Market Integration and Climate Resilience: Evidence from Agricultural Wholesale Markets in China

PENG Rongyi YU Jianyu GUO Mengmeng

Abstract: The increasing frequency of extreme weather events has created persistent challenges for agricultural production, significantly amplifying price volatility in agricultural markets. As a fundamental mechanism for optimizing resource allocation, the impact of market integration on mitigating climate-induced price fluctuations warrants thorough investigation. This study develops a three-sector equilibrium model incorporating production (farmers), distribution (new agricultural business entities), and consumption (markets), which theoretically elucidates the transmission mechanism whereby extreme weather reduces local supply and drives price increases, along with the conditions under which market integration can effectively mitigate these impacts. Utilizing a comprehensive dataset spanning 2011-2022, including price data from 96 national agricultural wholesale markets, county-level climate records, and micro-level data on new agricultural business entities, we empirically examine these relationships using Chinese cabbage as a case study. Our results demonstrate that extreme heat significantly increases cabbage prices primarily through production shocks, with local production capacity and distribution efficiency serving as key moderating factors, while demand-side factors show negligible effects.Further analysis reveals that local markets mitigate climate shocks through dual channels: enhancing their own production resilience and distribution efficiency, while also benefiting from spillover effects via interconnected markets. The mitigation effect strengthens with increasing market integration. Heterogeneity analysis distinguishes between peripheral markets, which rely predominantly on local production resilience with limited benefits from distribution improvements or regional coordination, and hub markets, which achieve more effective shock absorption through advanced distribution systems and robust inter-regional collaboration.These findings offer valuable insights for addressing market fragmentation and advancing market integration in agricultural systems. The study provides both theoretical contributions to understanding climate-risk transmission mechanisms and practical implications for designing differentiated regional policies to enhance market resilience.

Keywords: Extreme weather; agricultural product prices; market integration

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Peng Rongyi, Institute of Economics and Management, Southwestern University of Finance and Economics, 611130,RongyiPeng12@outlook.com, 15113782819, No.555 Liutai Avenue, Wenjiang, Chengdu, Sichuan; Yu Jianyu, Institute of Economics and Management, Southwestern University of Finance and Economics, 611130,yujianyu@swufe.edu.cn, 15196697556, No.555 Liutai Avenue, Wenjiang, Chengdu, Sichuan; Guo Mengmeng, School of Finance, Nanjing Agricultural University, 210014,gmm@njau.edu.cn, 15882443492, No.1 Weigang, Xuanwu District, Nanjing, Jiangsu Province, 210014.

1. Introduction

Under the background of global climate change, the frequent occurrence of extreme weather events poses a persistent threat to agricultural production and has become a major exogenous shock that disrupts the stability of the agricultural economy (Schlenker and Roberts, 2009; Nath, 2025). Agricultural production is inherently dependent on natural conditions, and extreme weather such as high temperatures and heavy rains can easily lead to reduced yields and supply contraction in local areas. Among these, the impact of high-temperature heat damage on vegetable crops is particularly significant, often disrupting the supply-demand balance and leading to drastic price fluctuations (Xin et al., 2024). The "China Climate Change Blue Paper (2021)" points out that since the mid-1990s, the frequency of extreme heat events in China has significantly increased, and the climate risk index has shown a continuous upward trend. This situation has further exacerbated the uncertainty in agricultural production and agricultural product markets, posing severe challenges to food security and livelihood protection. The 2024 Central Economic Work Conference explicitly stated the need to effectively ensure stable production and supply of grain and important agricultural products, improve the comprehensive benefits and competitiveness of agriculture, and pointed out the policy direction for addressing climate risks and stabilizing the agricultural market.

Theoretically, agricultural market systems can achieve spatial risk dispersion through establishing cross-regional production-consumption coordination mechanisms and improving emergency allocation systems, enabling "one-region shortage, multi-region supply". By maintaining dynamic supply-demand balance to stabilize price fluctuations, these systems can mitigate climate change impacts on agricultural production. Taking vegetable markets as an example: China launched the "Vegetable Basket Project" in the 1980s, implementing a mayoral accountability system to ensure local urban supply. Through suburban production base layouts, an initial network for meeting residents 'basic living needs was established. With deepening market reforms, agricultural wholesale markets rapidly expanded into a nationwide network, with core markets becoming production-consumption hubs that shaped the "large-scale market and circulation" framework. Subsequently, production base layouts were continuously optimized. Six major vegetable production areas developed specialized production based on resource advantages, leveraging improved logistics to connect with national consumer markets. Cross-regional circulation models like "vegetables from south to north" and "vegetables from west to east" matured, achieving efficient cross-seasonal and cross-regional allocation of agricultural products. However, in recent years, frequent extreme heatwaves have led to long-term upward trends and short-term sharp fluctuations in vegetable price indices, reflecting the current agricultural market system's failure to fully leverage price regulation effectiveness (see Figure 1).

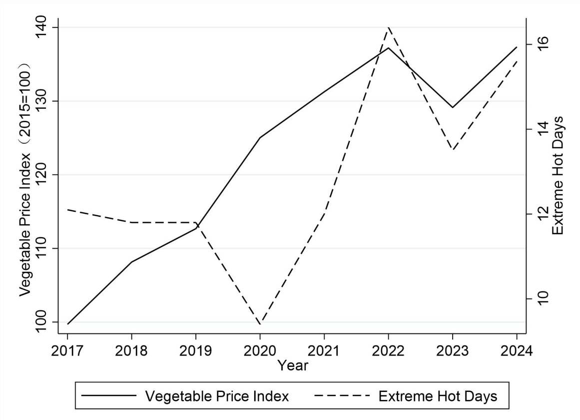

Figure 1 Vegetable price index and extreme high temperature days

Note: The vegetable price index is derived from the "National Agricultural Products Wholesale Market Price Information System" of the Ministry of Agriculture and Rural Affairs (with 2015 as 100), and the original index is monthly. This article aggregates the average to annual. The number of extreme high-temperature days is based on the national average high-temperature days (daily maximum temperature ≥35°C) published in the China Climate Bulletin over the years.

Against this backdrop, the deepening of China's national unified market initiative has created a pivotal institutional opportunity to fundamentally resolve agricultural price volatility. The 2022 "Opinions of the CPC Central Committee and the State Council on Accelerating the Construction of a National Unified Market" emphasized the need to "swiftly establish ①unified market rules, dismantle regional protectionism and market fragmentation, remove critical bottlenecks in economic circulation, and facilitate the free flow of goods, factors, and resources across broader regions." By integrating logistics, capital flows, and information networks through unified market infrastructure, and by strengthening the modern commercial distribution system, we can enhance the efficient coordination between production and sales markets, thereby building a resilient agricultural market that spans the entire production, distribution, and consumption chain.

This study therefore examines three pivotal questions: How do extreme weather events influence agricultural product prices? What market mechanisms can mitigate their impacts? What systemic variations exist in regional responses to extreme weather shocks? Against the backdrop of building a unified national market, how can we identify critical bottlenecks based on regional characteristics to develop tailored resilience enhancement strategies? Addressing these questions not only enriches the theoretical framework for price formation under climate risks but also provides crucial policy insights for optimizing market systems and advancing the development of a unified national market.

Building upon Nath's (2025) analytical framework, this study constructs a three-sector equilibrium model encompassing production (farmers), distribution (new agricultural business entities), and consumption (markets) to systematically examine how extreme weather impacts agricultural product prices through productivity effects. The model reveals a nonlinear threshold effect: prices rise significantly when weather-induced productivity shocks exceed a critical threshold. This threshold effect is moderated by three mechanisms: local market supply-demand conditions, distribution system efficiency, and inter-market coordination. Specifically, well-developed local markets raise the climate shock threshold, enhancing market resilience; distribution networks mitigate supply shortages through price discovery mechanisms, reducing price volatility; and interconnected markets create synergistic effects to stabilize local prices. These findings not only provide crucial hypotheses for testing risk transmission mechanisms in agricultural markets but also offer theoretical foundations for identifying regional bottlenecks in building a unified national market.

Based on a theoretical analytical framework, this study selects Chinese cabbage — a typical agricultural product with high yield, wide coverage, and frequent cross-regional transactions — as the research subject. By integrating monthly price data from 96 representative agricultural wholesale markets nationwide (2011-2022), county-level climate observation data, and micro-level data from new agricultural business entities, we constructed a dual fixed-effects model for empirical analysis. The results show that extreme heatwaves significantly elevate Chinese cabbage market prices through direct impacts on local production and traders' price sensitivity. Testing mitigation mechanisms reveals that local market resilience focuses on production and distribution aspects: production-side factors (e.g., cooperative, family farm, and agricultural enterprise stock, irrigation coverage, and plastic film usage) and distribution-side factors (e.g., wholesale-retail enterprise stock, transportation infrastructure) effectively mitigate extreme weather impacts. Demand-side factors, however, show no significant moderating effect. Further analysis indicates that under the national unified market framework, higher price correlations between local and external markets reduce extreme weather

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See Opinions of the CPC Central Committee and The State Council on Accelerating the Construction of a Unified National Market, https://www.gov.cn/zhengce/2022-04/10/content_5684385.htm impacts on local markets. Based on this, we define external markets with strongest price correlations to local markets as "associated markets" and examine their development conditions as mitigation mechanisms. The study finds that improved production-side conditions (cooperatives, family farms, agricultural enterprises, irrigation coverage, and plastic film usage) and enhanced distribution-side infrastructure (wholesale-retail enterprises, transportation networks) significantly amplify climate impact mitigation effects on local markets.

These findings provide crucial evidence for identifying regional market heterogeneity bottlenecks. By analyzing the coordination between local and related market prices, this study categorizes markets into high-coordination "hub markets" and low-coordination "peripheral markets." Heterogeneity analysis reveals distinct mechanisms in how these two market types respond to extreme weather shocks: Peripheral markets primarily rely on local production cooperatives, family farms, and agricultural enterprises to mitigate extreme weather impacts, with limited effectiveness in improving distribution efficiency and regional coordination. In contrast, hub markets can enhance distribution efficiency through logistics companies, e-commerce platforms, and transportation infrastructure, while strengthening collaboration with related markets to boost climate resilience. This discovery offers significant policy implications: When advancing the development of a unified national market, it is essential to fully consider regional differences in market development stages and implement differentiated policy guidance.

Compared to previous studies, this paper's innovations are primarily reflected in the following aspects. First, it provides a more comprehensive exploration of climate risk mitigation mechanisms. In the field of climate adaptation strategies, existing literature predominantly focuses on single-dimensional mitigation pathways. Some studies emphasize production-side adaptation behaviors, such as farmers adjusting production inputs (Xie et al., 2018) and innovating cultivation models (Howden et al., 2007). Others concentrate on localized optimization at the distribution end, including improving transportation efficiency (Badiane and Shively, 1998), enhancing storage facilities (Salazar et al., 2023), and upgrading transportation infrastructure (Shively and Thapa, 2016), yet none have formed a holistic chain analysis perspective. Even when market synergy is mentioned, it remains confined to local market characteristics (e.g., Bao et al., 2022 examining the integration effect of local supply with expressways), neglecting the systemic value of cross-regional coordination (Allen and Atkin, 2022). Grounded in the context of a unified national market, this study not only examines the resilience of local production end (cooperatives, family farms, agricultural enterprises, and irrigation/film facilities) but also analyzes resource allocation efficiency at the distribution end (logistics enterprises, transportation infrastructure). Furthermore, it incorporates cross-regional market collaboration into the analysis, comprehensively deconstructing multi-level climate risk mitigation mechanisms and expanding the research boundaries in this field.

