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# How climate change impacted the collapse of the Ming dynasty

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**Abstract** Based on the reconstructed temperatures, precipitation changes, and occurrences of extreme climate events, together with historical records on fiscal deterioration, food crises, and the frequencies of popular unrest, rebellions and wars, we identified three principal ways in which climate change contributed to the collapse in the Ming dynasty. Firstly, cooling, aridification, and desertification during a cold period destroyed the military farm system, which was the main supply system for the provisioning of government troops on the northern frontiers; these impacts increased the military expenditure from 64 % of total government expenditure in 1548–1569 to 76 % in 1570–1589 and thus aggravated the national fiscal crisis that occurred during the late Ming dynasty. Secondly, climate deterioration (e.g., cooling, aridification, and an increase in the frequencies of frost- and drought-related disasters, etc.) led to a 20–50 % reduction in the per capita production of raw grain in most areas of China, which resulted in widespread food crises and exacerbated the vulnerability of social structures during the last several decades of the Ming dynasty. Thirdly, the severe droughts occurring in 1627–1643 were a key trigger to the peasantry uprising. These droughts also played a significant role to promote the peasantry uprising, especially reviving the peasantry troops by recruitment of famine victims when they nearly perished in 1633 and 1638, and severely disrupting the food supply for the government troops, resulting in the final defeat of the government troops by the peasantry troops. This study contributes to an understanding of the climate-related mechanisms

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behind the collapse of the Ming dynasty, and provides a historical case study that enhances our understanding of the nature of interactions between climate change and social vulnerability.

## 1 Introduction

The impacts of climate change on human societies have a long and complex history, spanning many millennia, varying from place to place, and relating strongly to the vulnerability of society in the context of climate change (PAGES 2009). An increasing number of studies have confirmed that climate change has been an important contributor to societal collapse in prehistoric and pre-industrial times (Parry 1978; Halstead and O'Shea 1989; Weiss and Bradley 2001; de Monocal 2001; Haug et al. 2003; Oldfield 2008; Buckley et al. 2010, 2014; Richard and Wagner 2010; Zhang ZB et al. 2010c; Büntgen et al. 2011; Butzer et al. 2012). Case studies on the societal impacts of climate change provide insights into the complex synergies that exist between human activities and natural environmental change, which may also be valuable for the successful adaptation of human societies to future climate change (Dearing et al. 2006; Costanza et al. 2007).

The history of Chinese civilizations extends back 5,000 years, and Chinese historical records present a unique opportunity for studies on the nature of climate change impacts on human societies. Many studies have been conducted on the relationship between long-term changes in human dimensions (such as population, war, and dynastic cycles, etc.) and climate change in China (Hsu 1998; Zhang DD et al. 2006, 2007a, b; Lee et al. 2008; Zhang ZB et al. 2010c; Wang et al. 2010; Lee and Zhang 2010). The link between climate change and Chinese dynasties change has been also disputed recently (Yancheva et al. 2007; Zhang and Lu 2007; Zhang PZ et al. 2008; Zhang DE et al. 2010a, b; Cheng et al. 2010). For example, Zhang DD et al. (2006, 2007a, b) found that long-term fluctuations in the frequencies of war and population change followed cycles of temperature change; in particular, cooling was related to decreased agricultural production and increased societal problems, including price inflation and successive outbreaks of war, famine, and population decline. Yancheva et al. (2007) suggested that the summer rainfall deficit induced by the migrations in the tropical rain belt could have contributed to the declines of the Tang dynasty. Zhang PZ et al. (2008) concluded that the popular unrests occurring at the final decades of the Tang, Yuan, and Ming dynasties, which were all characterized by the weakening of the Asian Monsoon. However, Zhang DE et al. (2010a, b) commented that the strong spatial variations in precipitation rendered regional disparity between rainfall and the East Asian Summer Monsoon intensity over eastern China; thus, to link climate to Chinese dynastic change based on paleo-proxy records (e.g. the EASM intensity indicated by $\delta^{18}O$ values) from a single locality should be done with great care.

In these studies, the collapse of the Ming dynasty (1368–1644) in China, which was overthrown by a peasant uprising and replaced by the Qing dynasty (1644–1911, rising in Manchuria, northeastern China) as a consequence of military collapse, is usually provided as a representative case related to climate change, because the fall of the Ming dynasty coincided with drought, famine and rebellion in northern and central China (Tan et al. 2011). According to other researchers, the collapse also coincided with increased desertification in northern China (Wang et al. 2010) and weakening of the Asian summer monsoon (Zhang PZ et al. 2008). However, few studies have explored specific processes of climate change and their contributions to the social aspects of the collapse.

