Silver, Climate, and China's Price Revolution

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Abstract: *This study examines the price revolution in Qing China (1644–1911), focusing on silver flows, climate shocks, and socio-economic factors in the North China Plain (1736–1911). Using ARDL and NARDL models, the findings reveal strong long-term co-integration among these variables. Unlike early modern Europe, Qing China's price revolution was not solely driven by monetary expansion but resulted from the interaction between silver inflows and climate variability. Silver supply had a strong long-term positive effect on prices, yet the silver-to-copper ratio exhibited opposing short- and long-run effects, suggesting that liquidity constraints tempered inflation over time. Climate shocks had asymmetric effects, with droughts exerting a persistent upward pressure on prices, while floods and temperature variations primarily affected short-term volatility. Population growth had no significant impact, challenging conventional Malthusian narratives. These findings underscore the necessity of nonlinear models in historical economic analysis and provide a broader framework for understanding how climate and financial shocks shape price dynamics, both in historical contexts and contemporary economies vulnerable to similar risks.*

Keywords: Climate Change; Silver Supply; Societal Disturbances; Price Revolution; North China Plain; ARDL Model; NARDL Model; Financial Instability; Social Unrest; Historical China; Co-Integration; Global Integration.

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1 Introduction

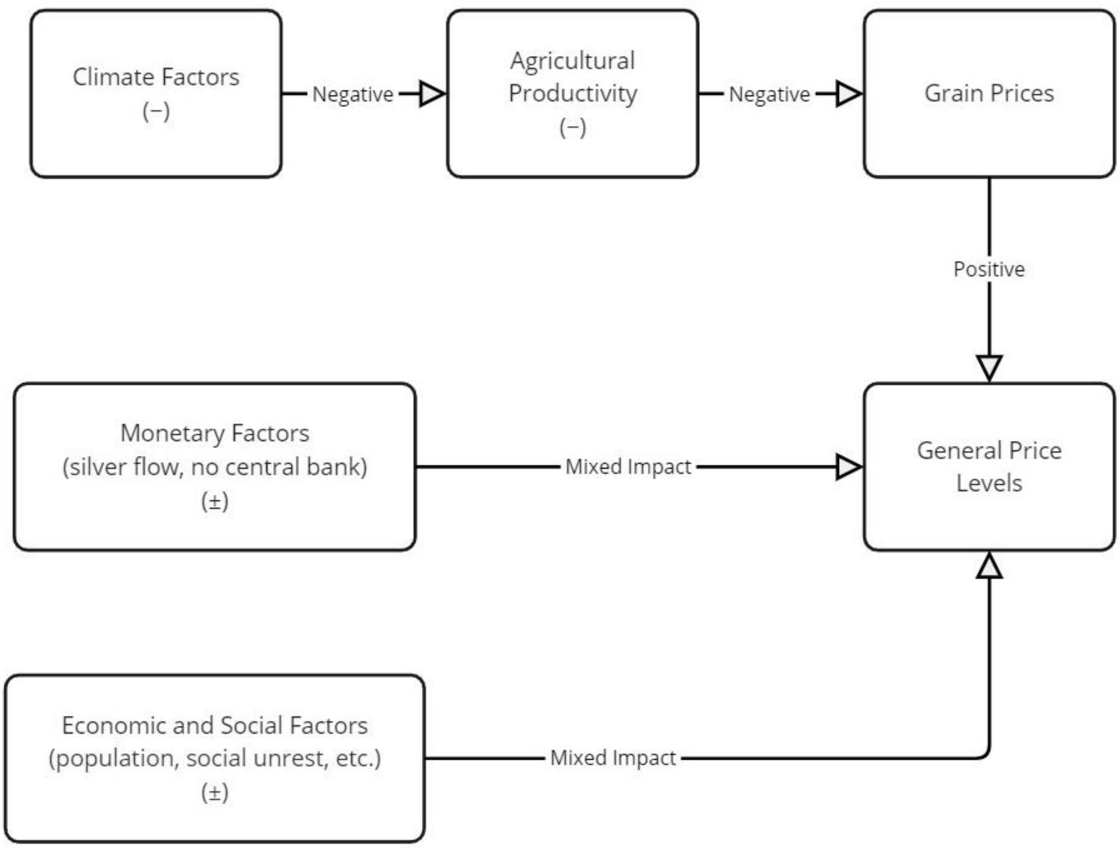
With growing global attention to climate change, financial risks, and their compound effects, historical case studies have become increasingly valuable for understanding how economic systems respond to environmental and monetary shocks. A substantial body of research suggests that adverse climate conditions-such as persistent droughts or extreme rainfall-can undermine agricultural productivity and potentially trigger broader social disruption and economic instability (Miguel et al., 2004; Dixon, 1999). However, while scholars have extensively examined the link between climate shocks and economic volatility, relatively little attention has been paid to how climate and monetary factors jointly shape price fluctuations.

China during the Qing dynasty (1644-1911) provides a unique setting for exploring these intertwined dynamics. During the Qing dynasty, the monetary system relied heavily on silver, while economic prosperity largely depended on agricultural output and a favorable natural environment. Massive inflows of silver from the Americas and Japan expanded the domestic money supply, leading some scholars to liken this phenomenon to Europe's "Price Revolution" (Quan, 1957; Zhao, 2016). Others argue that population growth and structural economic changes-rather than silver inflows-were the principal drivers of price movements (Goldstone, 1991). Moreover, climate events such as droughts and floods could compound these trends by disrupting agricultural production and trade networks, thereby intensifying or, in some cases, moderating grain-price volatility (Zhao et al., 2018). To date, there remains no consensus on the relative importance of these factors or on the extent to which they interact over time.

Against this backdrop, this study aims to address three central questions. First, a key inquiry in the study of historical Chinese price dynamics is whether price fluctuations during this period were primarily driven by inflows of American silver, substantially influenced by climate-induced agricultural supply shocks, or rather shaped by the long-run co-integration of these factors. In other words, did China experience a price revolution comparable to that of early modern Europe? Second, do silver flows and climate variations exhibit nonlinear and asymmetric effects, such that, under certain conditions, they collectively exacerbate or mitigate price fluctuations? Third, to what extent did population growth and economic restructuring function as influencing factors-either amplifying or mitigating effects-particularly in the North China Plain, an agricultural heartland, between 1736 and 1911?

To investigate these issues, this paper proposes three principal transmission mechanisms (see Figure 1). The first is the climate-price mechanism, which highlights how natural disasters (e.g., droughts, floods) directly reduce agricultural productivity, leading to food shortages and rising grain prices. In an agrarian economy such as Qing China, these price increases not only elevate overall inflationary pressures but also significantly impact farmers' incomes. Declining agricultural yields reduce farmers' earnings, weakening their purchasing power and potentially constraining overall economic activity. This income effect can further exacerbate market volatility, as lower rural demand interacts with rising subsistence costs, creating complex inflationary and deflationary pressures within the economy. The second mechanism highlights monetary factors, focusing on silver supply and circulation. In the absence of a modern central banking system, silver inflows-shaped by international trade and imperial fiscal conditions-could increase liquidity and thereby fuel inflation, while outflows or fiscal contraction might induce deflationary pressures or abrupt price swings. The third mechanism underscores economic and social factors, including population increases that amplify demand for grain and large-scale social unrest (e.g., the White Lotus Rebellion, the boxer Rebellion) that disrupts transportation or agricultural production, further heightening price volatility.

Figure 1. Conceptual Framework Linking Climate, Monetary, and Socioeconomic Factors to Price Fluctuations in Qing China



In empirical terms, this study adopts both Autoregressive Distributed Lag (ARDL) and Nonlinear ARDL (NARDL) models to detect long-run cointegration and potential asymmetric effects among price levels, silver supply, and climate indicators. This methodological innovation moves beyond the linear analyses common in previous work, promising more nuanced insights into the so-called "price revolution" in Qing China. It also offers historical parallels for contemporary debates on managing climatic pressures and financial uncertainties.

Four key findings emerge from the analysis. First, while silver flows influenced price dynamics, China did not experience a conventional price revolution driven solely by monetary expansion. Instead, long-term price trends were shaped by the co-integration of silver inflows and climate conditions, indicating broader structural forces at play. Second, silver supply and prices maintain a strong long-term correlation, but the silver-to-copper ratio has a positive short-term effect and a negative long-term impact, suggesting that while monetary expansion initially fueled inflation, sustained silver appreciation constrained liquidity and tempered price increases. Third, climate shocks had asymmetric effects, with droughts exerting a more persistent long-term influence on prices than floods or temperature changes, highlighting the role of agricultural disruptions. Fourth, population changes had no significant impact on prices, reinforcing that macroeconomic forces-particularly monetary conditions and climate variability-were the primary drivers of historical price movements.

This study's contribution lies not only in clarifying the key drivers of price volatility in Qing China but also in offering a historical lens on how climate conditions and monetary expansion may interact in modern economies. For instance, the ways in which extreme climate events affect agricultural prices, and how monetary policy might respond to inflationary or deflationary pressures, can be better understood by drawing on these historical precedents. Furthermore, the application of nonlinear models-new to the field of Qing economic history-provides a methodological advance for historical economics and macroeconomic analysis more broadly.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature and key debates. Section 3 explores the relationship between silver flows, natural disasters, and their impact on prices. Section 4 presents an empirical study of multiple crises in the North China Plain from 1736 to 1911. Section 5 describes the econometric methodology and models. Section 6 discusses the main results, and Section 7 concludes.

