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Epidemics in Ming and Qing China: Impacts of changes of climate and economic well-being

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ABSTRACT

We investigated the mechanism of epidemics with the impacts of climate change and socio-economic fluctuations in the Ming and Qing Dynasties in China (AD 1368–1901). Using long-term and high-quality datasets, this study is the first quantitative research that verifies the 'climate change → economy → epidemics' mechanism in historical China by statistical methods that include correlation analysis, Granger causality analysis, ARX, and Poisson-ARX modeling. The analysis provides the evidences that climate change could only fundamentally lead to the epidemics spread and occurrence, but the depressed economic well-being is the direct trigger of epidemics spread and occurrence at the national and long term scale in historical China. Moreover, statistical modeling shows that economic well-being is more important than population pressure in the mechanism of epidemics. However, population pressure remains a key element in determining the social vulnerability of the epidemics occurrence under climate change. Notably, the findings not only support adaptation theories but also enhance our confidence to address climatic shocks if economic buffering capacity can be promoted steadily. The findings can be a basis for scientists and policymakers in addressing global and regional environmental changes.

1. Introduction

Epidemics, as a threat to human health, have been highlighted by researchers exploring the impacts of climate change (K. R. Smith et al., 2014). In the current background of climate change literature, improving economic well-being remains a primary objective in order to prevent infectious diseases (Khasnis and Nettleman, 2005). However, studies that compare the influences of climate change and economic well-being in triggering infectious diseases are scarce (McMichael et al., 2006), mainly because of the absence of long-term and high-quality datasets (Patz et al., 2005). Here we analyze historical records of disease in order to explore long-term mechanism by which shocks of climate and economic factors affect epidemics (Lafferty, 2009).

China has numerous long-term historical records of epidemics, but only a few studies have examined epidemics as a consequence of climatic and economic change, especially in a quantitative manner. To fill the research gap, the history of epidemics in China has been investigated in relation to climate change and economic well-being. This study focuses not only on how climate change affects the occurrence of epidemics, but also on the role of economic well-being in this relationship between climate change and infectious diseases in historical China. The human buffering capacity is chiefly studied from the aspect of economy. Past research has shown that a large-scale geographic investigation can help us understand the complex interactions between nature and human society (MacDonald and Iain, 1998), and this is the approach we take. Therefore, the entirety of China is set as the study region.

The study period is delimited to the Ming and Qing Dynasties of China (i.e., AD 1368–1901), because there are relatively rich data available from this period. Documentary data on the period prior to these dynasties are minimal and insufficient, making its history less certain and more fragmented than our quantitative techniques require. Moreover, this time span can be reasonably associated with the specific socio-economic formation of imperial China to interpret the mechanism of epidemics at the national scale.

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The low levels of technology and technological advances were general problems in the pre-industrial periods of all world economies (Clark, 2007). Until AD 1910, China was still a country under control of emperor and the social development level cannot be compared to that of the western world. The Chinese economy was highly vulnerable to climate change during the study period. In fact, despite advances in technology, climate continues to affect modern society (Lobell et al., 2007; Oliver and Hidore, 2002). Although we do not deny the role of technological development in improving public health, in historical China its role was limited in preventing the public from getting infections.

Moreover, population dynamics are regarded as another indispensable internal factor in the development and well-being of society (Aceleanu, 2010). The population in imperial China increased rapidly, especially at the beginning of the Qing Dynasty (Ho, 1959). Based on Malthusian theory, population growth is frequently regarded as having a negative impact on social-economic development when explaining China's past (Chao, 1986; Mayhew, 2014). The major role of population as the consumer has been commonly accepted by different scholars (Elvin, 1973; Huang, 1990; J. Z. Lee et al., 1997). Thus far, the majority of research on the economy in historical China is from the aspect of the population pressure due to the unregulated population growth (Huang, 1990). Although these scholars acknowledge the potential for growth in the producing population to contribute to social development in historical China, scholars so far agree that the negative impact of consumption is the more important factor. The population increase could only add social burdens to historical China. However, we argue that there is little statistical support for extending this view about the influence of population pressure on epidemic occurrences in China's past. Moreover, the fundamental mechanism among climate change, agrarian economy, population pressure, and epidemic events has been ignored even further, particularly in a quantitative manner.

