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Temperature and precipitation effects on agrarian economy in late imperial China

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Abstract

Climate change has been statistically proven to substantially influence the economy of early modern Europe, particularly in the long term. However, a detailed analysis of climate change and the economy of historical China remains lacking, particularly from a large-scale and quantitative perspective. This study quantitatively analyzes the relationship between climate change and the economy in late imperial China (AD 1600–1840) at the national level. This study also compares the findings on the relationship between climate change and the economy in late imperial China with those in early modern Europe. Results of multivariate regression and Granger causality analyses indicate that (1) climate change induces economic fluctuations in late imperial China, particularly in the long term; (2) given that the economic center is located in South China during the study period, temperature has a greater influence on the economy than precipitation; (3) the population of China is statistically proven to primarily act as consumers in the long term; and (4) given the long-term role of the Chinese population, the economic vulnerability in late imperial China under climate change is further increased and is higher than that in early modern Europe, whose population mainly acts as producers in the long term. In conclusion, the late imperial Chinese society has a high economic vulnerability to climate change. These findings revisit Malthusian theory and 'Great Divergence' theory by including the perspective of economic vulnerability under climate change during the study period. The role of the population must be investigated further to address the socioeconomic vulnerabilities under climate change.

1. Introduction

Climate change has become a major concern because of its capacity to trigger socioeconomic disasters (Zhang *et al* 2011). Therefore, evaluating economic vulnerability is a key step in addressing climate change (IPCC 2014). This premise is true particularly in the past when the agrarian economy was the pillar of societies with low technological levels (Galloway 1986). Climatic fluctuations are crucial to economic growth (Dell *et al* 2012). The relationship between climate change and the economy of early modern Europe (AD 1500–1800) has been statistically investigated recently (Pei *et al* 2013, 2014).

However, only a few studies have assessed the agrarian economy under climate change in historical China, particularly in a quantitative manner. Consequently, the economic vulnerability of agrarian China to climate change cannot be scientifically scrutinized. Previous research indicated that an investigation on a large geographic scale can help us understand the complex interactions between nature and the human society (MacDonald 1998). Therefore, this study focuses on the entirety of China at a national scale.

Furthermore, such large scale of whole nation could guarantee the data availability on historical China rather than at regional scale (supplementary information).

Population dynamics is another indispensable internal factor that influences economic changes in history (Aceleanu 2010). The population of the late imperial China has rapidly increased since the 17th century (Ho 1959). Based on Malthusian thought, population growth is frequently regarded to negatively affect socioeconomic development when explaining the history of China (Deng 2000). However, statistical analysis is scant regarding the effect of population pressure on the early Chinese agrarian economy, not to mention the quantitative comparison between climate change and demographic pressure. The fundamental mechanisms of climate change, agrarian economy, and population pressure in China have also been ignored, particularly in quantitative research.

We limit our study period to the late imperial China (AD 1600–1840), which has the advantage of having relatively rich data. Earlier periods are less certain and more fragmented because of their minimal and insufficient documentary records. This time span can be reasonably set within a specific socioeconomic formation. The analysis results can also be compared with those of previous studies on early modern Europe during a similar period (AD 1500–1800) (Pei *et al* 2013, 2014, 2015). Given that the population of China and Europe accounts for approximately 60% of the world population during the study period (McEvedy and Jones 1978), the comparison between these two regions is the most vibrant area in economic history (Little 2008). Therefore, this study quantitatively compares the late imperial China with early modern Europe in terms of the 'climate change–economy' relationship.

The findings are derived by using the statistical analysis method. This study is the first to quantitatively analyze the climate change–economy relationship of imperial China at the macroscale and to measure the influence of climate change and population pressure on the economy of late imperial China according to the statistical results. The analysis results provide statistical evidence to support and review the findings from previous research. This study initially compares the late imperial China and early modern Europe on the basis of the statistical results and then evaluates the similarities and differences of economic fluctuations across Eurasia under climate change.

This study quantitatively examines the relationship between climate change and the vulnerability of Chinese agrarian economy at the national and long-term scales. Therefore, this study neither focuses on individual incidents nor explains certain circumstances. Despite its limitations, this broad-brush approach can quantitatively establish a relationship between climate change and the long-term, large-scale agrarian economy in late imperial China.

