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Abnormally low precipitation-induced ecological imbalance contributed to the fall of the Ming Dynasty: new evidence from tree rings

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Abstract
Climate change has played a crucial role in the subrogation of Chinese dynasties. In particular, the Ming-Qing transition coincided with the rapid decrease in precipitation and the sharp deterioration of agroecological conditions in northern China under the cold conditions brought on by the Little Ice Age. Here, we present a new precipitation reconstruction (June-April) for northern Chinese Loess Plateau since 1590 CE. The reconstruction was derived from a tree-ring width chronology of *Platycladus orientalis*, and made it possible to quantitatively assess the period of megadroughts during the late Ming Dynasty, with high resolution. Our analysis showed that these extreme drought events have been unprecedented in China for the last 500 years, and precipitation variation could be linked to ENSO activities. The environmental imbalance caused by these megadroughts magnified the negative impacts of the climate on agriculture and society, an important reason for considering these phenomena as catalysts for the demise of the Ming Dynasty.

Keywords Fall of the Ming Dynasty · Chinese Loess Plateau · Tree rings · Precipitation reconstruction · NDVI variations · Climate-human interaction

1 Introduction

Climatic change had repeatedly affected the human societies spanning some millennia, varying from place to place and influencing the ability of humans to adapt to extreme climate events (Beever et al. 2017; Zscheischler et al. 2018; Cattaneo et al. 2019; Feng

Highlights
• A tree-ring chronology has been used to reconstruct total June-April precipitation for the northern Chinese Loess Plateau since 1590 CE.
• The ENSO anomaly under the cold conditions during the Little Ice Age may cause extreme droughts toward the end of the Ming Dynasty.
• The ecological imbalance caused by climate change has played a crucial role in the transition between the Ming and Qing dynasties.

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et al. 2019; Yang et al. 2021; Chen et al. 2021). Extensive research indicates that climate change processes have been important factors in driving the collapse and reshaping of human societies in prehistoric and pre-industrial times (Weiss and Bradley 2001; de Monocal 2001; Büntgen et al. 2011; Butzer 2012; Buckley et al. 2014; Su et al. 2016; Evans et al. 2018; Lee et al. 2019; Petraglia et al. 2020; Yang et al. 2021; Brice et al. 2021). Some case studies on the potential influences of climate change on society provide people with an in-depth understanding of the interplay of between environmental changes and human activities, which may also be valuable for human society to successfully adapt to possible future extreme climate events (Dearing et al. 2006; Ford et al. 2018; Haldon et al. 2018).

As one of the most significant monsoon countries, China's social evolution has been heavily influenced by climate change over the past 5000 years. In this sense, historical records provide unique opportunity to explore the influences of climate change on human society. Various investigations on the relationship between historical social changes (regime change, wars, populations, etc.) and climate change have been conducted in China, revealing interactions between social resilience and climatic crises (Zhang et al. 2006, 2008, 2010, 2021; Su et al. 2016; Zheng et al. 2014; Yang et al. 2021; Zhao et al. 2021a, b; Liu et al. 2021a, b). Both low temperatures and the monsoon droughts would have caused great damage to the fragile agricultural production of ancient China, causing serious social conflicts (Zhang et al. 2006, 2008; Yancheva et al. 2007; Cook et al. 2010; Su et al. 2016). However, due to the vast territory of China, its regions have very different responses to changes in the intensity of the monsoon and consequently in the impact produced on agricultural production. Therefore, adverse climate conditions do not necessarily lead to lower agricultural yields, and fairly conclusive evidences must be provided accordingly.

A political event with far-reaching influences on Chinese society has been the transition of the Ming-Qing dynasties. These social and political changes have been cited as a typical case related to the influence of climate change, since the Manchu invasion was synchronous with a period of droughts, famine, plagues, and massive peasant revolts in northern China (Zhang et al. 2014; Cui et al. 2019). Other studies suggest that the fall of the Ming Dynasty coincided with the deterioration of the environment caused by the weakness of the summer monsoon in northern China during the Little Ice Age (LIA) (Wang et al. 2010; Cook et al. 2010; Zhao et al. 2021a, b). Several historians argue that the severe socio-economic crisis that accelerated the fall of the Ming Dynasty was a confluence of the environmental deterioration caused by the climate and political corruption (Atwell 1988, 2005; Bai 2004; Di Cosmo 2009). Another important factor that occurred during this period of political decline was the Black Death, a plague that devastated the population and caused destruction of the social order. Cao (1997) and Brook (2020) have linked these phenomena to extreme climate events in northern China during the late Ming Dynasty. As an important military zone, the ecological and economic situation of the Chinese Loess Plateau largely influences on the trend of the national destiny, and therefore, it is necessary to understand its climate conditions. However, previous high-resolution studies mainly focused on northern China or the other region (Zhang et al. 2008; Zhao et al. 2021a, b), and cannot accurately reflect the local climate information of northern Chinese Loess Plateau. Some scholars have used historical documents to discuss the late Ming drought and its desertification in this area (Cui et al. 2017), and however, the historical records here are discontinuous. We need to combine more high-resolution continuous proxy climate records to provide more evidences for the influences of these extreme climate events on the fall of the Ming Dynasty.

