Enhancement of state response capability and famine mitigation: A comparative analysis of two drought events in northern China during the Ming dynasty

Fangyu Tian[12], Yun Su[12], Xudong Chen[12], Le Tao[12]

[1] Faculty of Geographical Science, Beijing Normal University, Beijing, 100875, China
[2] Key Laboratory of Environmental Change and Natural Disaster, Ministry of Education, Beijing Normal University, Beijing, 100875, China

Correspondence to: Yun Su (suyun@bnu.edu.cn)

Abstract. Studying social impacts and responses to historical extreme climate events can offer valuable insights into coping with major disaster events and adapting to climate change better. This paper developed a model of the processes and responses to extreme drought-induced famines in ancient China. Based on this, the study explored the differences in famine causation and response effectiveness between Chenghua Drought (1483-1486 CE) and Wanli Drought (1585-1588 CE). The findings are as follows: (1) By the time of Wanli Drought, the increase in land reclamation and introduction of American crops had enhanced societal defence, preventing many drought-affected counties from experiencing famine. Even in cases where famines did occur, their severity was lower than during the Chenghua Drought. (2) State emergency measures, including exemption and relief, proved effective in mitigating famines. The stronger finance and economy during the Wanli Drought enabled more robust relief efforts, resulting in lower famine severity. (3) Famine response capabilities varied regionally. Shandong, Beijing, Tianjin and Hebei demonstrated strong defensive capabilities and effective state emergency responses, while Shanxi had weaker defensive abilities, making it more vulnerable to famine. The defensive capabilities in Henan, Shaanxi, Gansu, and Ningxia showed significant improvement.

1 Introduction

In historical periods with low agricultural productivity, extreme drought events had wide and profound impacts on human societies. Scholars have qualitatively described the link between human social development and climate change by identifying historical cases based on paleoclimate reconstruction. They argue that the disappearance of civilizations (Peterson and Haug, 2005), social unrest(Atwell, 2002; Zhang et al., 2005), and dynasty succession(Atwell, 2001; Zheng et al., 2014a) in various regions and countries in human history are temporally synchronized with extreme drought events. For instance, the rapid collapse of the Akkadian civilization in the Mesopotamian region, the Moche culture in northern Peru, and the Tiwanaku culture in South America coincides with periods of severe climate aridity(deMenocal, 2001) as revealed by reconstructions from natural proxies such as lake sediments and ice cores. Additionally, quantitative studies using

30 methods such as correlation and multiple regression analysis have demonstrated the connections between extreme drought events and production, economic and demographic systems including food availability(Hao et al., 2020), food prices (Brázdil et al., 2019), population migration(Pei and Zhang, 2014), and social unrest (Xiao et al., 2013; Yu et al., 2004), providing scientific arguments and empirical evidence for understanding the relationship between historical extreme drought events and human societal development(Pei, 2017).

35 The transmission process of the social impacts and responses of extreme drought events exhibits hierarchical and cascading effects(Zhang et al., 2011; Zheng et al., 2014a), implying that effective response actions have the potential to interrupt the transmission chain and mitigate the impacts of extreme drought. Conceptual models and causal chains reveal that when the impact of extreme drought events exceeds the capacity or resilience of a certain level, it is transmitted to the up level(Chen et al., 2021). The primary transmission pathway involves changes in resources and disasters that affect agricultural production,

40 subsequently influencing economic system such as food supply and population-related factors including migration, famine, and social unrest(Fang et al., 2014). Generally, the more severe the extreme drought event, the higher the level it affects and the longer the chain of consequences. Extreme drought events and the impacts, along with multi-level responses from human societies, exhibit a coupled process at various spatio-temporal scales, forming a network of interactions between extreme climatic events and society. Recent studies have attempted to identify key events or critical nodes in this network that are

45 influenced by climate change and have profound impacts on society through the study of complex networks(Chen et al., 2022). Targeted interventions that can alter these key nodes are likely to interrupt the transmission of the impacts of extreme climate events. At the same time, it is also implied that under different socio-economic conditions, the implementation of different responses or intervention measures can result in varying consequences for extreme climate events of the same magnitude(Tian et al., 2022). Human systems are socio-ecological or human-environment coupled systems, with interactions

50 between social subsystems and ecological subsystems. Typically, the transmission process of impacts is influenced by human society, which adopts responses based on socio-economic conditions, resulting in feedback processes in various domains such as production, economy, population, and society. These can either mitigate or amplify the consequences of extreme events(Engler et al., 2013b; Su et al., 2018), until a new equilibrium is achieved between human society and the natural environment.

55 Famine is one of the consequences of extreme drought events and a critical link in the impact transmission process of extreme drought. Reducing the impacts of famines, represents a common global challenge throughout history and into the present. As it stands, global food security remains on high alert, with 680 million people grappling with inadequate food consumption and 16 countries unable to break free from very high levels of hunger(HungerMap LIVE, 2024). Additionally, food security in large cities is also a significant concern. These cities, with their large populations and substantial resource

60 demands, exhibit a distinct outsourcing characteristic in their food systems, that is consuming internally while relying heavily on external supplies. Extreme weather events can disrupt resource transportation and trigger panic buying, posing famine risks even in large urban areas(Zhang et al., 2023). Moreover, according to the IPCC Sixth Assessment Report, the majority of the world's inhabited areas are projected to experience increasingly frequent and severe extreme events with

global warming. Moreover, agricultural and ecological droughts are expected to intensify and become more complex(Calvin
65 et al., 2023). Consequently, extreme droughts will continue to pose the obstacle to Zero Hunger for a long time to
achieve(Shi et al., 2022).

In the long-standing battle against famine, human societies have accumulated a wealth of experience, effective adaptation
and response measures. Give that famine often stems from poor harvests, it can be prevented by increasing cultivated land
area, optimizing crop planting structures, and constructing irrigation systems to maintain or enhance agricultural productivity,
70 thereby increasing food production and ensuring food security(Deng, 2011). Additionally, policies such as reducing
agricultural taxes and prohibiting food exports can ensure regional food self-sufficiency(Nyamwange, 1995; Shiue, 2005)
and reduce the exposure and risk of famine in affected areas. When famine does occur, policies, economic relief, and
humanitarian assistance can be used to transfer grain from surplus regions to deficit areas, balance food market, or manage
population migration-effectively mitigating the impact of the famine and preventing more serious social crises(Mishra and
75 Singh, 2010). Hence, case studies on extreme drought events and their responses, alongside understanding the famine
mechanisms, can provide valuable insights and replicable experiences for countries or regions at risk of food shortage.

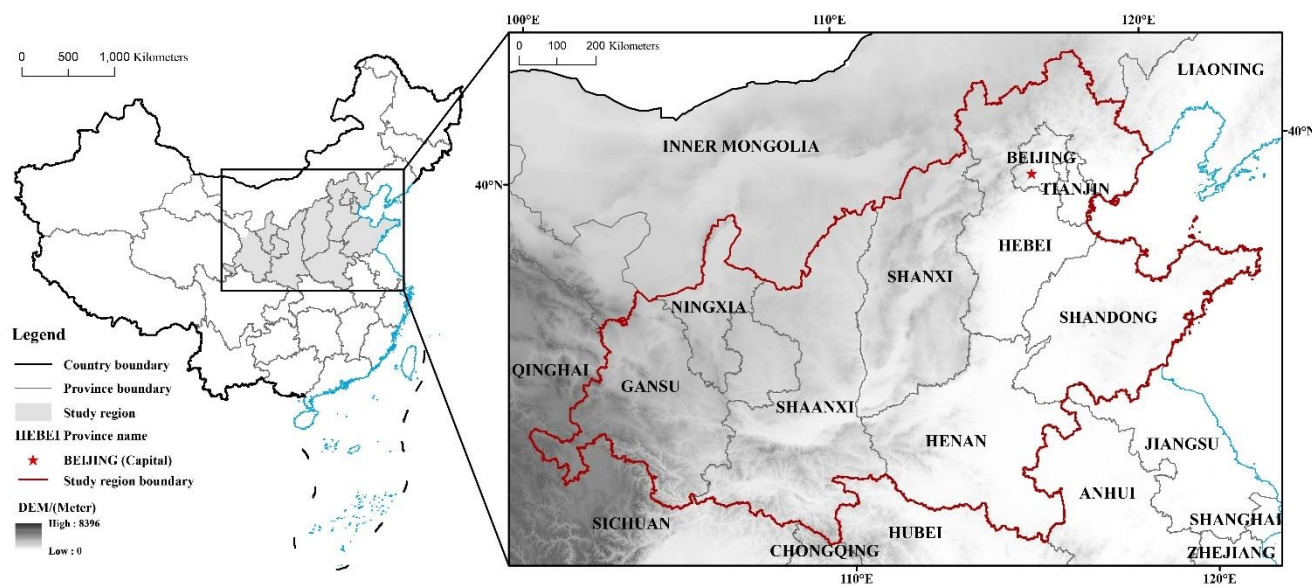
 Ming dynasty was a period marked by frequent extreme drought events in eastern monsoon region(Hao et al., 2020), as well
as a time when ancient famine response policies were highly well-develop in China. Research on the impacts and responses
to these extreme drought events during the Ming dynasty can enhance our understanding of disaster response mechanisms
80 and offer valuable insights from historical experience of China for global disaster reduction. Chenghua Drought (1483-1486
CE) and Wanli Drought (1585-1588 CE), which mainly affected the northern China, resulted in severe famines(Zhang,
2004). During the Chenghua and Wanli Drought, there were few country-scale wars to consume national food resources or
divert the attention of governmental administrations. Consequently, the central government implemented numerous famine
relief measures and responded actively to both the two drought events. The social and economic contexts of the two drought
85 events differed, however. Wanli Drought occurred after the state financial reforms, which mitigated the fiscal crisis and
substantially improved the national economy, which could provide more food and money for responses to famine.
Additionally, famine relief system was also continuously improved from the Chenghua to Wanli. Therefore, the comparative
analysis of the droughts, famines and social responses during the two drought events can enhance our understanding of how
institutional and economic factors play roles in mitigating famines. Such insights are vital for contemporary countries in
90 strengthening the capacity to respond to extreme climate events and ensuring the food security of citizens