2. Methodology and data

Multivariate regression analysis and Granger causality analysis (GCA) are applied in this study. Multivariate regression analysis can identify the role of each variable (Pindyck and Rubinfeld 1998) and the systematic interactions among all variables (Sanders and Smidt 2000). The regression analysis results indicate the basic impressions among climate change, agrarian economy, and population pressure in late imperial China. Given that no record on the inflation rate of the late imperial China exists, we apply the Prais–Winsten estimation method to address autoregressive disturbances and the flexible time trend (t, t^2, and t^3), which considers the possible long-term effects of inflation (Zhang *et al* 2011, Pei *et al* 2013). These methods have also been applied in the field of statistics to address time trend and autoregressive issues (Hamilton 1994).

The GCA is an effective method used to generate a causal relationship (Russo 2009). This method does not definitely suggest causality, but quantitatively supports causality analysis with statistical evidence (Zhang *et al* 2011). In this sense, GCA statistically indicates the quantitative closeness of the relationships among variables. Such statistical laws are considered important in interpreting historical laws based on numerous cases, but may be inapplicable to every specific case (Bunge 2009). For clarity, we only examine the causal mechanism from the perspective of statistical law. The supplementary information provides additional details on the GCA process.

The elements of long-term trends (low-frequency) and short-term disturbances comprise the time series of raw data, which contain unique information at diverse temporal scales (Assenmacher-Wesche and Gerlach 2008). We adopt the low-pass filter technique to estimate the trends from the time series (Pollock 2000). The Butterworth filter is adopted to smooth the data series into the long-term trend (low-frequency) by excluding short-term noises. This filter can also estimate cyclic economic dynamics to decrease the risk of inducing spurious results (Stove 1986).

Based on previous research, a 40 year low-pass filter is used to filter the data and to assess the general trend of climate change (Mann and Jones 2003). Within the 300 year study period, the 40 year low-pass filter also examines the effects of climate on the society and economy of early modern Europe (Zhang *et al* 2011, Pei *et al* 2014). Accordingly, the Butterworth filter is set to 40 years for the low-pass filter to examine the relationship between climate change and economy in late imperial China. Applying such filter will guarantee consistency in the comparison between the findings on late imperial China and those on early modern Europe.

Then, multivariate regression analysis and GCA are conducted on the raw and low-pass smoothed data. The influence of climate change and population