Tree rings are playing a vital role in indicating past drought change in northern China. To date, there are tree-ring-based precipitation/drought reconstructions for the northern China (Liu et al. 2007, 2019a, b; Cai et al. 2014; Li et al. 2016, 2022; Chen et al. 2016, 2020a). Nevertheless, precipitation reconstructions are still insufficient on the northern China for interpreting the late Ming Dynasty megadrought in a long-term perspective. Most of precipitation/drought reconstructions for the northern China were based on the tree-ring data of *Pinus tabulaeformis*, but few studies focused on *Platycladus orientalis*, a long-lived tree species (Sun et al. 2021a). Here, we present a new reconstruction of total June-April precipitation for the northern Chinese Loess Plateau based on tree rings of *Platycladus orientalis* and compared it to historical records on societal responses to extreme drought-induced ecological imbalances, particularly during the first half of the seventeenth century, and how this contributed to the downfall of the Ming Dynasty, especially the influences of the drought-induced ecological imbalances on the social stability in the late Ming Dynasty. Our study will aim to quantify abnormally low precipitation events in the study area where the earliest peasant uprisings occurred in the late Ming Dynasty, and determine the specific impacts of ecological imbalances caused by severe drought on the Black Death and the peasant uprisings, in order to explore the early origins of the collapse of the Ming Dynasty. Our study attempts to improve our understanding of climate–ecosystem–human interplay and the resilience of northern Chinese society in a context of climate change.

2 Data and methods

The study area is located at the northern Chinese Loess Plateau, and corresponds to the transition zone between monsoon and non-monsoon climate, with semiarid to arid conditions. It also represents the borderland between agricultural and nomadic regimes in the pre-modern period, where many dynasties built great walls and military strongholds to defend themselves against nomads, especially during the Ming Dynasty. After thousands of years of intense human influence, the northern Chinese Loess Plateau has preserved few old-growth forests and has become one of the most severe soil erosion areas in China. In June 2019, two wood samples per tree were collected with a 5.1-mm increment borer at the hillside near the abandoned castle (Bailin castle, 38°40′ N, 110°26′ E, 1180 m a.m.s.l.) (Fig. 1A). The native tree species under study was *Platycladus orientalis* (Cupressaceae). The trees grow in deep loess soils and have a reduced and open crown, which would indicate a priori that they are subjected to moisture stress.

The tree-ring width data from the sampling site represented 40 crossdated radii from 21 trees. The dendrochronological series were detrended and standardized with a negative exponential curve using the ARSTAN program (Cook 1985). The detrended series were combined into a standard (STD) version tree-ring width chronology by computing the bi-weight robust mean (Cook and Kairiukstis 2013). To reduce the impact of decreasing sample depth in the earlier part of the chronology, the variance of chronology was stabilized using the method proposed by Osborn et al. (1997). Both expressed population signal (EPS) and inter-series correlation (Rbar) were computed for 50-year running windows with 25-year overlaps, and the threshold value of 0.85 in EPS was considered to show the reliable period of this chronology (Wigley et al. 1984).

The STD chronology was compared with instrumental precipitation data to select the optimum seasonal predictand for precipitation reconstruction. Instrumental precipitation record (1970 to 2020) of Yulin city (38°12′ N, 109°42′ E, 1059 m a.m.s.l.) was used in