2 Data sources and research methods

2.1 Overview of the study region

The two drought events primarily occurred in northern China during the Ming Dynasty, with the study area bounded by 31°-
42°N and 100°-122°E. The study region encompasses the Loess Plateau and North China Plain, which were the earliest
95 regions of agricultural development in ancient China. In the Ming Dynasty, the main crops cultivated in this region were

wheat and millet, followed by rice and beans (Li, 2014; Lv, 2000). It fell under the category of dryland farming areas. Influenced by monsoon, precipitation in the study region is unevenly distributed across seasons, with precipitation from May to September accounting for more than 80% of the annual total. Precipitation shows significant interannual variability, leading to frequent drought and flood disasters and unstable agricultural yields. Furthermore, the population in northern
100   China experienced a rapid increase in the 16th century and by 1630, the total population in the north had increased to about 50 million(Cao, 2000). The provinces in the North China Plain, such as Beizhili, Shandong, Shanxi, and Henan, were densely populated regions at that time, experiencing substantial population pressure (Liu, 2005; Zhang, 2006). Beizhili, being the political center, and the northern parts of Shanxi and Shaanxi serving as military strongholds, required a supply of millions Dan (a weight unit in ancient China) of grain annually, which magnified the contradiction between grain supply and
105   demand.

During the process of information extraction and mapping in this study, historical place names within the study area were converted to present-day names, and modern maps were used. A total of 308 counties were involved in the study, and the study region is shown in Figure 1.

110   **Figure 1: A map of the study region**

2.2 Research model and data sources

2.2.1 Drought-induced famine and its responses in ancient China

The processes of drought-induced famine and its responses in ancient China serves as the cornerstone of this paper. This field has been extensively explored and deeply understood by many scholars (Figure 2).

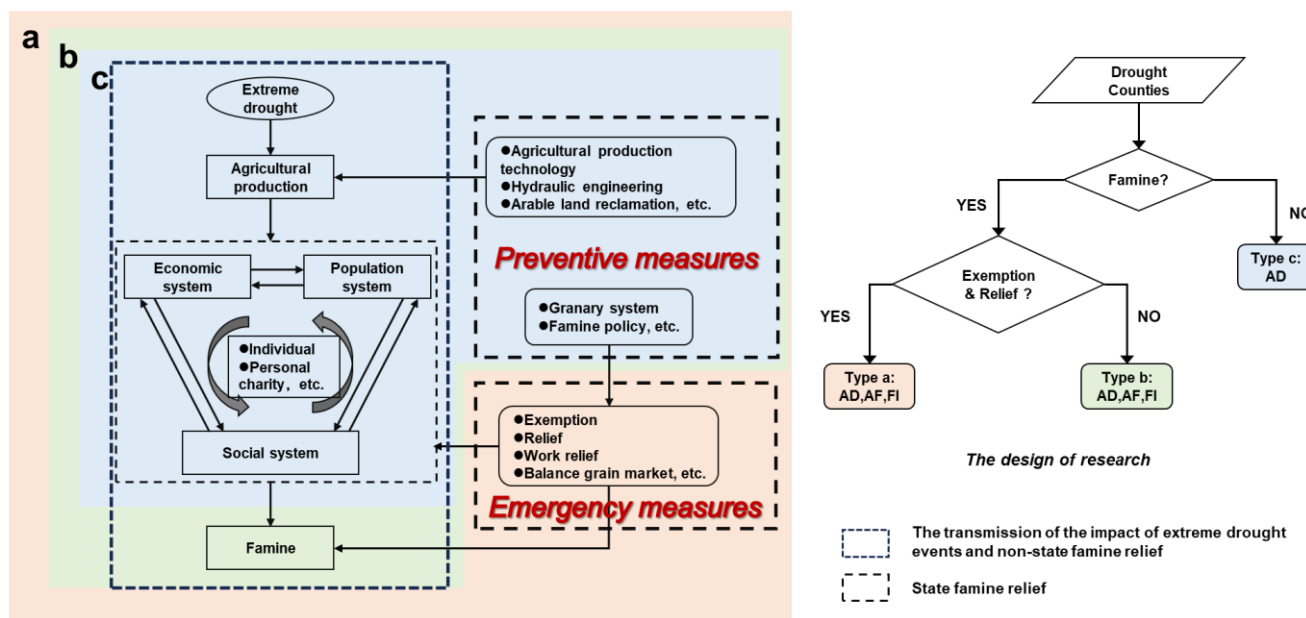



Figure 2: The model of processes and responses to extreme drought-induced famines in ancient China and research design

The process by which extreme droughts lead to famines is hierarchical. Numerous historical cases demonstrate that poor harvests and the collapse of agricultural production are the initial and most critical stages in this process(Baek et al., 2020; Engler et al., 2013a). In ancient China, the primary source of food was agriculture(Bu, 2007). When extreme drought events persisted for many years, the basic means of obtaining food from agricultural production almost collapsed, leading to a sharp decline in individual food security. This breakdown in agricultural production would subsequently trigger a rise in food prices, a deterioration in public health, and a surge in social unrest, including theft and robbery, resulting in widespread disorder across economic, demographic, and social systems(Brázdil et al., 2018, 2019; Hao et al., 2021; Xiao et al., 2015; Zheng et al., 2014a). These posed stress to the state and society in maintaining food distribution and consumption security. When food production, distribution, and consumption could no longer be secured, famine became inevitable (Figure 2).

In response to prolonged and widespread droughts, individuals and families would initially attempt to cope with food shortages by relying on household food reserves and local markets. However, given the underdeveloped productivity in ancient China, food production was low, and the commercialization of food was limited, leaving poor farmers with little capacity to cope with natural disasters(Guo, 2009; Ye, 1998). Occasionally, local gentry would donate money and grain to mitigate famine. But before the late Qing Dynasty, these private efforts generally served as a supplement to state-led relief(Li, 1993; Zhao, 2007). Overall, famine responses during the Ming Dynasty were predominantly government-led, with state relief being crucial for maintaining regional food security, ensuring individual food security for disaster victims, and mitigating famines. Consequently, this study focuses primarily on state relief.

Ancient China gradually developed a comprehensive famine response system that deal with each step of processes to extreme drought-induced famines (Figure 2). From the state perspective, these responses could be categorized into preventive and emergency measures, commonly referred to by historians as famine preparedness and famine relief(Deng, 2011). Preventive measures were implemented before the onset of famine, focusing on increasing food production and reserves(Shiue, 2005). The central government encouraged peasants to expand arable land, introduced high-yield and drought-resistant crops, constructed hydraulic engineering, and supported other methods to enhance land use efficiency, thereby securing food production(Deng, 2011). Additionally, the government paid more attention to building granaries and improving famine relief policies to ensure sufficient food supplies and effective relief efforts when needed. These preventive measures were typically long-term and routine adaptations, gradually building the defence of the natural-social system against natural disasters, thereby reducing the impact of drought on agricultural production and averting the onset of famine.