In contrast to those studies presented in the preceding, most historians (e.g., Bai 2004; Twitchett and Fairbank 1998; Fan and Cai 1994) have regarded the collapse of the Ming dynasty to have resulted from deterioration in the quality of the government induced mainly by political corruption, which resulted in a vicious circle of related economic crises and social turbulence starting in the middle Wanli Reign (1573–1620) or even the preceding Jiajing Reign (1522–1566). Additional causal factors were a peasant uprising related to a mega-drought and famine, and military pressure by northern nomadic tribes of Mongols and Manchu at the end of Ming dynasty. These interpretations tend to obscure well-understood pathways that relate societal responses to the impacts of both long-term climate change and short-term extreme events.

Here we synthesize a high-resolution paleo-climatic reconstruction with historical records on changes in human dimensions (including political corruption, fiscal deterioration, food crises, popular unrests, border crises and wars) to investigate how climate change contributed to the collapse of the Ming dynasty, especially the impacts of climate change on the functioning of societal systems in late-Ming times. As compared with previous studies which focused on relationships between long-term changes in human dimensions and climate, our study will aim to quantify the contributions of decadal–centennial climate change to the vulnerability of social and economic systems (e.g., the long-term decline in agricultural grain production and national fiscal deterioration), identify the specific impacts of severe droughts on peasant uprisings, and explore the interactions between climate change and social forces that drove the collapse of the Ming dynasty. These investigations thus will provide a historical case to better understand the link between climate change and Chinese dynasties change, and to improve the knowledge on the nature of human–climate–ecosystem interactions and the vulnerability and sustainability of society in the context of climate change, which may be sensitive to projected climate change in the future.

## 2 Materials and methods

The Ming dynasty has been roughly divided by historians into early (1368–1435), middle (1436–1566), and late (1567–1644) stages according to political and social characteristics, as well as national power (Bai 2004). To quantify climatic conditions during the late Ming, we used the high-resolution reconstructions of temperature and dry-wet index in China for the past 1,000 years (Ge et al. 2013; Zheng et al. 2006), together with the documentary records of climate extreme (Zhang 2004; Ge 2011). To quantify the vulnerability of social systems in the late Ming, datasets from a variety of publications were collected for analysis. It includes data on provincial population (Cao 2000), provincial cropland area and grain productivity (Fan 1984; Guo 2001), grain price (Peng 1958), fiscal conditions of central government (Quan 2011a; Huang 1974), popular unrests and wars (Bai 2004; Fan and Cai 1994; Twitchett and Fairbank 1998; Fu et al. 1986), and peasant uprising at the end of the Ming dynasty (Li 1948; Gu 1984; Yuan 1987; Liu 1983). In addition, the *Ming Shilu* (Annals of the Ming Dynasty) and some historical literature were also used to illustrate some important events, e.g., the development and decline of the military farm system and the direct expenses of major military campaigns. The territorial and administrative areas during the late Ming and regions with high-resolution paleo-climate series data are illustrated in Fig. 1.

The social impacts of climate change are a result of the interactions between climate change as an external perturbation and the vulnerability of social systems (Parry et al. 2007). To explore the roles of both long-term climate changes and short-term extreme climate events in the collapse of the Ming dynasty, we examined the link between climate change and social response by comparing series of data on climate change, grain prices, popular unrest, war, and governmental finance. To examine the impacts of droughts on the development of the peasant uprising, we compared the distribution of drought-stricken areas (CMA 1981) in 1627–1643 and the territories in which peasantry uprisings were active.