Second, this study innovates the perspective and methodology for evaluating the functionality of a unified national market, precisely mapping market interconnection networks through price correlation analysis. The core of a unified national market lies in the free flow of production factors and market integration (Liu Zhibiao, 2022). Existing research predominantly focuses on its construction factors (e.g., local preferences (Tang Xiaobin et al., 2025), institutional reforms (Xiong Lingyun et al., 2025)) or development metrics (e.g., market segmentation index (Fu Yangqi & Zhu Yuchun, 2024)), yet lacks empirical validation of its practical value. To address the practical constraints of limited access to agricultural wholesale market transaction data, this paper discards traditional index construction methods and adopts price correlation analysis (Asche et al., 1999). By capturing cross-regional network characteristics through price synchronization between markets, it not only avoids data scarcity challenges but also ensures indicator reliability through large-scale agricultural wholesale market reports. Building on this foundation, the study demonstrates how regional market coordination mitigates high-temperature price shocks, providing a new approach to identify the actual effectiveness and bottlenecks in constructing a unified national market.

Third, accurately identifying regional market heterogeneity bottlenecks provides empirical evidence for differentiated market policies. Existing research on agricultural market risk management primarily focuses on surface-level production characteristics like planting area and product mix (Ruan et al., 2021; Bao et al., 2022; Zhang Hao et al., 2022), failing to address deeper regional disparities in development stages and cross-regional coordination. This results in policy recommendations that lack specificity and struggle to resolve core bottlenecks across different markets. By analyzing price coordination between local and related markets, this study categorizes samples into high-coordination "hub markets" and low-coordination "peripheral markets". Through heterogeneity analysis, it reveals distinct mitigation pathways: peripheral markets rely on local production resilience with limited circulation efficiency and regional coordination, while hub markets enhance climate resilience through improved circulation efficiency and deepened regional collaboration. These findings precisely identify core weaknesses in different market types during the construction of a unified national market, addressing existing research gaps in market heterogeneity analysis. The study provides direct empirical support for implementing categorized guidance and localized solutions to overcome bottlenecks in advancing the national unified market initiative.

2. Basic facts

2.1 Basic Facts about Chinese Cabbage

As the world's largest vegetable producer, China cultivates over 300 million mu (approximately 20 million hectares) of vegetable fields annually, yielding more than 700 [①]million tons of produce with a total output value exceeding 2 trillion yuan. Remarkably, just 10% of the total planting area generates about 40% of the industry's value. Leveraging six major vegetable production zones and 580 key "vegetable basket" counties, the country maintains year-round production. Strategic initiatives like the "South-to-North Vegetable Transport" and "West-to-East Vegetable Distribution" ensure balanced supply. This makes the development of a unified national market crucial for securing stable supply and prices.

To accurately assess the mitigation effects of cross-regional allocation under high-temperature shocks, the research subject must satisfy three core requirements. First, industrial representativeness: the subject must occupy a critical position in the vegetable supply chain and exhibit characteristics similar to most categories, ensuring the conclusions can be generalized to the entire vegetable market (especially leafy vegetables). Second, heat sensitivity: the subject must be highly sensitive to external heat shocks to avoid causal identification interference from "shock effect ambiguity." Third, storage-transport compatibility: the subject must inherently rely on cross-regional allocation to minimize interference from local inventory and other factors in analyzing mitigation mechanisms. Based on these three requirements and data availability, this study ultimately selects Chinese cabbage as the core research subject, with the following specific reasons.

Chinese cabbage reigns as the most extensively cultivated and highest-yielding vegetable in China, with a planting area of approximately 39.34 million [②]mu (about 262,267 hectares) and an annual output of 100 million tons. This accounts for 13.1% of total vegetable cultivation area and 14.4% of total production volume. Its massive production scale and market presence solidify [③]its pivotal role in the vegetable supply chain. Ensuring stable supply of staple vegetables like cabbage,

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Source: Panorama of Vegetable Industry in Great Countries, https://www.agri.cn/sc/zxjc/scsc/202404/t20240423_8627330.htm

Source: Ministry of Agriculture and Rural Affairs, http://www.zzys.moa.gov.cn/tzgg/202312/t20231213_6442695.htm

Source: Ministry of Agriculture and Rural Affairs, https://www.moa.gov.cn/xw/qg/201912/t20191218_6333423.htm

Source: The agricultural product price monitoring system jointly operated by the Ministry of Commerce and the Ministry of Agriculture and Rural Affairs conducts high-frequency tracking of vegetable varieties critical to national livelihood. Leveraging this institutional framework, the frequency of different vegetables appearing in monthly monitoring data is quantified as a policy attention index, which indirectly reflects their strategic importance in China's national vegetable supply chain. The top six vegetables in order are tomato, Chinese cabbage, cucumber, potato, celery, and green pepper.

bell peppers, and cucumbers is crucial for maintaining overall market stability (Song Changming & Li Chongguang, 2012). According to price data from the Ministry of Agriculture and Rural Affairs, Chinese cabbage ranks second in statistical frequency after tomatoes, highlighting its strategic importance and data richness in the market. Sharing similarities with most leafy greens in perishability, storability, and nutritional value, it demonstrates substitutability with other vegetables (Ruan et al., 2021). Its price fluctuations exhibit significant synchronization and transmission effects, mirroring the general patterns of vegetable market dynamics.

Chinese cabbage exhibits high-temperature sensitivity (Xin et al., 2024), with yield losses being both immediate and severe. The autumn harvest in China's Yangtze River and Huaihai ①River basins accounts for two-thirds of the national total, coinciding with summer's peak heat period. This overlap makes heat stress particularly widespread and impactful. Specifically, high temperatures not only directly inhibit growth and trigger diseases like downy mildew and soft rot, reducing yields, but also accelerate growth-stage losses, further shrinking the available supply.

The cross-regional cultivation of Chinese cabbage (grown extensively in both northern and southern China) and its multi-seasonal production (spring, summer, and autumn) makes market supply highly dependent on regional allocation mechanisms ②like "south-to-north vegetable transportation" and "highland supply to supplement off-season demand." Data shows post-harvest storage losses can reach 30% due to rapid moisture evaporation and high respiration heat. As a bulk, low-cost vegetable lacking specialized cold storage infrastructure, Chinese cabbage struggles to achieve "off-peak supply" through local reserves. When high temperatures reduce yields, rapid external transportation becomes essential to fill the gap, underscoring the critical role of cross-regional allocation in mitigating heatwave impacts.

2.2 Extreme High Temperature and the Price Fluctuation of Chinese Cabbage

The average market price of Chinese cabbage exhibits a significant co-variation with the Growing Season Heat Degree Days (HDD) (see Figure 2). During peak extreme heat events in 2013 and 2020, market prices rose in tandem. This phenomenon provides preliminary evidence for the transmission mechanism where extreme heat suppresses production supply (e.g., through yield reduction and quality deterioration), causing regional supply-demand imbalances that subsequently drive up market prices. The findings clearly demonstrate the direct impact of climatic factors on agricultural markets.

The price dispersion of Chinese cabbage exhibits pronounced volatility. This study presents Figures 3 and 4, which map cabbage prices and their absolute deviations from the national average across low (P10), medium (P50), and high (P90) percentiles. Figure 3 reveals a consistent upward trend in prices at all three percentiles, with the P90-P10 price gap (indicating price dispersion) remaining persistently elevated. Notably, this gap significantly widened during peak heat years including 2013,2016, and 2022. These patterns underscore intensifying regional price disparities, demonstrate the inadequacy of a unified national pricing mechanism, and highlight persistent bottlenecks in market price regulation mechanisms that continuously influence price fluctuations. Figure 4 further shows the P90 percentile maintaining a high level over time, with its inter-percentile distance expanding through fluctuations. This directly indicates widespread and substantial regional price differences, reveals significant shortcomings in cross-regional price coordination mechanisms within the unified market, and highlights practical challenges in aligning regional prices and mitigating price disparities.

A deeper analysis of Figures 3 and 4 reveals that extreme heatwaves significantly amplify price dispersion. During high-temperature years like 2013 and 2020, the price gap between the 90th and 10th percentiles (p90-p10) and regional price differentials skyrocketed. Even areas with smaller initial price gaps (p10 percentile) showed marked resilience deficiencies. This phenomenon exposes the shortcomings of China's unified national market in its "cross-regional price coordination mechanism"

Source: Vegetable Research Center, Beijing Academy of Agriculture and Forestry Sciences

Source: Ministry of Agriculture and Rural Affairs, https://jgs.moa.gov.cn/fxpg/202202/t20220225_6389723.htm

— when heatwaves trigger localized supply shortages, the market fails to mitigate regional price disparities through efficient circulation, ultimately exacerbating price fragmentation. This provides a clear problem-oriented approach for future research on optimizing the unified national market.

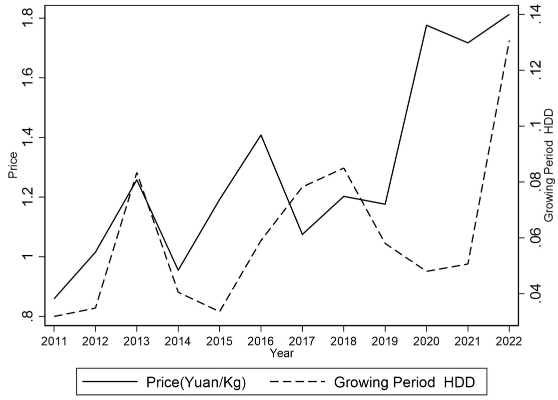

Figure 2 Cabbage prices and extreme heat (2011-2022)

Note: The Growing Period HDD (Heat Damage Degree) quantifies cumulative harmful heat exposure during Chinese cabbage's growth phase. For this crop, it corresponds to the three-month average temperature prior to market release, as detailed below.

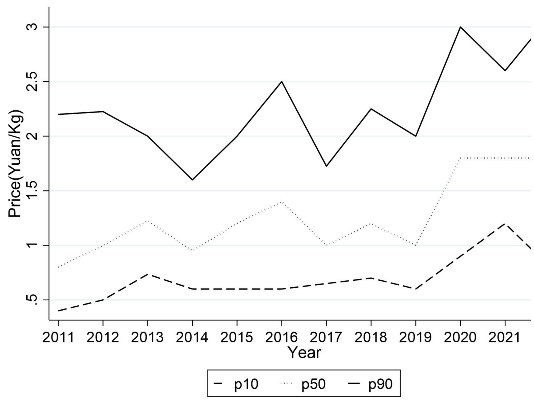

Figure 3 The price of Chinese cabbage

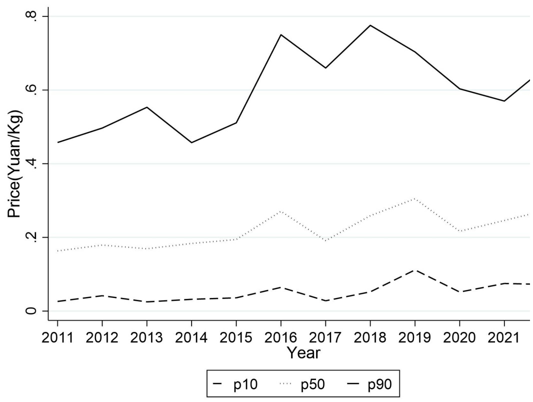

Figure 4: Price difference of Chinese cabbage

Note: The price difference of Chinese cabbage is calculated as |Wholesale price of Chinese cabbage-National average price|

2.3 Price Fluctuation with Market Heterogeneity

The market heterogeneity of Chinese cabbage prices is notably pronounced. This study utilizes wholesale price data to construct a regional market correlation matrix by calculating price correlation coefficients between any two markets within the region. The matrix enables intuitive assessment of inter-market linkage, with the average correlation coefficient serving as a proxy for regional market relevance (Wu Chengming, 1996). While this methodology has limitations, it effectively reflects the importance of markets in regional distribution networks. Higher average correlations indicate stronger capacity for price stabilization through efficient cross-regional circulation, whereas lower correlations suggest more volatile price fluctuations.