2 Literature Review

Extensive research has investigated how monetary dynamics and climatic shocks independently affect economic outcomes. However, the compounded effects of these factors remain insufficiently examined-particularly in the context of historical China, where silver inflows, climatic variability, and population pressures intersected to shape economic conditions. While existing studies often analyze these elements in isolation, understanding the nonlinear and interdependent relationships among them remains a significant challenge. This section reviews the key theoretical perspectives on the price revolution, monetary expansion, and climatic shocks, and identifies the research gaps that motivate further inquiry.

2.1 Silver Flows and the Price Revolution

From the 15th to the 17th century, Europe experienced a sustained period of high inflation commonly referred to as the “Price Revolution,” spanning roughly 150 years. A key explanation attributes this phenomenon to a massive influx of precious metals-chiefly gold and silver-from Spanish colonies in the New World (Gould, 1964). The silver mines at Cerro Rico de Potosí, for instance, yielded unprecedented quantities of silver for Spain (Dore, 2000), making it one of the first European nations to undergo a rapid rise in price levels. Because silver was the principal metallic currency in Europe at the time, the surge in its supply had a marked impact on inflationary trends (Zhao, 2016).

A substantial body of literature examines the global price revolution, primarily attributing it to monetary expansion. The classical quantity theory of money (Hume, 1752; Dimand, 2013) posits a direct relationship between money supply and price levels, later formalized in Fisher’s equation of exchange (Fisher, 1911). Hamilton’s (1934) seminal work on 16th- and 17th-century Spain established a causal link between American silver inflows and price inflation, a relationship extended to other European economies (Goldstone, 1984; Brenner, 1962; Fisher, 1989).

In parallel, some scholars have applied this framework to China, arguing that the 18th century saw a silver-driven price revolution similar to Europe’s (Quan, 1957; Zhao, 2016). Quan (1957) and Zhao (2016) provide evidence that American silver inflows increased China’s money supply and contributed to rising prices, with Zhao estimating that a 10% increase in silver inflows raised grain prices by 2.83–4.21%. However, other interpretations challenge this monetary explanation. Goldstone (1991) contends that population growth played a more decisive role in driving price increases, while Wang (2015) argues that China’s price fluctuations were shaped more by external economic conditions in Western Europe than by domestic monetary expansion. Despite ongoing debates, empirical investigations into China’s price dynamics remain constrained by historical data limitations (Glahn, 1996; Zhao, 2016), underscoring the need for further analysis.

Although there is no consensus on the exact volume of silver entering China, scholars continue to debate its broader economic impact. Lin (2011) argues that foreign silver met China’s demand for precious metals, stabilizing monetary transactions and stimulating economic activity. In contrast, Irigoin (2009) contends that China’s silver trade was primarily demand-driven, shaped by internal economic factors rather than external supply.

Glahn (2017) expands on this view by emphasizing the interplay between trade, monetary circulation, and economic cycles in Qing China. While silver inflows increased liquidity, their effect on prices depended on trade balances, market integration, and regional economic conditions. He also highlights China’s growing vulnerability to external trade disruptions as reliance on foreign silver deepened. Although 18th-century economic expansion fostered greater market centralization, by the late Qing, regional economic fragmentation intensified. Population migration into marginal agricultural areas further reduced productivity, exacerbating instability. Glahn thus interprets China's early 19th-century downturn as part of broader economic cycles of expansion and contraction, characteristic of many pre-modern economies.

2.2 Climatic Shocks and Price Fluctuations

Beyond monetary factors, climatic variability played a crucial role in shaping price movements. Historical evidence demonstrates that adverse climate conditions, such as prolonged droughts and temperature anomalies, can significantly disrupt agricultural production, leading to food shortages and inflationary pressures. This climate-price mechanism is well-documented in economic history, as seen in cases such as the Irish Great Famine (1845–1852) and the U.S. Dust Bowl (1930s), as well as in modern analyses (IMF 2019; Nordhaus 2018).

In the context of China, much scholarship has centered on conflicts between nomadic tribes and Han communities triggered by climatic shifts. However, relatively few studies have examined the intricate interplay among climate, monetary flows, and social crises-such as population pressures or rebellions. Early investigations, including Zhao and Yin (2011) and Xiao et al. (2011), provided descriptive analyses of how climate factors impacted the Tang and Ming dynasties. Chen (2015), using historical climate and dynastic data spanning from 221 BCE onward, identified droughts as a principal catalyst of peasant revolts in northern China. During the Qing period, climate shocks likely influenced grain supply and exacerbated price volatility. Yet, the question of how these shocks combined with silver flows to shape inflation remains underexplored. Zhao (2016) attempts to bridge this gap with panel data from the North China Plain (1736–1911) but employs a linear ARMA framework that does not fully capture potential nonlinearities or long-term cointegration among climate, monetary, and price dynamics. Therefore, whether climate shocks amplified or attenuated the inflationary effects of silver inflows remains an open inquiry.

2.3 Research Gaps

Despite extensive research, key gaps remain. Most studies on China's price revolution focus on linear relationships, overlooking the nonlinear and compounded effects of silver inflows and climate shocks. Moreover, monetary and environmental factors are often analyzed in isolation, lacking a systematic examination of their cointegration and broader socioeconomic variables such as population dynamics and rebellions.

To address these gaps, this study employs ARDL and NARDL models to examine the nonlinear interplay between prices, silver supply, and climate shocks, refining insights into Qing China's price dynamics and broader economic risks.

3. Silver Flows, Natural Disasters, and Their Impact on Prices

3.1 Silver Flows to China: Scale, Drivers, and Economic Implications

During the Qing dynasty, China was one of the central hubs in the global silver trade, receiving vast quantities of silver, primarily from the Americas. This continuous influx was driven by three key factors: domestic monetary demand, persistent trade imbalances, and global arbitrage opportunities. China's dual currency system relied on silver for large-scale transactions and tax payments, particularly following the collapse of the paper money system in the early Ming period. As commerce expanded and fiscal demands increased, silver remained indispensable, sustaining a consistently high demand.

Table 1. Estimation of total foreign silver inflows across the Ming and Qing dynasties

Data Time Period: Ming dynasty and Qing dynasty			Data Location: China
No.	Scholar	Time Period	Total Foreign Silver Inflows (Million Chinese Tael)
1	Angus Maddison	1550-1700	185.36
2	Hosea Ballou Morse	1700-1830	360
3	Zhuang, Guotu	1553-1830	500
4	Andre Gunder Frank	16th-18th century	1,360 - 2,053.36
5	Peng Xinwei, Lu Qing	Ming dynasty and Qing dynasty	600
6	Wang, Hongbin	16th-17th century	185-264
7	Lee, Lung-Sheng	1645-1911	5050

Source: 1. Liu, Jun, Research on Maritime Commodity Trade in Ming and Qing Dynasties, Dongbei University of Finance and Economics doctoral dissertation, June 2009, Page 155.

2. Wang, Hongbin. Qing Dynasty Measure of Value: Money Search Study. 1st ed., SDX Joint Publishing Company, 2015.

3. Lee, Lung-Sheng. "Estimating the Yearly Amount of Silver Inflow during the Ching Dynasty in China (1645-1911)." Journal of Humanities and Social Sciences, vol. 5, no. 2, 2009, pp. 31-58.

Trade asymmetries further reinforced silver inflows. European merchants, facing a chronic deficit due to their high consumption of Chinese tea, silk, and porcelain, had little to offer in return that was desirable to Chinese markets. As a result, American silver was funneled into China to settle trade imbalances, a pattern that persisted for centuries. The Spanish colonial economy, which dominated silver production in the Americas, played a crucial role in maintaining this dynamic. Additionally, as Japan's silver mines began depleting in the 1640s, China increasingly depended on American silver, reinforcing its role as a key destination in the global silver trade. The movement of silver through transpacific and transatlantic routes not only connected China with the Americas but also laid the foundation for an integrated early modern global economy.