In addition to population pressure, human migration is another demographic factor potentially contributing to the spread of disease that should not be ignored (Wilson, 1995). However, scholars generally believe that the historical Chinese were reluctant to leave ancestral homes (J. Lee, 1978; Perdue, 2002). This reluctance is further supported by genetic survey of regional differences, which suggests a long history of moderate isolation among regions (Diamond, 1998). In light of this, we focus on the consequences for epidemics of demographic pressure arising from population size rather than migration.

Notably, although the social pressure due to the climate change could be released by the food trade system, historical China was always isolated from the rest of world. In AD 1371, the emperor proposed a policy to ban all maritime shipping and the Qing Dynasty emperors followed these bans (King, 1965). Poor transportation also hinders international or interregional collaboration (Pounds, 1979; Vries, 1976), together making it impossible to import food from outside world in order to smooth prices in the food market of China during the study period.

Based on the theoretical and historical materials just covered, we outline a conceptual model for this study, as shown in Fig. 1. The findings have been identified following the quantitative results in the study as our research aims to examine the mechanism of epidemics at the national and long-term scale. Scale thinking is fundamentally important in interpreting the climatic effect in the past agrarian society (Pei et al., 2014). Therefore, attention is focused on neither individual incidents that can temporarily and regionally affect the infectious diseases nor explaining some certain specific cases. Despite limitations, we believe that this broad-brush approach suits the scope of the present study and our interpretive goals.

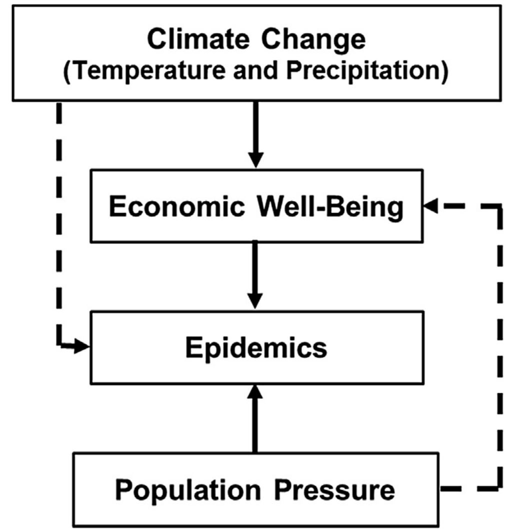

Fig. 1. Conceptual model of 'climate change → economy → epidemics' in historical China. Note: The arrows should be read as "change in X is associated with change in Y." The solid lines indicate that the two variables are significantly correlated and exist causal relationship. The dashed lines indicate that two variables are only significantly correlated.

2. Methodology and data

Correlation analysis, Granger causality analysis (GCA), ARX, and Poisson-ARX modeling are applied in this study. Extended details on the methodology beyond what is described in this section can be found in the Supplementary Information online.

Correlation analysis is a statistical process for estimating the relationships among variables. We have cross-correlated temperature, precipitation, rice price, epidemics and population.

GCA is an effective method to build a causal relationship (Russo, 2009), and it indicates the quantitative closeness of relations among variables. Although GCA does not definitely suggest causality, it is a method that quantitatively supports a proposed causal mechanism with statistical evidence (D. D. Zhang et al., 2011). In this sense, GCA more appropriately means the quantitative closeness of the relations among variables in statistics. Thus, GCA is only used to test the statistical strength among links as shown in Fig. 1. Statistical laws are likewise considered important in interpreting historical laws based on numerous cases, although statistical laws may be inapplicable to every specific case (Bunge, 2009). To clarify this we only name the causal mechanism and causal linkage in the study from the perspective of statistical law.

ARX is an autoregressive model with exogenous terms. This method is useful in simulating the influences of past self-conditions and external systems (Hamilton, 1994). ARX captures and reflects the variations of the time-changing system to meet theoretical and practical interests (Qin et al., 2010). This method has proven to be a useful tool to examine the short- and long-term consequences of climate change (Pei et al., 2013). Moreover, the ARX model is regarded as extremely suitable for control theories with simpler estimation in signal studies (Huusom et al., 2010). Therefore, through the application of ARX, we can identify the pattern of inner temporal dynamic mechanism of epidemics and external influences in historical China.