When famine did occur, preventive measures targeting food production have been ineffective. However, preventive measures for food distribution and consumption have become the material and institutional basis for emergency measures to famine relief. In ancient China, there were various emergency measures to mitigate famine, among which exemption and relied being the most common(Hao et al., 2021). From the perspective of food distribution, exemption worked by reducing the number of grain that disaster victims need to pay to the government, thus retaining more food in the affected areas to maintain individual food supply security(Zhao, 2016). Relief, on the other hand, involved transporting grain or silver to disaster areas to balance the local food market or directly distributing to the local victims, thus maintaining the food consumption or supply security of individuals in the affected areas and alleviating famine(Zhai et al., 2020). Tax exemption and relief proved to be effective famine responses, as evidenced by records from 1587 in Pu County and Hongtong County in Shanxi province, stating "distributing grain relieved famine, saving many lives (输粟赈饥，存活良多)" and "many were saved at that time (一时多所全活)." These measures helped to alleviate food shortages in disaster-stricken areas, slow down the progression of famine, and avoid more severe social consequences, such as uprisings, that could threaten feudal rule(Bohr, 2020; Xia, 1993). Typically, it was usually after extreme droughts had caused significant damages that the state would implement exemption and relief to alleviate severe social unrest such as famine.

2.2.2 Data sources

The literature and records related to drought and famine in this study primarily came from two compilations, A Compendium of Chinese Meteorological Records of the Last 3000 Years (hereinafter referred to as *Compendium*)(Zhang, 2013) and the series of books Chinese Encyclopedia of Meteorological Disasters (referred to as *Encyclopedia* hereafter) (Wen, 2008). The two compilations have compiled a wealth of information on historical meteorological disasters and their impacts and responses in ancient China, extracting from a variety of local chronicles and official historical records, such as Ming Shi Lu and Qing History Draft(Wang et al., 2018). The two compilations, which accurately document by years and locations, are recognized as high-quality research materials for meteorological science and are widely used in research focused on

reconstructing and analysing extreme drought events(Zhang and Liang, 2010). From the above compiled data, drought and famine records were extracted based on year, province, location, textual context, and source, using county as the spatial unit (Table 1). A total of 838 drought and famine records were extracted for the two drought events, and some of the records contained information on both drought and famine, such as "No rain in spring and summer, populace subsisting on grass and tree bark." It should be noted that only drought-related famines were extracted, such as "a severe drought with no rain for several months, the ground is cracked and the grass withered, and people eat each other." Famines triggered by floods, locust plagues, and so on, were not extracted.

Table 1. Example of drought and famine records during the Chenghua Drought

Year/CE	Province	County	Textual context	Data source
1483	Hebei	Huailai	No snow in winter, major drought	*Compendium*
1484	Shanxi	Dai	Little rain in spring and summer, populace subsisting on grass and tree bark	*Compendium*
1484	Henan	Weihui	Major drought in May	*Encyclopedia·Henan*
1485	Shanxi	Pu	Major drought, no rain for several months, cracked land, withered grass, cannibalism	*Encyclopedia·Shanxi*

In the *Compendium*, in addition to records of drought and famine, it also records the exemption and relief taken by the local government when the drought events occurred, which is the specific implementation of the state relief at the county level. *Compendium* provides location and form of responses, for example, in 1484, Xiong County in Hebei Province experienced drought again, and a granary was issued to provide relief and loans; in 1585 when Daming County experienced a major drought, one-third of the agricultural tax was exempted. Based on above information, the number of counties that received relief and exemption during the Chenghua Drought and Wanli Drought was counted.

2.3 Research framework and methods

2.3.1 Classification of drought grades

The classification of drought grade is an important quantitative indicator for assessing the degree of drought in a specific county and serves as a crucial factor for comparing drought severity across different counties. In the researches conducted by numerous scholars, the duration, timing, spatial extent, and severity of drought events as recorded in literature are key considerations for drought classification(Han et al., 2019; Zheng et al., 2014b). Ancient China was an agrarian society, and historical records of drought typically focused on describing the impact and perception of precipitation on agricultural production, specifically highlighting agricultural drought. Furthermore, crop yield played a vital intermediary role between natural factors such as climate and disasters, and famine(Xiao, 2020). Therefore, this study emphasized the classification of drought based on its impact on crop production. Considering that the northern region of China was primarily characterized by rainfed agriculture, the cultivation of autumn crops held a dominant position, with approximately 70% of the annual agricultural tax revenue derived from these crops(Li, 2014). Given that the spatiotemporal variability of precipitation in this

area, the period from May to September represented a critical growth phase for crops, as it served as a crucial period for

195 water supply. The amount of precipitation during this period directly affected the yield of crops(Meng, 2022) and had a greater impact on food production security in the northern China. Therefore, droughts occurring in the rainy season (May-September) were graded as Grade 1. Meanwhile, referring to the classification criteria of Yearly charts of dryness/wetness in China for the last 500-year period(CMA, 1981), the longer the drought duration and the more severe the drought in the rainy season, the higher the drought grade. Based on the above criteria, the textual information about drought was categorized into

200 three grades, as shown in Table 2.

Table 2. Classification criteria and example of drought grade (CMA 1981)

Drought Grade	Classification Criteria	Example
1 (Mild drought)	Drought during non-rainy season	Spring drought; winter without snow
2 (Moderate drought)	Drought lasting for a season or a month during the rainy season	Spring and summer drought; summer drought; autumn drought; drought; no rain/major drought in May
3 (Severe drought)	Severe drought lasting several months or seasons during the rainy season	Drought during summer and autumn; major summer drought; No rain from March to July

2.3.2 Classification of famine grades

205 Famine classification is an important means of evaluating the severity of famine across different regions. To compare the severity of famine in drought-affected counties, the extracted famine records are categorized into different grades. The most commonly used indicators for assessing regional food security and famine severity are mortality rate and nutritional status(FSIN, 2022). However, in ancient Chinese literature, descriptions of famines often pertain to the contextual portrayal of the famine scene, lacking quantitative information. Nevertheless, these descriptions use diverse vocabulary, symbolizing

210 differences about famine state, such as "it is not easy for the populace to make ends meet(民食艰难)", which means that the local residents were already suffering from the shortage of food, but they could still maintain the basic survival; "Eating grass roots, wood bark, guanyin soil (观音土)" and some other terms indicated that local residents had relied on other alternative foods to survive. What's worse, records such as cannibalism indicated that there was an extreme shortage of food, and that morality and ethics and social order had collapsed.

215 Thus, famine records are classified into grades based on semantic variations and the classification criteria are presented in Table 3(Xiao, 2020; Wei, 2020; Tian et al., 2022, 2024). The criteria have been used to reconstruct the famine sequences in North China and Jiangsu-Shanghai region during the Qing Dynasty (Xiao, 2020; Wei, 2020) and have been validated. Additionally, following the characteristic of ancient Chinese literature where "unusual events are recorded, but routine events are not", if there are no famine records in the drought-affected county for a particular year, it is assumed that no

220 famine occurred in that county during that year, and the famine grade is recorded as 0. According to Table 3, famine records

from all drought-stricken counties in the study area from 1483 to 1486 and from 1585 to 1588 were classified.

Table 3. Classification criteria and example of famine grade (Wei 2020; Xiao 2020)

Famine Grade	Example	Classification Criteria
0 **(No famine)**	No famine data were recorded	
1 **(Mild famine)**	Famine (饥), it is not easy for the populace to make ends meet (民食艰难), sporadic migration (路有流民), relief (money or grain) (赈), etc.	Severe shortage of food; can be sustained through rationing or receiving relief aid; sporadic population migration
2 **(Moderate famine)**	Major famine (大饥), eating grass roots and wood bark, Guanyin soil (食草根木皮、观音土), widespread migration(民流移), occasional deaths (间有死者), etc.	Extremely scarce of food; reliance on alternative food; widespread migration and displacement; occasional deaths and increasing social disorder
3 **(Severe famine)**	Cannibalism (民相食), countless starvation deaths (死者众多), corpses as pillows (死者甚众), etc.	Extreme food shortage; massive loss of life; collapse of moral ethics and societal order

2.3.3 Research framework

225 Drawing on famine response model in ancient China and data on droughts, famines, exemption and relief, drought-affected

counties could be classified into three categories (Figure 2).

Type A: Counties that experienced famine during the Chenghua Drought or Wanli Drought and received exemption or relief.

Type B: Counties that experienced famine during the drought but did not receive exemption or relief.

Type C: Counties that did not experience famine during the drought.