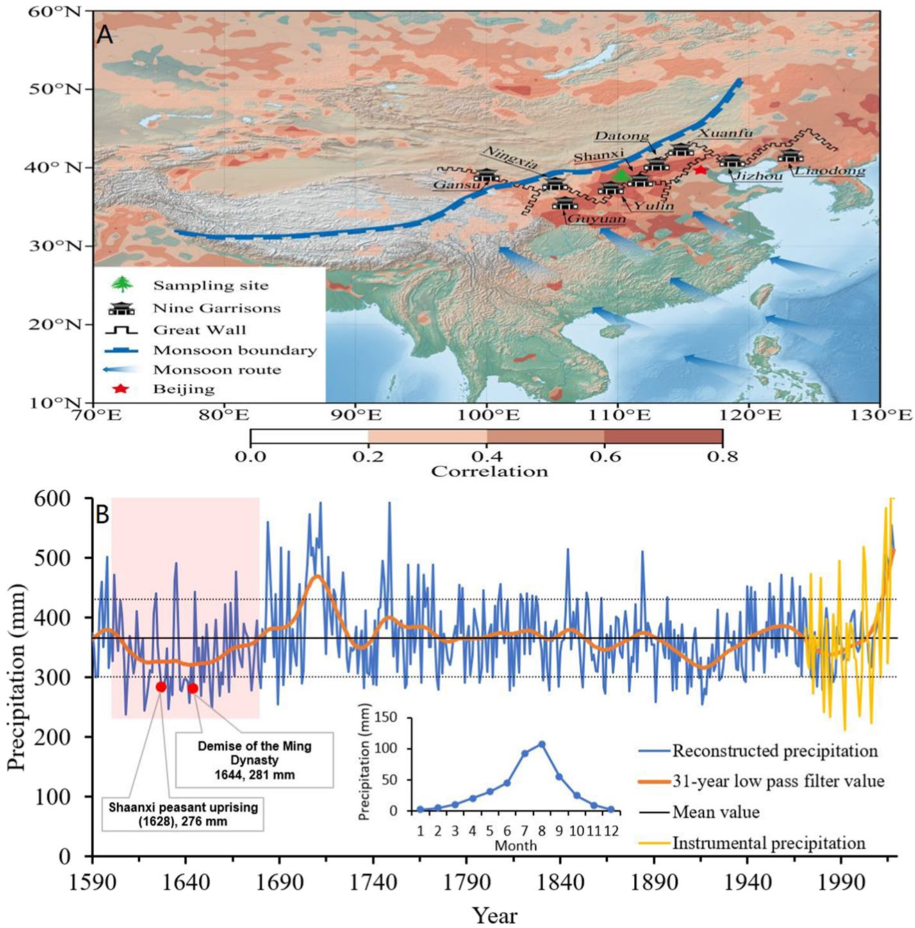

Fig. 1 **A** Map of the study area, showing the location of the sampling site, nine garrisons of Great Wall during the Ming dynasty. The tree-ring data is correlated with the gridded NDVI dataset for May–September growing season over northern China for the period 1982–2015. Note the positive correlations over the monsoon boundary region along the Great Wall. **B** The reconstructed total June-April precipitation and its 31-year low-pass filter value during 1590–2018 (blue line). Horizontal black line indicates average value of the reconstruction. The monthly total precipitation computed for the period 1970–2018 is also showed in the inset (yellow line)

this analysis. The grid-point normalized difference vegetation index (NDVI) data over the northern Chinese Loess Plateau for the period 1982–2015 were also extracted from the AVHRR GIMMS NDVI 3 g dataset (Pinzon and Tucker 2014). The data corresponded to the region between 38–39° N and 109–111° E and were averaged to assess summer changes of vegetation productivity in the long-term precipitation context.

The STD chronology was significantly correlated with the total precipitation from previous June to April, and was used as a predictor of a linear regression model that reconstructed the pre-instrumental precipitation. The model was evaluated based on adjusted r^2 and cross-validation statistics (Reduction of Error and Coefficient of Efficiency) (Cook and Kairiukstis 2013). In order to investigate linkages between precipitation in the northern Chinese Loess Plateau and the state of the Pacific ocean–atmosphere system, composites of previous June-April precipitation and 850 hPa water vapor transport anomalies were created for the El Nino and La Nina years during 1850–2005 based on the CESM model simulations (Hurrell et al. 2013). Furthermore, we also investigated the influences of ENSO activities in the precipitation reconstruction using superposed epoch analysis (SEA, Haurwitz and Brier 1981). The method of significance testing-random sampling was used to assess statistical significance, and strong El Nino and La Nina year lists based on Gergis and Fowler (2009) were used for the superposed epoch analysis.