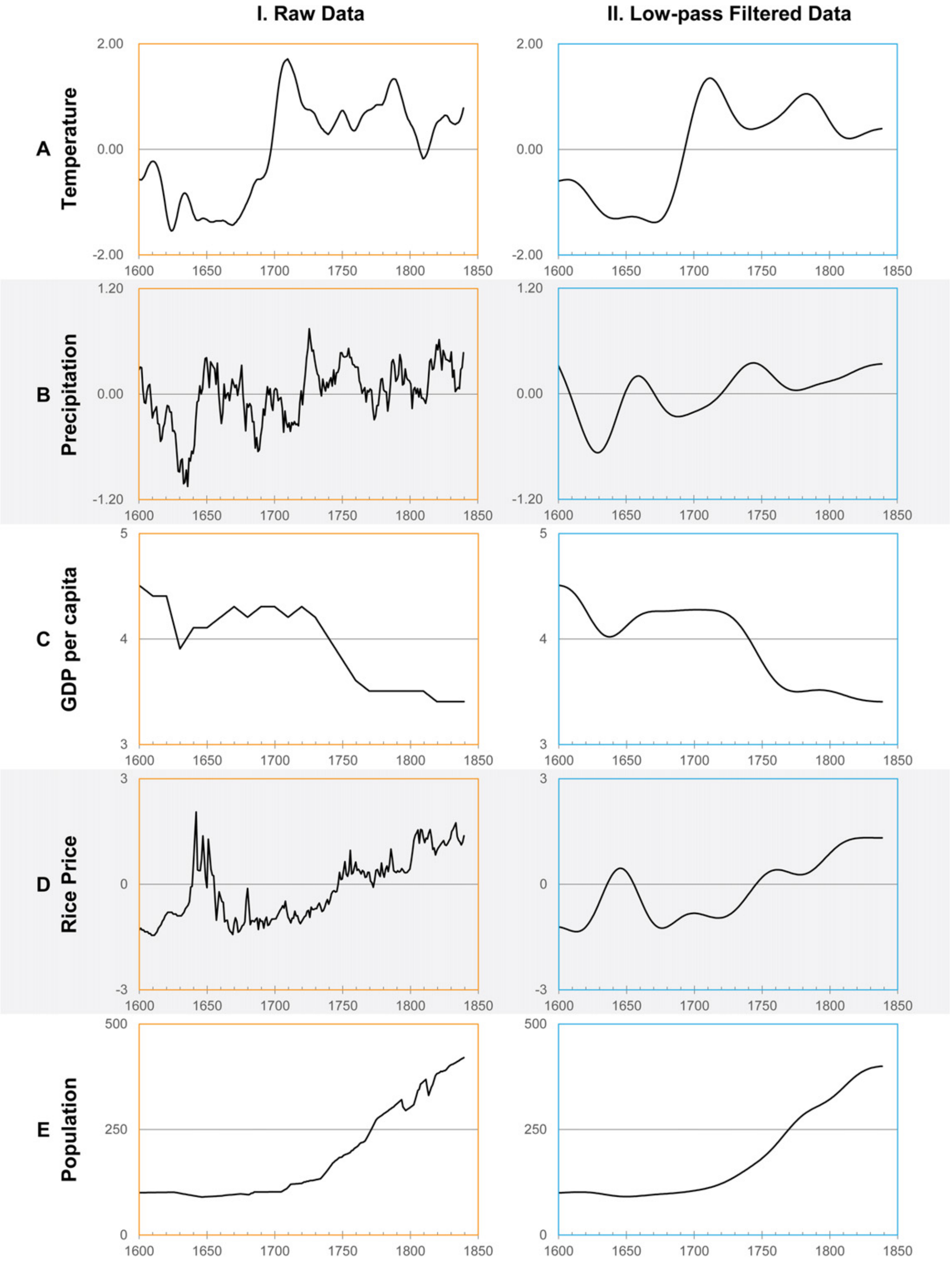

Figure 1. Raw and low-pass filtered data. Note: column I represents raw data, whereas column II represents low-pass filtered data. Row (A) represents temperature anomaly (°C), row (B) represents precipitation anomaly (mm), row (C) represents real GDP per capita (silver per tael), row (D) represents rice price index (gams of silver), and row (E) represents population size (million).

pressure on the agrarian economy will be identified via quantitative analysis within different temporal scales.

In order to guarantee data reliability, the data collected in this study have been either published in international refereed journals or confirmed by many scholars in their research, which will be discussed in the subsequent sections. The significance level is set to 0.05 (95%) in the analysis. Figure 1 shows the raw data and the 40 year low-pass filtered data.

2.1. Temperature

The temperature anomaly of this study is established from the two reconstructed temperature series by Yang *et al* (2002) and Shi *et al* (2012). The reconstruction of Yang *et al* (2002) comprises nine different proxies of the past 2000 years across the entire China, whereas that of Shi *et al* (2012) comprises a network of 415 well-distributed and accurately dated climatic proxy series. Both reconstructions include multi-proxies (e.g., ice cores and lake sediments) throughout China, which have been published in international refereed journals. These reconstructions are adopted as they cover the entire study period. The temperature anomaly observed by Yang *et al* is adopted as a reliable climatic indicator in investigating the relationship between climate change and social responses in historical China (Lee and Zhang 2013), whereas the temperature anomaly observed by Shi *et al* is reconstructed at an annual resolution. These two datasets are initially standardized and then arithmetically averaged to obtain the temperature anomaly in China. Please refer to the supplementary information for more details.