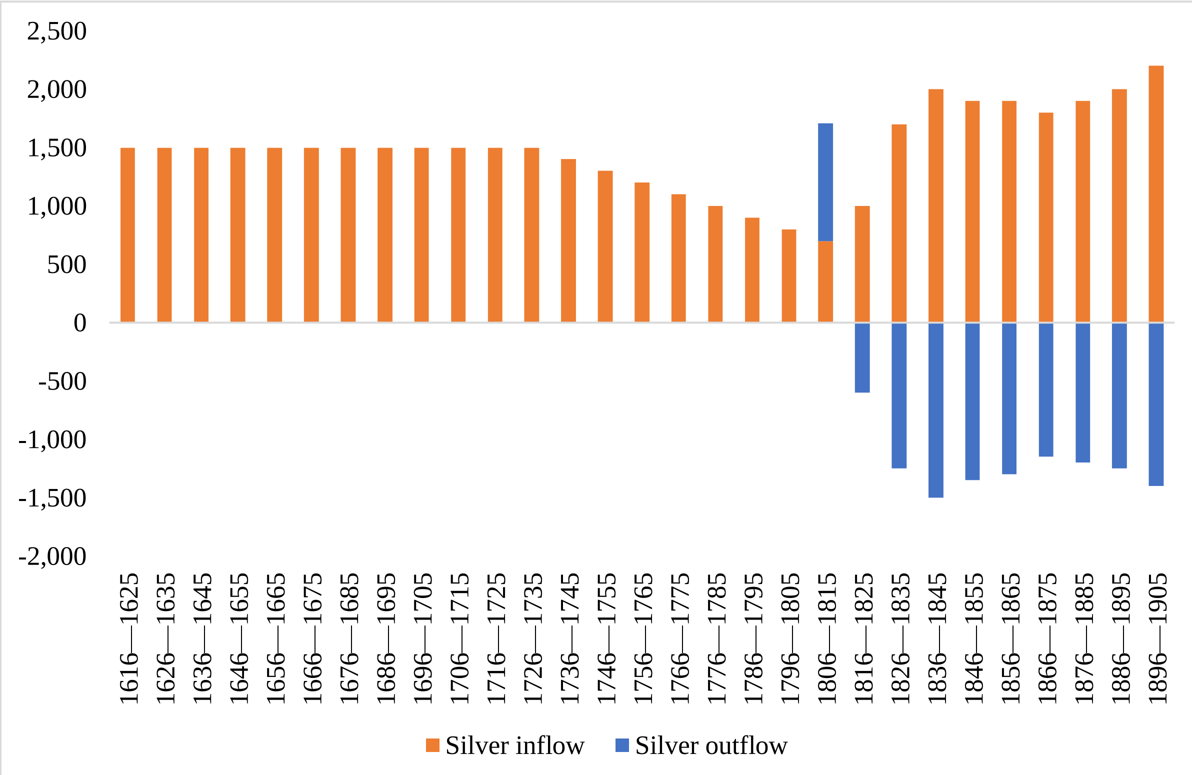
Although estimates of total silver inflows to Qing China vary (Table1), scholars generally agree on the vast scale of these imports. Glahn (1996) estimates that American silver accounted for approximately 25% of China's total silver supply. Wang (2015) calculates that between 7,000 and 10,000 tons of silver from the Americas ultimately entered China, while Lee (2009) suggests that the Qing period witnessed an inflow of 5,050 million taels, nearly seven times the domestic silver production. Regardless of the exact figures, the sheer volume of silver imports significantly expanded China's monetary base, influencing liquidity conditions, market integration, and overall price stability.

3.2 The Reversal of Silver Flows: The Opium Trade and External Shocks

Although silver continuously flowed into China for centuries, the 19th century saw a reversal (Figure 2), largely due to the opium trade and war indemnities, with an estimated annual silver drain of 100 million taels (Rowe, 2010). However, recent studies challenge the traditional view that opium was the primary driver of silver outflows. Lin (2011) suggests that silver outflows began as early as 1808 and argues that the decline in silver reserves cannot be solely attributed to opium imports. Instead, she highlights broader trade imbalances and fluctuations in global silver production. Similarly, Irigoin (2009) finds that silver imports to China remained positive until the mid-1820s and suggests that silver shortages, rather than trade deficits, disrupted inflows. Glahn (2017) critiques Lin's estimates, arguing that the scale and timing of silver outflows remain uncertain, though he acknowledges a significant decline in the later part of the Qing dynasty.

Despite these ongoing academic debates over the exact causes and timing of silver reversals, this study identifies the Opium War as a critical turning point. Beyond merely affecting silver flows, the war fundamentally altered China's economic structure, weakening state control over trade, increasing foreign economic influence, and exacerbating fiscal instability. By integrating monetary dynamics with broader socioeconomic transformations, this study highlights the Opium War's role in reshaping China's financial and economic trajectory.

Figure 2. Silver Inflow and Outflow (10,000 Silver Taels)



Data source: Li（2014）

3.3 Natural Disasters and Nonlinear Price Fluctuations

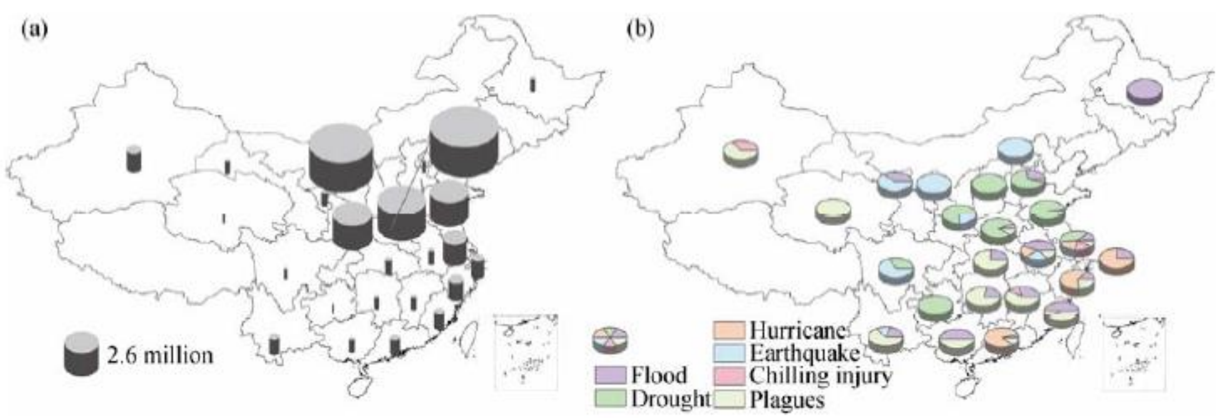
China's predominantly agrarian economy was highly dependent on climatic conditions, making it particularly vulnerable to natural disasters that frequently disrupted food supply and economic stability. Historical records indicate that from 180 BC to 1911, droughts were the most devastating natural disasters, accounting for 78.45% of all disaster-related deaths (Table 2; Yang & Liu, 2012). However, the economic impact of these disasters was highly nonlinear, as food supply shocks triggered chain reactions across different sectors, amplifying price fluctuations beyond what simple supply-demand models predict. Geographically, floods primarily affected the North China Plain and the middle and lower reaches of the Yangtze River, whereas severe droughts were concentrated in Shanxi, Hebei, Shandong, Henan, and Shaanxi-regions that were not only agricultural hubs but also among the most densely populated (Figure 3a and 3b).

Beyond disruptions to agricultural production, natural disasters influenced monetary circulation and price stability through nonlinear transmission mechanisms. First, extreme weather events led to sudden and severe grain shortages, pushing prices upward at an accelerating rate-a pattern characteristic of nonlinear price responses. During major droughts, the elasticity of grain supply diminished, meaning small reductions in output could result in disproportionately large price increases. Second, during severe famines, falling rural incomes and declining state revenues exacerbated liquidity constraints, triggering deflationary pressures in silver markets while inflation soared in grain markets. Third, climatic shocks disrupted trade networks, reducing silver inflows, but government relief expenditures created localized inflationary spirals, leading to regionally fragmented price movements rather than uniform trends.

Table 2. Deaths in major disasters from 180BC to AD 1911 in China

Type	Flood	Freezing injury	Drought	Plagues	Hurricane	Earthquake
Death toll (million)	2.58	0.44	26.66	2.00	1.04	1.27
Percentage (%)	7.59	12.95	78.45	5.88	3.05	3.74
Average death toll (1000 people/time)	40.9	55	1269.5	64.5	19.2	97.7

Figure 3: Distribution of death tolls (a) and structure (b) of natural disasters in China from 180BC to AD1911 (Data source: Yang and Liu, 2012)



These mechanisms indicate that the relationship between silver flows, climate shocks, and price levels was neither linear nor uniform across time and space. Extreme climate events intensified price swings in a nonlinear manner, amplifying inflationary and deflationary pressures in ways that standard linear models struggle to capture.

4. Empirical Study in the North China Plain

4.1 Research Time Frame and Geographical Scope

The North China Plain was one of China's key agricultural and economic regions, where silver circulation, price volatility, and climate shocks were deeply intertwined. This region in 1820, covering 22 prefectures and 198 counties within Qing-era Zhili Province and extending into northern Henan and northwestern Shandong, exhibited a relatively unified market system due to geographic homogeneity and the influence of the imperial capital (Table 3, Figure 4a). Silver circulation played a crucial role in economic stability, functioning as both a medium of exchange and a determinant of market liquidity (Shiroyama, 2009).

Table 3. Geographical Scope of North China Plain

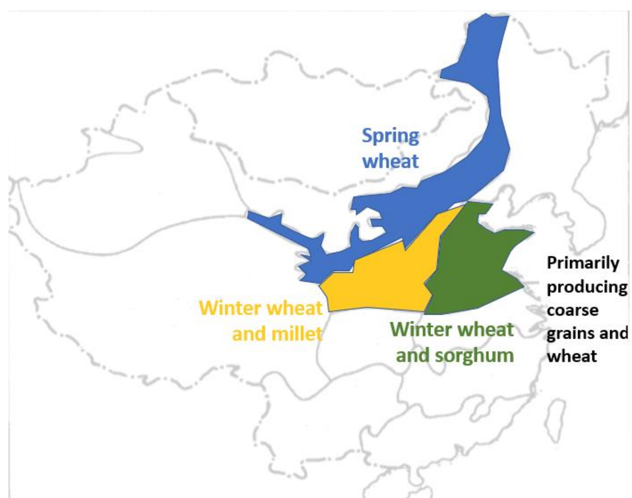
Zhili	Shandong	Henan
Xuanhua, Shuntian, Yizhou, Daming, Tianjin, Hejian, Zhengding, Shunde, Yongping, Zunhua, Baoding, Jizhou, Shenhou, Zhaozhou, Guangping, Dingzhou	Chechang, Wuding, Linqing, Jinan	Weihui, Zhangde

Source: Zhao et al 2018

Figure 4: A map of North China Plain and the main crops of the North China Plain

(a) Administrative division of study area in 1820

(b) Spatial Distribution of Chinese Crops



Source: Figure 4a is from Xiao et al. (2011), and Figure 4b is adapted from Fan et al. (2024).