Based on price correlation grouping (≤ P25 as low correlation group,>P75 as high correlation group), Figure 5 clearly illustrates the price fluctuation differences among markets with varying correlations. In terms of price levels, the high correlation group exhibits relatively smoother price fluctuations and consistently lower prices over the long term compared to the low correlation group. The low correlation group, however, not only shows greater price volatility but also maintains higher price centers. From the perspective of spread fluctuations, the low correlation group demonstrates significantly larger spread amplitudes than the high correlation group, with particularly noticeable peak differences. This characteristic indicates that markets with weaker cross-regional circulation coordination mechanisms are more susceptible to price discrepancies caused by localized supply-demand mismatches. The existence of such market heterogeneity reveals fundamental differences in bottlenecks faced during circulation processes across correlation levels, providing crucial empirical evidence for targeted heterogeneity analysis and exploring differentiated market optimization strategies.

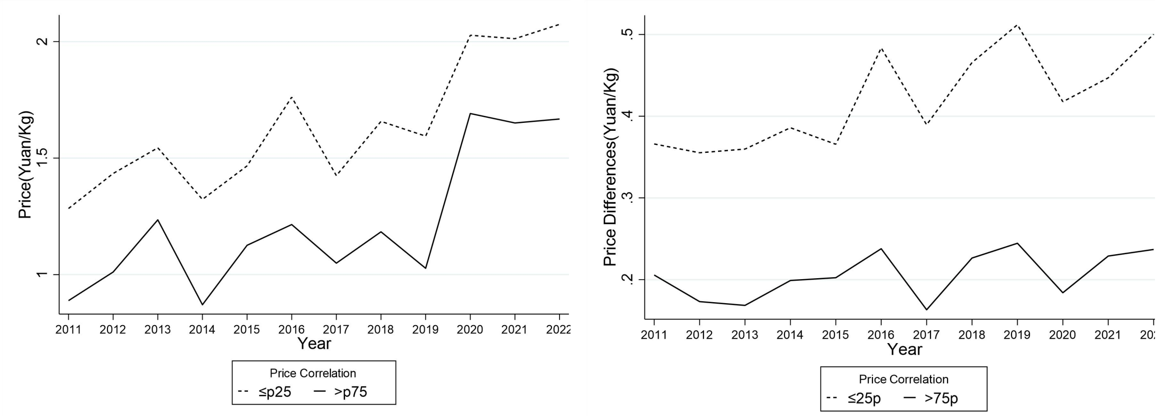

Figure 5 Price Fluctuation in Different Correlation Markets

Note: This study categorizes the sample market into two groups based on the 25th/75th percentile (low ≤P25, high>P75) for correlation analysis. The average price differences of Chinese cabbage between these groups and the national average were statistically calculated to generate the aforementioned chart.

3. Theoretical framework and research hypotheses

To elucidate the underlying mechanisms of the unified national market in mitigating agricultural price volatility, this study builds upon Nath's (2025) theoretical framework for trade solutions to food security challenges. It constructs a three-sector equilibrium model encompassing production (farmers), distribution (modern agricultural entities), and demand (markets), examining how extreme weather triggers price surges in agricultural products. Furthermore, by analyzing the conditions and influencing factors that enable the unified market to cushion extreme weather impacts, the research establishes a set of testable theoretical hypotheses for subsequent empirical analysis.

Consider a wholesale market for agricultural products $iS_i(p_i, A_i, \eta_i)p_iA_i\eta_i\frac{\partial S_i}{\partial p_i} > 0, \frac{\partial S_i}{\partial A_i} > 0, \frac{\partial S_i}{\partial \eta_i} > 0\varepsilon A_i\frac{\partial A_i}{\partial \varepsilon} < 0\frac{\partial S_i}{\partial \varepsilon} = \frac{\partial S_i}{\partial A_i}\frac{\partial A_i}{\partial \varepsilon} < 0\frac{\partial^2 S_i}{\partial \varepsilon \partial \eta_i} > 0$ with self-sufficiency capacity. The market's representative produce is sourced from local farmers and distributed by modern agricultural operators. The supply function at the production end can be expressed as, where represents the procurement price set by modern operators, denotes productivity, and accounts for supply-impacting factors such as [①]irrigation, mulching film, operational characteristics, and factor supply elasticity. For simplicity, we

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The $S_i(p_I, A_I, \eta_i)S_i = A_iL_i^{\alpha_i}L_i\alpha_i w\max_{L_i} p_i A_iL_i^{\alpha_i} - wL_iS_i(p_I, A_I, \eta_i) = A_i^{1+\eta_i}\left(\frac{\alpha_i}{w}\right)^{\eta_i}p_i^{\eta_i}$其中$\eta_i = \frac{\alpha_i}{1-\alpha_i}$specific form can be derived from the traditional production function. Assuming a representative farmer as a producer facing a production function, where represents the agricultural factor input and denotes the input-output elasticity. If the assume that agricultural supply increases with rising prices, productivity gains, and improved production conditions. Specifically, climate shocks negatively affect supply by reducing productivity (). From the supply side, enhanced production conditions mitigate adverse effects of climate risks ().

From the demand perspective, the general form of the wholesale $Q_i(P_i, \sigma_i) P_i \sigma_i \frac{\partial Q_i}{\partial P_i} < 0, \frac{\partial^2 Q_i}{\partial P_i \sigma_i} > 0$ market demand function can be expressed as. Here, represents the market selling price, while other factors affecting demand include agricultural product demand elasticity, scale, consumer demographics, and other market characteristics. Without losing generality,. Intuitively, rising market prices reduce demand, but favorable market conditions can effectively mitigate the adverse effects of price increases on demand.

In the context of building a unified national market, the supply-demand efficiency of distribution channel operators directly impacts the magnitude of climate shocks. To examine the behavior of distribution entities while incorporating empirical $n_i z_i q_i x_i i j \tau_{ij} \tau_{ij} > 1$ identification strategies for production areas, we focus on an agricultural wholesale market with export capabilities (origin warehouse). Assuming a market operator that purchases agricultural products from local and external market units, the iceberg cost of transporting goods between markets is (). The profit-maximization problem for distribution entities can be formulated as:

$$max_{q_i, z_i, x_i} P_i q_i + P^X x_i - \tau_{ii} p_i z_i \quad (1)$$

The optimal $P^X \equiv \max_j \left\{\frac{P_j}{\tau_{ij}}\right\} i$ effective price is the price that the business entity exports. Assuming that the business entity in the circulation link is the price acceptor, the general equilibrium condition of the three sectors of production, circulation and consumption in the market is:

（1） clearing the market：

$$Q_i(P_i, \sigma_i) + X_i = S_i(p_i, A_i, \eta_i) \quad (2)$$

（2） The local selling price and effective purchase price are anchored to the effective export price of the relevant market.

$$P_i = \tau_{ii} p_i = P^X \quad (3)$$

The equilibrium conditions above highlight how new agricultural business entities function as market organizers to stabilize local prices within $Q_i = n_i q_i;\ Z_i = n_i z_i;\ X_i = n_i x_i \tau_{ii} p_i P_i P^X$ a unified market. (2) The equation represents market clearing conditions, where the total volume comprises individual sales, export volumes, and procurement volumes of these entities. (3) This implies that market prices in the unified market — resilient to local extreme weather — stabilize procurement and sales prices in local markets. Specifically, if a price gap exists between local (effective) procurement prices, demand prices, and export prices, distributors can arbitrage by adjusting procurement volumes, local supply, or export volumes, ultimately aligning the three market prices. This conclusion embodies the one-price law of the unified market (Jensen, 2007).

Under the anchor effect of the related market price, the impact of extreme weather on the local market may present nonlinear characteristics. Proposition 1 is summarized as follows:

Proposition 1: The volatility of agricultural product prices is determined by the intensity of productivity shocks caused $\bar{A} \equiv \left\{A \middle| Q_i(P^X, \sigma_i) = S_i\left(\frac{P^X}{\tau_{ii}}, A, \eta_i\right)\right\}$ by extreme weather and the price discovery capacity of market participants. Specifically, there exists a critical productivity threshold at which

1. When extreme weather impacts $A \geq \bar{A} P^* = P^X$ on actual productivity are small, the net

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production factor price is, the farmer's production decision problem can be expressed as:. Through first-order conditional derivation, the farmer's supply function is obtained as, where represents the supply price elasticity.

export attribute of local market is not changed by extreme weather impact, and the equilibrium price is not affected, which is still anchored by the export price of related market.

2. When the extreme weather impacts $A < \bar{A}P^M \equiv min_{j\in J(n_i)}\{\tau_{ji}P_j\}P^* = P^M > P^X$ the actual productivity, the local market changes from net export to net import, and the equilibrium price jumps to the lowest effective import price that the circulation subject can find.

The explanation of Proposition 1 can be illustrated in Figure 1. In $iP_i = Q_i^{-1}\tau_{ii}p_i = \tau_{ii}S_i^{-1}P^XS_i > Q_iiX_i > 0i\tau_{ii}p_i^{'}P^XS_i^{'}Q_iP^X\tau_{ii}p_iS_i^{''}Q_i^{''}X_i^{''}0P^M$ the diagram, the black lines represent the inverse demand curve and the inverse supply curve considering iceberg costs. When the effective export price of the associated market is, the market reaches equilibrium supply, indicating agricultural exports to external markets. When the market experiences extreme weather shocks, the local supply curve shifts leftward to the dashed line () due to reduced productivity. If the unified market exerts regulatory effects, the associated market's price remains stable at. Although local supply decreases to, local demand remains unaffected and stays at. Local selling prices and agricultural purchase prices also remain unaffected, anchored at the level of. When extreme weather shocks are more severe, the local market supply shifts leftward to '', failing to meet export demand (<) and requiring imports from external markets to satisfy local demand (<). In this case, the market equilibrium price is anchored at the minimum import price observable by market participants.

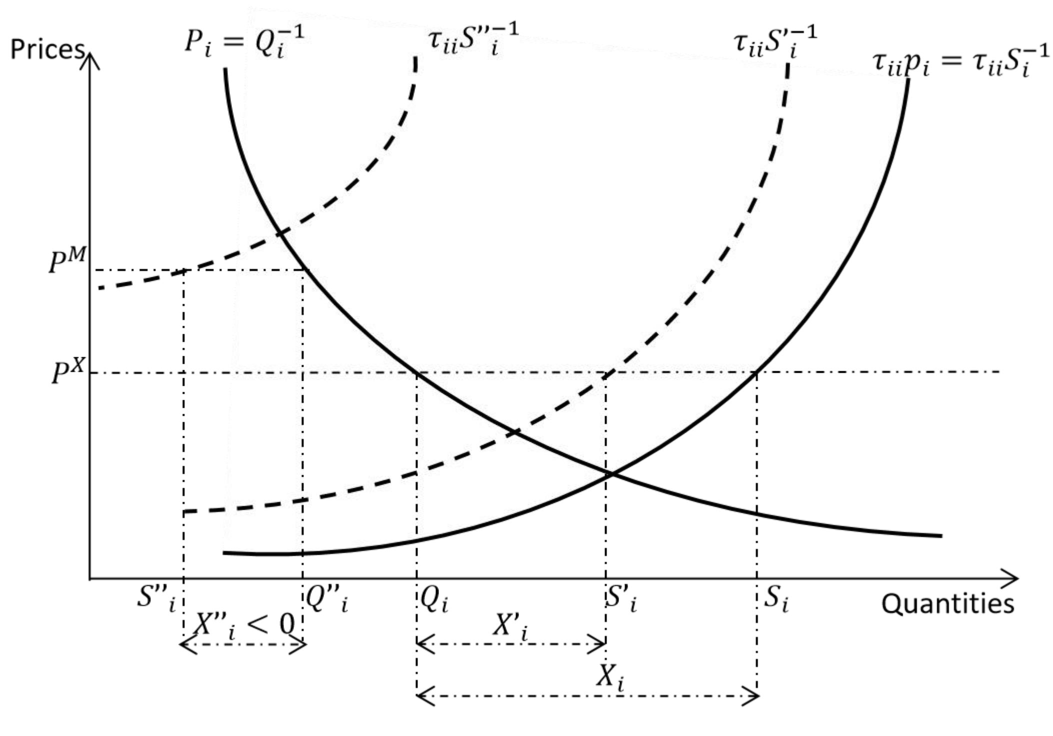

Figure 6 Impact of extreme weather on local markets and mitigation effect of market coordination

Proposition 1 establishes a foundational framework for investigating the mitigation mechanisms of extreme weather. It demonstrates that whether extreme weather $\bar{A}\bar{A} \equiv$

$\left\{A \middle| Q_i(P^X, \sigma_i) = S_i\left(\frac{P^X}{\tau_{ii}}, A, \eta_i\right)\right\} \bar{A}$ elevates market prices depends on whether its productivity impact falls below a critical threshold. The definition of this threshold reveals that it is influenced by local demand and supply conditions. Specifically, the implicit function theorem can be derived to conclude:

$$\frac{\partial \bar{A}}{\partial \sigma_i} = \frac{\partial Q_i}{\partial \sigma_i} / \frac{\partial S_i}{\partial A_i} > 0; \ \frac{\partial \bar{A}}{\partial \eta_i} = \frac{\partial S_i}{\partial \eta_i} / \frac{\partial S_i}{\partial A_i} > 0;$$

In other words, favorable local market and production conditions help push up the critical value of climate shocks, making it less likely for extreme weather to affect local markets. This leads to the following hypothesis:

Hypothesis 1: The more complete the local market demand and supply conditions are, the less impact extreme weather has on agricultural product prices.