The main cereal crops in the northern province of Shaanxi during the Ming Dynasty were millet and oats, crops for which 300 mm of precipitation has been indicated as the minimum threshold for achieving normal growth (ICRISAT and FAO 1996; Suttie and Reynolds 2004). To evaluate whether the probability of meeting this minimum precipitation differed between pre-instrumental periods and the instrumental period, we used the cumulative distribution function (CDF) of reconstructed precipitation. Based on the log-normal CDFs, we compared the specific probabilities (non-exceedance probability) of not meeting the 300-mm minimum precipitation between the instrumental period (1970–2018) and (1) the full reconstructed period (1590–2018) and (2) the reconstructed driest period (1605–1679). Moreover, the transfer function between ring width index and NDVI was also developed (not shown), and we also compared the specific probabilities of not meeting the mean instrumental NDVI between the instrumental period (1970–2018) and (1) the full reconstructed period (1590–2018) and (2) the reconstructed driest period (1605–1679).

3 Results

After correlating the STD chronology with several seasonal subsets of total precipitation from June of the previous year and September of the current year, it was found that the highest correlation ($r=0.64$, $P<0.01$) was with total June-April precipitation (Fig. 1B). Precipitation during these months corresponds to the previous monsoon season and winter precipitation, periods that represent very well the opportunity for precipitation in the study region. Based on the precipitation reconstruction model ($Y=175.495+190.548X$), we reconstructed total June-April precipitation for the northern Chinese Loess Plateau to 1590 CE. The precipitation reconstruction model accounted for 40.4% ($r^2_{adj}=39.1\%$, $P<0.01$) of the instrumental precipitation variances over the calibration period from 1970 to 2018. The positive RE (0.33) and CE (0.32) indicated predictive skill of the precipitation reconstruction model. The significant correlation ($r=0.57$, $P<0.01$), sign test ($36^+/12^-$, $P<0.01$), and product mean test (4.45, $P<0.01$) between the reconstructed precipitation and the leave-one-out estimates are all indications of validity of our precipitation reconstruction model.

The reconstructed total June-April precipitation contains interannual to multi-decadal variations (Fig. 1B). The reconstruction spanned 429 years with an average precipitation of 366 mm and a standard deviation (σ) of 64.7 mm. Several dry episodes occurred during 1600s–1670s, 1730s, 1890s–1930s, and 1970s–1990s. Marked periods with high precipitation occurred during 1680s–1720s, 1740s–1770s, and 2000s to present. Of particular interest are the abnormally low precipitation (drought) events during 1600s–1670s, which characterizes the most intense and extended dry period during the past four centuries. At the same time, the late 1920s drought events are also recorded by our reconstruction (Liang et al. 2006). Significant positive correlations with NDVI are found with the monsoon boundary region along the Great Wall (Fig. 1A), and significant positive correlations with regional NDVI were found for the February-June

($r = 0.73$, $P < 0.01$) and May–September ($r = 0.65$, $P < 0.01$) months. This result implies that precipitation plays an important role in driving vegetation productivity and maintaining ecological balance along the Great Wall (Fig. 1).

During El Nino years, the precipitation anomaly is negative in the northern China, with mean winds at 850 hPa exhibiting strong westerly flow over eastern China; during La Nina years, the opposite pattern occurs (Fig. 2A, B). Such patterns suggest a relationship between precipitation anomalies in the northern Chinese Loess Plateau with thermal anomalies in the surrounding oceans and the regional atmospheric circulation anomalies. Figure 2C and D show the SEA results based on the lists of strong El Nino (37) and La Nina (38) years from Gergis and Fowler (2009). A statistically significant ($P < 0.05$) reduction in regional precipitation is indicated at the beginning of El Nino year, and the opposite precipitation condition occurred at northern China during La Nina years.

4 Discussion

4.1 Regional comparison and possible climate mechanisms for extreme low precipitation during the late Ming Dynasty

The reconstructed precipitation was compared with the precipitation index (PI) in north-central China based on drought/flood index and tree-ring records (Yi et al. 2012), summer