Notably, the data on epidemics are from historical documents and in the form of count data. Thus, the ARX model will be further implemented with Poisson regression, which is the most suitable method for treating and validating count data (Cameron and Trivedi, 1998). A Poisson regression is designed in a format of logarithm model (Brouhns et al., 2002). A Poisson–ARX model is established based on the ARX results.

2.1. Temperature

The temperature index (Fig. 2A) for this study was obtained from the latest reconstructed temperature series by Ge et al. (2013) on the basis of multi-proxies (e.g., ice cores and lake sediment) throughout China. Other temperature reconstructions have been conducted in China, for instance Tan et al. (2003) and Yi et al. (2012), but the spatial coverage of these studies failed to include the entire country. Furthermore, this reconstruction of paleoclimate by Ge et al. (2013) has been regarded as one representative climatic reconstruction in China (Mauelshagen, 2014).

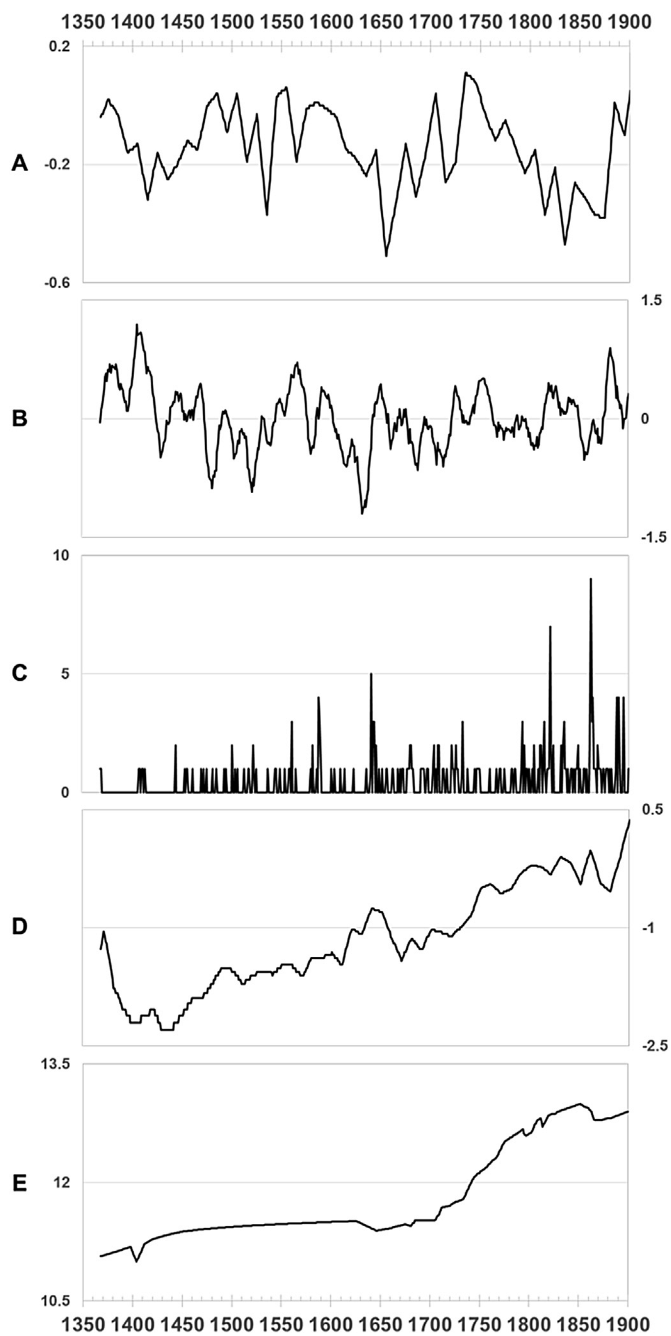

Fig. 2. (A) Temperature anomaly (°C), (B) Precipitation anomaly (mm), (C) Epidemics (number of incidents/yr), (D) ln(PRICE) (grams of silver per liter), and (E) ln(POPULATION) (10^3 person).