2.2. Precipitation

The precipitation anomaly of this study is established from the reconstructed precipitation series by Pei *et al* (2014) which is only based on documentary records. The reconstruction by historical records only could exclude other proxies with mixed temperature signals, such as tree rings (Liu *et al* 2005) and speleothems (Tan 2014), to reveal the pure signal of precipitation. The reconstructed precipitation series by Pei and Zhang (2014) has adopted a total of 27 documentary-based, single-proxy, and hydroclimatic reconstructions are synthesized because of the absence of China-wide paleo-precipitation data. The spatial and temporal abundance of historical records of weather events in China provides a good proxy network for detecting the variability of large-scale precipitation (Zhang *et al* 2015). Please refer to the supplementary information for more details.

2.3. Real gross domestic product (GDP) per capita (per person)

The real GDP per capita is an important indicator of the macroeconomic well-being and economic performance of a country (Stiglitz *et al* 2009). Although the historical economic datasets of ancient China are not well-compiled, real GDP per capita of historical China at the national scale has been developed recently by Liu (2009). Such achievement also has been highlighted by Professor Deng (2012) to prompt a quantitative investigation on the political economy of early modern China. Economists have further maintained their interest in the long-term relationship between population pressure and per capita output (Kelley 2001). The real economic data can eliminate the effects of the inflation rate over a long investigation period (Pindyck and Rubinfeld 1995). Therefore, given the availability of data, real GDP per capita is adopted as an essential economic indicator in this study.

2.4. Rice price

Data on the rice price index are obtained from the studies of Peng (1957) and Wang (2003) to examine the historical Chinese economy extensively. The dataset of Peng has been used in analyzing epidemics, economic well-being, and climate change (Pei *et al* 2015). Price is adopted as an essential economic indicator in analyzing early modern Europe (Pei *et al* 2013, 2014, 2015, 2015). The data series of Peng (1957) has also been used in the comparative study of Allen *et al* (2011) on the European and Chinese economies. The data series of Wang (2003) has been used to examine the past economic crisis in China (Glahn 1996). The quality of these price data has already been verified in previous research. During the study period (AD 1600–1840), only these two data series could cover the whole study period as shown in supplementary information. Therefore, so far, data of Peng (1957) as well as Wang (2003) are still two most reliable and widely adopted datasets with the longest duration (Cheung 2013).

The price series of Peng, which shows the rice market fluctuations in China, covers AD 961–1910, whereas that of Wang, which reflects the rice price in Yangtze Delta, the center of rice production in China, covers AD 1638–1935. The variations of rice price in the Yangtze Delta are closely linked to the rice price in the entire country. These two datasets are initially standardized and then arithmetically averaged according to the overlapping period to obtain the rice price index series.

Social organization is excluded from the analysis. Although we do not deny the importance of social organization before the 20th century (Zheng 2001), its influence on the economy is less important than that of climate change (Elvin 1973), particularly in the long term and in large-scale scenarios.

2.5. Population data

Population data are retrieved from the History of Chinese Population (Zhao and Xie 1988) to estimate the size of the historical Chinese population. We use the population series of Zhao and Xie, which has a higher resolution and reliability than the other series (Turchin 2006). The common logarithm of data points is obtained, linearly interpolated, and anti-logged to create an annual time series and to prevent any distortions in population growth rate resulting from data interpolation.

3. Analysis and results

This study aims to statistically examine the association between climate change and the vulnerability of Chinese agrarian economy at the national and long-term scales. The statistical results presented below are based on smoothed data. In the supplementary information, it provides the statistical results by raw data and the robustness test of our statistical results.

Table 1. Regression model on real GDP per capita (low-pass filtered data).

Variable	Coefficient	Standard error	t statistic	Sig.
Constant	−906.525	233.229	−3.887	0.000
Temperature	0.117	0.017	6.688	0.000
Precipitation	0.181	0.039	4.678	0.000
Population	−5.67E-06	7.840E-07	−7.235	0.000
t	1.662	0.401	4.149	0.000
t^2	−1.008E-03	2.290E-04	−4.411	0.000
t^3	2.04E-07	4.330E-08	4.698	0.000

Note: adjusted $R^2 = 0.934$.

Table 2. Regression model on rice price (low-pass filtered data).