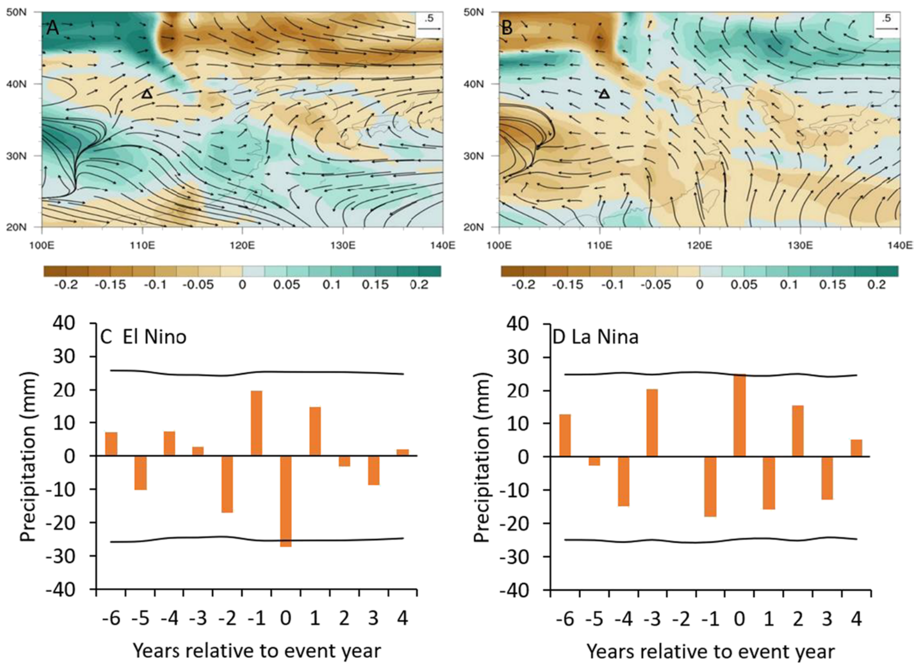

Fig. 2 Spatial distribution of precipitation and 850 hPa water vapor transport anomalies (vectors, where uq and vq are multiplied by 1000) in El Nino (**A**) and La Nina (**B**) years during 1850–2005 in the CESM model simulation. Results of superposed epoch analysis (SEA) testing the impact of ENSO activities on regional precipitation variation in Yulin. The lists of strong El Nino and La Nina years, based on Gergis and Fowler (2009), were used for tests

monsoon season streamflow of the Middle Yellow River (Chen et al. 2020a), and the stalagmite $\delta^{18}O$ records of Xiniu Cave and Qujia Cave (Zhao et al. 2021a, b). The correlation between this study and Chen et al. (2020a), computed over the 1590–1700 common period, is 0.44 after a 21-year smoothing. All proxy records showed relative low level and remarkable downward trend, including precipitation and streamflow during the late Ming Dynasty (Fig. 3), reaching the mean reconstructed precipitation during the period 1605–1679 a value of 338 mm (8.9% lower than the average). Some differences existing between the reconstructions may reflect the local influence of different geographic features or difference in seasonality of the various climate reconstructions. Of particular interest is the recent wetting trend ($mean_{2004\text{-}2018}$: 428 mm, 17% higher than the average) in the context of global warming (Gao et al. 2017; Sun et al. 2019), which is quite different from other drought reconstruction results (Cai et al. 2014; Li et al. 2016; Liu et al. 2019b; Hua et al. 2019; Li et al. 2022), and this also may be linked with the implementation of the grain for green project. The increase in precipitation has resulted in the restoration of vegetation in the northern Chinese Loess Plateau and significant improvement of the regional ecological environment after the implementation of the grain for green project, especially the alleviation of soil erosion (Feng et al. 2016; Zhao et al. 2018; Wu et al. 2020; Wang et al. 2021), and the wetting trend recorded in our precipitation reconstruction. However, if the effect of the drying trend, such as those that occurred in surrounding areas, extends to our study area due to the effect of increased evaporation caused by anthropogenic warming; then this wetting trend could be reversed in the near future (Sun et al. 2019; Lu et al. 2021), so the ecological and economic systems in the Loess Plateau will be forced to adapt.

The Yulin city is located in the northern Chinese Loess Plateau, which is influenced by the Asian summer monsoon during the warm season (Fig. 1B). The June–September precipitation probably originates from the monsoon circulation pattern and accounts for

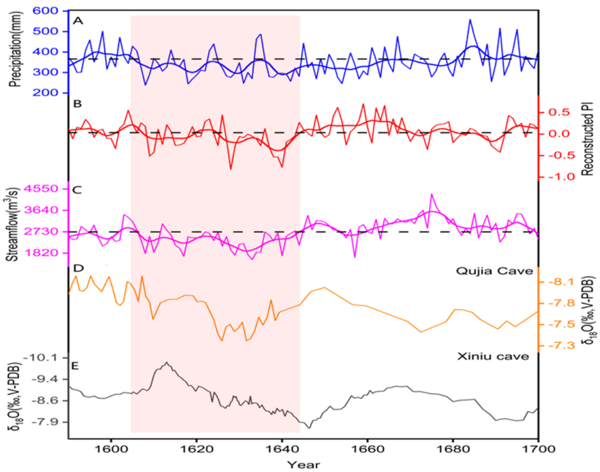

Fig. 3 Comparison of the proxy records from different climate regions. (**A**) Reconstruction of June-April precipitation for 1590–1700 derived from tree rings for the northern Chinese Loess Plateau (this study); (**B**) summer precipitation index reconstruction based on dryness-wetness index record and tree rings for north-central China (Yi et al. 2012); (**C**) summer monsoon season streamflow reconstruction in the middle Yellow River derived from tree rings (Chen et al. 2020a); two stalagmite $\delta^{18}O$ records from Qujia Cave (**D**) and Xiniu Cave (**E**) in China, reflecting large-scale drought signal. All precipitation and streamflow series were smoothed with a 10-year low-pass filter to highlight long-term fluctuations