2.2. Precipitation

The precipitation data (Fig. 2B) for this study was obtained from the work of Pei et al. (2014), based on historical documents. In China, the spatial and temporal abundance of the historical records of weather events provides a good proxy network to detect the centennial variability of large-scale precipitation (D. E. Zhang, 1998). The adopted precipitation index with the annual resolution could well present the past wet–dry patterns of whole China at the national scale.

In terms of temperature and precipitation, these two indicators are all anomalies but not the instrumental records. In the field of paleoclimate study, the climate conditions are reconstructed based on different proxies, including tree ring, lake sediments, ice core, and so on (Mann et al., 2008, 2009). The reconstruction is always compared with instrumental records to verify the reliability, but it only is used to reflect the temperature or precipitation fluctuations (PAGES-2k-Consortium, 2013). We therefore use this divergences above and below modal conditions rather than direct climatic records as measured by instruments used in present day.

2.3. Epidemics

The dataset on epidemics (Fig. 2C) was derived from the chronological table of Sun (2004), based on historical records. The year of the outbreak and the magnitude of epidemic events have been recorded clearly. In total, 244 events were recorded during the study period. These epidemics records mainly include the infectious diseases that can be passed on through food, breathing, touching and so on. Based on these records, a general mechanism of epidemics could be identified by statistical analysis.

It should also be noted that China had a different medicine system from western societies. As a consequence, in the historical records, the ancient records only used “plague” or “epidemics” in these historical documentary records. Furthermore, due to the low level of medical treatment and because the modern Epidemiology only began in the 19th century with John Snow, it was also hard to name every kind of epidemic during the study period (Vachon, 2005). Therefore, the epidemics in the study generally imply all kinds of widespread and infectious diseases in historical China.

2.4. Rice price

The data on rice price (Fig. 2D) in this study were obtained from the work of Peng (1957), which has been used extensively in the historical study of the Chinese economy. The price series developed by Peng is from AD 961–1910, which shows the rice price fluctuations in China. We were unable to get data on the price of wheat in whole China for the study period. As a consequence, we use rice price data to represent whole Chinese economy. In fact, the rice has been spread to North China and taken as a staple food during the study period (Peng, 1957).

Following analyses of pre-industrial Europe (Pei et al., 2015a, 2014, 2013, 2015b; D. D. Zhang et al., 2011), we adopt price as an indicator of economic well-being in China. The high price reduces the consuming capacity, which dampens the economic well-being in the society. Consequently, the high price is negatively correlated with economic well-being, and vice versa. Available records and dietary importance make the price of rice a reasonable indicator of economic conditions in historical China.

Historical China in the period which we are examining was not a free market. Before the 20th century, the agrarian economy in

China was mainly dominated by household and lineage organization, which determines the local social and economic mechanisms (Wang, 2008). However, the buffering capacity of these family units to climate change was limited, especially in the past. Their food-pricing decisions were largely confined by the agricultural harvest conditions during the time (Elvin, 1973). While we do not deny the influence of demand or of those organizations on food prices, the price was mainly decided by the harvest (i.e., food supply), which was highly dependent on climatic conditions during this time.

2.5. Population data

The data on the size of the historical Chinese population (Fig. 2E) were retrieved from the *History of Chinese Population* by Zhao and Xie (1988) because it has a higher resolution than that of other researchers, such as Jiang (1993), and Cao (2000–2002). Furthermore, the population data of Zhao and Xie are evaluated and found to be the most reliable by other researchers (Turchin, 2006).

However, there are many missing data in the population records. In order to interpolate the missing data, the common logarithm of data points is obtained, linearly interpolated, and anti-logged to create an annual time series. This method prevents any distortions in the population growth rate originated from the process of linear data interpolation, because population growth follows exponential changes. The log transformation stabilizes the variances of these variables (Durbin et al., 2002). This practice of ours follows the traditional method of interpolation on missing population data (Galloway, 1986; D. D. Zhang et al., 2011).

