br>(834.289) | 4021.295***<br>(394.529) |
| N                 | 220                      | 260                      |
| R2                | 0.289                    | 0.439                    |

Robust standard errors are in parentheses. \*\* and \*\*\* represent the statistical significance levels of 5% and 1%, respectively.

periods of intense heat, making crops particularly susceptible to heat stress and resulting in substantial yield losses.

In contrast, the coefficient of extreme high temperature days in the southern region (Model 1) is  $-1.255$ , which does not reach statistical significance, suggesting that the influence of high temperature on maize yield in southern provinces is comparatively weaker. On the other hand, extreme low temperature days show a more pronounced effect in the southern region. In Model 1, the regression coefficient of extreme low temperature days is  $-6.546$ , significant at the 10% level, implying that maize yields in southern China are more vulnerable to cold stress. This may be attributed to the predominance of spring-sown maize in the south, where crops are prone to damage from late frosts or abrupt cold spells during the seedling or jointing stages. In northern China (Model 2), the coefficient for extreme low temperature days is 3.879, which is positive but not statistically significant, indicating that maize production in these regions is less sensitive to extreme low temperatures.

## 4.3 Temporal heterogeneity analysis

To further examine the dynamic effects of extreme temperature frequency on maize yield, the sample period is divided into two stages for group regression analysis. Model 1 corresponds to the period from 2000 to 2010, while Model 2 covers the period from 2011 onward. This temporal division captures the evolving trends in climate change and aligns with the timeline of China's progressive agricultural modernization and climate adaptation policies. By comparing results across these two stages, we aim to identify how the impacts of climate shocks on maize yield have changed over time. The regression results are presented in [Table 4](#).

From the results presented in [Table 4](#), it is evident that the number of extreme high temperature days exerted a negative impact on maize yield during both periods, with a more pronounced effect observed in the latter stage. Specifically, during the 2000–2010 period, the regression coefficient for extreme high temperature days was  $-3.453$ , which did not reach statistical



TABLE 5 Robustness check results.

| Variables         | Model 1                  | Model 2                 | Model3                   |
|-------------------|--------------------------|-------------------------|--------------------------|
| TTD               | −3.746***<br>(1.430)     | -                       | -                        |
| HTD               | -                        | −3.605**<br>(1.474)     | 4.000**<br>(1.858)       |
| LTD               | -                        | −1.651<br>(1.746)       | −2.493<br>(1.515)        |
| Control variable  | Yes                      | Yes                     | Yes                      |
| Individual effect | Yes                      | Yes                     | Yes                      |
| Time effect       | Yes                      | Yes                     | Yes                      |
| _cons             | 4226.844***<br>(261.225) | 4119.491***<br>(199.71) | 3137.167***<br>(190.642) |
| N                 | 480                      | 720                     | 480                      |

Robust standard errors are in parentheses. \*\* and \*\*\* represent the statistical significance levels of 5% and 1%, respectively.

significance, although it demonstrated a clear negative tendency. In contrast, for the period after 2011, the coefficient was  $-4.547$  and statistically significant at the 5% level, indicating that as climate warming has intensified and high-temperature events have become more frequent, the constraining effect of heat stress on maize production has become increasingly prominent.

In comparison, the impact of extreme low temperature days revealed distinct temporal variations. During 2000–2010, the coefficient for extreme low temperature days was  $-8.085$ , significant at the 1% level, suggesting that cold spells during this period severely affected maize yield. However, in the post-2011 period, the regression coefficient turned positive and was statistically insignificant. This shift may reflect improvements in farmers' adaptive capacity through enhanced policy support, the widespread adoption of cold-tolerant varieties, and the optimization of sowing schedules, which collectively mitigated the adverse effects of low temperatures on maize yield in recent years.