Variable	Coefficient	Standard error	t statistic	Sig.
Constant	−1272.011	981.736	−1.296	0.196
Temperature	−0.253	0.073	−3.439	0.001
Precipitation	0.189	0.163	1.160	0.247
Population	1.23E-05	3.300E-06	3.710	0.000
t	2.113	1.686	1.253	0.211
t^2	−1.165E-03	9.620E-04	−1.211	0.227
t^3	2.13E-07	1.820E-07	1.166	0.245

Note: adjusted $R^2 = 0.799$.

Table 3. GCA results on climate change, agrarian economy, and population pressure (low-pass filtered data).

Null hypothesis	F statistic	Sig.
(1) Temperature does not Granger cause real GDP per capita	13.271	0.000
(2) Temperature does not Granger cause the rice price	4.932	0.027
(3) Precipitation does not Granger cause real GDP per capita	0.212	0.646
(4) Population does not Granger cause real GDP per capita	0.161	0.689
(5) Population does not Granger cause the rice price	2.829	0.094

3.1. Regression analysis of climate change, agrarian economy, and population pressure

The real GDP per capita of historical China is regarded as the combined result of different climate-related and society-related factors (Li and Zanden 2012). Table 1, which uses real GDP per capita as the dependent variable, shows that the coefficients of temperature, precipitation, and population are all significant ($p < 0.01$). As indicated by the positive regression coefficients, the real GDP per capita increases under higher temperature and more rainfall. The negative coefficient of population implies that a larger population size decreases the real GDP per capita.

Table 2, which uses rice price as the dependent variable, shows that only the coefficients of temperature and population are significant ($p < 0.01$). The negative coefficient of temperature indicates that the warm climate increases the supply of agricultural products in the market to avert any price increase. By contrast, the positive coefficient of population indicates that a larger population size increases the demand to increase the price in the market.

3.2. Verification of causal mechanisms

Based on previous studies, the climate change–economy relationship is an instantaneous relationship whose lag is set as 1 (Zhang *et al* 2011, Pei *et al* 2014). Notably, the GCA will not be implemented on precipitation and rice price because the regression analysis rejects the connection between these variables, which is the first step of the causality analysis (Schumm 1991).

As shown in table 3, the link of temperature–real GDP per capita and of temperature–rice price can pass the GCA ($p < 0.05$). Nevertheless, the links of population–real GDP per capita and population–rice price relationships cannot pass the GCA at all. The GCA results quantitatively indicate that the agrarian economy in late imperial China has a stronger link with temperature than with population.

3.3. Climate change and agrarian economy in late imperial China

The statistics show that climate change is more important to the agrarian economy than population pressure in late imperial China. However, the p value of GCA on the population–rice price relationship is 0.094 (table 3). Population change exhibits a slight influence on rice price though it cannot meet the significance criterion of 0.05 in the study.

Consequently, climate change dominates the real GDP per capita and rice price in the market, particularly in the long term, according to the regression analysis and GCA. Moreover, temperature has a greater influence than precipitation on the agrarian economy of the late imperial China. Precipitation is insignificant in the regression analysis with rice price and does not pass the GCA on real GDP per capita (table 3).

The less influence of precipitation may be triggered by the spatial location of the economic center. Rice is the major staple food of residents in southern China, where rainfall is more frequent than in other regions (Ren 1999). The economic center of the country is also mainly located in South China since the Song Dynasty. The bio-productivity of North China is primarily controlled by rainfall (Sternberg 2008), whereas that of South China is sustained by temperature (Zhang *et al* 2007). However, we do not refute the importance of rainfall in perturbing the economy in the regional and short term scale.

3.4. Special role of population in late imperial China

The population has two roles in the agrarian economy, namely, as producers and consumers. Table 2 shows that the population mainly acts as the consumer in China, which is manifested by the positive coefficient of population, of which more population will lead to higher rice price in the market. Only if population mainly acts as consumer, the more population will increase the demand in the market and result in price increase. However, the regression results do not imply that population in China did not act as producer at all in the past. The statistical results show that the role of the consumer exceeds the role of the producer in late imperial China in the long term. The major role of the population as the consumer has been accepted by different scholars (Elvin 1973, Huang 1990, Lee *et al* 1997). However, our study only attempts to support this notion by providing quantitative evidence. The figures and regression results all support the finding that the increased population during the study period have consumed more than what they have produced. In this regard, population increase dampened the buffering capacity of the economy in late imperial China, which is consistent with our statistical results. Eventually, economic scarcity is driven by climatic effects and population growth (Lee 2014).