Agricultural production, primarily wheat, millet, and sorghum (Figure 4b), relied heavily on monsoon rainfall. However, frequent droughts and floods disrupted food supply and drove price volatility. During the 18th and 19th centuries, the region faced compounding crises, including harvest failures, population growth reducing per capita arable land, and monetary fluctuations. Catastrophic flooding in the 1820s, particularly the Yellow River floods of 1824–1826, led to severe famines in northern China. When food shortages drove up grain prices, silver demand surged, while trade imbalances or fiscal constraints leading to silver shortages further destabilized the economy. These interlinked factors make the North China Plain a crucial case study for understanding the nonlinear dynamics between silver flows, climate shocks, and price fluctuations.

4.2 Data

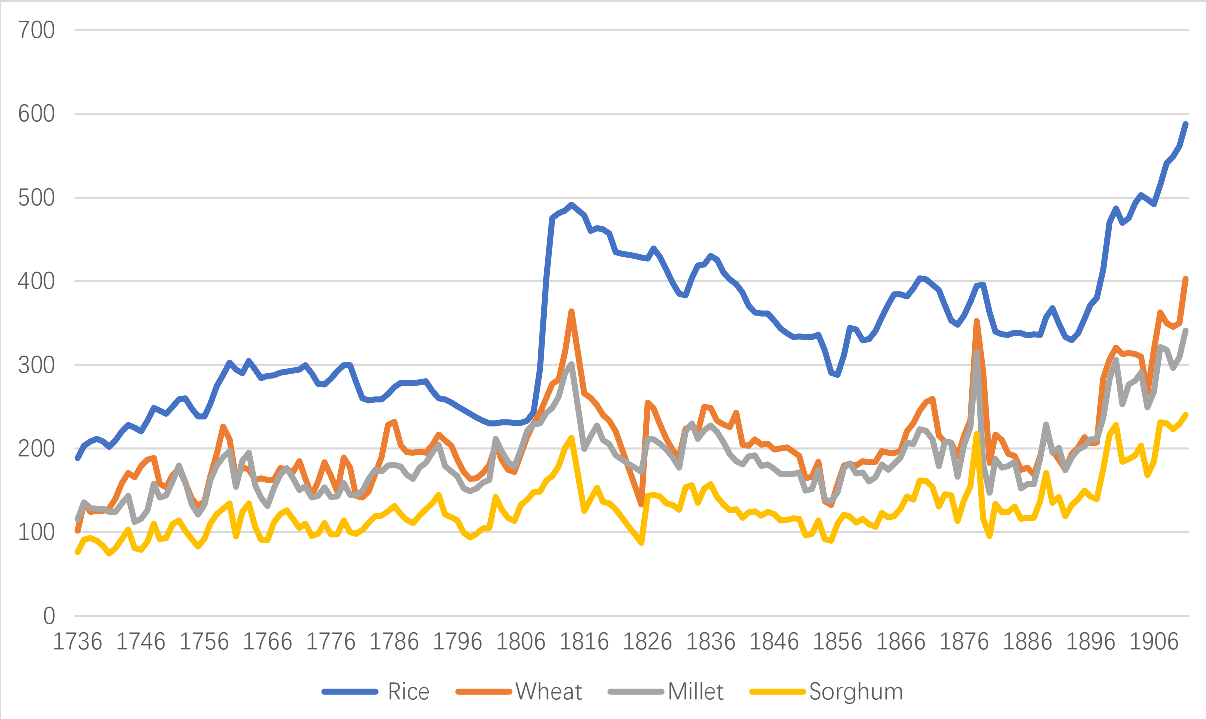
The dependent variable in this study is price. Due to the absence of a comprehensive price index, grain prices are selected as a key indicator of agricultural economic transactions. While trade data from late 19th-century China is relatively complete, real economic activity data remains scarce, as China did not establish an official statistical agency until 1919. Therefore, this study relies on local records to reflect regional market development and price levels. Given the low degree of market integration, significant price variations existed for the same commodity across counties, making regional data insufficient for representing national price trends (Lin & Makram, 2016).

Nevertheless, historical records of grain prices are extensive and indicate a relatively high degree of market integration. Peng (2006) demonstrates that rice prices across different regions exhibit strong co-movement (Figure 5). This study utilizes price data for four major crops-rice, winter wheat, maize, and sorghum-by calculating their weighted annual averages based on monthly price records from 22 prefectures in the North China Plain between 1736 and 1911 (Yeh-Chien Wang, 1992).

The key explanatory variables in this study fall into three categories: monetary factors, climate shocks, and population dynamics. First, monetary factors include silver stock and the silver-to-copper ratio. Since silver stock and silver flow exhibit high correlation, including both in the model would likely result in multicollinearity. To avoid this issue, this study adopts silver stock data from Li (2010) while also incorporating the silver-to-copper ratio from Lin (2010) to measure the value of silver circulation.

Second, climate shocks are captured using drought and flood indices, as well as summer temperature fluctuations. The drought and flood indices are derived from Xiao et al. (2011), who compiled climate event records from historical sources. These indices range from 0 to 1, with higher values indicating greater disaster severity. In addition, temperature data is obtained from Tan et al. (2003), which reconstructs temperature variations based on stalagmite ring thickness in Beijing's Shihua Cave. These climate indicators serve as proxies for environmental volatility and its potential impact on economic conditions.

Figure 5: Major Crop Prices in North China Plain (1736–1911)



Source: Yeh-Chien Wang, 1992

Third, given the lack of annual population data for the North China Plain, this study follows Zhao et al. (2018) in using the Qing Dynasty's total population as a proxy for regional demographic trends.

To account for external shocks and breaks, this study incorporates additional dummy variables. The first is the external invasion dummy (Dum1), which captures the impact of foreign military interventions following the Opium Wars and significant socioeconomic changes in 1850. The second control variable is the Taiping Rebellion dummy (Dum2), set to 1 for the years 1851–1864 to account for the rebellion's influence on economic and social instability in the North China Plain. Furthermore, Unlike the binary dummy for rebellions, we also incorporate Xiao et al.'s (2011) Rebellion Index as a continuous variable for robustness checks, ensuring result stability across model specifications. Data sources are summarized in Table 4.

Table 4. Logarithmic Representation of Variables with Source References

Variable Name	Definition	Data Source
Drought	North China Plain's Drought Index	Xiao et al. (2011)

Flood	North China Plain's Flooding Index	Xiao et al. (2011)
Temperature	North China Plain's Temperature	Tan et al. (2003)
Price	Prices of grains in the North China Plain	Author's compilation from modern history database
Population	National population size	Author's compilation (sources from Liang (1980), Durand (1960) and Lee (1921)
Silver stock	Total overseas silver inflow	Li (2010)
Silver to copper ratio	National silver-to-copper price ratio	Lin (2011)
Rebellions index	North China Plain's Rebellion Index	Xiao et al. (2011)
Dum1	Foreign invasion and the turning points of silver inflow after 1850	Dummy variable
Dum2	Taiping Rebellion (1851–1864)	Dummy variable

5. Model and Methodology

5.1. ARDL and nonlinear ARDL

5.1.1 ARDL and NARDL

This study employs the ARDL model to examine the dynamic relationships among key variables. The ARDL model, originally developed for standard least squares regression, integrates lagged values of both dependent and independent variables, making it well-suited for analyzing time-series data (Greene, 2008). Its application in cointegration analysis gained prominence through the work of Pesaran and Shin (1998) and Pesaran, Shin, and Smith (2001), who demonstrated its effectiveness in estimating both short-run and long-run relationships. Unlike traditional vector autoregressive (VAR) and vector error correction models (VECM), which require all variables to be of the same order of integration, the ARDL approach accommodates mixed integration orders, making it particularly valuable for historical economic studies where data stationarity conditions may vary.

Building on the ARDL framework, this study also incorporates a nonlinear ARDL (NARDL) model to account for potential asymmetries in the relationships between monetary dynamics, climate shocks, and price fluctuations. While the linear ARDL model assumes symmetric responses of the dependent variable to changes in explanatory variables, real-world economic interactions often exhibit nonlinear and asymmetric effects, particularly in periods of crises. Historical data from the Qing dynasty suggests that external shocks-such as wars, natural disasters, and monetary disruptions-may not have had uniform effects on price levels, as responses could vary based on the magnitude and direction of shocks. To capture these complexities, the NARDL model, proposed by Shin et al. (2014), decomposes explanatory variables into positive and negative components, allowing for a more precise estimation of asymmetric effects. This method has been widely applied in recent economic research to analyze nonlinear adjustments to external shocks (Lin, 2019).

5.1.2. Long-run and short-run regression forms and bounds tests for models

The long-run relationship between price levels and key explanatory variables is specified as:

$$\Delta \ln(\text{ Price }_t) = \beta_0 + \sum_{i=1}^{p} \beta_i \Delta \ln\left(X_{i,t-i}\right) + \lambda_1 \ln(\text{ Price }_{t-1}) + \sum_{k=2}^{q} \lambda_k \ln\left(X_{k,t-1}\right) + \sum_{j=1}^{m} \alpha_j d_{j,t} + \varepsilon_t \tag{1}$$

where X_k represents the set of independent variables including silver stock, the silver-to-copper ratio, climate indicators (drought, flood, temperature), and population. $d_{j,t}$ are dummy variables capturing structural breaks, and ε_t is the error term.
The short-run adjustment mechanism is represented as:

$$\Delta \ln(\text{Price}_t) = \beta_0 + \sum_{i=1}^{p} \beta_i \Delta \ln\left(X_{i,t-i}\right) - \theta ECT_{t-1} + \sum_{j=1}^{m} \alpha_j d_{j,t} + \varepsilon_t \tag{2}$$

A significantly negative θ indicates that deviations from equilibrium are gradually corrected over time.