#### 4.4 Robustness test

To verify the reliability of the main findings, three robustness checks were conducted, and the results are reported in Table 5. In Model 1, we constructed a combined indicator—the total number of extreme temperature days (TTD)—by summing extreme high temperature days and extreme low temperature days, to assess the comprehensive impact of extreme thermal stress on maize yield. The regression coefficient for TTD was  $-3.746$ , significant at the 1% level, indicating that an increase in the overall frequency of extreme temperature events significantly suppresses maize yield. This confirms the overarching inhibitory effect of extreme temperature on maize production.

Model 2 expands the sample scope by incorporating maize yield data from all provinces across China to test the broader applicability of the results. The findings remain consistent: the coefficient for extreme high temperature days was  $-3.605$ , statistically significant at the 5% level, reinforcing the robustness of the negative association between heat stress and maize yield

across a more diverse regional landscape. Meanwhile, the national-level coefficient for extreme low temperature days was  $-1.651$ . Although the sign aligns with theoretical expectations, the result is not statistically significant, possibly due to strong heterogeneity in cold temperature impacts across different agro-ecological zones.

To further ensure that our findings are not confounded by long-term yield growth due to technological progress and agronomic improvements, we re-estimated the baseline models using detrended maize yield data. The detrending procedure removed province-specific linear time trends, and the residuals were used as the dependent variable. The results, as shown in Model 3, remained broadly consistent with the baseline estimations: the coefficient for extreme high-temperature days remained positive and statistically significant, while the coefficient for extreme low-temperature days was negative but statistically insignificant. This robustness check confirms that our estimated climate effects are not driven by secular yield trends.

#### 4.5 The mitigation role of agricultural insurance and protected agriculture

As climate change intensifies, the risks posed by extreme temperature events to agricultural production are becoming increasingly prominent, particularly in major food crops such as maize. As an important risk management tool, the role of agricultural insurance in agricultural disaster mitigation has received widespread attention in recent years. Existing research suggests that agricultural insurance is not only able to provide financial compensation after a disaster, but is also likely to play a role in risk mitigation and behavioral guidance in farmers' decision-making before and during a disaster. Therefore, it is of great practical and policy significance to explore whether and how agricultural insurance moderates its impact on agricultural output under extreme weather conditions. In order to further explore whether agricultural insurance can mitigate the impact of extreme temperature frequency on maize yield, this paper will introduce agricultural insurance data to conduct an interactive regression, and the results are shown in Table 6. Were Model 1 is the regression result of the impact of agricultural insurance to mitigate the impact of extreme high temperatures on maize yield reduction. Model 2 is the regression result of the effect of agricultural insurance to mitigate the effect of extreme low temperature on corn yield reduction.

From the results of the interaction term, in Model 1, the coefficient of the interaction term between extreme heat and agricultural insurance is  $-0.001$ , although the direction is negative, suggesting that agricultural insurance may attenuate the impact of extreme heat on maize yields to a certain extent, but this coefficient does not pass the test of significance, and therefore it cannot be assumed that agricultural insurance has a significant buffering or moderating effect in high temperature scenarios. This may be related to the limitations of current agricultural insurance in terms of what it covers, claims mechanisms, or farmers' coping behavior in response to heat damage. In contrast, the coefficient of the interaction term between extreme low temperatures and agricultural

TABLE 6 The moderating effect of agricultural insurance.

| Variables         | Model 1                  | Model 2                  |
|-------------------|--------------------------|--------------------------|
| HTD               | −5.14**<br>(2.249)       | -                        |
| LTD               | -                        | −2.595<br>(2.671)        |
| HTD × Insurance   | −0.0047<br>(0.065)       | −                        |
| LTD × Insurance   | −                        | 0.126*<br>(0.067)        |
| Control variable  | Yes                      | Yes                      |
| Individual effect | Yes                      | Yes                      |
| Time effect       | Yes                      | Yes                      |
| _cons             | 4177.794***<br>(264.616) | 4743.893***<br>(162.748) |
| N                 | 480                      | 480                      |
| R2                | 0.556                    | 0.504                    |

Robust standard errors are in parentheses. \* and \*\*\* represent the statistical significance levels of 10% and 1%, respectively.

insurance in Model 2 is 0.126 and is significant at the 10% significance level, which suggests that agricultural insurance plays a significant positive moderating effect under extreme low temperatures, helping to mitigate the negative impacts of low temperatures on maize yields. Specifically, the effect of yield reduction due to extreme low temperatures is mitigated when agricultural insurance is purchased, suggesting that the insurance mechanism has a certain protective function against cold weather shocks.