Thus far, the majority of research on the economy of historical China is from the aspect of population pressure because of the unregulated population growth (Huang 1990). Productivity is only indirectly surveyed according to the wage in China (Allen *et al* 2011), which serves as an indicator of labor productivity (van Zanden 1999, Allen 2001). However, only a few studies have quantified the roles of the producer and consumer in the population of historical China. This work quantitatively supports the long-existing notion that the unsustainable population pressure in historical China (Elvin 1973) negatively affects the economy because of the long-term role of the population as the consumer. Consequently, the increased population resulted in the tension of resources in historical China (Lee *et al* 1997).

4. Discussion

4.1. Comparative analysis between late imperial China and early modern Europe

Climate change and economy in early modern Europe (AD 1500–1800) have been quantitatively investigated (Pei *et al* 2013, 2014, 2015). The late imperial China (AD 1600–1840) and early modern Europe (AD 1500–1800) are compared based on the quantitative results of previous studies and the current study.

First, climate change influenced the agrarian economy in late imperial China and early modern Europe. The climatic conditions in Europe and China show consistent regional patterns if examined at a multi-decadal scale (Jones and Mann 2004). Temperature also has a greater influence than precipitation in these two regions. Such similarities justify the general low levels of development in the early modern world (Clark 2007).

Second, the statistical analyses imply that the economy of early modern Europe has a higher buffering capacity than that of late imperial China. Despite short-term disturbances, the temperature–real GDP per capita relationship still passes the GCA, which quantitatively proves that climate change and economy in late imperial China has a tightly bound relationship. However, climate change is the determinant of macroeconomy in early modern Europe only in the long term (Pei *et al* 2014). This finding is consistent with the climate change–war relationship and the occurrence of five major population collapses in agrarian China over the past 1000 years (Lee *et al* 2009). However, only two population collapses have occurred in early modern Europe (McEvedy and Jones 1978).

Third, in the long term, the population of China mainly acts as the consumer, whereas that of Europe chiefly acts as the producer (Pei *et al* 2014). Therefore, the analysis of early modern Europe indicates that population growth may stimulate economic growth (Pleijt and Zanden 2013), which is not the case in historical China. The late imperial China also has a lower labor productivity than early modern Europe (Allen *et al* 2011). Such gap explains the different long-term development paths of these two regions (Zanden 2009). Although population pressure is not a

Table 4. Regression model with a crisis period on real GDP per capita (low-pass filtered data).

Variable	Coefficient	Standard error	t statistic	Sig.
Constant	−2025.625	241.158	−8.400	0.000
Temperature	0.148	0.016	9.454	0.000
Precipitation	0.386	0.042	9.279	0.000
Population	−2.48E-06	7.980E-07	−3.105	0.002
t	3.577	4.135E-01	8.650	0.000
t^2	−2.096E-03	2.360E-04	−8.900	0.000
t^3	4.09E-07	4.460E-08	9.173	0.000
Crisis	−0.229	0.027	−8.500	0.000

Note: adjusted $R^2 = 0.950$.

unique trigger, this factor may increase the economic vulnerability of the late imperial China under climate change.

4.2. Social crisis and economic development in historical China

The distinct historical short-term events during the study period deserve equal attention particularly because this period coincides with the transitional period of the Ming and Qing dynasties. A Chinese rebel leader named Zicheng Li established the Shun Dynasty in AD 1643 and overthrew the Ming Dynasty in the following year. Afterward, Manchu invaded and conquered the entirety of China. Such chaos did not end until AD 1662, when the 'Kang–Qian Heyday' or 'High Qing' began.

We include a dummy variable, *Crisis*, during the period of AD 1643–1662 into our multivariate regression on real GDP per capita, as shown in table 4, to justify the effect of social crisis on the national economy quantitatively. This variable takes the value of 0 or 1 to indicate the absence or presence of several categorical effects (Draper and Smith 1998). Therefore, the dummy variable *Crisis* is equal to 1 during the period of AD 1643–1662 and is equal to 0 for the remainder of the study period.