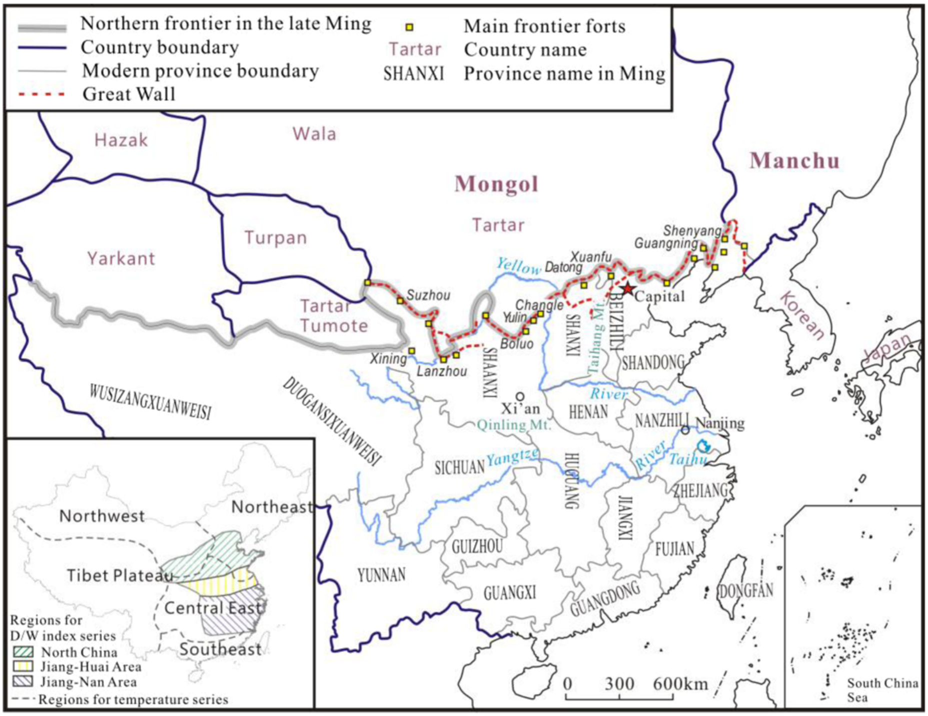


**Fig. 1** Territorial and administrative areas in the late Ming and regions having high-resolution paleo-climate series data

## 3 Results and discussion

### 3.1 The characteristics of climate deterioration and social vulnerability in the late Ming

Many Northern Hemisphere (NH) millennial temperature reconstructions (Christiansen and Ljungqvist 2012; Mann et al. 2009; Frank et al. 2007; Hegerl et al. 2006; D'Arrigo et al. 2006; Moberg et al. 2005; PAGES 2k Consortium 2013) show that the late 16th to the end of the 17th centuries (i.e., the late Ming) was the coldest period of the Little Ice Age, which was also the coldest century during the past 1,000, or even 2,000 years. During the late Ming period, China also experienced one of the coldest periods for the past 1,000 years, with a rapid cooling starting in approximately the 1550s. Data from a recent multi-proxy reconstruction (Ge et al. 2013) show that the temperature over China (Fig. 2a) during the 1560s to 1650s was at least 0.5 °C lower than that during 1951–2000, and the cooling rate in the 1550s to 1650s was ca. 0.4 °C/100 year. Regionally in China, the cold appeared more prominently in northern China (the temperature in the 1560s to 1650s was ca. 0.7 °C less than that in 1951–2000; Fig. 2b), where the military farms were distributed, than in southern China (Ge et al. 2013). This cold climate resulted in cold damages, frosts, and freezing injuries, which were reported 36 times on the North China Plain during 1571–1644 (i.e., approximately one cold disaster per 2-year period), and which were recorded in all years in the 1620s (Zhang 2004).

Moreover, the reconstructed dry–wet index shows that the climate dried rapidly three times in eastern China (Fig. 2c), especially on the North China Plain and in the Jiang-Huai area in the

1580s, 1610s, and 1630s (Zheng et al. 2006). This aridification was also significant at the northern fringe of the Asian summer monsoon region (Yang et al. 2014). Meanwhile, more severe droughts and heavy floods (Table S1 of the electronic supplementary material, ESM) occurred for frequent climatic variations and large inter-annual variability, in every sub-region of eastern China during 1581–1644 (Ge 2011). For example, frequency of severe drought and heavy flood was 12.3 and 4.3 % of years respectively during 1368–1644 in North China Plain, but it was 21.7 and 4.7 % of years respectively during 1581–1644. Specifically, the frequency of severe drought on the North China Plain and in the Jiang-Huai area during 1581–1644 was 76 and 62 % higher, respectively, than that during the entire Ming dynasty. In addition, episodes of persistent severe drought occurred more frequently (Fig. 2c); for example, the drought occurring in 1627–1643 (at the end of the Ming dynasty) was very likely the most persistent severe one in eastern China since AD 500, particularly on the North China Plain and in the Jiang-Huai area (Zheng et al. 2006).

Meanwhile, the late Ming was in the socially and economically vulnerable conditions mainly characterized by political corruption, border crises, poor financial capacities and societal turbulence (Text S1 of the ESM). The political corruption was mainly recorded including: the Emperor's misdeeds of indolence and irresponsibility, power abuses of the eunuch; power struggles by different parties, malpractice and malversation for most officeholders, land grabs by nobility from farmers, etc.; all of them led to a malfunctioning government, especially the ineffective administration of social and economic systems.

The border crises were evident from the high frequency of military conflicts, the scale of powerful campaigns expanded and the victories of Ming troops declined (Fig. 2d). The poor financial capacities were characterized by a long-term decline in agricultural production and subsequent price inflation (Fig. 2f) and severe defaults on central revenue payments, but the government expenditures were dramatically increased (Fig. 2e). The societal turbulence was characterized by a rapid increase in popular unrests from 1560 (Fig. 2f), especially the rapid development of the peasant uprising that started in Shaanxi Province in 1628, and extended to most of the northern and central provinces by 1634–1638, and to most parts of the country by 1640–1644 (Table S2 of the ESM). This peasant uprising overthrew the Ming dynasty in 1644 finally.