74% of total annual precipitation at Yulin. Previous studies have shown that the monsoon failures in northern China are closely related with ENSO activities, and our precipitation series show low values in some strong El Nino years, such as 1877 (277.4 mm) and 1918 (271.2 mm) (Zhang et al. 1999; Zhou and Yu 2005; Cook et al. 2010). The possible connection of regional precipitation with ENSO also has been supported by the results of climate model simulation and SEA analysis (Fig. 2). In this scenario, the ENSO phenomenon also may have played an important role in the occurrence of extremely low precipitation on the northern Chinese Loess Plateau during the late Ming Dynasty. Comparisons of our precipitation reconstruction with some ENSO reconstructions (Gergis and Fowler 2009; Li et al. 2013) reveals no systematic relationship, likely linked to the regional character of both the precipitation and reconstruction errors. Detailed analysis, however, suggests some low precipitation years following some El Nino events, such as 1607–1609, 1618–1621, 1630, and 1638–1642. Moreover, low temperature during the LIA and the mid-seventeenth century eruption cluster not only makes the regional temperature colder, such as the cold summers in the Eastern Tibetan Plateau (Zheng et al. 2014; Wang et al. 2015; Chen et al. 2020b), but also, to a certain extent, affected the regional water cycle (weak summer monsoon and low streamflow) and formed the dry-cold climate in the northern edge of the Asian summer monsoon region, which has played an important role for the demise of the Ming Dynasty (Chen et al. 2020a; Zhao et al. 2021a, b; Stoffel et al. 2022). To sum up, the mechanism(s) that triggered the dramatic and strongly decrease of precipitation in northern China during the late Ming Dynasty may be multifaceted, possibly involving the combined influence from the different external forcing factors.

4.2 Link between extreme low precipitation and ecological crisis during the late Ming Dynasty

During the period 1605–1679, the frequency of extreme droughts increased dramatically, with a concentration of more than 40% of the extreme drought years (precipitation $\leq$ the mean $-$ 1σ) for the last 429 years. The probability distribution of the reconstructed precipitation during the pre-instrumental periods provided comparisons with normal conditions during the instrumental period that indicate a level of satisfaction with the water requirements of the vegetation. The probability of not meeting the 300-mm precipitation condition calculated from the CDF of the reconstruction during the period 1580–2018 (0.15) was remarkably higher than that derived from the instrumental record (0.05). Based on the range of precipitation reconstructed from 1605 to 1679, there would be a 33.3% chance that June-April precipitation would not meet or exceed 300 mm. Thus, in almost three out of every 10 years, the natural precipitation supply would not be sufficient to meet the water demands of crop millet and forage crop. More seriously, more than 70% of the years during the period 1605–1679 are below the mean instrumental May–September NDVI, which may lead to supply–demand imbalances of material and energy for the regional ecosystems. Zheng et al (2014) indicated the impact of climate change on the collapse of the Ming Dynasty in the two pathways, which both are closely related to decline of agricultural production. The grain prices in the late Ming Dynasty were risen continuously because of the war and the bad climate (Fig. 4C). Not only the grain prices in the border areas were continuously rising, but also the grain prices of the whole country were also rising, and grain prices in Yulin have more than tripled (Zheng et al. 2014; Liu et al. 2018). Meanwhile, due to food shortages, the Ming government had to provide more money to the troops on the border, which increased the financial burden (Quan 1970). There is no doubt that the famines resulting from the droughts were the important reason for the collapse of the Ming Dynasty.