When extreme weather events trigger supply shortages in local markets, Proposition 1 indicates that market price increases are determined $P^M \equiv min_{j \in J(n_i)}\{\tau_{ji} P_j\} n_i J(n_i) min_{j \in J(n_i)}\{\tau_{ji} P_j\}$ by two factors. Firstly, as defined by import pricing principles, a larger number of distributors in the supply chain allows for broader market coverage, thereby enabling the identification of more competitive import prices.

$$\frac{\partial P^M}{\partial n_i} < 0.$$

This price discovery mechanism can be summarized as Hypothesis 2:

Hypothesis 2: The more developed the local market circulation system is, the less impact extreme weather has on agricultural product prices.

On the other hand, import $\{\tau_{ji} P_j\} P_j$ prices are also determined by the supply-demand conditions and distribution efficiency of the related markets. Specifically, the more developed the production and distribution conditions in these markets, the lower the import prices will be, thereby alleviating upward pressure on local prices. This leads to Hypothesis 3:

Hypothesis 3: The more perfect the market demand, supply and circulation conditions of the local market, the less impact extreme weather has on the price of local agricultural products.

The analysis demonstrates that extreme weather exerts a significant threshold effect on agricultural product prices, mediated by three key mechanisms: (1) buffering capacity determined by local supply-demand elasticity; (2) price discovery efficiency within distribution networks; and (3) synergistic stabilization effects from interconnected markets. However, these regulatory mechanisms may exhibit substantial heterogeneity in practice — regional variations in resource endowments, infrastructure, and development stages inevitably lead to divergent approaches in building market resilience. Under the framework of establishing a unified national market, which regions should prioritize domestic market development, while others should emphasize cross-regional collaboration through interconnected markets? These questions require empirical validation based on national-level market data.

4. Data and research design

4.1 Sample selection and data sources

The price data for Chinese cabbage in this study was sourced from the National Key Agricultural Products Market Information Platform operated by China's Ministry of Agriculture and Rural Affairs. This platform consolidates multi-source price data from over 200 agricultural wholesale markets across the country, covering diverse geographical regions and market types. Given the representative nature of Chinese cabbage in agricultural product distribution, the research analyzed monthly wholesale price data from January 2011 to December 2022. To ensure data quality and time series integrity, the study implemented rigorous screening criteria, retaining only wholesale markets with continuous price records. This resulted in a sample of 96 markets with long-term stable monitoring of Chinese cabbage prices. This selection strategy effectively addressed data gaps, providing a reliable data foundation for subsequent analyses of climate change impacts.

The climate data originates from the National Meteorological Science Data Center. This study employs spatial interpolation methods to convert discrete meteorological station data into grid data with a resolution of $0.1^\circ \times 0.1^\circ$, followed by further rasterization processing. Through regional mean calculations, monthly average climate indicators such as temperature and precipitation are obtained for various districts and counties in China. To avoid excessive smoothing during interpolation, a five-point neighbor interpolation method is adopted, using data from only the five meteorological stations surrounding the target grid node for estimation.

The geographical coordinates of agricultural product wholesale markets and vegetable price data are sourced from the National Agricultural Product Wholesale Market Price Information System Platform. The production cycles and major export regions of the six major vegetable-producing areas in China are obtained based on the "National Vegetable Industry Development Plan (2011-2020)" and market analysis. The existing data of new agricultural entities such as vegetable cooperatives, family farms, and agricultural enterprises at the county level are acquired after cleaning and processing by the Zhejiang University Carter-Enterprise Research China Agricultural Research Database (CCAD). Other adjustment and control variables are sourced from data sources such as the "China County Statistical Yearbook" and the "China City Statistical Yearbook".

This study matched price data with climate data across county-level and annual-month time dimensions. Control variables were integrated at the county-year level, while moderating variables were consolidated at the county/city-year level, ultimately constructing a monthly panel dataset covering 96 agricultural product wholesale markets nationwide from 2011 to 2022. It should be emphasized that this paper could not collect panel data such as monthly Chinese cabbage production at the county level, making it impossible to use yield variables to test whether extreme weather impacts production and drives up prices. To address this limitation, when selecting empirical analysis samples, we retained only prices during Chinese cabbage's market season based on the National Vegetable Industry Development Plan (2011-2020) and typical market conditions. Furthermore, we calculated the cumulative extreme heat during the growing season corresponding to the market period according to Chinese cabbage's growth characteristics (see details below).

4.2 model specification

To test the relationship between high temperature and cabbage price, and to explore the relief mechanism of market conditions in local and related markets, the following regression models are constructed:

$$Price_{ic,mt} = \alpha_0 + \beta_0 HDD_{ic,mt} + \delta_k X_{ic,mt} + \theta_p Z_{ct} + \gamma_i + \mu_{mt} + \varepsilon_{ic,mt} \quad (4)$$

Here, represents $Price_{ic,mt} HDD_{ic,mt} X_{ic,mt} Z_{ct} \gamma_i \mu_{mt} \varepsilon_{ic,mt} \alpha_0 \beta \delta_k \theta_p$ the price of Chinese cabbage in the i-th agricultural wholesale market in month m of year t, while indicates the harmful heat accumulation during the corresponding growth period of Chinese cabbage in county c (where market i is located) in month m of year t. Other variables include other climatic conditions in county c during month m of year t, and the annual county economic variable set. The fixed effects for individuals and time effectively control for potential confounding factors such as market heterogeneity, seasonal supply-demand patterns, and macroeconomic trends, thereby enabling precise identification of causal relationships between core explanatory variables and the dependent variable, ensuring consistency and robustness of the estimation results. The random error term is, the constant term is, and the model estimation parameters are. In this regression model, standard errors are clustered at the wholesale market level.

4.3 Variable definition and description

Dependent Variable. This study employs the natural logarithm of monthly Chinese cabbage prices as the dependent variable. Given that high temperatures in the research context significantly inhibit cabbage growth, reducing production yields in growing regions thereby tightening local market supply and driving price increases, the model is constructed using price data from the cabbage harvest season. This approach effectively eliminates non-production cycle interference factors, enabling precise capture of supply-demand fluctuations' impact on pricing.

Core explanatory variables. The growing season HDD (Harmful Degree Days) serves as the primary explanatory variable in this study, often used in conjunction with GDD (Growing Degree Days). Building upon the research of Schlenker and Roberts (2009) and Chen et al. (2016), this paper employs HDD to characterize extreme heat stress in Chinese cabbage, typically paired with GDD to represent temperature suitability for growth. These two metrics precisely quantify the heat accumulation processes affecting crop growth: HDD measures the negative impact of extreme heat on crop yield, while GDD reflects the heat accumulation that promotes growth within optimal temperature ranges. The calculation formulas for HDD and GDD are as follows:

$$GDD_{c,mt} = \sum_{d} \Big(min\big(T_{c,mtd} - \tau_1,\ \tau_2 - \tau_1\big)\Big)\, \mathbf{1}\ \left(T_{c,mtd} \in [\tau_1, +\infty\right) \tag{5}$$

$$HDD_{c,mt} = \sum_{d} \left(T_{c,mtd} - \tau_2\right)\, \mathbf{1}\ \left(T_{c,mtd} \in [\tau_2, +\infty\right) \tag{6}$$

In Equations (5) and $T_{c,mtd}\tau_1\tau_2 GDD_{c,mt} HDD_{c,mt}$(6): T_c represents the average temperature in county c during day d of year t for market m, with T_c representing the minimum temperature tolerable for normal cabbage growth ①and T_d representing the maximum temperature tolerable for normal cabbage growth. The minimum temperature unfavorable for cabbage growth ranges from 5°C to 28°C (Guo Fengling and Li Baoguang, 2018). Specifically, T_c denotes the monthly effective accumulated temperature and T_d denotes the harmful high-temperature accumulated temperature for cabbage in county c.

To verify the mechanism through which climate impacts drive price increases by affecting production, this study systematically analyzed cabbage market entry dates from the National Vegetable Industry Development Plan (2011-2020) and representative wholesale markets including Wuhan Baishazhou, Shouguang Dili, and Mengyang. Drawing on Guo Fengling and Li Baoguang's (2018) research, the complete growth cycle of Chinese cabbage is divided into three key phases: 20-25 days for germination and seedling stage, 20-25 days for rosette stage, and 25-30 days for early-maturing varieties' bolting stage, while late-maturing varieties require 40-50 days (Figure 7). Using actual market entry months as benchmarks, the study defined 1-month delay as maturity stage, 2-month delay as rosette stage, and 3-month delay as germination/seedling stage. This methodology successfully obtained climate indicators including HDD, GDD, and rainfall data for each growth phase, with detailed calculations presented in Equation (6). Given the lack of high-frequency yield data at the county level, this approach provides a reliable basis for accurately identifying the intrinsic relationship between production shocks and price fluctuations.

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https://www.cma.gov.cn/kppd/kppdqxyr/kppdnyqx/201212/t20121216_197325.html

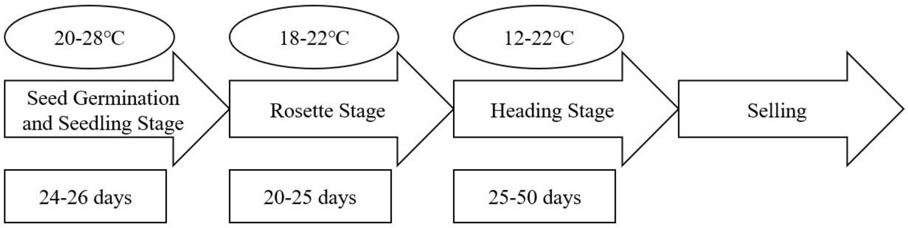

Figure 7: Growth cycle of Chinese cabbage at different stages

$$\text{Growing period HDD}_{c,mt} = \underbrace{\text{HDD}_{c,(m-3)t}}_{\text{Seed Germination and Seedling Stage}} + \underbrace{\text{HDD}_{c,(m-2)t}}_{\text{Rosette Stage}} + \underbrace{\text{HDD}_{c,(m-1)t}}_{\text{Heading Stage}} \quad (7)$$

Control variables. To account for other factors affecting Chinese cabbage prices, this study incorporates climate variables by extending the framework of (Schlenker & Roberts, 2009; Chen et al., 2016). In addition to the core explanatory variable—harvest-day degree-day (HDD) during the growing season—normal-day degree-day (GDD) and average precipitation during the growing season are included to comprehensively assess the impact of climatic conditions on cabbage production and pricing.