## 3.2 The contribution of climate change to social collapse in the late Ming

### *3.2.1 Contribution to breakdown of the military farm system and fiscal deterioration*

The military farm system played an important role in providing food supplies to northern frontier troops, which was established during the rapid development of the Ming dynasty in the late 14th century, when farmlands were reclaimed around the northern frontier, extending from northwest to northeast China. The area of farms reached its peak in the mid-16th century (during the Jiajing Reign) with a total of ca. 2.9 million ha of cultivated land that supplied 310 million kg/year of grain to the military (Ge 2011). However, damage to crops were increased because rapid aridification during the cold period in northern China and successive severe droughts were common in military farm areas from the 1570s to the end of the Ming dynasty (see sample records in Table S3 of the ESM), resulting in the abandonment of almost all military farms outside the Great Wall, and sharp decreases in the yields of military farms inside the Great Wall. It was reported that yields on the military farms on the northern frontier decreased by 60–70 % from the end of the Jiajing

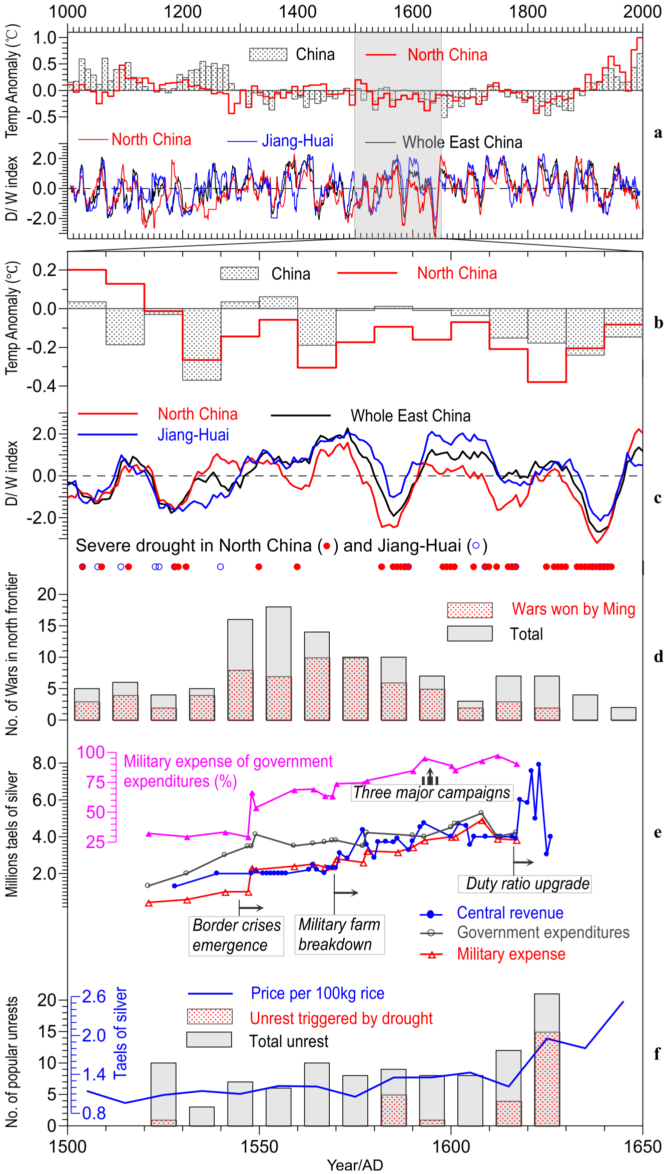


**Fig. 2** Comparison of changes in temperature, dry–wet index, severe drought, border crises, financial conditions, food prices, and popular unrest during 1500–1650. **a** Decadal temperature anomalies in China and northern China and the dry–wet index for eastern China, the North China Plain, and the Jiang-Huai area during AD 1000–2000. **b** Decadal temperature anomalies in China and northern China during AD 1500–1650. **c** Dry–wet index for eastern China, the North China Plain, and the Jiang-Huai area, and the occurrence of severe drought on the North China Plain and in the Jiang-Huai area during 1500–1650. **d** Frequency of wars between the Ming and the Mongols or the Manchu on the northern frontier during 1500–1650. **e** Financial conditions, including central revenue, government expenditures, military expenses and its proportion of total government expenditure (%), during 1520–1630. The starting years of emerging border crises, the military farm system breakdown, duty ration upgrades, and the period of the "three major campaigns" are shown for comparison. **f** Changes in the price of rice during 1500–1650, and the frequency of popular unrest, both the total unrest and that was triggered directly by drought, during 1520–1630

Reign (1566) to the end of the Wanli Reign (1620).[1] Such evident breakdown of the military farm system led to a sharp increase in military expenditures on the northern frontier starting in 1570 (Fig. 2e), and thus exacerbated the intensity of fiscal deterioration during the late Ming dynasty.