The fall of a vast empire should be considered a long-term process. However, the Ming Dynasty collapsed in less than 20 years after the outbreak of the peasant uprising in northern Shaanxi in 1628. Thus, climate change alone cannot fully explain the Ming Dynasty's rapid decline. Among the many explanations for the rapid collapse of the Ming Dynasty, the outbreak of the Black Death is often cited as an important reason (Cao 1997; Liu et al. 2018; Li et al. 2020; Brook 2020). Related research has shown that the outbreak of the Black Death may be affected by climate change (Schmid et al. 2015; Chen et al. 2022). The Black Death appeared in the nearby northern Shanxi during the Yuan Dynasty, but a southward expansion was not occurred until the late sixteenth century (Cao 1997). During the early seventeenth century, a long dry period was accompanied by a marked increase in the frequency of more deadly extreme drought events, followed by the outbreak of the Black Death (Chongzhen pandemic, 1640–1644) (Cao 1997; Brook 2020). There is abnormally low precipitation (<300 mm) in 1627–1629 and peasant uprising broke out in northern Shaanxi in 1628, and during the period of 1637–1644; only the 1643 year has

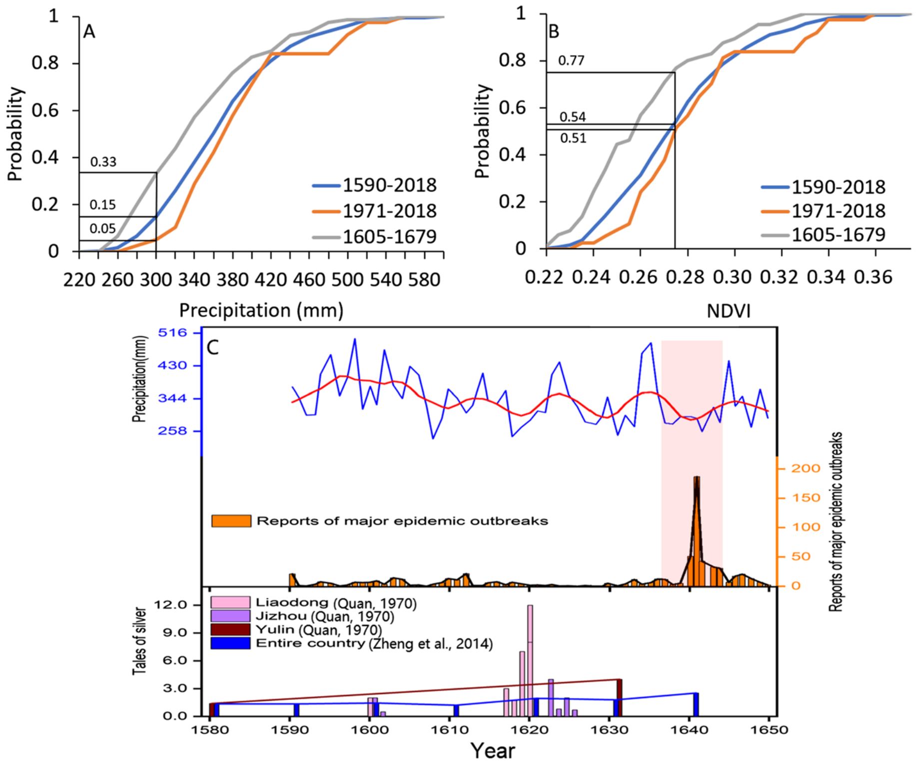

Fig. 4 **A**) Cumulative distribution functions (CDFs) of reconstructed precipitation. CDFs plotted for different periods: full-length (1590–2018), instrumental (1971–2018), and driest period 1605–1679. Smooth lines are lognormal fits to CDFs. Annotated are probabilities of not exceeding the specified 300-mm precipitation target. **B**) Cumulative distribution functions (CDFs) of NDVI. CDFs plotted for different periods: full-length (1590–2018), instrumental (1971–2018), and driest period 1605–1679. Smooth lines are lognormal fits to CDFs. Annotated are probabilities of not exceeding the mean $NDVI_{1982\text{-}2018}$. **C**) Comparison of changes in precipitation, food prices (Quan 1970; Zheng et al. 2014), and major epidemics in Ming China (Brook 2020) during 1580–1650