This study considers two error correction specifications to assess different assumptions about price behavior.

Case One (with Constant Term):

In this case, a constant term is included, allowing for an independent price shift. The error correction term (ECT) is defined as:

$$\mathrm{ECT}_t = \ln\ \mathrm{Price}_{t-1} - \sum_{j=2}^{q} \frac{\lambda_j}{\lambda_1} \ln\ X_{j,t-1} - \frac{\beta_0}{\lambda_1} \tag{3}$$

The corresponding null hypothesis of bounds test for case one can be rewritten in a more compact form as:

$$H_0: \beta_0 = \boldsymbol{\lambda} = \mathbf{0}$$

Case Two (Without Constant Term):

Here, price is assumed to be fully determined by the explanatory variables without an independent shift:

$$\mathrm{ECT}_t = \ln\ \mathrm{Price}_{\ t-1} - \sum_{j=2}^{q} \frac{\lambda_j}{\lambda_1} \ln\ X_{j,t-1} \tag{4}$$

The corresponding null hypothesis of bounds test for case two can be rewritten in a more compact form as:

$$H_0: \boldsymbol{\lambda} = \mathbf{0}$$

where:

$\boldsymbol{\lambda}$ is a vector of long-run coefficients $(\lambda_1, \lambda_2, \lambda_3, \dots, \lambda_q)$, and

0 represents the null vector, indicating that all long-run coefficients are equal to zero.

If rejected, this confirms the existence of a long-term relationship.

5.2 Non-linear ARDL Models

This study assumes that climate variables have a nonlinear impact on price, alongside the linear effects of silver stock, the silver-to-copper ratio, and population. The long-run NARDL model is specified as follows:

$$\ln\ \mathrm{Price}_t = \lambda_0 + \lambda' \mathrm{X_t} + \gamma' \mathrm{C_t^+} + \eta' \mathrm{C_t^-} + \sum_{j=1}^{m} \alpha_j d_{j,t} + \varepsilon_t \tag{5}$$

where:

$X_t = (\text{ silver stock, silver to copper ratio, population}))'$ is a 3×1 vector representing the set of linear explanatory variables.

$C_t^+ = (\text{drought}^{\ +}, \text{flood}^{\ +}, \text{temperature}^{\ +})'$ and $C_t^- = (\text{drough}^{\ -}, \text{ flood}^{\ -}, \text{ temperature}^{\ -})'$

are 3×1 vectors representing the positive and negative components of climate variables.

$\lambda = (\lambda_1, \lambda_2, \lambda_3)'$ is a 3×1 vector of coefficients for linear explanatory variables.

$\gamma = (\gamma_1, \gamma_2, \gamma_3)'$ and $\eta = (\eta_1, \eta_2, \eta_3)'$ are 3×1 vectors capturing the asymmetric effects of climate variables.

$d_{j,t}$ represents dummy variables, and ε_t is the error term.

If cointegration exists, the error correction term (ECT) is given by:

$$ECT_t = \ln \text{ Price }_{t-1} - \Lambda' \mathrm{X}_{t-1} - \Gamma' \mathrm{C}^{+}_{t-1} - \Theta' \mathrm{C}^{-}_{t-1} \tag{6}$$

where:

$$\Lambda = \begin{bmatrix} \frac{\lambda_1}{\lambda_0} \\ \frac{\lambda_2}{\lambda_0} \\ \frac{\lambda_3}{\lambda_0} \end{bmatrix}, \ \Gamma = \begin{bmatrix} \frac{\gamma_1}{\lambda_0} \\ \frac{\gamma_2}{\lambda_0} \\ \frac{\gamma_3}{\lambda_0} \end{bmatrix}, \ \Theta = \begin{bmatrix} \frac{\eta_1}{\lambda_0} \\ \frac{\eta_2}{\lambda_0} \\ \frac{\eta_3}{\lambda_0} \end{bmatrix}$$

are 3×1 vectors capturing the normalized long-run coefficients.

The corresponding short-run NARDL equation is:

$$\Delta \ln \text{ Price }_t = \delta_0 + \sum_{i=1}^{p} \delta_i \Delta \ln \text{Price}_{t-i} + \beta' \Delta \mathrm{X}_{\mathrm{t}} + \gamma' \Delta \mathrm{C}^{+}_{\mathrm{t}} + \eta' \Delta \mathrm{C}^{-}_{\mathrm{t}} - \theta ECT_t + \sum_{j=1}^{m} \alpha_j d_{j,t} + \varepsilon_t \tag{7}$$

where:

θ represents the speed of adjustment toward the long-run equilibrium. $\beta = (\beta_1, \beta_2, \beta_3)'$ is a 3×1 vector capturing short-run effects of linear explanatory variables. $\gamma = (\gamma_1, \gamma_2, \gamma_3)'$ and $\eta = (\eta_1, \eta_2, \eta_3)'$ are 3×1 vectors capturing the short-run asymmetric effects of climate variables.

6. Empirical Results

6.1 Lag Length Test

Selecting the appropriate lag length is crucial for cointegration analysis. Table 5 presents the lag order selection results, showing some variation across different criteria. For price revolution tests, LR, FPF, and AIC suggest a lag length of 3, while SC and HQ indicate shorter lags. Based on these results, a maximum lag of 3 is chosen for the ARDL and NARDL models.

Table 5. Lag order selection

VAR Lag Order Selection Criteria
Endogenous variables: LOG_PRICE LOG_S_STOCK LOG_SCP LOG_DROUGHT L...
Exogenous variables: C DUM1 DUM2
Date: 08/04/23 Time: 21:40
Sample: 1736 1911
Included observations: 171

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-827.8981	NA	4.84e-05	9.928633	10.31445	10.08518
1	172.6085	1883.995	7.11e-10	-1.200099	0.085962*	-0.678270
2	261.6129	160.3121	4.47e-10	-1.667987	0.518317	-0.780878*
3	316.5166	94.39590*	4.21e-10*	-1.737037*	1.349510	-0.484647
4	340.2011	38.78159	5.74e-10	-1.440948	2.545841	0.176721

* indicates lag order selected by the criterion
LR: sequential modified LR test statistic (each test at 5% level)
FPE: Final prediction error
AIC: Akaike information criterion
SC: Schwarz information criterion
HQ: Hannan-Quinn information criterion

6.2 Unit Root and Symmetric Cointegration Tests.

Time series model statistical inference reliability depends upon stationarity of the data. Literature provides multiple tests for stationarity; however, in this study, we have used Augmented Dickey-Fuller (ADF) and Lee-Strazicich-(LM) unit root test to accommodate any structural breaks in the data of the variables. I applied the unit root test at the level and the first difference of the variables, as shown in Table 6. The tests suggest that all variables are stationary at either I(0) or I(1). The break years identified through LM are not exactly identical to the real historical events. This LM with break years is only useful for Unit root tests, and overall, the selection of structural breaks is tied to significant historical events and data results from the North China Plain. For instance, the year 1850 was a pivotal juncture, when Emperor Xianfeng ascended the throne in China and the Taiping Heavenly Kingdom was re-established. Moreover, in the aftermath of the Opium War and the Taiping Rebellion, an influx of silver was observed in the post-1850.

Table 6. Unit root Tests

Methodology	ADF	Lee-Strazicich-(LM) unit root test	
Variables	t-stat.	t-stat.	Break Years

At level			
Price	-1.5556	-1.8032***	
Silver stock	0.6111	-2.7421	1816, 1850
Siver to copper ratio	-1.7751	-5.3879	1841, 1861
Drought	-11.03626***	-11.3869***	1824, 1871
Flood	-11.38192***	-11.1905 ***	1758, 1894
Temperature	-6.202216***	-7.2927 ***	1785, 1869
Population	-0.9708	-5.2404	1776, 1853
Rebellions	-3.7978***	-13.7714***	1810, 1894
At first difference			
d(Price)	-11.18355***	-7.5917***	1857, 1876
d(Silver stock)	-0.4269***	-6.1785*	1822, 1894
d(Silver to copper ratio)	-7.285***	-7.5917***	1857, 1876
d(Population)	-16.2726***	-16.7807***	1774, 1820

*Note: ***, ** and * show significance at 1, 5 and 10% level respectively.*

Null Hypothesis of Augmented Dickey-Fuller Unit Root Test (ADF) and Lee-Strazicich- LM unit Root Test (LEE) Null Hypothesis: Variable has a unit root.

6.3 ARDL and NARDL Model Results

6.3.1 Results for ARDL models

Both error correction term (ECT) models—Case One (restricted constant in Model 1) and Case Two (unrestricted constant with no trend in Models 2-4)—produce highly similar results, as shown in Table 7. To streamline our analysis, we focus on Case Two (Models 2-4), assuming that price movements are fully driven by fundamental shocks, making it the preferred choice when prices exhibit no independent trends or shifts. The F-statistic results for the baseline Eq. (1) confirm the existence of a long-run relationship among the study variables (Table 7). The computed F-statistic values exceed the upper bound critical value at the 1% significance level, as specified in Narayan (2005), regardless of the inclusion of deterministic terms. Additionally, The negative and statistically significant coefficient of the error correction term (ECT_{t-1}) confirms the presence of a long-run equilibrium, with deviations adjusting at a rate of 15–18% per year (Pesaran et al., 2001). This suggests that any deviation from the long-run equilibrium is gradually adjusted over a period of about five to seven years. The structural break dummy included in the models is also statistically significant, indicating that major historical events likely played a crucial role in shaping price dynamics.