From the Jiajing Reign, the Ming dynasty slipped into fiscal deterioration. This fiscal crisis worsened owing to the evident increases in military expenses required to support the northern frontier. Triggered by the rapid increase of military conflicts against the Mongols on the northern frontier starting in the 1540s (Fig. 2d), military expenditure (as a proportion of total government expenditure) increased sharply, from 31 % in 1520–1547 to 64 % in 1548–1569 (Fig. 2e). Although the revenues of the central government appeared stronger on account of reforms initiated by grand secretary Zhang Juzheng in 1570s, and the military conflicts abated and troop numbers remained constant during 1570–1589 (Fig. 1d), the fiscal deterioration continued due to the decline of agricultural production resulting from the breakdown in the military farm system caused by climate change and severe desertification in northern China that started in the late 1560s, as well as related increases in the price of rice over all of the northern frontier (Quan 2011b). Government expenditure for military operations increased abruptly from 64 % in 1548–1569 to 76 % in 1570–1589. Since 1590, it increased to 90 % owing to the direct expenses of the "Three Major Campaigns" occurring in 1592–1600 (the campaign to put down a mutiny of Sino-Mongolian troops in the northwest in 1592, with direct expenses of more than 2.0 million taels of silver; the wars with Japan on the Korean Peninsula in 1592–1598, with direct expenses of more than 7.0 million taels of silver; and the campaign to eradicate an aboriginal chieftain in the southwest in 1599–1600, with direct expenses of ca. 3.0 million taels of silver).[2] However, the expenses remained high after these campaigns until the end of the Ming dynasty, suggesting that the negative impacts of climate change on the military farms became more and more severe as the climate continued to worsen. Such persistent and extraordinarily high military expenses finally brought the central financial system to the brink of collapse, resulting in an upgrading of the duty ratio for peasantry in 1618–1620, 1637, and 1639 (Fig. 2e).

### *3.2.2 Contribution to the large decrease in crop yields and the food crisis in China*

Even in the 20th century, a decrease in the mean annual temperature of 1 °C could result in a potential reduction of crop production in China by 10 % owing to a deficit of growing season and cropping system induced by decrease in accumulated temperature (Zhang 1982). Furthermore, higher reductions in crop yields could also result from more cold-related damages to crops, especially in northern China. For instance, in the 5 cold years of 1954, 1957, 1969, 1972, and 1976 in northeast China, the total crop yield was reduced on average by 12.7 % as compared with yields in preceding years (Zhang 1982). Moreover, high precipitation variation increased frequencies of drought and flood disasters to cause the reduction of crop production. It is assessed that the average annual loss due to natural disasters was approximately 11.6 % of the total yield, with annual maximum losses of over 25 % over China during 1950–1990, of which, ca. 86 % was induced by droughts and floods (Zheng and Huang 1998). Specifically, within the semi-humid zone on the North China Plain, the average annual grain loss caused by droughts and floods was ca. 11.3 % of the total yield, with an annual maximum of over 35 %

[1] See *Huang Ming Jingshi Wenbian* (*Classic selection on governance on society and economy during Ming Dynasty*), vol 61: Tunzheng Kao (On the military farm system governance).
[2] See *Ming Shilu*: *Shenzong Shilu* (*Annals in the Wanli Reign*), Vol. 441

in 1961 when the precipitation from March to June decreased by 30–65 % over most of the area (Zheng and Huang 1998).

Since the late Ming, colder temperatures and accompanying cold damages and drought have been more severe than those in 1951–2000, and the capacities of farming technology to reduce such disasters are believed to have been limited in the pre-industrial era; thus, the impacts of climate deterioration (including cooling, aridification, and more frequent cold damage and severe droughts) on agriculture would have been more pronounced during late Ming than in modern times. For example, the average grain yield in Hebei Province, North China, dropped from ca. 1,168 kg/ha during the Jiajing Reign, to 584 kg/ha during the Wanli Reign, and to only 230–350 kg/ha during the last decades of the Ming dynasty (1620s–1640s).[3] Although such large reductions in grain yields did not likely occur everywhere in China, the long-term reductions induced by climate deterioration were recorded in most regions. For instance, rice yields in the Taihu Basin dropped from 3,505–7,010 kg/ha during the Jiajing Reign to 2,337–4,674 kg/ha at the end of the Ming dynasty; in Zhejiang Province dropped by ca. 50 %; in Hunan Province dropped by 584–1,168 kg/ha (20 %–40 %). In Chaoyang, Guangdong Province, average rice yields dropped from 4,440 kg/ha in 1590s to 2,921 kg/ha in 1620s–1630s (Ge, 2011). All of these records show that crop yields dropped by 20–50 % throughout China from 1570s to 1630s.