Protected agriculture has gained increasing attention as an important strategy for enhancing agricultural resilience to climate risks. By controlling the growing environment, such as through greenhouses or plastic tunnels, protected agriculture can reduce the adverse effects of temperature fluctuations on crop production. However, the impacts of different types of extreme temperature events—such as extreme heat and extreme cold—on crops may vary, and the moderating effect of protected agriculture can differ accordingly. To further assess whether protected agriculture can mitigate yield losses under extreme temperature conditions, this study incorporates interaction terms between temperature extremes and protected agriculture in the regression models. Model 1 presents the moderating effect of protected agriculture on maize yield under extreme heat, while Model 2 examines the effect under extreme cold conditions. The detailed results are reported in Table 7.

Significant moderating effect under extreme low-temperature conditions, but not under extreme high temperatures. Specifically, in Model 2, the interaction term “LTD × Protected” has a coefficient of 1.321 and is significant at the 10% level, indicating that protected agriculture can significantly mitigate yield losses under cold conditions. This suggests that its capacity for heat retention and insulation provides tangible protective benefits in cold climates. In contrast, in Model 1, the interaction term

TABLE 7 The moderating effect of protected agriculture.

| Variables         | Model 1                  | Model 2                  |
|-------------------|--------------------------|--------------------------|
| HTD               | −11.900<br>(8.770)       | -                        |
| LTD               | -                        | 1.12.912*<br>(6.925)     |
| HTD × Protected   | 1.372<br>(0.913)         | -                        |
| LTD × Protected   | -                        | 1.321*<br>(0.683)        |
| Control variable  | Yes                      | Yes                      |
| Individual effect | Yes                      | Yes                      |
| Time effect       | Yes                      | Yes                      |
| _cons             | 3764.155***<br>(518.491) | 5245.594***<br>(408.050) |
| N                 | 480                      | 480                      |
| R2                | 0.151                    | 0.161                    |

Robust standard errors are in parentheses. \* and \*\*\* represent the statistical significance levels of 10% and 1%, respectively.

“HTD × Protected” has a coefficient of 1.372 but fails to reach statistical significance, implying that the buffering effect of protected agriculture under heat stress is not evident. This result may reflect the current limitations of cooling and shading technologies in protected agriculture for coping with extreme heat. Therefore, protected agriculture appears more effective in addressing yield risks caused by cold temperatures, while its capacity to adapt to extreme heat needs further improvement and technological enhancement.

Although our statistical results indicate that agricultural insurance and protected agriculture can mitigate the adverse effects of low temperatures, their capacity to offset extreme heat shocks remains limited. This discrepancy may be attributed to several factors. First, the design of insurance coverage in China remains primarily oriented toward conventional risks such as drought, flood, or frost. Claims mechanisms often fail to adequately capture the complex and rapid losses induced by extreme heat, and compensation processes may lag behind actual production needs, thereby reducing the efficacy of insurance as an immediate buffer. Second, farmer behavior plays a critical role: participation rates in agricultural insurance remain uneven, and many smallholders underinsure due to limited risk awareness or financial constraints, which diminishes the overall protective effect of insurance against high-temperature shocks. Third, protected agriculture faces technical limitations. While structures such as plastic greenhouses and shading nets are effective against frost and moderate cold, their cooling capacity under persistent extreme heat is constrained. High temperatures can inhibit photosynthesis, accelerate soil moisture loss, and disrupt reproductive processes in crops such as maize—impacts that cannot be fully counteracted by existing infrastructure. Together, these factors help explain why insurance and protected agriculture provide discernible protection against low-temperature stress yet demonstrate limited efficacy in the face of increasingly frequent and intense heat waves.