Further refinement shows that the Opium War dummy is insignificant in Models 1 and 2, leading to its exclusion in Model 3, which otherwise mirrors Model 2. Model 4, identical to Model 2 except for the inclusion of rebellion data from Xiao et al. (2011), assesses the impact of social unrest on prices. Across all models (1–4), long-run estimates (Table 7) suggest a significant positive association between price levels and droughts, indicating that prolonged drought conditions contributed to price increases, likely due to supply constraints and agricultural disruptions. In contrast, the short-run relationship between the silver-to-copper ratio and prices is positive and statistically significant (Table 8), whereas the long-run correlation is negative. This suggests that in the short term, an increase in the silver-to-copper ratio raises the money supply, driving up prices. However, over the long run, the strengthening purchasing power of silver may suppress inflationary pressures, offsetting the initial impact. These results align with previous studies by Wang (2015) and Zhao (2016), confirming that silver inflows played a crucial role in the price revolution between 1736 and 1911.

The findings also suggest that social unrest contributes to short-term price surges. This is evidenced by the statistical significance of the rebellion dummy variables (dum2 for the Taiping Rebellion and the broader rebellion variable from Xiao et al., 2011). However, in the long run, social disturbances appear to have no lasting impact on price trends, implying that while conflicts cause immediate market disruptions, their long-term effect on price stability is negligible.

Moreover, the influence of climate variables on prices appears to be heterogeneous. In the short run, prices respond significantly to flooding but show no notable sensitivity to temperature and droughts. Conversely, in the long run, droughts exhibit a strong and persistent relationship with price levels, whereas floods and temperature variations do not. This suggests that while floods have an immediate impact on market supply and transportation, droughts exert more enduring effects on agricultural output and price stability.

Table 7. ARDL Long-run estimates along with diagnostic tests

ARDL Long-run estimates along with diagnostic tests				
Price Revolution				
	Model 1	Model 2	Model 3	Model 4
Silver stock	0.444* (-0.240)	0.444* (-0.240)	0.450*** (0.140)	0.355 (0.268)
Siver to copper ratio	-0.553** (0.239)	-0.553* (0.239)	-0.550*** (0.212)	-0.699** (0.293)
Drought	0.043*** (0.013)	0.043*** (0.013)	0.054*** (0.018)	0.055*** (0.018)
Flood	0.009 (0.012)	0.009 (0.012)	0.009 (0.011)	0.021 (0.016)
Temperature	0.089 (0.082)	0.089 (0.082)	0.170 (0.109)	0.174* (0.102)
Population	0.406 (0.301)	0.406 (0.301)	0.400* (0.231)	0.661* (0.368)
Rebellions				-0.014 (0.011)
Constant	2.657 (1.833)			
ARDL bound test				
Form of error correction term	Case 2	Case 3	Case 3	Case3
F-stat.	4.173***	4.68***	4.785***	4.701***
Sel. Model	(3, 0, 3, 2, 2, 1, 0)	(3, 0, 3, 2, 2, 1, 0)	(3, 0, 3, 2, 2, 1, 0)	(3, 0, 3, 2, 3, 1, 0, 3)
Model statistics				
R-sq.	0.919	0.919	0.919	0.924
Adj. R-sq.	0.909	0.909	0.909	0.912
F-stat.	90.719***	90.719***	96.389***	74.691
Residual diagnostic tests				
Normality	0.180	0.180	0.179	0.066
Serial-Corr.	0.114	0.114	0.117	0.280
Hetero.	0.315	0.315	0.490	0.044
Stability Test				
CUSUM	Stable	Stable	Stable	Stable
CUSUM-Sq.	Stable	Stable	Stable	Stable

*Note: ***, ** and * show significance at 1, 5 and 10% level respectively. Standard errors in brackets. Jarque-Bera (Normality) test; Breusch-Godfrey LM Serial Correlation test; Breusch-Pagan-Godfrey Heteroscedasticity test; Cumulative Sum (CUSUM) stability test; Cumulative Sum of Square (CUSUM-Sq.) stability test. The table reports two F-statistics: the NARDL bound test F-statistic, which checks for a long-run cointegration relationship among variables, and the model statistics F-statistic, which tests the overall significance of the regression.*

Table 8 ARDL Short-run estimates along with diagnostic tests

ARDL short-run estimates				
Price Revolution				
	Model 1	Model 2	Model 3	Model 4
Price	F. 102.619 ***	F. 7.356***	F. 7.409***	F. 5.940***
Rebellions				F. 3.271**
Siver to copper ratio	F. 4.960***	F. 2.786**	F. 5.112***	F. 2.742**
Drought	F. 1.090	F. 2.012	F. 2.092	F. 7.124***
Flood	F. 8.031***	F. 7.067***	F. 7.195***	F. 7.520***
Temperature	-0.011 (0.014)	-0.011 (0.014)	-0.011 (0.014)	-0.004 (0.014)
Dum1				0.021* (0.011)
Dum2	0.054 ** (0.017)	0.054** (0.023)	0.055*** (0.010)	0.060*** (0.022)
Constant		0.480*** (0.082)	0.471*** (0.079)	0.277*** (0.047)
Coint. Eq. (−1)	-0.181 *** (0.031)	-0.181*** (0.031)	-0.181 (0.031)	-0.160*** (0.025)

*Note: ***, ** and * show significance at 1, 5 and 10% level respectively. Standard errors in brackets. "F." refers to the F-statistic, which is derived from the Wald test. It evaluates the joint significance of a set of predictors within a regression model. In essence, it tests the collective impact of these predictors on the dependent variable, providing insight into the combined importance of the variables under consideration.*

6.3.2 Results for NARDL models

Building on the ARDL framework, we estimate four NARDL models to capture the asymmetric effects of silver flows, climate variables, and population on price dynamics. Models 1 and 2 use price as the dependent variable, with Model 1 incorporating a deterministic term in the error correction term (case 1) and Model 2 omitting it (case 2). Model 3 excludes the Opium War dummy, while Model 4 extends Model 2 by incorporating rebellion data from Xiao et al. (2011) for the North China Plain.

As shown in Table 9, computed F-statistics exceed the upper bound critical values the 1% significance level, confirming long-run relationships across all models. The negative and significant coefficients of the lagged error correction term (ECT_{t-1}) suggest that deviations from equilibrium adjust at a rate of approximately 19% per year, implying a return to equilibrium within five years-slightly faster than the 5–7 years estimated in the ARDL model.

The nonlinear ARDL long-term estimation results, presented in Tables 9, align with ARDL findings, reinforcing the “price revolution” hypothesis while rejecting the population hypothesis. In the long run, these models highlight substantial robustness. "Silver stock" in all models presents a significant positive correlation with prices. The "silver to copper ratio" exhibits a noticeable negative correlation, an observation that mirrors ARDL's results.

NARDL models allow for asymmetric responses to positive and negative changes in explanatory variables. For instance, in the case of drought, an increase in drought severity (drought+) raises prices by 2.9%, reflecting supply constraints and reduced agricultural yields. Conversely, when drought conditions improve (drought-), prices decline by 2.6%, indicating a supply recovery. The smaller magnitude of the price decline suggests that markets adjust more slowly to improving conditions than to worsening ones, possibly due to production lags and storage behavior. However, factors like "flood," "temperature," and "population" do not seem to influence prices in the long run since they are statistically insignificant.

Short-term effects of climate variables also differ between NARDL and ARDL models (Table 10). NARDL results indicate that price increases are associated with rising drought and flood intensity in the short run, while their decline shows no significant correlation with prices. However, NARDL results suggest that both rising and falling temperatures lead to price declines, a relationship that appears counterintuitive at first.

The key to understanding this pattern lies in the fact that our temperature data specifically capture summer conditions. From a market perspective, seasonal supply dynamics and trade expectations drive this effect. In North China, winter wheat is harvested in summer, while millet and sorghum mature in autumn. A warmer summer may signal favorable autumn yields, encouraging farmers and merchants to release stored wheat early, thereby increasing supply and pushing prices down.

Conversely, a cooler summer may raise concerns about crop growth, prompting precautionary grain sales to mitigate potential losses, which similarly boosts short-term supply and lowers prices.

Additionally, summer coincides with peak trade activity, bringing an influx of silver that enhances liquidity and reduces inflationary pressures. In contrast, winter temperature fluctuations likely have different asymmetric effects. However, due to data limitations, we lack reliable indicators for winter or annual temperatures in this region, leaving room for further research.