a precipitation of more than 300 mm (Fig. 4C). Considering the relationship between the vegetation productivity and precipitation, it is understood that at that time, the probability of maintaining normal grain production was much lower, threatening human food security. Due to food shortages, high food prices made it more difficult for farmers to maintain a normal life, and as a result, a large number of farmers went bankrupt and became refugees, which triggered the massive uprising of peasants (Zheng et al. 2014). More serious was that as the vegetation productivity was drastically reduced, the ecological balance was broken, and the rodents also could also not get enough food and therefore moved to the heart of the empire (Cao 1997). Refugees with the Black Death ravaged the northern part of the Ming Empire, killing more than 40% of the population (Cao 2000; Zheng et al. 2014). The consequence was the destruction of the social order and the economic base, greatly weakening the military power of the garrisons along the Great Wall (Cao 1997; Zheng et al. 2014). This produced weak resistance from garrisons along the Great wall to the attack on Beijing by Zhicheng Li's peasant army, which led to the downfall of the Ming Dynasty (Cao 1997). Thus, this reveals that the societal turbulence and fiscal deterioration were closely linked with the influences of climate deterioration during late Ming Dynasty, through the third possible pathway: climate deterioration → decline in agricultural production → food crisis for humans and rodents → epidemic outbreaks → rapid declining population → increase of social vulnerability. The influence of the plague on the Ming Dynasty may be even more deadly under relatively poorer hygienic sanitary conditions in ancient times.

4.3 Implication for management

The drying trend in northern China has been a wake-up call for many government agencies throughout the northern China (Ma and Fu 2006; Su et al. 2018; Zhao et al. 2021b). The late Ming Dynasty megadrought is an unprecedented severe event in the context of the precipitation reconstruction extending to 1590 CE. However, the characteristics of this megadrought have rarely been revealed in the past dendroclimatic studies. Of the 429 years of precipitation reconstruction, 70 years (16.3%) were categorized as "extremely dry" ($<$ mean $- 1\sigma$); however, no consecutive drought years (≥ 3 years) have occurred after the late Ming Dynasty, except for 1916–1918. Overall, these analyses suggest that severe, persistent droughts are not the defining feature of the hydroclimate along the northern monsoon fringe of China. The precipitation along the Great Wall of northern China is also shown to be nonstationary at interannual and interdecadal scales, making short-term instrumental records inappropriate for most planning and forecasting applications.

Although our reconstruction differed in some respects from those of Liu et al (2019b), some new climate information, such as the recent wetting trend and late Ming Dynasty megadrought, is provided. The long-term perspective provided by our tree-ring record shows that the monsoon fringe in northern China may have a sharp environmental deterioration due to some climate extreme events. This finding has even greater relevance today. With the rapid development of China's economy, demands in northern China over the past decades have risen to meet or exceed mean water availability (Shen et al. 2013; Liu et al. 2021a, b). Any variations or shifts in climate may have some significant influences on the fragile ecosystems. The sensitivity of fragile systems in northern China became abundantly clear with the onset of the recent drying under the background of global warming (Xu et al. 2018; Sun et al. 2021b). Although many measures have been taken in northern China to resist the impacts of climate change, such as South-to-North Water Diversion Project, these measures need to be tested because no consecutive droughts occurred during the recent decades. In the future, projected climate change, including warming-induced drought and more frequent monsoon failure (Yuan et al. 2019; Li et al. 2021; Piao et al. 2022), will likely compound risks of climate change throughout the entire northern China. In concert with information on long-term climate change, information on projected future changes must guide planning for sustainable development and drought management in northern China, if we are to adequately face the challenges of climate change that coming decades will undoubtedly present.

5 Conclusions

Based on a tree-ring width chronology of *Platycladus orientalis* from the northern Chinese Loess Plateau, a total June-April precipitation was reconstructed over the past 429 years. This new reconstruction provided a detailed picture of the precipitation variation in the northern Chinese Loess Plateau during the late Ming Dynasty, which has made it possible to assess the magnitude of the impacts produced by major droughts on agricultural civilization and in the ecological balance in ancient China. This work has shown that there was a long period of low precipitation that affected the northern Chinese Loess Plateau during the last stage of the Ming Dynasty. ENSO, cool temperatures, volcanic eruption, and other factors seem to have the combined effects on the regional precipitation variations, generating intense and prolonged droughts toward the end of the Ming Dynasty, coinciding with the Little Ice Age. The abnormally low precipitation-induced ecological imbalance in northern China severely disrupted the food supply, sustaining the large-scale peasant uprising and mass deaths produced by the Black Death. The resulting destruction of the political, social and economic order of the northern China forced the demise of the Ming Dynasty in just over 20 years.

Author contribution Conceptualization: FC and HM.

Methodology, validation, investigation, resources, writing—review and editing, and visualization: FC, HM, XZ, FR, HZ, YC, SW, and WY.

Formal analysis and data curation: FC, WY, and XZ.

Writing—original draft preparation: FC.

Supervision: FC and HM.

Project administration and funding acquisition: FC.

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Data availability Data can be made available on request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent to publish All authors consent to publish in the journal of “Climatic Change.”

Competing interests The authors declare no competing interests.

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