At the county level, drawing on existing research (Zhao Xiaofei and Tian Ye, 2016; Zhang Hongyu, 2018; Li Lanbing and Zhang Congcong, 2022), we selected control variables covering multiple dimensions including economy, agriculture, resources, finance, consumption, and human capital. The per capita GDP measures economic development, while the proportion of primary industry added value reflects agricultural development. Cultivated land area indicates land resource endowment, and the ratio of local general public budget expenditure to GDP reflects fiscal expenditure. The year-end ratio of financial institution loan balance to GDP measures financial development, and per capita retail sales of consumer goods reflect local consumption levels. The ratio of ordinary secondary school students to the county's total population characterizes human capital levels. Detailed definitions of key variables and descriptive statistics are presented in Table 1.

Table 1 Definition of main variables Table 1 Definition of main variables

type of variable	Variable name	variable-definition	average value	standard deviation
explained variable	The price of Chinese cabbage	Monthly price of Chinese cabbage during the market season (yuan)	1.314	0.671
explanatory variable	HDD	The threshold of harmful accumulated temperature (high temperature) during the growth period is 28℃ (100℃·day).	0.063	0.176
controlled variable	GDD	The normal accumulated temperature during the growth period is 5/28℃ (100℃·day).	7.667	5.826
	precipitation	Average precipitation during the growing season (100ml)	1.855	1.540
	economic development	GDP per capita (RMB)	73553	43118
	agricultural development	The proportion of the added value of the primary industry in the regional GDP	0.086	0.080

arable land resources	Cultivated land area (thousand mu)	48.32	42.91
fiscal expenditure	Expenditure of local general public budget / revenue of local general public budget	2.155	1.341
financial development	ratio of the balance of all loans of financial institutions to GDP at the end of the year	1.224	0.703
local consumption	Total retail sales of consumer goods per capita (in yuan)	29750	18001
human capital	The ratio of students in regular middle schools to the total population of the county	0.047	0.016

Note: In the regression, the price of Chinese cabbage, economic development and local consumption variables are all logarithmized in yuan, and the cultivated land resources are logarithmized in ten thousand mu.

5. Empirical results

5.1 regression analysis of base line

Table 2 presents the regression results of high temperatures (HDD) during the growing season and harvest season on the market price of Chinese cabbage. All results are adjusted for market fixed effects and year-month fixed effects, with columns (2) and (4) controlling for a series of county-level characteristic variables. Columns (1)-(2) show the impact of high temperatures during the growing season on prices, while columns (3)-(4) demonstrate the effect of high temperatures during the harvest season.

The regression analysis reveals significant positive HDD coefficients in columns (1)-(2), indicating that extreme heat during the growing season drives up Chinese cabbage prices. However, columns (3)-(4) show no significant impact of summer heat on market prices, creating a stark contrast. The key rationale behind this divergence lies in how heatwaves fundamentally disrupt local production supply. Growing-season heat directly suppresses crop growth and induces diseases, rigidly reducing local supply volumes. This supply contraction directly translates into sustained upward price pressure. In contrast, summer heat during harvest season may cause transportation losses and short-term stockpiling expectations among consumers, which essentially represent "secondary supply shocks." If local production maintains adequate supply (as in temperate years or non-primary production areas), these secondary shocks can be quickly absorbed without supply gaps or sustained price inflation. Economically significant, each one-standard-deviation increase in harmful growing-season heat (0.176) correlates with a 6.4% price increase for Chinese cabbage (0.363×0.176).

Table 2 Regression results of high temperature affecting the market price of Chinese cabbageTable 2 Regression results of the market price of Chinese cabbage affected by high temperature

variable	(1) period of growth	(2) period of growth	(3) listing period	(4) listing period
HDD	0.324***	0.363***	0.067	0.080
	(7.05)	(7.56)	(0.52)	(0.61)
GDD		-0.011		-0.015
		(-1.02)		(-1.28)
sample capacity	6,010	6,010	6,010	6,010
R-squared	0.648	0.652	0.643	0.646

Note: The asterisk denotes a 1% significance level. The t-values in parentheses reflect cluster-adjusted values at the wholesale market level (as applicable). All analyses control for market and time fixed effects, with control variables consistent with the baseline regression. Models (1)-(2) estimate the impact of high temperatures during the growing season on Chinese cabbage prices, while models (3)-(4) assess the effect of high temperatures during the marketing period.

5.2 mechanism analysis

The impact of extreme heatwaves on agricultural product prices exhibits multidimensional characteristics. While existing research suggests that high temperatures may indirectly affect prices through changes in demand-side expectations (Letta et al., 2021; Su et al., 2025), this study emphasizes that the core mechanism remains substantial supply shocks at the production end. If local production supply remains unaffected (e.g., in temperate years or non-major production areas), even minor losses during harvesting and transportation, coupled with short-term stockpiling expectations from consumers, can be quickly absorbed by sufficient total supply, making sustained price increases unlikely. Limited by the availability of high-frequency growth data for vegetables and Chinese cabbage, traditional causal inference methods struggle to directly quantify how production-side supply changes drive cabbage prices. Therefore, this research constructs a dynamic analytical framework of "climate shock-market response-price transmission" using real-time transaction data from representative wholesale markets like Wuxi Chaoyang Market. By integrating text mining techniques and in-depth analysis of typical cases, it systematically reveals the nonlinear transmission mechanism between extreme heatwaves and agricultural price fluctuations. Additionally, the study constructs demand-side price attention metrics based on Baidu Index's "Chinese cabbage price" search index to examine the role of expectation mechanisms in price responses to heatwaves.

The Wuxi Chaoyang Agricultural Products Market, with its unique geographical advantages and rich data resources, serves as a highly valuable research case. As a key agricultural distribution hub in the Yangtze River Delta, it is located in the winter-spring vegetable production zone of the Yangtze River [1]Basin. It also maintains close collaboration with the Huang-Huai[2]-Hai and Bohai Rim regions, which collectively produce 65% of China's cabbage output. Within the local market, vegetables account for over 95% of both trading volume and consumption, combining multiple attributes: a regional distribution center, a high-dimensional data sample, and a climate-sensitive area. These composite characteristics enable the market data to not only accurately capture regional price fluctuation patterns but also, through in-depth mechanism analysis, yield nationwide applicable research conclusions. This provides crucial evidence for addressing key challenges in climate change-pricing volatility studies.

This study draws data from 353 weekly vegetable market reports published by Wuxi Chaoyang Agricultural Products Market between January 2016 and December 2022, covering key information such as price fluctuations, root cause analysis, and transmission pathways. Compared to the monthly agricultural wholesale market index released by the Ministry of Agriculture, the weekly data offers higher temporal resolution, enabling precise capture of short-term price volatility under high-temperature impacts. Detailed records in the reports, such as "Sustained high temperatures caused leafy vegetable loss rates to surge by 30%," provide direct evidence for constructing causal models of price fluctuations. This paper systematically analyzes the data using Python text mining techniques and manual cross-validation methods to identify high-temperature-induced price anomalies and fully reconstruct their transmission trajectories (specific event lists are detailed in Appendix 1).

Table 3 illustrates the impact of high temperatures on agricultural prices and its underlying causes. The findings reveal that extreme heat primarily affects agricultural production through supply chain disruptions. During the study period, 29 price fluctuations triggered by heatwaves were recorded, with over 90% of cases demonstrating that elevated temperatures significantly hinder crop

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[1] see appendix

[2] https://pfsc.agri.cn/?eqid=bdfcf69700055466000000364476807#/MarketIntroductionDetail?id=76E4F160C0B7936CE040A8C020017257

growth, alter maturation cycles, and increase preservation costs. Notably, the inter-regional vegetable distribution mechanism effectively mitigated price surges caused by heatwaves in 2016,2018, and 2019. This confirms the positive role of cross-regional allocation in stabilizing prices during climate anomalies, clearly showing that reduced crop yields due to heatwaves are the primary driver of price increases, while efficient market mechanisms can substantially reduce the volatility caused by climatic shocks.

Table 3 Impact of High Temperature on Prices and Adjustment Path of Supply Side Table 3 Impact of High Temperature on Prices and Adjustment Path of Supply Side

a particular year	time	cause	mechanism of transmission	price changes
2022	July-September	sustained high temperature	Reduced production; increased transportation costs	continuous rise
2021	July–October	High temperatures + heavy rain	Reduced production; storage and transportation are hindered	rise
2019	August	high temperature	Reduced production; sufficient guest dishes	undulate
2018	July	High temperatures + the rainy season	reduction of output	rise
2018	August	High temperatures + heavy rain	Reduced production; increased customer dishes	undulate
2017	June-July	High temperatures + the rainy season	Reduced production; increased storage costs	rise
2016	July–August	High temperatures + the rainy season	Reduced production; increased customer dishes	fall

Note: In time, a "-" indicates the period from month to month, showing that the price changes and their causes are consistent during this period; in causes, a "+" indicates that both causes led to the price change.

Based on the theoretical analysis in this paper, supply contraction serves as the primary mechanism driving the price increase of Chinese cabbage due to high temperatures, while the impact of demand-side changes on pricing requires further verification. To this end, we construct price attention using the "Chinese cabbage price" Baidu Index to characterize demand-side expectations. Table 4 illustrates the influence of high temperatures on prices and the moderating path of psychological expectations. Columns (1)-(2) reveal a significantly positive interaction term between price attention and high temperatures (HDD), indicating that heightened price awareness amplifies the upward pressure from high temperatures. This phenomenon stems from short-term emotional demand fluctuations—when price signals are detected, it triggers stress responses like "short-term stockpiling" or "pre-emptive purchasing," temporarily exacerbating supply-demand imbalances. However, it should be clarified that this moderating effect essentially represents short-term demand feedback under supply contraction. Its effectiveness hinges on the premise that "high temperatures have already caused supply shortages," and it only manifests as temporary emotional amplification, incapable of independently triggering sustained price increases.

Table 4 Effect of High Temperature on Price and the Adjustment Path of Price Attention Table 4 The Effect of High Temperature on Price and the Adjustment Path of Price Attention

variable	(1)	(2)
	price	

HDD	0.425***	0.455***
	(7.38)	(7.65)
HDD ×price is a topic of interest.	0.177***	0.169***
	(3.63)	(3.52)
controlled variable	deny	yes
market fixed effect	yes	yes
year-month fixed effect	yes	yes
sample capacity	5,870	5,870
R-squared	0.650	0.654

Note: The sample size in the table is smaller than the benchmark regression due to the lack of matching price reverse attention data for some observations, as will be explained below. Here, 'price attention' is defined as the standardized provincial-level Baidu Index value corresponding to the 'Chinese cabbage price' during the listing period, which reflects the regional demand elasticity for Chinese cabbage during its market season.

5.3 robustness test

This section presents a series of robustness tests to examine the HDD threshold. In addition to the HDD used in the benchmark regression, this study also demonstrates the use of adjacent cutoff values for HDD definition, as referenced by Cui and Tang (2023), with qualitatively similar results. The test results in Columns (1)-(2) of Table 5 show that both HDD27 and HDD29 coefficients are significantly positive, with HDD27 coefficients being lower than those of HDD and HDD29. Compared to the HDD calculated at 28°C, high-temperature shocks exceeding 29°C lead to greater price increases in Chinese cabbage, while temperatures above 27°C result in smaller price increases.

The HDD was calculated during the growth phase. This study adopted the established methodology in existing literature, applying a fixed threshold to calculate HDD without considering the temperature threshold heterogeneity across different growth stages of Chinese cabbage. Based on the previous analysis, we calculated HDD separately for each growth stage and aggregated them into a growth-phase HDD to examine the impact of high temperatures on market prices. As shown in Column (3), HDD remains significantly positively correlated with Chinese cabbage prices. However, the baseline regression overestimated this effect, as it assumed HDD represented more severe heat stress conditions.