3. Analysis and results

Rice price and population size are detrended by natural log to extract the real association among the assorted variables before the statistical analysis (Turchin, 2003). In fact, there are many methods to detrend data and each method has it special advantages and drawbacks (Hamilton, 1994). In our study, we aim to exclude the exponential trend by taking logarithm. Therefore, the log transformation could meet our aim and further stabilizes the variances of these variables (Durbin et al., 2002) to make them suitable for use in the regression (R. J. Smith, 1993; Tsiatis, 1990). Among different log transformation setting, the natural logarithmic transformation is commonly adopted in economics and other applied studies (Koop, 2005; Pemberton and Rau, 2007). Therefore, the price data and population data are taken as the natural log to exclude the trend of exponential increase.

3.1. Correlation analysis

As shown in Table 1, rice price is negatively and significantly correlated with temperature ($p < 0.01$) and precipitation ($p < 0.05$). As temperature anomalies grow more and more negative, the price of rice increases; lessened precipitation has the same effect at this national scale. Epidemic is negatively associated with temperature at the significance level of 0.01 but not with precipitation. Lower temperatures elevate the frequency of epidemics. The negative correlation results between agrarian economy and climate indicate that the rice market has sufficient supply to decrease price under warmer and wetter climate. Therefore, economic well-being improves. The negative correlation between epidemics and temperature also means that the warm climate could have decreased the occurrence of infectious disease in the past.

Second, both price and epidemics are positively correlated with population at the significance level of 0.01. The positive correlation between epidemics and population can only be explained by the observation that high population pressure increases the possibility of plague occurrence, as per Malthusian theory (Malthus, 1798). The positive correlation between price and population confirms that population increase could intensify market demand relative to supply, resulting in higher prices.

Third, the positive correlation between rice price and epidemics ($p < 0.01$) deserves full scrutiny. On the one hand, the high price makes food less affordable for the people. As a consequence, hunger and malnutrition increase the risk of infectious diseases (McMichael and Haines, 1997). On the other hand, infectious disease is also believed to dampen economic development (Bloom and Mahal, 1997; Lagerlöf, 2003). Through this second mechanism, an increase in epidemics deteriorates economic well-being, which is represented by high price level. The relation of economy and epidemics is further examined in Section 3.2.

3.2. Verification of causal linkages

Prior to GCA, the Augmented Dickey–Fuller (ADF) test is necessarily employed to check the stationarity of the time-series as the precondition assessment. If necessary, differencing is used to transform the time series into stationary ones (Thornton, 2001). This is also the common practice is the application of Granger causality analysis (Magnus and Fosu, 2008; Thornton, 1997, 2001). The detailed process of ADF test for differencing has been illustrated in Supplementary Information. The lag of GCA is set in two ways. The first method is based on the theoretical and empirical knowledge of relationships, such as instantaneous cause. The second method is based on statistical criteria for others (Granger, 1988; Saunders, 1988). Based on whether lag selections following theoretical background or statistical criteria, we categorize our causal linkages (null hypotheses) into two groups. The causal linkages in Group 1 materialize almost instantaneously, and the time lag for GCA is set to 1 (D. D. Zhang et al., 2011). For Group 2, Akaike's information criterion is adopted as the statistical criterion to determine the appropriate lag length (Akaike, 1974). More details on ADF test and lag selection are shown in Tables S1–S3 in Supplementary Information.

Table 1
Correlation analysis on climate change, economy population, and epidemics.

	Precipitation	Temperature	ln(Price)	ln(Population)
Epidemics	−0.018	−0.145***	0.280***	0.264***
Precipitation		0.076*	−0.097**	−0.003
Temperature			−0.229***	−0.301***
ln(Price)				0.882***

*** Correlation is significant at 0.01 level (2-tailed).
** Correlation is significant at 0.05 level (2-tailed).

Causal linkages (null hypotheses)
Group 1
(1) TEMPERATURE does not Granger Cause ln(PRICE)
(2) PRECIPITATION does not Granger Cause ln(PRICE)
(3) ln(POPULATION) does not Granger Cause ln(PRICE)
Group 2
(1) TEMPERATURE does not Granger Cause EPIDEMICS
(2) ln(PRICE) does not Granger Cause EPIDEMICS
(3) ln(POPULATION) does not Granger Cause EPIDEMICS
(4) EPIDEMICS does not Granger Cause ln(PRICE)

Table 2
GCA results on temperature, precipitation, and price.