230 Type c can reflect the resistance of the natural-social system to the impact of natural disaster, which means that the affected

counties have successfully blocked the transformation from drought to famine. This resistance stems from the long-term

preventive measures, including advances in agricultural production, the construction of water conservancy, and the

development of robust food markets. Therefore, the average drought grade (AD) and the proportion of different drought

grades in the type c of the two drought events were calculated. Then the differences in the defensive ability of the two

235 drought events to prevent drought from turning into famine were compared. Based on the classification of drought grades,

AD is presented in Eq. 1. The distinction between type a and type b counties lies in whether they received state relief. By

calculating AD, average famine grade (AF), and famine intensity (FI) for these two scenarios, we quantitatively evaluate the

effectiveness of state relief efforts in ancient China. Additionally, comparing the FI across type a for different drought events

enables an analysis of changes in state emergency response capacity between the two events (Figure 2). The methods for

240 calculating AF and FI are detailed in Eq. 2 and 3.

$$AD = {\sum_{n=1}^{N} \sum_{i=1}^{4} d}/{4 \times N} \tag{1}$$

$$AF = {\sum_{n=1}^{N} \sum_{i=1}^{4} f}/{4 \times N} \tag{2}$$

$$FI = {AF}/{AD} \tag{3}$$

Where: AD represents the average drought grade; AF represents the average famine grade. FI represents the famine intensity; 4 refers to the four-year duration of the two drought events; i is the i-th year of the drought; n is the n-th drought-affected county. N is the total number of drought-affected counties; d refers to the drought grade; f refers to the famine grade.

3 Results

3.1 Spatial distribution and impacts of drought and famine of the two drought events

Following the research methodology described in Section 2.3, the AD and AF for each drought-affected county during the Chenghua Drought and Wanli Drought could be calculated. And the spatial distribution of drought and famine was reconstructed (Figure 3). During the Chenghua Drought, a total of 187 counties were affected, while during the Wanli Drought, the number of affected counties reached 225, indicating that the scope of Wanli Drought was more extensive. In terms of the distribution of drought (Figure 3), it could be observed that the high-value points of drought for both drought events were concentrated in the North China Plain. Specifically, during the Chenghua Drought, the high-value drought areas were scattered, with serious drought occurring in large areas of western Shandong, southwestern Shanxi, and the vicinity of central Shaanxi. While during the Wanli Drought, the high-value drought areas were more extensive, encompassing the southern part of Hebei, western Shandong, northern Henan, and southwestern Shanxi. According to historical records, during the Chenghua Drought, many areas in the study region experienced consecutive droughts in summer and autumn, with two consecutive growing seasons of crops without sufficient rainfall, severely affecting food harvest. Some areas in western Shandong and southwestern Shanxi experienced two consecutive years of autumn drought or summer and autumn drought, resulting in population displacement. Unlike the Chenghua Drought, during the Wanli Drought, the study region experienced consecutive droughts in spring and summer, and what's worse, such as western Shandong and southwestern Shanxi, there were continuous spring and summer droughts or summer droughts lasting for three years without rainfall for up to five months, leading to a scarcity of food resources. The northern part of Henan experienced consecutive spring and summer droughts or a major summer drought for four years, causing the collapse of agricultural activities.

The number of counties suffering famine in the two drought events was similar: 98 counties during the Chenghua Drought and 103 counties during the Wanli Drought. However, there were some differences. During the Wanli Drought, the high-value points of famine were located in the southern part of Shanxi, with sporadic occurrences in the central Shaanxi and

northern Henan regions. In contrast, during the Chenghua Drought, the high-value famine points were more widely

270 distributed, encompassing not only the southern part of Shanxi but also most parts of the central Shaanxi and northern Henan regions, where severe famine occurred. During the two drought events, sustained severe droughts inflicted critical damage on food production, leading to complete crop failures in many areas of Shanxi, Henan, and Guanzhong, causing severe supply-demand imbalances, market collapses, and skyrocketing rice prices. In 1484, rice prices in various parts of Henan surged from "100 Qian (a unit of currency in ancient China) per Dou (a volume unit in ancient China)" to "300 Qian per

275 Dou". By 1486, records in Shaanxi indicated rice prices of "10,000 Qian per Dou." In contrast, during the Wanli Drought, rice prices were high but relatively more controlled. From 1586 to 1588, rice prices in many parts of Shanxi remained around "150 Qian per Dou." In 1587, many areas in Shaanxi reported rice prices of "1000 Qian per Dou," with no records of prices reaching "10,000 Qian." Food production and consumption safety could not be ensured, forcing the populace to resort to consuming tree bark and resin to stave off hunger. As alternative food sources were exhausted, massive numbers of people

280 starved to death, leading to extreme breakdowns of social and moral norms, including instances of cannibalism.

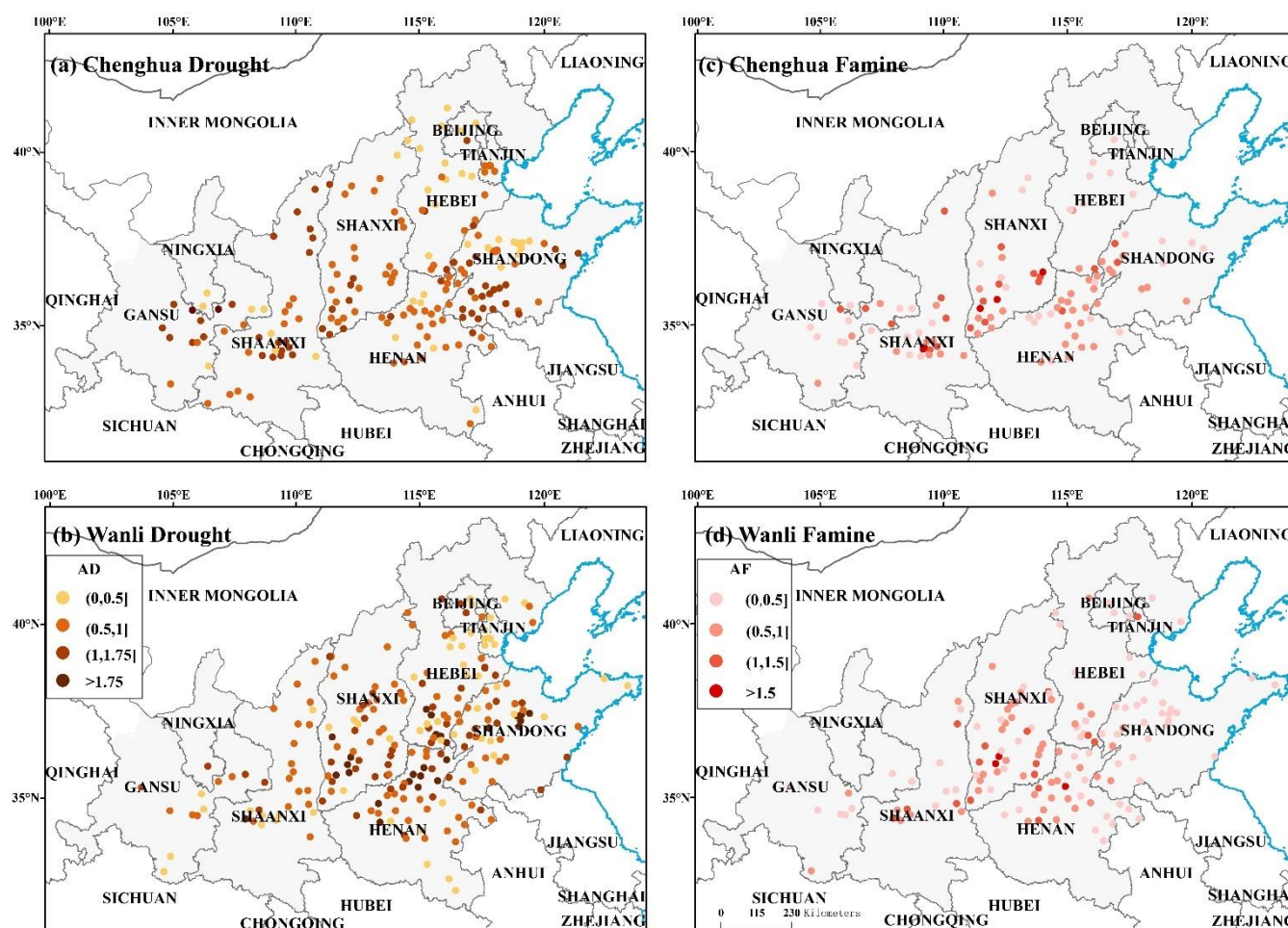



Figure 3. Spatial distribution of drought and famine during the two drought events

3.2 Changes and causes of famine defence during the two drought events

Referring the figure 2, drought-affected counties that did not receive state relief, that is type c and type b, were analyzed to explore changes in the state famine resistance. According to the research method mentioned in 2.3.3, AD, AF, FI under the three scenarios of two drought events could be calculated (Table 4). As shown in Table 4, the AD for all three types of Wanli Drought were higher than those during the Chenghua Drought, indicating that Wanli Drought was more severe. However, the proportion of type c during the Wanli Drought (53%) was higher than that of Chenghua Drought (48%), suggesting that despite facing with more severe drought, more counties during the Wanli Drought did not experience famine. Additionally, by exploring the proportion of famine-free counties under different drought grades for both drought events (Table 5), it was evident that, generally, higher drought grade with a lower proportion of famine-free counties. Compared to the Chenghua Drought, except for drought grades of 0.25 and 1.25, the Wanli Drought consistently showed a higher proportion of famine-free counties across other drought grades. This indicated that during the Wanli Drought, the state exhibited a stronger capacity to resist drought from escalating into famine.