Extreme heat events. The sensitivity of Chinese cabbage to temperature variations may differ across regions. To further examine the impact of extreme heat on prices, this study evaluates the price increase effect of climate shocks using extreme heat data from various areas. Following Pan Min et al. (2022), extreme heat is defined as months with temperatures exceeding the 90th percentile of historical averages. As shown in Table (4), the results demonstrate a significant positive correlation between extreme heat and price increases.

To control the cross effect of other vegetables on Chinese cabbage, the paper introduces the prices of lettuce, tomato, white radish and other alternative agricultural products as control variables. The results are shown in column (5), and the coefficient of HDD is still significantly positive.

Table 5 Robustness test Table 5 Robustness test

variable	(1) Lower the 1°C threshold	(2) Increase the 1℃ threshold	(3) phase of cell division count HDD	(4) Extreme heat replace HDD	(5) Join the Alternative Vegetable Price Initiative

HDD (threshold =27℃)	0.284***				
	(7.99)				
GDD (threshold =27℃)	-0.009				
	(-0.86)				
HDD (threshold =29℃)		0.436***			
		(6.93)			
GDD (threshold =29℃)		-0.006			
		(-0.52)			
HDD (Phase-Shifted Threshold)			0.126***		
			(5.63)		
extreme heat				0.004***	
				(2.87)	
HDD					0.237***
					(4.84)
GDD					-0.022**
					(-2.13)
sample capacity	5,778	5,778	5,054	5,778	3,941
R-squared	0.659	0.656	0.658	0.653	0.712

Note: All analyses controlled for market fixed effects and time fixed effects, with control variables consistent with the baseline regression. Columns (1)-(2) recalculated HDD and GDD by adjusting the optimal growth temperature for Chinese cabbage by ±1°C for testing purposes. Column (3) calculated harmful accumulated temperature for each growth stage of Chinese cabbage and aggregated it into the growing-season HDD. Column (4) defined extreme heat as months with temperatures exceeding the 90th percentile of historical averages. Column (5) included prices of alternative crops (lettuce, tomatoes, white radish) as control variables.

6. Mitigation Mechanism of Market Integration

The preceding theoretical analysis has established that agricultural price fluctuations under extreme heatwaves are determined by both productivity thresholds and external supply capacities of interconnected markets. Building on this framework, Chapter 5 has completed benchmark regression, mechanism analysis, and robustness testing, preliminarily confirming that extreme heatwaves drive price increases by suppressing local production. This chapter further examines whether factors in local and interconnected markets can effectively mitigate price surges through demand, production, and distribution channels. To this end, the paper constructs the following moderating effect model based on the benchmark regression framework:

$$Price_{ic,mt} = \alpha_0 + \beta_1 HDD_{ic,mt} + \beta_2 HDD_{ic,mt} \times M_{it} + \beta_3 M_t + \delta_k X_{ic,mt} + \theta_p Z_{ct} + \gamma_i + \mu_{mt} + \varepsilon_{ic,mt} \tag{8}$$

$$Price_{ic,mt} = \alpha_0 + \beta_1 HDD_{ic,mt} + \beta_2 HDD_{ic,mt} \times M_{jt} + \beta_3 M_t + HDD_{jc,mt} + \delta_k X_{ic,mt} + \theta_p Z_{ct} + \gamma_i + \mu_{mt} + \varepsilon_{ic,mt} \quad (9)$$

Equations (8)-(9) provide a systematic framework to examine whether the local market and associated markets exhibit $M_{it}M_{jt}HDD_{jc,mt}$a moderating effect across demand, production, and distribution dimensions. The moderating variables and represent specific factors influencing the development of these three aspects in local or associated markets, while other variables are defined as in Equation (4). To address potential overlaps in heatwave impacts between local and associated markets — or the potential transmission of extreme heat effects from associated markets to local markets—Equation (9) further controls for extreme heat events in associated markets to prevent estimation bias in moderating effects.

Guided by the theoretical framework of the climate impact price mitigation mechanism in the construction of a unified agricultural product market, and drawing on existing literature (Wang Xuhui and Zhang Qilin, 2016; Zhao Xiaofei and Tian Ye, 2016; Hao et al., 2017; Zhang Hongyu, 2018; Li Lanbing and Zhang Congcong, 2022; Bao et al., 2022; Zhao Xue et al., 2023; Salazar et al., 2023; Li Lanbing and Lu Haiyong, 2024; Zheng, 2024), this study conducts empirical analysis by constructing a multi-dimensional adjustment variable system (see Table 6). Specifically, on the demand side, the annual number of vegetable trading categories in agricultural wholesale markets is selected as a proxy variable for the availability of substitutes to measure consumers 'alternative choice space in response to price fluctuations. At the same time, population density is introduced to quantify the impact of consumption demand scale on demand elasticity. On the production side, lagged first-period stock data of farmers' specialized cooperatives, family farms, and agricultural production enterprises are selected to accurately measure the development level of agricultural business entities. Indicators such as irrigation coverage and plastic film usage are combined to assess the resilience of agricultural production to disasters. On the distribution side, lagged first-period stock data of distribution-type agricultural enterprises and agricultural industrialization leading enterprises are selected as indicators to measure the organizational level of market circulation. Additionally, variables such as highway import/export density, the establishment of national e-commerce rural demonstration counties, and the implementation policy dummy variable of the "Broadband <China>" strategy are incorporated to characterize the regional market's transportation and logistics infrastructure and digitalization level. The above variables provide systematic data support for the empirical test of the hypothesis.

Table 6 Definition of adjustment variables Table 6 Definition of adjustment variables

variable type	Variable name	variable-definition	local market		related market	
			mean	standard error	mean	standard deviation
demand side	Number of alternatives	The wholesale market sells a variety of vegetables throughout the year.	40.97	12.04	41.496	12.044
	density of population	density of population	6.654	1.173	7.202	1.283
supply side	cooperative	Previous period cooperative stock (hundreds)	1.704	2.755	0.585	0.766
	Family farm	Last period family farm stock (hundreds)	0.176	0.810	0.243	0.795
	Agricultural enterprises (production)	Last period's agricultural enterprises (production) stock (hundreds)	1.110	1.906	0.739	0.985
	irrigation cover	Effective irrigated area / Crop sown area	0.491	0.158	0.543	0.226

	Thin film usage	Agricultural plastic film usage per crop sown area (tons per 1,000 hectares) × 100%	22.181	15.523	28.31	21.16
circulation end	Agricultural enterprises (distribution)	Last period's agricultural enterprises (circulation) stock (hundreds)	1.841	3.349	3.265	6.856
	corporate champion	Number of leading enterprises in the previous period	0.837	1.641	0.786	1.319
	E-commerce Demonstration County	Is it a model county for e-commerce?	0.126	0.331	0.124	0.330
	Broadband China	Whether to implement the broadband China policy	0.365	0.481	0.350	0.477
	transportation condition	Highway import and export density	0.649	1.094	1.090	1.489

6.1 The Mechanism of Alleviation of Local Market Supply and Demand

Table 7 presents the regression results of supply-side mitigation mechanisms in the local market. Columns (1)-(3) show that the interaction coefficients between HDD and cooperatives, family farms, and agricultural enterprises (production) are all significantly negative. This indicates that cooperatives, through their resource integration capabilities and production scheduling optimization mechanisms; family farms, by leveraging large-scale and specialized production models; and agricultural enterprises (production), through advanced production management systems, can effectively mitigate the positive impact of HDD on agricultural product prices. These mechanisms establish an effective regulatory framework between yield fluctuations and price changes, thereby maintaining market supply stability. Columns (4)-(5) further reveal that the interaction coefficients between HDD and irrigation coverage/film usage are also significantly negative, suggesting that both irrigation coverage and film application can significantly enhance agricultural production's risk resistance. This dual approach effectively curbs supply imbalances and severe price volatility caused by external environmental changes, ultimately alleviating price fluctuations triggered by HDD fluctuations.

Table 7 Local market supply side mitigation mechanism Table 7 Local market supply side mitigation mechanism

variable	(1)	(2)	(3)	(4)	(5)
			price		
HDD	0.417***	0.379***	0.412***	0.771***	0.594***
	(7.58)	(7.51)	(7.64)	(5.04)	(7.98)
HDD ×cooperative	-0.030***				
	(-2.82)				
HDD ×Family Farm		-0.036***			
		(-5.04)			
HDD × Agricultural Enterprise (Production)			-0.032***		
			(-4.08)		
HDD ×irrigation coverage				-0.587*	
				(-1.96)	
Application ×of HDD Thin Films					-0.007**
					(-2.54)

sample capacity	5,915	5,915	5,915	4,256	3,821
R-squared	0.653	0.652	0.652	0.625	0.609

Note: All analyses have controlled for market fixed effects and time fixed effects, with control variables consistent with the baseline regression. Cooperatives, family farms, and agricultural production enterprises are represented by their stock from the previous year. Irrigation coverage is measured as the ratio of effective irrigated area to total crop sown area, while plastic film usage is quantified by the amount of agricultural plastic film per unit of crop sown area (tons per thousand hectares).

Table 8 presents the regression results of mitigation mechanisms on local market demand. Columns (1)-(2) further examine the moderating effects of long-term demand characteristics, using substitute quantity (reflecting potential substitution space) and population density (reflecting consumption scale) as proxy variables. The interaction terms between these variables and high temperatures showed no significant results. This indicates that the long-term stability of demand-side characteristics does not dynamically adjust to high-temperature shocks, failing to effectively moderate the "high temperature-price" transmission. More importantly, the absence of significant moderating effects on long-term demand characteristics further confirms that demand-side factors are not the dominant driver of sustained price increases. If demand could independently cause price hikes, its structural variables should exhibit moderating effects, yet empirical results do not support this logic. These findings reaffirm that extreme heat impacts cabbage prices primarily through supply contraction. Therefore, subsequent analysis will focus on supply-side mechanisms and efficiency-enhancing factors (such as market coordination and loss control) to explore mitigation pathways for high-temperature price shocks. In summary, the more complete the local market demand and supply conditions, the less severe the impact of extreme weather on agricultural product prices, validating Hypothesis 1.

Table 8 Local market demand side mitigation mechanism Table 8 Local market demand side mitigation mechanism

variable	(1)	(2)
	price	
HDD	0.343***	0.586**
	(2.98)	(2.57)
Number ×of HDD alternatives	0.001	
	(0.25)	
HDD ×density of population		-0.032
		(-0.99)
sample capacity	5,870	5,870
R-squared	0.652	0.652

Note: All fixed effects of market and time have been controlled, and the control variables are consistent with the benchmark regression. The number of substitutes is calculated by the author from the annual sales varieties of vegetables in the agricultural wholesale market; the population density is from the landscan database.

6.2 The Mechanism of Alleviating the Local Market Circulation

Table 9 reports the regression results of the mitigation mechanism of local market circulation on price fluctuations. In column (1), the interaction term coefficient between HDD and agricultural enterprises (circulation) is significantly negative, indicating that deep participation in the circulation process by enterprises can effectively alleviate the upward price pressure caused by high temperatures. In column (3), the interaction term coefficient between HDD and e-commerce demonstration counties is significantly negative, suggesting that the construction of e-commerce demonstration counties can effectively weaken the impact of HDD on prices. In column (5), the interaction term coefficient between HDD and highway import/export density is also significantly negative, confirming the mitigating effect of transportation infrastructure density in suppressing price fluctuations. In contrast, the interaction term coefficients between HDD and leading enterprises, as well as HDD and broadband China, in columns (2) and (4) did not pass the significance test. The possible reason is that leading enterprises focus on production-side integration, brand building, and long-term supply chain layout, with limited immediate response to short-term price fluctuations caused by extreme heat; while the core of broadband China is to enhance digital infrastructure, and supply-demand information has not been effectively translated into dispatch decisions or circulation optimization, making it difficult to exert a mitigating effect. The above results indicate that the more complete the local market circulation conditions, the less the impact of extreme weather on agricultural product prices, thus verifying Hypothesis 2.