## 5 Discussion

The empirical results of this study demonstrate that extreme high temperature days exert a significant negative impact on maize yield, a finding that remains robust across various model specifications and sample divisions. These results indicate that, even after accounting for key agricultural input variables, the suppressive effect of high temperature stress on maize yield is substantial and cannot be ignored. From a physiological perspective, extreme heat often coincides with critical growth stages of maize—such as tasseling, pollination, and grain filling—leading to reduced pollen viability, disrupted photosynthesis, and insufficient grain development, all of which contribute to yield losses. These findings are broadly consistent with those of Wang et al. (2018), who investigated the effects of extreme temperatures on maize from a biophysical standpoint. Unlike prior studies that primarily focus on the occurrence of extreme events, this research innovatively employs the frequency of extreme temperatures as a continuous explanatory variable, offering a more nuanced understanding of temperature-related yield risks.

Regional heterogeneity analysis further reveals that extreme high temperature days primarily affects maize yields in northern China, particularly in the summer maize-producing regions. This can be attributed to the synchronization between high temperature periods (typically in July and August) and the sensitive reproductive phases of maize in these areas. Exposure to heat stress during these stages often results in reduced pollen viability, failed pollination and fertilization, and inadequate grain filling, culminating in substantial yield reductions. Similar conclusions were drawn by Tao et al. (2009), who also emphasized the detrimental impacts of heat stress on crop productivity. Moreover, the arid climate in northern China exacerbates this issue, as extreme heat events are frequently coupled with droughts, forming compound “hot-dry” stress conditions. These intensify plant water deficits and physiological strain, thereby compounding the damage to crop development. The high degree of planting concentration and uniform sowing periods in northern provinces further amplify exposure risks, and the delayed adoption of heat-tolerant cultivars and limited irrigation infrastructure in some areas increase the vulnerability of maize production to high temperature shocks (Dong et al., 2023; Song et al., 2020; Wang et al., 2025; Tao and Zhang, 2010).

In contrast, southern China shows a more pronounced sensitivity to extreme low temperature days. Most maize in this region is sown in spring, with seedling and jointing stages occurring in early spring, making crops highly susceptible to late frosts or sudden cold snaps (Wei et al., 2017). During this early growth period, maize plants are physiologically fragile and highly sensitive to temperature fluctuations. Low temperatures can suppress seed germination, delay shoot differentiation, and hinder leaf expansion, resulting in reduced emergence rates, prolonged vegetative phases, and—in severe cases—frost damage or seedling mortality. These conditions directly impair fruit set and grain development (Song et al., 2022; Yuan et al., 2024). In addition, southern China's humid climate often causes low temperatures to coincide with excessive rainfall and limited sunlight, further reducing photosynthetic efficiency, slowing nutrient accumulation, and increasing the risk

of pest and disease outbreaks. Compounding these effects is the predominance of smallholder and fragmented maize cultivation systems in the south, which tend to lack robust disaster resilience. This structural fragility further intensifies the yield impacts of low temperature events. The findings of Zhang et al. (2022) similarly point to the low disaster resilience of small-scale agricultural systems in southern China.