Table 4: AD, AF, FI of the three types

	Type c		Type b				Type a			
	%	AD1	%	AD2	AF2	FI2	%	AD3	AF3	FI3
Chenghua Drought	48%	0.79	45%	0.99	0.70	71%	7%	1.04	0.69	67%
Wanli Drought	53%	0.86	33%	1.20	0.61	51%	14%	1.23	0.61	49%

Table 5: Proportion of famine-free counties under different drought grades

AD	0.25	0.5	0.75	1	1.25	1.5	>1.5
Chenghua Drought	100%	63%	43%	33%	57%	15%	0
Wanli Drought	63%	73%	65%	50%	22%	29%	35%

At the same time, during the Wanli Drought, the AF and FI for type b were lower than those during the Chenghua Drought, further indicating that even when famine occurred, its severity was milder during the Wanli Drought. In terms of FI distribution of drought-affected counties for type b (Figure 4) showed that the lower quartile, median and mean during the Wanli Drought were lower than those of Chenghua Drought. This underscored that the severity of famine during the Wanli Drought was notably less severe than during the Chenghua Drought. This suggested that, despite the absence of state relief, the protective measures implemented during the Wanli Drought effectively reduced the severity of famine, demonstrating a stronger capacity for famine defence.

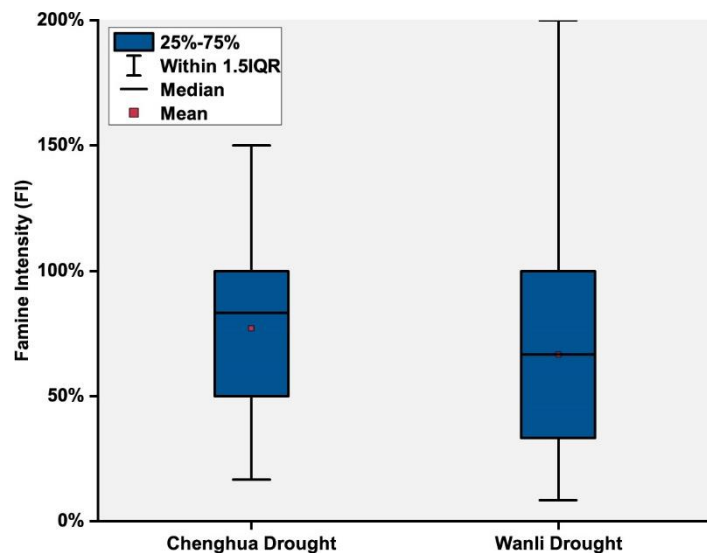



Figure 4: The distribution of FI of drought-affected counties for type b

The improvement of state famine defence is closely linked to advancements in agricultural production. These advancements

310 are primarily manifested in land reclamation and the introduction of American crops. During the Ming Dynasty, considerable

efforts were made to reclaim land in order to maintain social stability and deal with land-population conflicts. By 1583, the

area of cultivated land had doubled compared to 1391, and the per capita arable land area had nearly doubled as well(Zhang,

2005). In the research area, Henan experienced a nearly twofold increase in land area from 1491 to 1578, with significant

development in previously uncultivated mountainous regions(Tian et al., 2022). By the Wanli period, the amount of arable

315 land in Luonan and Shanyang counties in southern Shaanxi had grown to 2.7 times and 4.8 times of that in Jiajing period(Lv,

1996). That implied a significant advance in agricultural production in southern Shaanxi during the Ming dynasty. From the

late 14th century to the end of the 16th century, the North China Plain, after nearly two centuries of intensive development,

reemerged as a major agricultural base in China(Cong, 1986). Meanwhile, during the mid-Ming dynasty, crops such as corn

and potatoes were introduced from the America(Zhao, 1991). By the Jiajing and Wanli, corn cultivation had spread

320 throughout the research area, playing a revolutionary role in increasing per-acre yield and total food production(Yang and

Chen, 2006). The increase in land reclamation and use significantly bolstered both individual and state food reserves, playing

a crucial role in preventing famine

3.3 Changes and causes of famine emergency response during the two drought events

Table 4 showed that, for both the Chenghua and Wanli Droughts, the ADs for type a were slightly higher than those for type

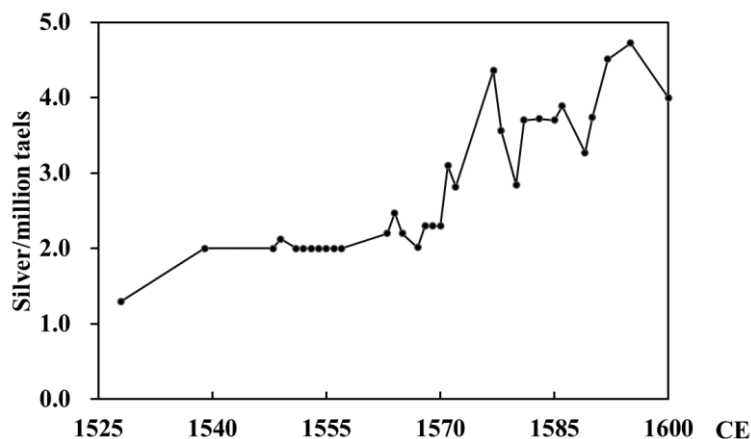
325 b, yet the FI was lower in type a. This suggested that state emergency measures, such as exemption and relief, effectively

mitigate famine. The proportion of type a during the Chenghua Drought was lower compared to the Wanli Drought,

indicating the scale of state relief during the Chenghua Drought was less extensive. Data extracted from the *Compendium*

revealed that the number of counties receiving exemption and relief during the Wanli Drought was 2.5 times and 2.8 times

that of the Chenghua Drought, respectively. This reflected a significant increase in the scope of state relief. Moreover, the
330   strengthening of state relief also had a marked impact: the FI in type a during the Wanli Drought was less than during the
Chenghua Drought. This demonstrated that the famine emergency responses during the Wanli Drought were more effective
than those during the Chenghua Drought.

The increased intensity of state relief preserved and delivered more food to disaster-stricken areas, which helped to alleviate
the hardships and burdens faced by the peasants. Intensity of the emergency responses was closely related to the financial
335   resources and economic conditions at that time(Chen, 2015). If the finance was strained and the economy was in a slump, the
priority of famine relief measures naturally competed to other national affairs(Will, 2006). Wanli Drought coincided with the
aftermath of reforms implemented by Zhang Juzheng, which significantly enhanced the national finances. Consequently, the
tax grain in the Jing and Tong Granaries substantially increased, leading to abundant food supplies, with the Jing granary
once holding as much as 18.18 million Dan of grain. Starting from the middle of the Ming Dynasty, the Taicang Treasury
340   gradually evolved into a central core financial institution responsible for important national financial expenditures such as
northern border provisions, national relief, and significant financial levies(Su, 2010). Its income and expenditure closely
related to the national finances. The increase or decrease in its income reflects the social and economic dynamics at that time
and the position of silver in the circulating currency(Quan, 2011). In terms of silver income in the Taicang Treasury after the
middle of the Ming Dynasty, it significantly increased from the Mid-16th century onwards (Figure 5). On one hand, this was
345   related to the promotion of the silver currency at that time. On the other hand, it was related to the vigorous development of
national salt policies and the commodity economy. Meanwhile, scholars have compiled the Ming Dynasty's fiscal revenue
situation from the 15th to 17th century(Liu, 2012). Rice and wheat were major sources of fiscal revenue, which exhibited an
upward trend from the 15th to 17th century. Overall, the total revenue after converting to silver showed a clear upward trend.
Therefore, it can be inferred that the development of the national economy provided the material basis for relief and
350   exemption measures. With the increase in national fiscal revenue and economic development, the ability to provide
exemptions and relief also grew stronger. The significant magnitude of exemption and relief allowed for the retention and
distribution of more relief grains in disaster-hit areas during the Wanli Drought, thereby mitigating the development of
famine.