Table 9. Local market circulation end mitigation mechanism Table 9. Local market circulation end mitigation mechanism

variable	(1)	(2)	(3)	(4)	(5)
			price		
HDD	0.394***	0.369***	0.396***	0.398***	0.565***
	(7.71)	(7.38)	(7.68)	(6.97)	(8.63)
HDD × Agricultural Enterprise (Distribution)	-0.025**				
	(-2.08)				
HDD ×corporate champion		-0.006			
		(-0.29)			
HDD × E-commerce Demonstration County			-0.119*		
			(-1.71)		
HDD ×broadband China				-0.084	
				(-1.18)	
HDD ×transportation condition					-0.070**
					(-2.05)
sample capacity	6,010	6,010	6,010	6,010	4,534
R-squared	0.653	0.652	0.653	0.653	0.633

Note: The fixed effects of market and time have been controlled, and the control variables are consistent with the benchmark regression. Agricultural circulation enterprises and leading enterprises are represented by the stock of the previous year; e-commerce demonstration counties and broadband China are derived from policy pilot data; transportation conditions are indicated by the density of expressway entrances and exits.

6.3 The Mechanism of Supply, Demand and Circulation End of the Associated Market

Previous analysis demonstrates that market participants can identify the lowest import price in interconnected markets, which depends on demand, supply, and distribution conditions in those markets. To address this, this study adopts the methodology of Asche et al. (1999) to construct interconnected markets using price correlations and actual transaction data from sample wholesale markets. Specifically, we identified each market's most correlated counterpart based on the Pearson correlation coefficient matrix of Chinese cabbage prices in wholesale markets. To enhance matching rationality, we implemented dual verification by incorporating geographical distance between wholesale markets and publicly available market information. Ultimately, 85 markets were successfully matched with corresponding interconnected markets (see Figure 8). From a structural perspective, these 85 markets correspond to 36 interconnected markets. Notably, markets 26,91,39, and 41 exhibit strong radiation capabilities, forming interconnected pairs with six or more markets respectively. This reflects their pivotal role in regional agricultural product distribution networks, where they may mitigate price fluctuations in local markets through cross-regional allocation functions. Taking market 26 (Anhui Huaibei Zhongrui Market) as an example, it serves as an interconnected market for seven wholesale markets: Anhui Bozhou Company, Jiangsu Fengxian Agriculture and Rural Affairs Bureau, Shandong Zhangqiu Vegetable Market, Hebei Handan Fruit and Vegetable Market, Shaanxi Jingyun Yunyang Vegetable Market, Jiangsu Lingjiatang Company, and Henan Shangqiu Market.

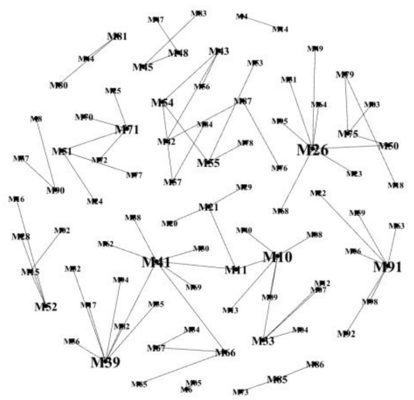

Figure 8: Wholesale Market Network of Chinese Cabbage

Note: This graph, created with Gephi software, uses black nodes to represent agricultural wholesale markets and line segments to indicate market connections between nodes. It illustrates the network relationships among 85 wholesale markets and 36 first-price correlation markets.

Table 10 presents the mitigating effects of interconnected markets on local market prices. Columns (1)-(2) estimate the impact of interconnected market correlation, while columns (3)-(4) assess the effect of average market correlation. The interaction term coefficient between interconnected market correlation and HDD shows a significantly negative value, indicating that interconnected markets can partially reduce the price surge caused by extreme heatwaves. Similarly, the negative coefficient for average market correlation suggests that integration into the national market network also helps mitigate the price impact of high temperatures. Building on these findings, the subsequent analysis will examine the specific mechanisms of this mitigating effect from three dimensions: supply-side, demand-side, and distribution channels of interconnected markets.

Table 10: Mitigation mechanisms for associated markets Table 10: Mitigation mechanisms for associated markets

variable	(1)	(2)	(3)	(4)
	price			
HDD	1.218***	1.213***	0.959***	1.044***
	(4.16)	(3.55)	(4.36)	(4.11)

HDD × (Hard Disk Drive) is associated with market-related factors.	-0.011***	-0.010**		
	(-3.15)	(-2.56)		
HDD × local market average correlation			-0.011***	-0.011***
			(-2.97)	(-2.81)
controlled variable	deny	yes	deny	yes
market fixed effect	yes	yes	yes	yes
year-month fixed effect	yes	yes	yes	yes
sample capacity	5,359	5,359	5,359	5,359
R-squared	0.651	0.655	0.650	0.655

Note: The correlation with related markets is the highest value in the correlation matrix between the local market and other markets, reflecting the strength of the connection between the local market and related markets. The average correlation is the mean of the correlations between the local market and other markets, reflecting the strength of the connection between the local market and the national market.

Table 11 illustrates the market supply-side mitigation mechanism for local price fluctuations. Columns (1)-(3) show statistically significant negative interaction terms between HDD and three market entities: cooperatives, family farms, and agricultural producers. These findings demonstrate that these entities can mitigate the price surge caused by extreme heat. Columns (4)-(5) reveal negative interaction terms between HDD and irrigation coverage/film usage, indicating that advanced irrigation infrastructure and plastic film application enhance market resilience against heatwaves, thereby stabilizing local supply chains and reducing price volatility. The negative interaction terms between market supply variables and HDD collectively indicate that strengthening supply-side capabilities effectively mitigates heat-induced price shocks. This provides crucial empirical evidence supporting the improvement of cross-regional resource allocation mechanisms.

Table 11: Mitigation mechanisms on the supply side of the associated market Table 11: Mitigation mechanisms on the supply side of the associated market

variable	(1)	(2)	(3)	(4)	(5)
	local market price				
HDD	0.366***	0.340***	0.393***	0.795***	0.622***
	(5.10)	(5.09)	(5.84)	(5.25)	(6.54)
linked market HDD	0.119**	0.119**	0.132**	0.196**	0.155**
	(2.02)	(2.13)	(2.20)	(2.62)	(2.20)
HDD × Associated Market Cooperative	-0.089*				
	(-1.97)				
HDD × Associated Market Family Farm		-0.113***			
		(-4.12)			
HDD × Related Market Agricultural Enterprise (Production)			-0.117***		

			(-4.26)		
HDD × Associated Market Irrigation Coverage				-0.692**	
				(-2.30)	
HDD × Use of Thin Films in Related Markets					-0.009**
					(-2.64)
sample capacity	4,364	4,364	4,364	3,224	2,900
R-squared	0.664	0.665	0.666	0.641	0.625

Note: All analyses have controlled for market fixed effects and time fixed effects. While maintaining consistency with the baseline regression in control variables, we further adjusted for high temperatures (HDD) in the associated markets during the same period. The associated markets represent those with the strongest price correlations in agricultural wholesale markets. Cooperative, family farm, and agricultural production enterprises are represented by their stock from the previous year. Irrigation coverage is measured as the ratio of effective irrigated area to total sown area, while plastic film usage is quantified by the amount of agricultural plastic film per unit sown area (tons per thousand hectares).

Table 12 presents the regression results of the market demand-side mechanism's mitigation effect on local market prices. Columns (1)-(2) show that the interaction term coefficients between HDD and the quantity of substitutes in the associated market, as well as population density, failed to pass the 10% significance level test. This indicates that, under the current sample data and model framework, key variables such as the quantity of substitutes in the associated market and population concentration have not significantly mitigated the upward pressure on local market prices caused by HDD. Column (3) reveals a significantly negative interaction term between the associated market's vegetable production and HDD, suggesting that sufficient supply in the associated market can more effectively alleviate price increases in the local market.

Table 12: Mechanisms for Alleviating Demand-side Issues in the Associated Market Table 12: Mechanisms for Alleviating Demand-side Issues in the Associated Market

variable	(1)	(2)
	local market price	
HDD	0.306**	0.280
	(2.54)	(1.09)
linked market HDD	0.112**	0.133**
	(2.17)	(2.34)
Number ×of HDD-related market substitutes	0.000	
	(0.13)	
HDD ×(Hard Disk Drive) related market population density		0.002
		(0.06)
sample capacity	4,949	5,035
R-squared	0.658	0.659

Note: All analyses have controlled for market fixed effects and time fixed effects. While maintaining consistent control variables with the baseline regression, we further adjusted for high temperatures (HDD) in the associated markets during the same period. The associated markets represent those with the strongest price correlations in agricultural wholesale markets, with the number of substitutes calculated by the author based on annual vegetable varieties sold in these markets. Population density data was sourced from the LandScan database.

Table 13 presents the moderating effects of variables related to associated market circulation on the relationship between high temperatures (HDD) and local market prices. In column (1), HDD has a significant positive impact on local prices, while its interaction term with associated market agricultural enterprises (circulation) is significantly negative, indicating that the development of associated market agricultural enterprises (circulation) helps mitigate the upward pressure of extreme high temperatures on local market prices. Circulation enterprises can directly connect associated local production areas with local market sales areas, quickly filling the supply gap caused by high-temperature-induced production reduction in the local market, thereby curbing excessive price increases. Additionally, circulation enterprises, relying on self-built or cooperative pre-cooling facilities and refrigerated vehicles, can effectively reduce spoilage during transportation caused by high temperatures, ensuring that the available supply from associated markets can be effectively converted into effective replenishment for the local market. Moreover, large circulation enterprises generally establish cross-regional procurement networks, enabling them to allocate goods from external production areas even when local areas in associated markets experience high temperatures, thus stabilizing the scale of replenishment to the local market. Columns (2)-(5) report the interaction coefficients between HDD and leading enterprises in associated markets, e-commerce demonstration counties, broadband China, and transportation conditions, respectively. Among these, e-commerce demonstration counties and transportation conditions significantly play a mitigating role, while the other mitigating effects are not significant. This suggests that circulation enterprises and e-commerce in associated markets can optimize distribution channels and improve the efficiency of agricultural product allocation, thereby mitigating price fluctuations in agricultural products. This indicates that the development of circulation enterprises in important associated markets can effectively mitigate local market price fluctuations, and the extent of mitigation by the circulation end of associated markets is not significantly different from that of the local market. The empirical results of this section show that the more perfect the demand, supply and circulation conditions of the local market, the less the impact of extreme weather on the price of agricultural products, and hypothesis 3 is verified.

Table 13: Mechanisms for Alleviating the Circulation Side of the Associated Market Table 13: Mechanisms for Alleviating the Circulation Side of the Associated Market

variable	(1)	(2)	(3)	(4)	(5)
	local market price				
HDD	0.319***	0.286***	0.335***	0.319***	0.390***
	(5.22)	(4.39)	(5.12)	(4.66)	(4.73)
linked market HDD	0.128**	0.127**	0.145***	0.129**	0.252***
	(2.42)	(2.36)	(2.85)	(2.43)	(4.04)
HDD ×related market agricultural enterprise (circulation)	-0.017**				
	(-2.25)				
Leading × enterprise in the HDD-related market		0.014			
		(0.65)			
HDD ×(Hard Disk Drive) Related Market E-			-0.165**		

commerce Demonstration County					
			(-2.18)		
HDD ×related market broadband China				-0.059	
				(-0.77)	
HDD ×(Hard Disk Drive) is associated with market transportation conditions.					-0.066*
					(-1.74)
sample capacity	5,035	5,035	5,035	5,035	3,621
R-squared	0.659	0.658	0.659	0.659	0.631

Note: The fixed effects of market and time have been controlled. On the basis of keeping the control variables consistent with the benchmark regression, the high temperature (HDD) of the associated market during the same period has been further controlled. The associated market is the one with the highest price correlation in the agricultural wholesale market. Agricultural circulation enterprises and leading enterprises are represented by the stock of the previous year; e-commerce demonstration counties and broadband China are derived from policy pilot data; transportation conditions are represented by the density of expressway entrances and exits.