Based on data on population, agricultural acreage, and crop yields, it is estimated that grain rations in North China were, on average, 393.3 kg/year in around 1580 (see Table S4 of the ESM), but only 289.4 kg/year in Shanxi Province and 339.9 kg/year in Shaanxi Province. The large reductions in crop yields (i.e., 20–50 %), together with a growing population, reduced grain rations in North China from an average of 393.3 kg/year in around 1,580 to 167–267 kg/year in the 1630s, resulting in a persistent food crisis that contributed to the vulnerability of social systems during the last several decades of the Ming dynasty. Among the decrease (of 32.1–57.5 %) in grain rations, the population growth of 18.4 % only contributed to a decrease of 12.4 %, with the other 19.7–45.1 % was caused by climate deterioration.

Between 1570s and 1580s, the price of rice increased sharply (by ca. 30 %) (Fig. 2f); this time period corresponds with the aridification that started in the 1570s and severe droughts (especially persistent drought) in the 1580s (Fig. 2c). Thus, the severe drought and its induced famine played important roles in the triggering of popular unrest in the 1580s (Fig. 2f). Rapid cooling and severe droughts occurred again during the 1610s to 1630s, and the price of rice again increased sharply during this time (by 110 %; Fig. 2f). Consequently, popular unrest became more frequent, and the severe drought in North China and its induced famine became a key role to trigger the popular unrest. In 1620s, events of popular unrest increased to 21 times, and all 15 events during 1628–1630 were triggered directly by the drought (Fig. 2f).

### *3.2.3 Contribution to peasant uprisings and the development of peasantry troops*

In 1627, a large-scale climate anomaly occurred in most of China which induced large-scale droughts in Shaanxi and Shanxi and flooding in Shandong and Hunan, and resulted in severe reductions in grain production over the entire country and an inability of the government to provide sufficient food to prevent a famine. In 1628, a severe drought prevailed again in Shaanxi and Shanxi, and a series of peasant uprisings and soldier mutinies erupted on account of the famine and food crisis, respectively. Early in 1629, to deal with the worsened situation, the emperor cut government expenditures by reducing the number of imperial post stations and

[3] Recorded in *Diao-Qiu-Za-Lu* (*A miscellaneous records for the period of later Ming*), edited by a scholar named Liang Qingyuan, who lived in central Hebei Province in 1606–1683.

dismissing attendants, including Li ZC, who later became the leader of the peasant uprising. The dismissed attendants, together with the deserters and mutineers from the government troops, swelled the ranks of the peasant uprising. Even worse, severe drought continued for the next several years, and the famine prevailed annually. Consequently, hundreds of thousands of famine victims joined the peasant uprising and the ranks of the peasantry troops.

Figure 3 briefly illustrates the comparisons of droughty areas and regions of active peasantry uprisings during the period 1627–1643 (see detail in Fig. S1 of the ESM). It shows that the counties in which peasant uprisings occurred in 1628–1631 were mostly located in the droughty area (see Fig. S1b of the ESM). In 1632–1633, the Ming troops largely quelled the uprisings in Shaanxi and Shanxi by use of both forceful and peaceful measures. By the end of 1633, the Ming troops had contained the beleaguered peasantry troops in a narrow area between the Yellow River and Taihang Mountains in northern Henan and killed Wang ZZ, the early leader of the peasantry troops (see Fig. S1c of the ESM). However, extremely cold weather in late December 1633 caused the middle reach of the Yellow River to freeze, which allowed the peasantry troops to cross the river and escape to central Henan.

During 1634–1636, the drought spread to central China, particularly to the whole of Henan Province. Large numbers of famine victims of the drought resulted in plentiful recruits to the fatigued peasantry troops. The peasantry forces rapidly increased to more than 0.6 million soldiers in the vast drought-affected area and rebuilt three powerful peasantry armies led by Gao YX, Li ZC, and Zhang XZ; thus, imposing significant military pressure on the Ming government. Furthermore, the peasantry troops expanded their activities to non-drought areas located to the north of the Yangtze River to replenish their food supplies for upcoming winters, and recruited soldiers from drought-affected areas in the summer (see Fig. S1d of the ESM).