355 **Figure 5. Annual silver income of Taicang Silver Treasury after the Mid-Ming dynasty (Su 2010)**

Discussion: regional differences in response capacity

When comparing the impacts and responses of the two drought events, it was evident that there were differences in the impacts and responses of drought among different provinces. Using the provincial boundaries of the Ming Dynasty as a

360 reference(Han and Yang, 2021), Beijing, Tianjin, and Hebei were combined into the B/T/H. This area was the political center of the state, characterized by advanced agricultural practices and dense populations. Shaanxi, Ningxia, and parts of Gansu were grouped as the S/G/N, all located in the Ming-era Shaanxi Province, a frontier region at that time. Although Henan, Shandong, and Shanxi were all situated in northern China, they displayed significant differences in their ecological environments and economic development. According to AD, AF, and FI (Figure 6 and Table 6), the study regions can be

365 categorized into three groups:

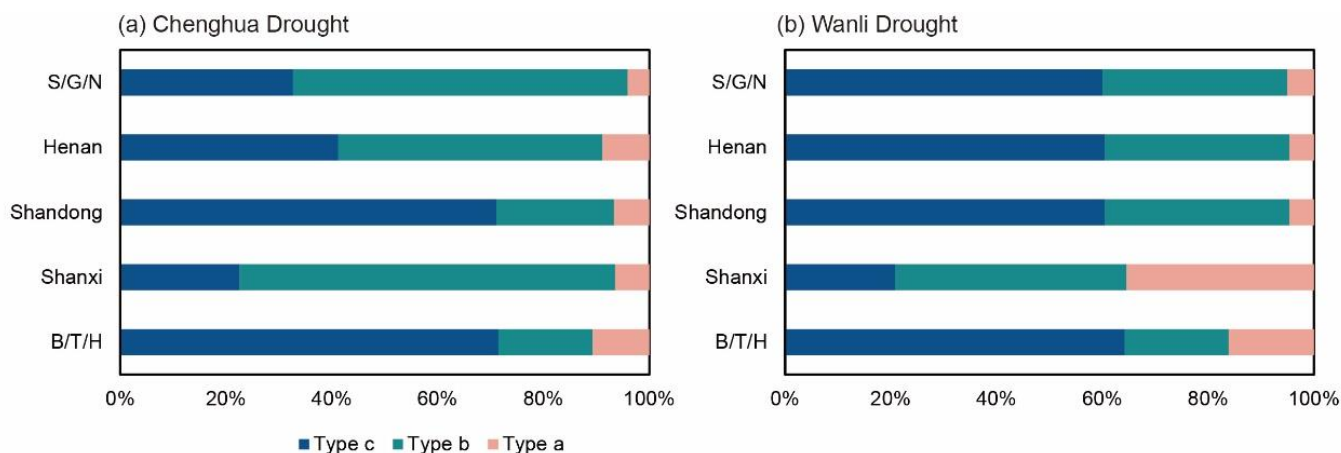



Figure 6: The proportion of drought-affected counties in each region by three types

Table 6: AD, AF, FI in different regions of the two drought events

	Chenghua Drought				Wanli Drought			
		Type a & Type b				Type a & Type b		
	AD	AD1	AF1	FI	AD	AD1	AF1	FI
B/T/H	0.6	0.8	0.6	73%	0.9	1.3	0.6	46%
Shandong	1.0	1.0	0.7	63%	1.1	1.5	0.4	30%
Shanxi	0.9	1.0	0.8	82%	1.1	1.1	0.8	66%
Henan	0.8	0.8	0.7	82%	1.2	1.4	0.7	46%
S/G/N	1.1	1.2	0.7	61%	0.8	0.9	0.6	65%

370

The first category included the B/T/H and Shandong. In both regions, type c dominated. In the Chenghua and Wanli Droughts, type c consistently accounted for over 60% of the total (Figure 6). This meaned that even during droughts, even severe droughts (such as Shandong with AD of 1.0 and 1.1), more than half of the affected areas did not experience famine. Moreover, famine intensity in both regions where famine did occur (type a and type b) showed that the degree of famine was

375 relatively low, with FI in the Wanli drought being just 46% and 30%, respectively. These findings indicated strong famine response capabilities in the two regions. As the political center of the Ming Dynasty, it was critical for maintaining B/T/H food security. Therefore, during droughts, this region received a substantial share of state relief efforts. Table 6 and Table 7 revealed that even with moderate drought (AD of 0.6 and 0.9), more than 20% of the total relief efforts were concentrated in this area, reflecting a significant allocation of national resources. Additionally, both the B/T/H and Shandong housed major

380 granaries, which bolstered their grain reserves. During the Wanli drought, approximately 88% of the relief grain came from the Linqing and Dezhou granaries in Shandong province(Tian et al., 2024).

Table 7: Proportion of state effort across different regions

	B/T/H	Shanxi	Shandong	Henan	S/G/N
Chenghua Drought	23%	15%	23%	23%	15%
Wanli Drought	35%	48%	9%	4%	4%

The second category was Shanxi. In Shanxi, the majority of counties in Shanxi fell under type b and type a, accounting for nearly 80% of all counties affected by the two drought events. Particularly during the Chenghua Drought, type b made up 70% of the total, highlighting limited ability to prevent drought from escalating into famine in Shanxi. Moreover, Shanxi consistently exhibited the highest famine severity across all provinces during both droughts. Even though the ADs in Shanxi were similar to those in Shandong, AF was significantly higher. Despite receiving substantial relief during the Wanli Drought, Shanxi still experienced the most severe famine, underscoring its weak resilience. This vulnerability could be attributed to severe land pressure and vulnerable ecological environment. During the Ming dynasty, the average land area per capita in Shanxi was just 6.51 mu per person, much lower than the national average of 11.56 mu per person, indicating significant population-land conflict(Liang, 2008). Additionally, over 80% of soil in Shanxi consisted of loess and secondary loess, which were prone to erosion. Moreover, Shanxi was predominantly mountainous with limited plains, making its ecological environment vulnerable, which posed significant challenges to grain production (Shuang and Wang, 2020). As a result of agricultural damage, Shanxi also had the highest number of migrants among the provinces in the study area(Li, 1998).

The third category included Henan and the S/G/N. In both regions, the distribution of the three types shifted significantly: the proportion of type c increased, while that of type b decreased. This indicated that many drought-affected counties in these regions had greatly improved their ability to prevent drought from evolving into famine. Although the FI remained high, especially in the S/G/N where it exceeded 60% during both drought events, Henan experienced a notable reduction in FI, dropping to 46% during the Wanli drought. As discussed in Section 3.2, the expansion of cultivated land and the introduction of American crops during the Ming dynasty played a crucial role in enhancing famine resilience in both regions. Further research and historical documentation are required to explore additional factors contributing to these changes.

Main conclusion

This study developed a model of extreme drought-induced famine processes and response mechanisms in ancient China, drawing on historical records and research findings. Spatial distribution of drought and famine during the Chenghua Drought and the Wanli Drought was constructed. By categorizing drought-affected counties into three types, a comparative analysis of the differences in famine severity and response effectiveness between the Chenghua and Wanli droughts was conducted. The study also tried to explain changes in response ability based on historical sources. The key findings were as follows:

(1) Comparison of Drought Events: Although the Wanli Drought presented more severe than the Chenghua Drought, the famine it caused was less severe, with a lower famine intensity. The proportion of type c during the Wanli Drought was

415   higher than during the Chenghua Drought, while the Ads were also higher. This indicated that society demonstrated stronger defence during the Wanli Drought, preventing many drought-affected counties from descending into famine. Furthermore, in both drought events, the FI in type b counties was higher than in type a, suggesting that state relief were effective. The increased intensity of state relief during the Wanli Drought further contributed to its lower famine severity.

(2) Factors Influencing Response Capacity: Factors such as the expansion of cultivated land, the introduction of new crops,

420   and the economic and fiscal health of state all influenced societal response capacity. During the Wanli Drought, the expansion of arable land, the introduction of American crops, sound economic conditions, and the trend toward silver monetization all played positive roles in improving famine preparedness and relief.

(3) Regional Variations in Response Capacity: Significant regional differences in response capacity were evident. Shandong and the B/T/H (Beijing, Tianjin, and Hebei) displayed strong resistance to famine, with the majority of drought-affected

425   areas in these regions avoiding famine, likely due to their political significance and substantial grain reserves. In contrast, Shanxi remained highly vulnerable to famine, likely due to its vulnerable ecological environment. From Chenghua Drought to Wanli Drought, the resistance of Henan and S/G/N (Shaanxi, Gansu, and Ningxia) to drought improved significantly. The causes of this change require further investigation.

Additionally, this research highlights many areas that warrant further exploration, such as the relationship between

430   individual and state efforts in famine preparedness and relief. In Ming China, an agrarian society, the state's grain taxes were primarily drawn from land production. After paying taxes and setting aside enough for daily subsistence, peasants could continue agricultural production. The state, in turn, used these tax revenues for famine preparedness and relief. The complex interactions between these efforts need deeper exploration.