6.4 Heterogeneity Analysis Based on Market Correlation

Sections 1-3 of this chapter have systematically examined the mitigation mechanisms of extreme weather impacts from the supply, demand, and distribution perspectives of local and related markets. However, China's agricultural wholesale markets exhibit significant heterogeneity in regional linkage effects. Hub markets typically demonstrate smoother integration with regional and national distribution networks, featuring higher resource allocation efficiency and faster information transmission rates, inherently possessing the radiating and driving characteristics of hub nodes. In contrast, peripheral markets maintain strong regional isolation, with their supply-demand balance primarily relying on local supply systems and distribution channels. Market correlation essentially reflects the spatial linkage intensity of regional agricultural product circulation and the efficiency of resource element coordination, with its numerical magnitude directly determining the functional positioning of markets within the national unified agricultural product distribution system. Based on this analytical framework, this study uses the P25 and P75 percentiles of average local market correlation as thresholds to categorize samples into three types of correlated markets (low-correlation corresponding to peripheral markets, high-correlation corresponding to hub markets), aiming to systematically reveal the heterogeneity in mitigation pathways for different functional market positions during heatwave impacts. Previous analyses identified that production entities and foundational conditions on the supply side, along with certain entities and foundational conditions in distribution channels, play mitigating roles. This section will further explore the differences in these mitigating effects between peripheral and hub markets.

Table 14 examines the differential mitigation effects on supply chains across two market categories. The core findings indicate that the interaction term between production entities and high HDD (High Degree of Demand) is statistically significant only in marginal markets. This demonstrates that cooperatives, family farms, and agricultural enterprises serve as the primary supply resilience anchors for marginal markets in withstanding heatwaves. As market types with limited connectivity in distribution networks, marginal markets cannot rely on external supply to bridge local shortages. Their core function lies in maintaining internal supply-demand balance. Consequently, marginal markets depend more on coordinated efforts among internally scaled and organized production entities to build localized supply resilience against extreme weather.

Table 14 Heterogeneity of Supply-side Mitigation Effect in Local Market Table 14 Heterogeneity of Supply-side Mitigation Effect in Local Market

variable	(1) fringe market	(2) hub market	(3) fringe market	(4) hub market	(5) fringe market	(6) hub market
HDD	0.469***	0.181**	0.477***	0.177**	0.518***	0.215***
	(5.47)	(2.66)	(5.52)	(2.64)	(5.53)	(2.75)
HDD ×cooperative	-0.102**	-0.037				
	(-2.44)	(-1.14)				
HDD ×Family Farm			-0.267**	-0.046*		
			(-2.37)	(-2.06)		
HDD × Agricultural Enterprise (Production)					-0.104**	-0.067**
					(-2.40)	(-2.23)
sample capacity	1,201	1,238	1,201	1,238	1,201	1,238
R-squared	0.628	0.768	0.629	0.768	0.630	0.768

Note: All analyses have controlled for market fixed effects and time fixed effects, with control variables consistent with the baseline regression. Columns (1)-(6) present the mitigation effects of cooperatives, family farms, and agricultural production enterprises. The results on irrigation use and mulch film area show no significant differences between the two markets, hence they are presented in Appendix 1.

Table 15 further examines the mitigation effect differences between the two market types at the distribution end. The results indicate that the interaction term between agricultural distribution enterprises, e-commerce demonstration county construction, and transportation conditions with HDD is significantly negative only in hub markets, confirming that distribution-end factors serve as the key support for hub markets to cope with high-temperature shocks. As core nodes in highly correlated market networks, their primary function is to link multiple production and consumption regions, enabling cross-regional resource optimization rather than relying on self-supply regulation. Therefore, when facing extreme weather shocks, hub markets leverage their cross-regional allocation capabilities at the distribution end to resolve supply-demand conflicts.

Table 15 Heterogeneity of Mitigation Effect of Local Market Circulation Table 15 Heterogeneity of Mitigation Effect of Local Market Circulation

	(1) fringe market	(2) hub market	(3) fringe market	(4) hub market	(5) fringe market	(6) hub market
HDD	0.237*	0.019	0.289**	-0.014	0.345***	0.044
	(1.75)	(0.31)	(2.22)	(-0.27)	(2.92)	(0.74)
HDD × Agricultural Enterprise (Distribution)	-0.048	-0.081**				
	(-0.43)	(-2.18)				
HDD × E-commerce Demonstration County			-0.158	-0.153*		
			(-1.14)	(-1.92)		
HDD ×transportation condition					0.249	-0.238**

					(1.62)	(-2.53)
sample capacity	1,118	1,125	1,118	1,125	967	833
R-squared	0.629	0.770	0.629	0.769	0.603	0.749

Note: All fixed effects of market and time have been controlled, and the control variables are consistent with the benchmark regression.

Table 16's empirical results examine the interaction effect between hub market correlation and HDD. The findings indicate that only the hub market's correlation with HDD shows a statistically significant negative interaction term, demonstrating that hub markets can leverage external markets to achieve price adjustments. Specifically, the high correlation between hub and associated markets enables cross-regional resource coordination, allowing hub markets to rapidly utilize supply redundancies and shared distribution channels from associated markets to alleviate local supply-demand pressures. This outcome aligns with the observation that peripheral markets rely on enhancing their own supply capabilities, while hub markets depend on distribution support systems.

Table 16 Heterogeneity of the mitigation effect of the associated markets Table 16 Heterogeneity of the mitigation effect of the associated markets

variable	(1) fringe market	(2) hub market
HDD	-0.254	7.681**
	(-0.39)	(2.62)
linked market HDD	0.169**	-0.007
	(2.34)	(-0.13)
HDD×Correlation with the related market	0.598	-8.388**
	(0.69)	(-2.64)
sample capacity	1,272	1,343
R-squared	0.633	0.771

Note: The fixed effects of market and time have been controlled, and the control variables are consistent with the baseline regression. The correlation between related markets refers to the correlation between the local market and its related markets.

In summary, the edge market and the hub market have developed distinct pathways to mitigate high-temperature impacts. The edge market primarily relies on enhancing local supply capabilities, while the hub market focuses on circulation support and leverages related markets for price adjustments. This divergence directly reflects the functional positioning of these two market types within China's unified national market, providing empirical evidence for formulating differentiated extreme weather response strategies.

7. Conclusion and policy implications

This study investigates the impact of extreme heatwaves on agricultural product prices and the mitigation mechanisms in local and regional markets. Based on monthly cabbage price data from 96 agricultural wholesale markets across China (2011-2022) and county-level climate data, we employ a three-sector equilibrium model (production-distribution-demand) and a dual fixed-effects empirical model. The research reveals two key findings: 1) Extreme heatwaves significantly affect agricultural product prices; 2) Local markets and regional markets demonstrate effective price stabilization mechanisms.

First, extreme heatwaves drive up agricultural prices by suppressing local production. Benchmark regression and mechanism analysis demonstrate that extreme heat during the growing season significantly increases Chinese cabbage prices through reduced agricultural productivity and decreased local supply, while heat during the harvest period shows no significant impact. This conclusion holds true across multiple robustness tests, including adjustments to the HDD threshold, growth stage-specific calculations, and control for substitute effects. The intensity of this heat shock is significantly moderated by supply-side and distribution-side factors. Supply-side elements such as large-scale producers (cooperatives, family farms, agricultural enterprises) and production conditions (irrigation, mulching films), along with distribution-side factors like organizational structure and infrastructure (logistics companies, transportation networks, e-commerce platforms), effectively mitigate the price-increasing effects of heatwaves. However, demand-side factors like availability of substitutes and consumption scale show no significant moderating effects on the heat shock.

Second, the resilience of local markets against extreme heatwaves depends not only on their production resilience and distribution efficiency, but also significantly benefits from the empowerment of interconnected markets. The larger the scale of production entities in these interconnected markets, the stronger their disaster resistance, and the higher their distribution efficiency, the more pronounced their role in mitigating local market price shocks. Moreover, when interconnected markets exhibit stronger synergy with local markets, this cross-regional mitigation effect becomes even more significant, fully demonstrating the institutional value of cross-regional resource optimization in the unified market for stabilizing price fluctuations.

Third, the mitigation approaches of peripheral markets and hub markets in responding to extreme heatwaves exhibit significant heterogeneity, fundamentally reflecting their distinct functional positioning. Peripheral markets, with weaker integration into external distribution networks, primarily rely on local production capacity building for resilience, while their distribution channels and associated markets play limited regulatory roles. In contrast, hub markets—as core nodes in regional distribution networks—depend more on cross-regional allocation efficiency and can further distribute heatwave impacts through resource coordination with affiliated markets. This difference clarifies the functional division and adaptive mitigation strategies of these two market types within China's unified national market framework.

The research findings provide strategic directions for enhancing agricultural product markets' resilience to extreme weather, addressing market bottlenecks, and advancing the development of a unified national market. First, strengthening climate adaptation capabilities in agricultural production. This involves increasing support for new agricultural entities like family farms and enterprises, with a focus on cultivating large-scale, specialized producers. Through fiscal subsidies, these entities can adopt smart agriculture technologies such as IoT monitoring devices and intelligent temperature control systems to achieve real-time monitoring and precise regulation of field temperature, humidity, and crop growth conditions, thereby improving their risk resistance against extreme heat. Simultaneously, in major vegetable-producing regions, promoting drought-resistant crop breeding and water-saving irrigation techniques—combined with upgraded irrigation infrastructure and widespread use of agricultural films—will establish a dual production support system of "technology + facilities" to ensure stable supply at the source.

Second, establish a seamless cross-regional circulation and coordinated allocation mechanism. Using counties and cities as key nodes, create a regional agricultural supply-demand information platform to facilitate production planning coordination and emergency resource allocation among neighboring areas. Building on this foundation, leverage vegetable production advantages in the Huang-Huai-Hai and Bohai Rim regions to develop cross-regional industrial collaboration belts. Simultaneously, advance cross-regional brand initiatives like "South Vegetables to North" and "West Vegetables to East." Through unified quality standards and integrated logistics resources, establish a collaborative model of "production complementarity, smooth circulation, and brand synergy."

Ultimately, with these cross-regional collaboration belts as the backbone, dismantle local protectionism and market fragmentation, and establish nationwide production-sales channels. This will enable unified market regulation under extreme climate conditions, achieving "one-region shortage, multi-region supply" through coordinated regional efforts.

Third, refine tiered market regulation strategies. Implement differentiated policies for different market tiers: For marginal markets, prioritize support for new production entities like cooperatives and family farms by subsidizing disaster-resistant facilities such as smart irrigation systems and agricultural films to strengthen local production resilience against heatwaves. For hub markets, accelerate the construction of regional cold chain logistics centers and establish cross-regional emergency transport routes to enhance distribution efficiency. Simultaneously, promote the establishment of supply-demand information sharing and emergency allocation mechanisms between hub markets and related markets to collectively alleviate pressure through coordinated resource distribution.

It is crucial to emphasize that while this study focuses on Chinese cabbage, the mechanisms of the national unified market in mitigating climate impacts and stabilizing price fluctuations demonstrate universal applicability. Whether for leafy vegetables, root vegetables, grains, fruits, or other agricultural products, market operations all rely on cross-regional supply-demand coordination and resource integration. Therefore, the policy conclusions from this research can serve as a reference for broader agricultural market stabilization. In practice, we must remain vigilant about policy adaptation challenges arising from regional resource disparities, such as cost constraints in implementing smart agriculture technologies in remote areas and coordination difficulties in interest distribution during cross-regional collaboration. Future efforts should involve dynamic adjustments and refined improvements tailored to specific regional characteristics and agricultural product categories. In the long run, these measures not only provide practical pathways for stabilizing agricultural prices under extreme climate conditions but also help strengthen the agricultural industry foundation, enhance agricultural quality and efficiency, and provide solid support for implementing the rural revitalization strategy and achieving common prosperity goals.

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