Starting in late 1636, the Ming troops heightened their efforts to attack peasantry troops and cut off the routes for the return of the peasantry troops to the vast drought-affected area located in central and north China. The government forces defeated one of the most powerful of the peasantry armies and captured the veteran leader Gao YX in August 1636, forced the Zhang

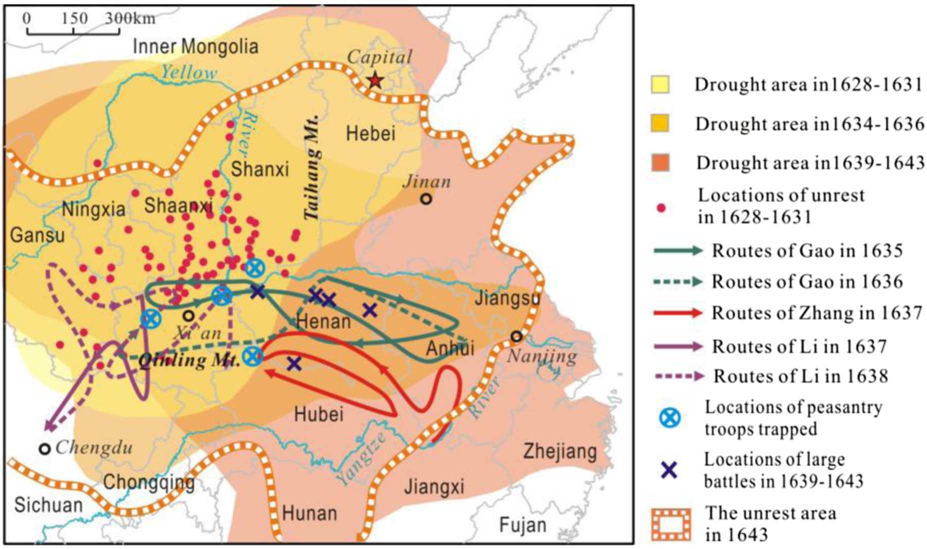


**Fig. 3** Comparisons of drought-affected areas and regions of active peasantry uprisings during the period 1627–1643

XZ army to surrender in 1637, and overwhelmingly defeated the Li ZC army in 1638, forcing them to retreat to the Qinling Mountains (see Fig. S1e of the ESM).

However, severe droughts persisted in 1637–1638, increasing numbers of famine victims and encouraging Zhang and Li to rise again in 1639. From 1639 to 1641, the severe drought extended to most of China, including the Yangtze valley (see Fig. S1f of the ESM), which provided a great opportunity for peasantry troops to revive. When Li ZC returned to Henan in 1640, the severe famine provided him with willing recruits, and during the first 3 months of 1641, his troops increased once again to ca. 1 million. Meanwhile, Zhang XZ broke through the Ming defensive line on the Yangtze River in the summer of 1640 and pushed into Sichuan Province. In 1641, Li and Zhang achieved several victories in Henan and the Yangtze River Valley, respectively. In particular, the severe drought that prevailed across most of China from 1639 destroyed the food supplies for the Ming troops. This situation led Li ZC to win five decisive battles in Henan in 1641–1643 (see Fig. S1f of the ESM), as the hungry Ming soldiers scattered helplessly, thus leading to the final destruction of the Ming forces.

### 3.3 Interactions between climate change and social forces driving the collapse of the Ming dynasty

Historians have concluded that societal development and collapse in historical times were mainly driven by combinations of social, political, and economic factors. The collapse of the Ming dynasty was also driven by political corruption, poor financial capacities, societal turbulence, together with border crises. As summarized in the dashed box embedded in Fig. 4, government malfunctioning (ineffective administration of social and economic systems) was mainly induced by political corruption, and then aggravated fiscal deterioration and price inflation. Fiscal deterioration further led to unreasonable upgrading of the duty ratio for citizens, which increased risk of societal turbulence and, hence, to increased demands on the military besides dealing with border crises from external influences. The upgrading of military pressure led to further fiscal deterioration, which resulted in deep-seated administrative problems and ineffective governance, and to the misconduct of those in the inner circles, which caused further worsening and the final breakdown of the system (Bai 2004; Twitchett and Fairbank 1998; Fan and Cai 1994).