435   **Author contributions.** Fangyu Tian developed the research method, collected drought, famine and state relief data, and drafted the manuscript. Yun Su supervised the research of this study and developed the research method. Xudong Chen and Le Tao reviewed the manuscript and revised the data.

Competing interests. The authors declare that they have no conflict of interest.

440

Acknowledgements. Supported by the Major Program of National Fund of Philosophy and Social Science of China [grant number: 22&ZD223].

References

HungerMap LIVE: https://hungermap.wfp.org/, last access: 2 May 2024.

445   Atwell, W.: Volcanism and short-term climatic change in East Asian and world history, c.1200-1699, J. WORLD Hist., 12, 29–98, https://doi.org/10.1353/jwh.2001.0002, 2001.

Atwell, W.: Time, money, and the weather: Ming China and the "great depression" of the mid-fifteenth century, J. ASIAN Stud., 61, 83–113, https://doi.org/10.2307/2700190, 2002.

Baek, S. H., Smerdon, J. E., Dobrin, G.-C., Naimark, J. G., Cook, E. R., Cook, B. I., Seager, R., Cane, M. A., and Scholz, S.

450   R.: A quantitative hydroclimatic context for the European Great Famine of 1315–1317, Commun. Earth Environ., 1, 1–7, https://doi.org/10.1038/s43247-020-00016-3, 2020.

Bohr, P. R.: Famine in China and the Missionary: Timothy Richard as Relief Administrator and Advocate of National Reform, 1876–1884, BRILL, 317 pp., 2020.

Brázdil, R., Kiss, A., Luterbacher, J., Nash, D. J., and Řezníčková, L.: Documentary data and the study of past droughts: a

455   global state of the art, Clim. Past, 14, 1915–1960, https://doi.org/10.5194/cp-14-1915-2018, 2018.

Brázdil, R., Dobrovolný, P., Trnka, M., Řezníčková, L., Dolák, L., and Kotyza, O.: Extreme droughts and human responses to them: the Czech Lands in the pre-instrumental period, Clim. Past, 15, 1–24, https://doi.org/10.5194/cp-15-1-2019, 2019.

Bu F.: Assessment on the Level of Food Security in Traditional Agriculture Period of China, Agricultural Hist. China, 19–30, 2007. (in Chinese)

460   Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, Y.-Y., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F. E. L., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H.-O., Revi, A., Roberts, D. C., Roy, J., Ruane, A. C., Skea, J., Shukla, P. R., Slade, R., Slangen, A., Sokona, Y., Sörensson, A. A., Tignor, M., Van Vuuren, D., Wei, Y.-M., Winkler, H.,

465   Zhai, P., Zommers, Z., Hourcade, J.-C., Johnson, F. X., Pachauri, S., Simpson, N. P., Singh, C., Thomas, A., Totin, E., Arias, P., Bustamante, M., Elgizouli, I., Flato, G., Howden, M., Méndez-Vallejo, C., Pereira, J. J., Pichs-Madruga, R., Rose, S. K., Saheb, Y., Sánchez Rodríguez, R., Ürge-Vorsatz, D., Xiao, C., Yassaa, N., Alegría, A., Armour, K., Bednar-Friedl, B., Blok, K., Cissé, G., Dentener, F., Eriksen, S., Fischer, E., Garner, G., Guivarch, C., Haasnoot, M., Hansen, G., Hauser, M., Hawkins, E., Hermans, T., Kopp, R., Leprince-Ringuet, N., Lewis, J., Ley, D., Ludden, C., Niamir, L., Nicholls, Z., Some, S.,

470   Szopa, S., Trewin, B., Van Der Wijst, K.-I., Winter, G., Witting, M., Birt, A., Ha, M., et al.: IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland., Intergovernmental Panel on Climate Change (IPCC), https://doi.org/10.59327/IPCC/AR6-9789291691647, 2023.

Cao, S.: Population History of China - Ming Dynasty Volume, Fudan Press, 2000. (in Chinese)

475   Chen, Q.: Climate Shocks, State Capacity and Peasant Uprisings in North China during 25–1911 ce, Economica, 82, 295–318, https://doi.org/10.1111/ecca.12114, 2015.

Chen, X., Su, Y., and Fang, X.-Q.: Social impacts of extreme drought event in Guanzhong area, Shaanxi Province, during 1928–1931, Clim. Change, 164, 27, https://doi.org/10.1007/s10584-021-02978-5, 2021.

Chen, X., Tian, F., and Su, Y.: How did the late 1920s drought affect northern Chinese society?, Weather Clim. Extrem., 36,
480   100451, https://doi.org/10.1016/j.wace.2022.100451, 2022.

CMA.: Yearly charts of dryness/wetness in China for the last 500-year period, Sinomap press, 1981. (in Chinese)

Cong, H.: An investigation of the rural economic development in the North China Plain from the late 14th century to the late
16th century, Res. Chin. Econ. Hist., 11–26, 1986. (in Chinese)

deMenocal, P.: Cultural responses to climate change during the Late Holocene, SCIENCE, 292, 667–673,
485   https://doi.org/10.1126/science.1059827, 2001.

Deng, Y.: Jiangsu Education Publishing House, The Commercial Press, Beijing, 2011. (in Chinese)

Engler, S., Mauelshagen, F., Werner, J., and Luterbacher, J.: The Irish famine of 1740-1741: famine vulnerability and
"climate migration," Clim. PAST, 9, 1161–1179, https://doi.org/10.5194/cp-9-1161-2013, 2013a.

Engler, S., Mauelshagen, F., Werner, J., and Luterbacher, J.: The Irish famine of 1740–1741: famine vulnerability
490   and "climate migration," Clim. Past, 9, 1161–1179, https://doi.org/10.5194/cp-9-1161-2013, 2013b.

Fang, X., Zheng, J., and Ge, Q.: Historical Climate Change Impact-Response Processes Under the Framework of Food
Security in China, Sci. Geogr. Sin., 34, 1291–1298, 2014.

FSIN, F. S. I. N.: 2022 Global report on food crises: Joint analysis for better decisions, Rome, Italy; and Washington, DC.
Food and Agriculture Organization (FAO); World Food Programme (WFP); and International Food Policy Research Institute
495   (IFPRI), 2022.

Guo S.: Research on the Grain Circulation about North China Region in Qing Dynasty, Master's thesis, Shanxi University,
2009. (in Chinese)

Han, J. and Yang, Y.: The socioeconomic effects of extreme drought events in northern China on the Ming dynasty in the
late fifteenth century, Clim. Change, 164, 26, https://doi.org/10.1007/s10584-021-02972-x, 2021.

500   Han J., Yang Y., and Man Z.: Reconstruction and analysis of sequence of extreme drought events in north of China during
AD1000-2000, Journal Palaeogeography., 21, 675–684, 2019. (in Chinese)

Hao, Z., Wu, M., Zheng, J., Chen, J., Zhang, X., and Luo, S.: Patterns in data of extreme droughts/floods and harvest grades
derived from historical documents in eastern China during 801-1910, Clim. PAST, 16, 101–116, https://doi.org/10.5194/cp-
16-101-2020, 2020.

505   Hao, Z., Xiong, D., and Zheng, J.: How ancient China dealt with summer droughts—a case study of the whole process of the
1751 drought in the Qing dynasty, Clim. Change, 165, https://doi.org/10.1007/s10584-021-03049-5, 2021.

Li Q.: Planting Wheat and Its Position in the North China Plain Ming Dynasty Grain Planting Structure, Lanzhou Acad. J.,
50–58, 2014. (in Chinese)

Li W.: The rise and development of charitable relief efforts (义赈) during the late Qing dynasty, Qing Hist. J., 27–35, 1993.
510   (in Chinese)

Li X.: Examining migrants in the Ming dynasty from an ecosystem perspective: focusing on Shanxi and Hebei in the Middle
and Lower Reaches of the Yellow River, J. Chin. Histotical Geogr., 137-152+1, 1998.

Liang, F.: Historical statistics on popultion, land area, and land tax in China Across Dynasties, Zhonghua Book Company, Beijing, 2008. (in Chinese)

515 Liu S.: Distribution of population during the Ming Dynasty, Master's thesis, Zhengzhou University, 2005. (in Chinese)

Liu Y.: The comparative study about financial income and expenditure structure of China and England from 14 to 17 century, Master's thesis, Northeast Normal University, 2012. (in Chinese)

Lv Z.: The development of agricultural economy in southern Shaanxi in Ming dynasty, J. Northwest Univ. Soc. Sci. Ed., 86–90, 1996. (in Chinese)

520 Lv Z.: Planting and Distribution of Major Grain Crops in the Northwestern Region during the Ming Dynasty,Agricultural Hist. China, 57-66+40, 2000. (in Chinese)

Meng, J.: Food Crisis in Extreme Droughts in North China from 1637 to 1643, Areal Res. Dev., 41, 169–174, https://doi.org/10.3969/j.issn.1003-2363.2022.01.028, 2022.