Temporal heterogeneity analysis reveals a clear trend: as global warming intensifies, the frequency and severity of extreme heat events have escalated, and their adverse effects on maize productivity have become increasingly pronounced. During the early study period (2000–2010), high temperatures exerted a modest and statistically insignificant impact on yields. However, in the latter period (2011 onwards), as the probability of heat waves during critical reproductive stages increased, high temperature stress emerged as a principal limiting factor to yield improvement. This temporal shift underscores not only the direct physiological disruptions caused by heat stress—such as impaired photosynthesis, reduced pollen viability, and lower grain filling rates—but also reflects the lagging capacity of current agricultural systems to adapt effectively to rising climate extremes. Research by Kornhuber et al. (2023); Porter (2005); and Feng et al. (2021) likewise suggests that increasing temperatures significantly heighten the risk of crop yield declines. As such, climate warming has become a pressing threat to China's grain production system, especially given the growing frequency of high temperature anomalies. Adaptive strategies—such as enhancing meteorological monitoring, promoting heat-tolerant varieties, and improving irrigation regulation—are urgently needed (Grigorieva et al., 2023; Manescu et al., 2025).

This study also systematically explores the mitigating role of agricultural insurance and facility-based agriculture in maize yield shocks in terms of extreme temperature events, and the results show that there are significant differences between the two in response to different types of temperature extremes. On the one hand, agricultural insurance and facility-based agriculture have a significant role in mitigating maize yield losses under extreme low temperature scenarios. Agricultural insurance improves farmers' production confidence and resilience in cold weather and strengthens the stability of the agricultural system through risk transfer and financial compensation mechanisms (Sun et al., 2024; Manescu et al., 2025). Protected agriculture, on the other hand, constructs a physical barrier to a certain extent by regulating the temperature environment for crop growth, effectively mitigating the adverse effects of low temperatures such as cold waves and frost (Gruda et al., 2019). This result suggests that both agricultural insurance and protected agriculture can be used as effective adaptation tools in regions with frequent low temperatures or significant cold seasons. On the other hand, under extreme high temperature conditions, the adjustment effects of agricultural insurance and protected agriculture are not obvious, suggesting that there are still institutional or technological shortcomings in both of them to cope with high temperature stress. High-temperature stress often occurs suddenly, loss identification is difficult, and the recovery cycle is long, which brings challenges for insurance compensation and prevention and control interventions. At the same time, the

limited application of existing technologies for high-temperature ventilation and cooling, and shading, makes it difficult for existing facilities to provide effective protection against persistent high temperatures.

Despite the strengths of this study—including its use of multi-provincial panel data and control for key agricultural inputs—it is not without limitations. First, the extreme temperature indices were constructed using monthly meteorological station data, which may fail to capture short-term or compound climate events. Future research could integrate higher-frequency meteorological data and multidimensional extreme climate indices to refine mechanism identification. Second, while the fixed effects model mitigates some omitted variable bias, it cannot fully account for heterogeneity in farmer behavior, regional agronomic practices, or institutional adaptability. Combining econometric analysis with process-based crop simulation models or spatial econometric techniques may offer a more comprehensive understanding of the non-linear and threshold dynamics between climate and yield. Finally, the regional heterogeneity analysis in this study was restricted to a north–south division, which provides only a coarse representation of spatial variation. Future research should conduct finer-scale analyses at the provincial or agro-ecological zone level to capture more localized differences in climate impacts and adaptation effectiveness.

## 6 Conclusions and policy recommendations

### 6.1 Research conclusions

Drawing on panel data from China's major corn-producing provinces between 2000 and 2023, this study systematically evaluates the effects of extreme high and low temperature events on corn yields and reveals the potential threat of climate extremes to food security. The main conclusions are as follows:

- (1) Extreme high temperatures significantly suppress corn yields. Whether in national-level regressions or in regional and temporal sub-sample analyses, the number of extreme high temperature days exhibits a consistently significant and negative impact on corn yields. This effect is particularly pronounced in the main summer maize-growing areas in northern China, suggesting that heat stress has become a key constraint to stable grain production and supply.
- (2) The effect of extreme low temperatures varies regionally. Corn yields in southern China are more sensitive to low temperature stress, mainly because spring-sown maize is vulnerable to late frosts during the seedling or jointing stages. In contrast, in northern China where maize is typically sown in summer, extreme cold usually occurs before sowing and thus exerts a relatively limited impact on yield.
- (3) The effects of extreme temperatures have intensified over time. In recent years, the adverse impacts of extreme heat on corn yields have grown more pronounced, reflecting the cumulative risk posed by climate change and the vulnerabilities within existing agricultural systems. Meanwhile, the negative effects of extreme low temperatures, which were significant during 2000–2010, appear to have weakened in recent years, indicating an improvement in farmers' adaptive capacity.
- (4) Agricultural insurance and protected agriculture demonstrate significant effectiveness in mitigating the adverse impacts of extreme low temperatures on maize yields, highlighting their protective role in cold climates. However, both measures show limited effectiveness in alleviating yield reductions caused by high temperature stress, indicating that current insurance mechanisms and protective technologies require further enhancement to better manage heat-related risks.

### 6.2 Policy recommendations

Based on the above findings, the following policy implications are proposed:

- (1) Strengthen extreme climate monitoring and agricultural early warning systems. Given the increasing frequency, intensity, and duration of extreme temperature events, which pose a serious threat to stable maize yields, it is imperative to enhance the agricultural climate monitoring network. This can be achieved by integrating meteorological stations, remote sensing technologies, and smart weather equipment to improve real-time tracking of extreme weather events. Additionally, a multi-tiered and precise early warning mechanism for agricultural production should be established, enabling timely information dissemination and responsive planning by local authorities and farmers, thereby supporting national food security.
- (2) Accelerate the breeding and dissemination of heat- and cold-tolerant maize varieties. Since extreme heat significantly affects northern maize production and low temperatures pose threats in the south, investment in the development of climate-resilient maize varieties must be intensified. This includes supporting innovation in germplasm resources, molecular breeding technologies, and multi-location field trials. A sound varietal promotion system should also be developed to prioritize the dissemination of climate-adapted varieties in regions most prone to temperature extremes, thus enhancing the overall resilience of cropping systems.
- (3) Promote the integration of agronomic optimization and water-saving technologies. The extent of yield loss under extreme temperatures is shaped not only by climatic conditions but also by on-farm management practices. Farmers should be encouraged to adjust sowing dates, planting density, and water-fertilizer strategies in accordance with local climatic and varietal characteristics to minimize the risk of heat or cold stress during critical growth periods. Additionally, efficient irrigation technologies—such as drip irrigation, sprinkler systems, and fertigation—should be promoted to mitigate soil moisture deficits caused by high temperatures and improve the agricultural system's adaptive capacity to climate stress.
- (4) Develop regionally differentiated response strategies. Given that extreme heat predominantly affects northern maize-producing areas, while extreme cold poses greater risks to spring maize in the south, targeted response strategies

are essential. In the north, emphasis should be placed on enhancing technical support and infrastructure for managing heat stress, as well as optimizing cropping patterns. In the south, efforts should focus on frost prevention and cold wave response mechanisms, adjusting planting calendars, providing agronomic guidance, and implementing locally adapted risk mitigation policies.

- (5) Enhance agricultural climate risk insurance and disaster compensation mechanisms. As the frequency of extreme temperature events rises, traditional agricultural insurance schemes often fail to provide adequate protection against systemic climate risks. It is recommended to incorporate events such as extreme high and low temperatures into the coverage scope of policy-based agricultural insurance. Efforts should be made to diversify insurance products, refine payout mechanisms, and explore innovations such as weather index-based insurance. Moreover, a rapid post-disaster assessment and compensation system should be developed to facilitate timely recovery and reinforce farmers' confidence in resuming production. These institutional measures are vital for improving the overall resilience and disaster preparedness of the agricultural sector.

## Data availability statement

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

## Author contributions

FY: Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. JH: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. JL: Data curation,

Investigation, Methodology, Software, Writing – review & editing. JW: Software, Validation, Visualization, Writing – review & editing.

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## 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

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