However, the social operating system, especially the vulnerability of the societal system, was related to the natural environment via the land-carrying capacity (as measured by agricultural production in the preindustrial era), which was directly affected by climate change. Among the four main social driving forces behind the Ming's collapse, poor financial capacity and fiscal deterioration could have resulted not only from government malfunctions directly

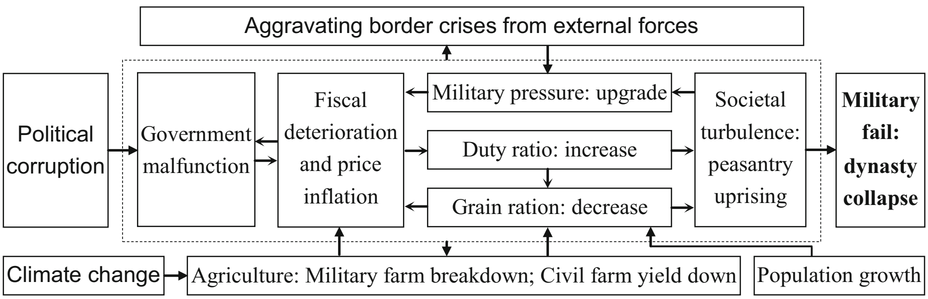


**Fig. 4** The driving forces and pathways of political, financial, and social factors leading to the collapse of the Ming dynasty

induced by political corruption, but also from the intensification of border crises, and especially the long-term decline in agricultural production from both military and civilian farms during the late Ming (Fig. 4). Meanwhile, the long-term decline in agricultural production, together with population growth, induced a decrease in grain rations, led to food crisis, price inflations, and famine, and consequently triggered the frequent occurrences of popular unrest, especially the large-scale peasant uprising (Fig. 4). To improve the financial capacity for eliminating the peasant uprising in the last decade of the Ming dynasty, the Ming government upgraded the duty ratio from peasants in 1637 and 1639, which further intensified the conflict between the government and the peasants, thus promoting the development of the peasant uprising.

As illustrated in the preceding, the long-term decline in agricultural production was mainly induced by climate deterioration (including cooling, aridification, and more frequent cold damage and severe droughts) from the 1570s. In addition, the formation of peasantry troops was promoted by persistent severe droughts and related famine in 1627–1643. This indicates that the fiscal deterioration and societal turbulence (especially the peasant uprising) were closely related to the impacts of climate deterioration from the 1570s, through the following pathways: (1) climate deterioration → decline in agricultural production → fiscal deterioration vs unreasonable upgrade in the duty ratio → increase in social vulnerability, and (2) climate deterioration → decline of agricultural production → decrease of grain ration → food crisis, price inflation and famine → popular unrest. Both of these pathways led to the peasant uprising and increased military pressure.

In the last decades of the Ming dynasty, pressure on the military was brought about not only by the peasant uprising, but also by border crises caused by incursions of northern nomadic tribes, especially the Manchu in the northeast. These incursions were also related to climate deterioration (Ge 2011). Compelled by shrinking pastoral resources, the Manchu started to invade China in 1619. To resist the invasion by the Manchu, the Ming government upgraded the duty ratio thrice during 1618–1620 for the high military expenses on the northern frontier. Such extraordinary and irrational upgrading of the duty ratio also played an important role in the social turbulence by intensifying social vulnerability. Finally, the Manchu took advantage of peasant uprisings triggered by severe droughts and economic collapse as well as a food crisis worsened mainly by climate deterioration, invaded southward in 1644, and built the Qing dynasty.

## 4 Conclusions

This study examined the impact of climate change on social aspects of the collapse of the Ming dynasty (1368–1644) in China. It's found that climate change in China during the late Ming dynasty was characterized by rapid cooling and the onset of one of the coldest periods in the region during the past 1,000 years, as well as severe aridification and frequent severe droughts. In the 1560s to 1650s, the temperature in China was ca. 0.5 °C lower than that in 1951–2000, and the cooling rate was ca. 0.4 °C/100 years. During the period 1581–1644, the frequencies of severe droughts on the North China Plain and in the Jiang-Huai area were 76 and 62 % higher, respectively, than those during the whole of the Ming dynasty. The severe drought occurring in 1627–1643 was very likely the most persistent in eastern China since AD 500, particularly on the North China Plain and in the Jiang-Huai area. This climate deterioration contributed to the collapse of the Ming dynasty through two pathways that led to the peasant uprising and increased pressure on the Ming military regime. In details, the significant impacts of climate change included:

1. Climate deterioration starting in the 1570s led to a reduction in the production of raw grain per capita by 20–50 % over most of China, resulting in a severe food crisis and enhanced social vulnerability during the last several decades of the Ming dynasty.
2. Cooling, aridification, and related desertification during the cold period destroyed the military farm system on the northern frontiers starting in the 1570s, which resulted in the military expenditure from 64 % of total government expenditure in 1548–1569 to 76 % in 1570–1589, which further aggravated the national fiscal deterioration during the late Ming.
3. The severe droughts occurring in 1627–1643 were a key trigger to the peasantry uprising. These droughts also played a significant role in promoting the peasantry uprising, especially reviving the peasantry troops by recruitment of famine victims when they nearly perished in 1633 and 1638, and severely disrupting the food supply for the government troops, resulting in the final defeat of the government troops by the peasantry troops.

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