Table 9. NARDL Long-run estimates along with diagnostic tests

NARDL Long-run estimates along with diagnostic tests					
Price Revolution					
		Model 1	Model 2	Model 3	Model 4
Silver stock		0.664** (0.301)	0.664** (0.301)	0.656** (0.302)	0.592* (0.301)
Siver to copper ratio		-0.589** (0.234)	-0.589** (0.234)	-0.595 (0.235)	’-0.774*** (0.255)
Drought	+	0.029*** (0.009)	0.029*** (0.009)	0.030*** (0.009)	0.036*** (0.011)
	-	0.026*** (0.008)	0.026*** (0.008)	0.027*** (0.008)	0.033*** (0.033)
Flood	+	0.002 (0.007)	0.002 (0.007)	0.002 (0.007)	0.006 (0.007)
	-	0.000 (0.007)	0.000 (0.007)	0.000 (0.007)	0.001 (0.007)
Temperature	+	0.034 (0.082)	0.034 (0.082)	0.036 (0.082)	0.128 (0.085)
	-	0.116 (0.093)	0.116 (0.093)	0.124 (0.087)	0.246** (0.103)
Population		0.323 (0.380)	0.323 (0.380)	0.391 (0.228)	0.543 (0.413)
Constant		1.350 (3.207)			
NARDL bound test					
Form of error correction term		Case 1	Case 2	Case 2	Case2
F-stat.		5.670***	5.031***	5.279***	5.989***
Sel. Model		(3, 0, 3, 2, 0, 3, 0, 1, 1, 0)	(3, 0, 3, 2, 0, 3, 0, 1, 1, 0)	(3, 0, 3, 2, 0, 3, 0, 1, 1, 0)	(3, 0, 3, 2, 0, 4, 0, 1, 0, 0, 4)
Model statistics					
R-sq.		0.927	0.927	0.927	0.932
Adj. R-sq.		0.915	0.915	0.915	0.918
F-stat.		77.095***	77.095***	80.970***	0.918***
Residual diagnostic tests					
Normality		0.707	0.707	0.731	0.959
Serial-Corr.		0.141	0.141	0.130	0.098
Hetero.		0.470	0.470	0.476	0.829
Stability Test					
CUSUM		Stable	Stable	Stable	Stable
CUSUM-Sq.		Stable	Stable	Stable	Stable

*Note: ***, ** and * show significance at 1, 5 and 10% level respectively. Standard errors in brackets. Jarque-Bera (Normality) test; Breusch-Godfrey LM Serial Correlation test; Breusch-Pagan-Godfrey Heteroscedasticity test; Cumulative Sum (CUSUM) stability test; Cumulative Sum of Square (CUSUM-Sq.) stability test.*

Table 10 NARDL Short-run estimates along with diagnostic tests

NARDL short-run estimates					
Price Revolution					
		Model 1	Model 2	Model3	Model 4
Price(lags)		F. 107.265***	F. 5.078***	F. 5.127***	F. 6.242***
Rebellions(lags)		-	-	-	F. 4.412***
Silver stock		F. 3.062**	F. 4.151***	-	-
Siver to copper ratio		F. 4.421***	F. 5.078***	F. 4.194***	F. 4.049***
Drought	+	F. 2.503*	F. 2.766*	F. 3.627**	F. 4.182***
	-	-	-	-	-
Flood	+	F. 11.418***	F. 12.417***	F. 8.449***	F. 9.299*
	-	-	-	-	-
Temperature	+	-0.096*** (0.001)	-0.096*** (0.027)	-0.096*** (0.027)	-0.073 (0.024)
	-	0.066*** (0.024)	0.066*** (0.026)	0.067*** (0.026)	
Population		-	-	-	-
Dum1		-0.009 (0.012)	-0.009 (0.012)	-	0.003 (0.011)
Dum2		0.060*** (0.004)	0.060*** (0.022)	0.055*** (0.019)	0.084*** (0.022)
Constant		-	0.265***	0.218***	0.238***
Coint. Eq. (−1)		-0.196*** (0.024)	-0.196*** (0.027)	-0.193***	-0.191*** (0.023)

*Note: ***, ** and * show significance at 1, 5 and 10% level respectively. Standard errors in brackets. "F." refers to the F-statistic, which is derived from the Wald test. It evaluates the joint significance of a set of predictors within a regression model. In essence, it tests the collective impact of these predictors on the dependent variable, providing insight into the combined importance of the variables under consideration. A dash ("-") indicates that the variable is either not applicable or has no effect.*

6.4. Results for Cumulative Dynamic Multiplier

The cumulative dynamic multiplier graph in the NARDL framework illustrates how the effects of drought, flood, and temperature shocks evolve over time, with distinct differences between short- and long-term asymmetric dynamics (Figure 6).

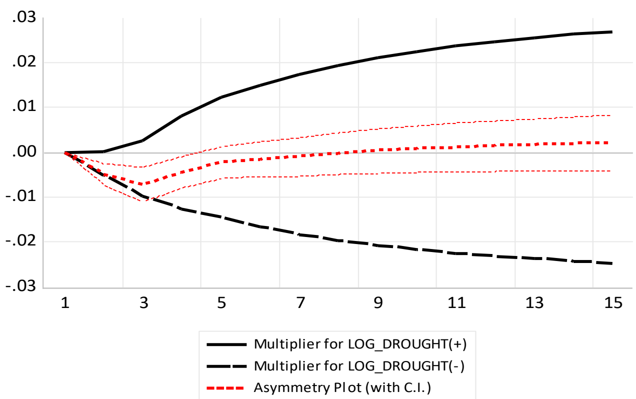
The impact of drought shocks on grain prices exhibits notable asymmetry. An increase in drought severity leads to a persistent rise in grain prices. Conversely, improvements in drought conditions lead to a decline in prices, though with a smaller magnitude than the price surge caused by worsening droughts. This asymmetry suggests that markets react more strongly to adverse conditions than to improving ones. Furthermore, the long-run effects of drought shocks remain significant for several years, highlighting the crucial role of droughts in shaping historical price trends in Qing China. These results are consistent with NARDL regression estimations in Table 10.

Flood shocks, in contrast, display a more symmetric impact on grain prices. Both positive and negative flood shocks influence prices to a comparable degree, though their effects manifest with a delay. Unlike droughts, which exert a prolonged influence on agricultural productivity, flood-induced disruptions are relatively short-lived, peaking within three to five years. This pattern suggests that while floods disrupt crop yields and transportation networks in the short run, their long-term effects on market equilibrium and supply chains are less pronounced.

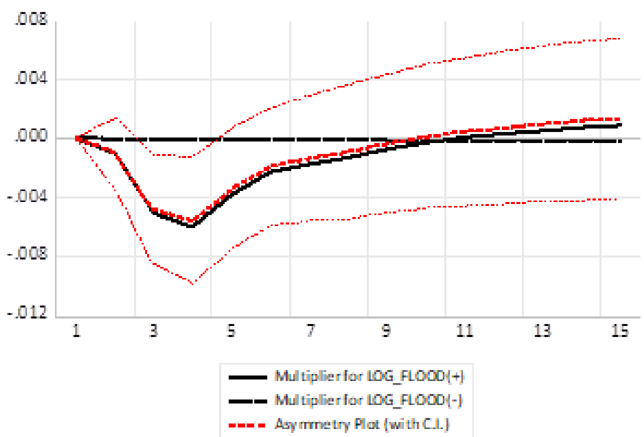
Temperature shocks exhibit a distinct pattern. Initially, both rising and falling temperatures correlate with price declines, reflecting short-term agricultural disruptions and shifting trade expectations. However, over time, positive temperature shocks begin to exert upward pressure on prices, with the effect becoming significant after approximately seven years. This delayed response likely stems from long-term agricultural adaptations and structural shifts in crop productivity due to sustained climatic changes.

Figure 6: Cumulative dynamic multipliers

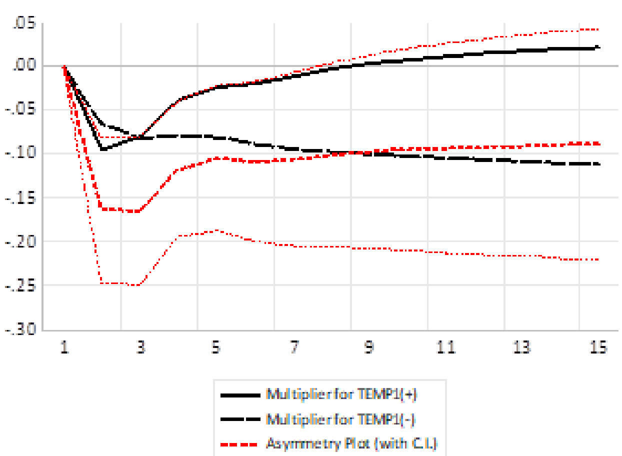
Drought→ Grain Price



Flood →Grain Price



Temprature →Grain Price

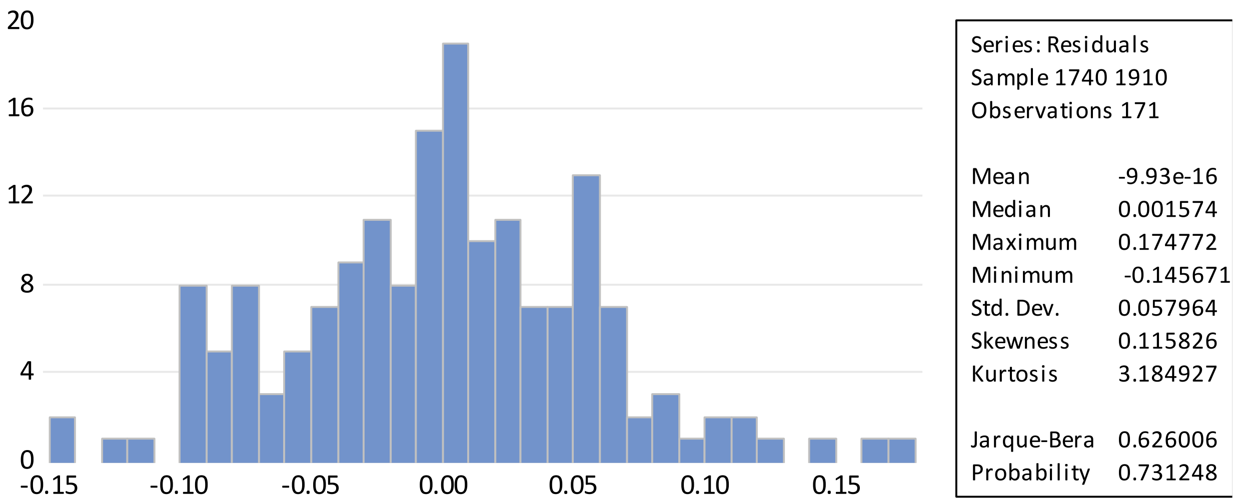


Note: The two light red dot curve is presented in its lower and upper bands as red dotted lines at 95 percent confidence interval to highlight the statistical significance of measuring asymmetry at a given horizon. The dashed red line in the middle represents the difference between dynamic multipliers (i.e. positive multiplier minus the negative multiplier). If the axis line (line zero) is located between the upper and lower bands (i.e. dotted red lines), the asymmetric effect of the respective energy future is considered insignificant at a five percent confidence interval. The two black lines, continuous and dashed, represent positive and negative change curves and highlight adjustments in rice price returns to positive and negative shocks at forecast horizons, respectively (Rehman, 2019).