Table 4 shows that the dummy variable, *Crisis*, is significant. According to the statistical results, the national economy is also negatively affected by social crisis. Therefore, the rebellion of Zicheng Li and the invasion by the Manchus have resulted in an economic crisis during the transitional period of the Ming and Qing dynasties (Lorge 2005, Perdue 2005). Meanwhile, the *temperature*, *precipitation*, and *population* variables are all significant ($p < 0.01$). The adjusted R^2 in table 4 also increases, which quantitatively justifies the influence of social crisis on the agrarian economy in historical China during the study period.

5. Conclusion

This study analyzes the climate change–economy relationship in late imperial China quantitatively and compares the findings with those in early modern Europe. The underlying mechanisms of climate change, agrarian economy, and population pressure have been statistically investigated. However, this study does not necessarily yield 'environmental determinism' and does not refute other theories on agrarian China within differentiated temporal and spatial scales. Furthermore, some hidden variables might also determine the vulnerability of the agrarian economy, though it is currently attributed to climate change according to the statistical results in this study.

The study on economic vulnerability under climate change in late imperial China has theoretical and practical implications. The findings revisit the key notion of Malthusian theory, which assumes that an increased population pressure causes human misery and a decline in socioeconomic well-being (Malthus 1798). Malthus, Darwin, and many other ecologists merely focused on the role of population pressure, but ignored the effect of climate change. The fluctuations in economic well-being are triggered by climate change, particularly in the long term, although population pressure may increase the potential vulnerabilities of the economy under climate change.

In addition, the Chinese economy is arguably more advanced than pre-industrial Europe, although the Chinese economy did not emerge in a period of sustained modern economic development since the 18th century, which is named as 'Great Divergence' (Pomeranz 2000). Although climate change has been closely linked to socioeconomic development (Parker 2013), only a few studies have examined the role of climate change in explaining such divergences between the two regions. Statistical evidence also shows that the population in late imperial China is less productive than that in early modern Europe, which is essentially regarded as a key factor in explaining the divergences between these two regions along with technology, colonization, property institution, and other factors (Little 2008). Overall, this study not only provides statistical proof to existing theories on the 'Great Divergence', but also opens a new direction in investigating the divergences between late imperial China and early modern Europe under climate change.

Notably, the study clarified that it only provides the understandings on climate change and China's economy from the paradigm of climate history. However, we do not intend to deny the roles of other social-economic factors in Chinese history. Particularly, there should be more possible reasons which lead to 'Great Divergence' in Europe and China. While, our analysis is only aiming to open a new routine to understand such phenomena under impact of climate change and population's role in two regions as supplement based on statistical evidences. Last but not least, the study is implemented at a large spatial and long term scale. Each scale brings new problems and information coinciding with a new nature or social interface (Pei *et al* 2016). Besides being a research question at the research level, scale is also an issue of recognizing how our living planet has been regarded in history (Chaplin 2012). At the scale in the study, we could identify the significant influences of climate change on late imperial China. If the scale is narrowed down or shortened, other socio-economic factors should be considered, and their influences will possibly exceed those of climate change (Gibson *et al* 2000).

Detecting economic vulnerabilities is the first step in adapting to climate change. Many underdeveloped countries or regions continue to hold a development level similar to that of the late imperial China or early modern Europe. Therefore, our findings present several implications for the modern society. First, the level of vulnerabilities in one country or region may differ from those of the other countries or regions. The vulnerabilities in different regions within one country may also vary. Second, a large population size increases such vulnerabilities by decreasing the economic growth potential (Barro 1997). However, the role of population deserves equal attention as population size when examining socioeconomic vulnerability. For early modern Europe, a larger population size provided more labor. In these similar countries or regions, population pressure may accelerate technological innovation and boost the growth of agricultural production according to Boserup (1965). However, for the late imperial China and other similar countries, a larger population size will increase the burden on society and the vulnerability of an economy to climate change because the population mainly acts as the consumer. Notably, population pressure emanates from the size and role of the population. Overall, the size and role of the population must be considered when examining socioeconomic vulnerability to climate change.

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Authors' declaration

The authors declare no conflicts of interest.

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