Mishra, A. K. and Singh, V. P.: A review of drought concepts, J. Hydrol., 391, 202–216, 525 https://doi.org/10.1016/j.jhydrol.2010.07.012, 2010.

Nyamwange, M.: Famine mitigation in Kenya: some practices, Impact and Lessons, 1995.

Pei, Q.: The Review of Causality Analysis on the Relationship Between Paleo-Climate Change and Socio-Economic Dynamics, Progress. Inquisitiones Mutat. Clim., 13, 375–382, 2017.

Pei, Q. and Zhang, D.: Long-term relationship between climate change and nomadic migration in historical China, Ecol. Soc., 530 19, https://doi.org/10.5751/ES-06528-190268, 2014.

Peterson, L. and Haug, G.: Climate and the collapse of Maya civilization, Am. Sci., 93, 322–329, https://doi.org/10.1511/2005.4.322, 2005.

Quan, H.: Collected Essays on Modern Chinese Economic History, Zhonghua Book Company, 2011. (in Chinese)

Shi, Y., Zhang, Y., Wu, B., Wang, B., Li, L., Shi, H., Jin, N., Liu, D. L., Miao, R., Lu, X., Geng, Q., Lu, C., He, L., Fang, N., 535 Yue, C., He, J., Feng, H., Pan, S., Tian, H., and Yu, Q.: Building social resilience in North Korea can mitigate the impacts of climate change on food security, Nat. Food, 3, 499–511, https://doi.org/10.1038/s43016-022-00551-6, 2022.

Shiue, C. H. (Carol H.: The Political Economy of Famine Relief in China, 1740-1820, J. Interdiscip. Hist., 36, 33–55, 2005.

Shuang J. and Wang S.: Astudy about food production in Shanxi during the Ming dynasty, J. Sanmenxia Polytech., 19, 85–91, https://doi.org/10.3969/j.issn.1671-9123.2020.02.014, 2020. (in Chinese)

540 Su X.: A study of Taicangku in the Ming Dynasty, PHD diss., Northeast Normal university, 2010. (in Chinese)

Su, Y., He, J., Fang, X., and Teng, J.: Transmission pathways of China's historical climate change impacts based on a food security framework, The Holocene, 28, 1564–1573, https://doi.org/10.1177/0959683618782600, 2018.

Tian, F., Chen, X., and Su, Y.: Comparative Analysis of Extreme Drought Events and Social Impacts in Henan Province during the Middle Ming Dynasty, Weather Clim. Soc., 14, 1009–1021, https://doi.org/10.1175/WCAS-D-22-0015.1, 2022.

545 Tian, F., Su, Y., and Gong, Z.: How did ancient China prevent the transition from extreme drought to famine? Taking Wanli Drought of the Ming dynasty as an example, Int. J. Disaster Risk Reduct., 110, 104618, https://doi.org/10.1016/j.ijdrr.2024.104618, 2024.

Wang, P. K., Lin, K.-H. E., Liao, Y.-C., Liao, H.-M., Lin, Y.-S., Hsu, C.-T., Hsu, S.-M., Wan, C.-W., Lee, S.-Y., Fan, I.-C., Tan, P.-H., and Ting, T.-T.: Construction of the REACHES climate database based on historical documents of China, Sci.

550 Data, 5, 180288, https://doi.org/10.1038/sdata.2018.288, 2018.

Wei, Z.: Spatio-temporal characteristics of famine and its environmental causes in the Jiangsu-Shanghai region during the Qing Dynasty (1644-1911), Prog. Geogr., 39, 1333–1344, https://doi.org/10.18306/dlkxjz.2020.08.008, 2020.

Wen, K.: Chinese Encyclopedia of Meteorological Disasters, China Meteorological Press, Beijing, 2008. (in Chinese)

Will, P.-E.: Bureaucratie et Famine en Chine au XVIIIe siècle, Phoenix Publishing; Jiangsu Education Publishing House,

555 2006. (in Chinese)

Xia M.: A Preliminary Study on the Relief and Rehabilitation Issues of the "Ding Wu Qi Huang" in the Qing Dynasty., Modern Chin. Hist. Stud., 21–36, 1993. (in Chinese)

Xiao L.: Spatio-temporal Distribution of Famine and Its Relationship with Climate, Disaster, Harvest in North China During 1736-1911, Advances Earth Sci., 35, 478–487, 2020. (in Chinese)

560 Xiao, L., Fang, X., and Ye, Y.: Reclamation and revolt: Social responses in Eastern Inner Mongolia to flood/drought-induced refugees from the North China Plain 1644-1911, J. ARID Environ., 88, 9–16, https://doi.org/10.1016/j.jaridenv.2012.07.022, 2013.

Xiao, L., Fang, X., Zheng, J., and Zhao, W.: Famine, migration and war: Comparison of climate change impacts and social responses in North China between the late Ming and late Qing dynasties, The Holocene, 25, 900–910,

565 https://doi.org/10.1177/0959683615572851, 2015.

Yang, G. and Chen, Z.: Ming history, People's Publishing House, Beijing, 2006. (in Chinese)

Ye Y.: Famine Relief in Qing Dynasty, Agricultural Hist. China, 59–68, 1998. (in Chinese)

Yu, Y., Xiuqi, F., Quansheng, G., and Jingyun, Z.: Response and Adaptation to Climate Change Indicated by the Relationship Between Revolt and Drought-flood in Shandong Province During Middle and Late Qing Dynasty, Sci. Geogr.

570 Sin., 24, 680–686, 2004.

Zhai, X., Fang, X., and Su, Y.: Regional Interactions in Social Responses to Extreme Climate Events: A Case Study of the North China Famine of 1876-1879, Atmosphere, 11, https://doi.org/10.3390/atmos11040393, 2020.

Zhang C., Shen T., Xu S., and Yu J.: Study on the security risk of "water-energy-food" in mega cities under extreme weather, Journal of Economics of Water Resources, 41, 55-61+105, https://doi.org/10.3880/j.issn.1003-9511.2023.01.008, 2023.

575 Zhang D.: Variation of Day-Wet Climate and Severe Drought Events as Revealed in the Climate Records of China over the Past 1000 Years, Science Technology Rev., 47–49, 2004. (in Chinese)

Zhang, D.: A Compendium of Chinese Meteorological Records of the Last 3000 Years, 1st ed., Phoenix Publishing; Jiangsu Education Publishing House, Nanjing, 2013. (in Chinese)

Zhang, D. and Liang, Y.: A Long Lasting and Extensive Drought Event over China in 1876–1878, Adv. Clim. Change Res.,
580   1, 91–99, https://doi.org/10.3724/SP.J.1248.2010.00091, 2010.

Zhang, D., Jim, C. Y., Lin, C. S., He, Y. Q., and Lee, F.: Climate change, social unrest and dynastic transition in ancient
China, Chin. Sci. Bull., 50, 137–144, https://doi.org/10.1360/03wd0641, 2005.

Zhang, D., Lee, H. F., Wang, C., Li, B., Pei, Q., Zhang, J., and An, Y.: The causality analysis of climate change and large-
scale human crisis, Proc. Natl. Acad. Sci., 108, 17296–17301, https://doi.org/10.1073/pnas.1104268108, 2011.

585   Zhang M.: The Impacts of Population Distribution to Social Economy, Collected Pap. Hist. Stud., 27–33, 2006. (in Chinese)

Zhang X.: The progress of food production in the late Ming dynasty, Acad. Explor., 96–105, 2005. (in Chinese)

Zhao S.: Historical development and geographical distribution of agriculture in China, Geogr. Res., 1–11, 1991. (in Chinese)

Zhao, X.: Natural Disasters and the Development of Chinese History, J. Cult. Interact. East Asia, 7, 25–34,
https://doi.org/10.1515/jciea-2016-070103, 2016.

590   Zhao Z.: Charitable Relief Activities in the Ming Dynasty, Acad. J. Zhongzhou, 160–162,
https://doi.org/10.3969/j.issn.1003-0751.2007.02.041, 2007. (in Chinese)

Zheng, J., Xiao, L., Fang, X., Hao, Z., Ge, Q., and Li, B.: How climate change impacted the collapse of the Ming dynasty,
Clim. Change, 127, 169–182, https://doi.org/10.1007/s10584-014-1244-7, 2014a.

Zheng J., Hao Z., Zhang X., Liu H., Li M., and Ge Q.: Drought/flood spatial patterns in centennial cold and warm periods of
595   the past years over eastern China, Chinese Sci. Bull., 59, 2964–2971, 2014b. (in Chinese)