6.5 Post-Estimation Tests for ARDL Models and NARDL Models

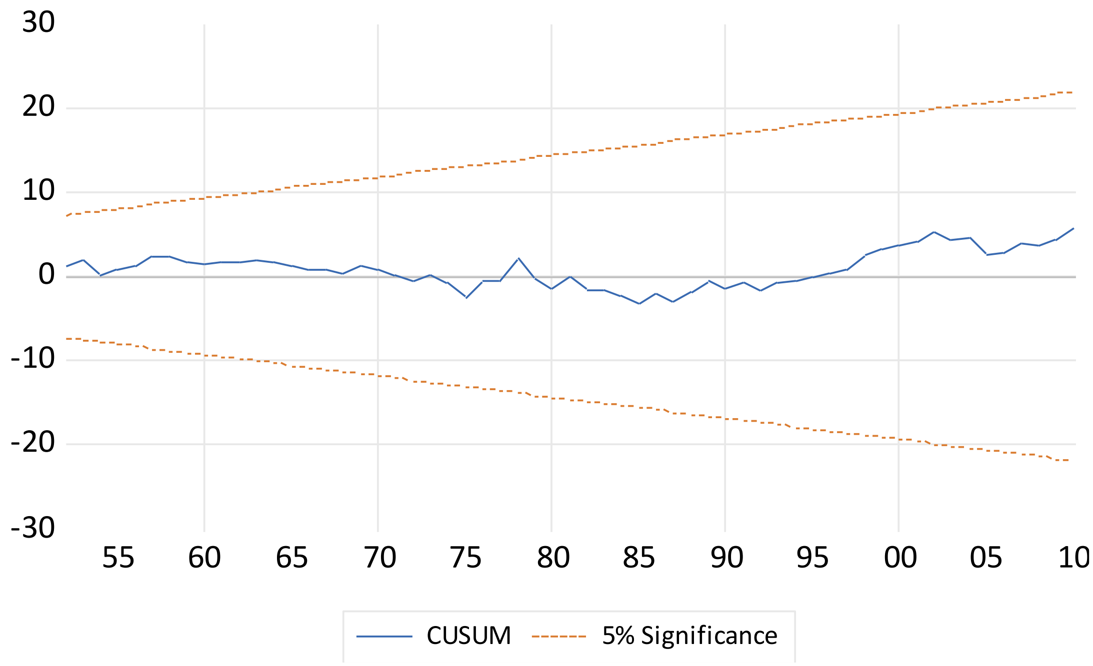
The lower section of Table 9 displays our diagnostic test results. The paper utilized the Breusch-Godfrey Serial Correlation LM test for serial correlation and the Jarque-Bera test for data normality. For both of these tests, the chi-square probability values proved to be statistically non-significant, indicating data normality (as shown in Figure 7) and an absence of serial correlation within our model. Further, for heteroscedasticity analysis, we applied the Breusch-Pagan-Godfrey test. The derived chi-square probability values were not significant, which implies that the null hypothesis of homoscedasticity remains intact.

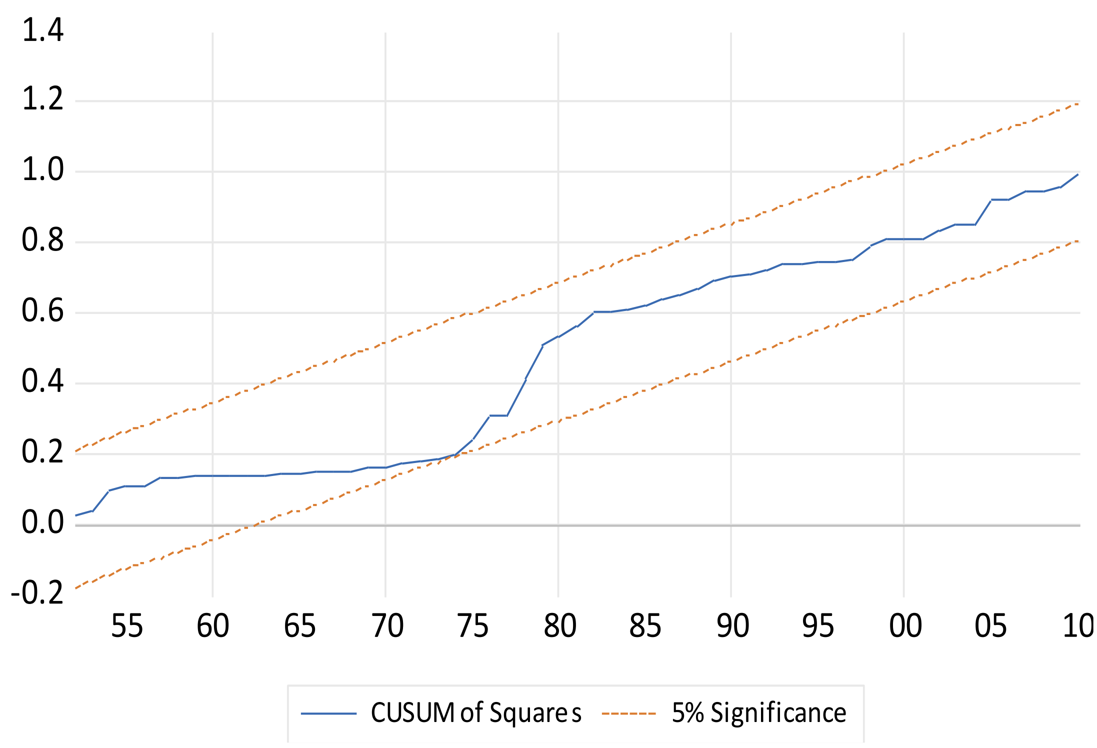
Figure 7: Normality-Jarque-Bera Test



To further solidify the robustness of our findings, we assessed the dynamic stability of our model using both the cumulative sum of recursive residuals (CUSUM) and the cumulative sum of recursive residual square (CUSUMQ) as per Brown et al. (2003). Figure 8 shows that both blue lines are within the 95 percent significance level in both CUSUM and CUSUMQ, which means the regression results are not sensitive to any systematical changes or any sudden changes. The results indicate that the estimated models' overall performance is satisfactory.

Figure 8: Stability Test - Cumulative sums (CUSUM) and CUSUM of squired test for residuals





Notes: Cumulative sum test helps to show if coefficients of regression are changing systematically. Cumulative sum of square Test is to show if the coefficients of regression changing suddenly (Bhatti, AlShanfari et al, 2006)

7. Conclusions

This study examines the long- and short-run dynamics between silver circulation, climate shocks, economic and social factors (population growth and rebellions), and grain prices in Qing China (1644–1911), with a particular focus on compounded crises in the North China Plain from 1736 to 1911. Using both linear ARDL and nonlinear NARDL models, the findings indicate that while silver flows influenced price dynamics, China did not experience a conventional price revolution driven solely by monetary expansion. Instead, long-term price trends were shaped by the interaction of silver inflows and climate conditions, suggesting broader structural forces at play.

Monetary factors played a dominant role in shaping long-term price trends, as evidenced by a significant positive relationship between silver stock and prices. However, while the silver-to-copper ratio had a short-run inflationary effect, it turned negative in the long run, implying that silver liquidity initially fueled inflationary pressures but was later offset by adjustments in its purchasing power. These results challenge the notion of a price revolution similar to early modern Europe.

Climate shocks also had asymmetric effects on price fluctuations. Floods primarily influenced short-term volatility, whereas droughts had a more persistent long-run impact. Nonlinear analysis reveals that worsening droughts significantly increased prices, while relief efforts had weaker mitigating effects. Temperature variations had limited long-term influence but contributed to short-term price adjustments, underscoring the importance of accounting for nonlinear climate effects in historical economic analysis.

In contrast, population changes did not have a statistically significant impact on prices, challenging conventional Malthusian explanations. By integrating monetary, climatic, and broader socio-economic factors, this study provides a comprehensive understanding of historical price volatility. This approach not only refines our interpretation of price dynamics in Qing China but also offers a methodological framework for studying macroeconomic fluctuations in economies vulnerable to both climate and monetary shocks.

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