Null hypothesis	F-statistic	Prob.
TEMPERATURE does not Granger Cause ln(PRICE)	25.166	0.000
PRECIPITATION does not Granger Cause ln(PRICE)#	1.662	0.198
ln(POPULATION) does not Granger Cause ln(PRICE)#	0.949	0.330

Notes: # means 1st differencing.

Table 3
GCA results on temperature, population, price, and epidemics.

Null hypothesis	F-statistic	Prob.
TEMPERATURE does not Granger Cause EPIDEMICS#	1.317	0.193
ln(PRICE) does not Granger Cause EPIDEMICS	7.312	0.000
ln(POPULATION) does not Granger Cause EPIDEMICS ^	2.125	0.006
EPIDEMICS does not Granger Cause ln(PRICE)	0.159	0.959

Notes: # means 1st differencing; ^ means 2nd differencing.

In Table 2, temperature–price rejects the null hypothesis but precipitation–price and population–price cannot reject the hypothesis at 0.01 significant level. In Table 3, both price–epidemics and population–epidemics reject the null hypothesis but temperature–epidemics and epidemics–price cannot even at the 0.1 significant level. If the link pass the GCA, the results will imply a close linkage between two variables in a statistical perspective. In this regard, the GCA results from Tables 2 and 3 quantitatively indicate that temperature cannot lead to the occurrence of epidemics directly even though temperature closely affects economy. Therefore, in Fig. 1, temperature and economic well-being are connected in bold lines, but temperature and epidemics are only linked by dash line. In contrast, the tighter bonds exist among economic well-being, population pressure, and epidemics which have been statistically verified. Thus, economic well-being-epidemics, and population-epidemics are connected in the format of bold lines. Overall, based on the analysis in Sections 3.1 and 3.2, the conceptual model of study as shown in Fig. 1 has been statistically verified.

3.3. ARX and Poisson–ARX modeling

Based on the conceptual model, the quantitative relationship among climate change, economic well-being, population pressure and epidemics will be constructed. Among various test methods, the autocorrelation function (ACF) and the partial autocorrelation function (PACF) are useful in checking the data series over different periods to summarize properties in the time domain (Harvey, 1993). Based on the ACF/PACF in Fig. 3, epidemics show autocorrelation and ARX (2) is finally set, as shown in Table 4. Poisson–ARX (2) is formulated based on the results of ARX (2) modeling, as shown in Table 5. Please refer to Supplementary Information for detailed process of calculation and model selection.

ARX (2) and Poisson–ARX (2) are calculated in the following three formats: (1) epidemics-price, (2) epidemics-population; and (3) epidemics-(price and population), of the links including epidemics which pass GCA as shown in Tables 2 and 3. Based on the results of ARX (2) and Poisson–ARX (2) modeling, we demonstrate that increased price and population size lead to increase in epidemics, following Models 1 and 2 of Tables 4 and 5. The higher the rice price is, the worse the economic well-being will be. Therefore, economy degradation with scarce food supply increases the occurrence of epidemics. The accumulated population pressure also increases the risk of epidemics. However, if we include both price and population in the modeling, only the coefficient of price is significant and that of population is insignificant in Model 3 of Tables 4 and 5.

4. Discussion

4.1. Epidemics, climate change, and economic well-being in Ming and Qing China

The results of the correlation analysis and GCA in Tables 1–3 indicate that climate change has a stronger association with economy than with epidemics. Climate change has been regarded as a significant factor in triggering historical epidemics, but climate change is only the ultimate cause of increased occurrence of epidemics in Ming and Qing China. The direct cause of epidemics is economic well-being. A strong economic buffering capacity of a society would result in minimal increase in epidemics under climatic impacts.

This case in Ming and Qing China is also similar to that of pre-industrial Europe (AD 1500–1800), that is, climate change is not the direct trigger of social disasters in the historical society of Europe (D. D. Zhang et al., 2011). Several infectious agents are

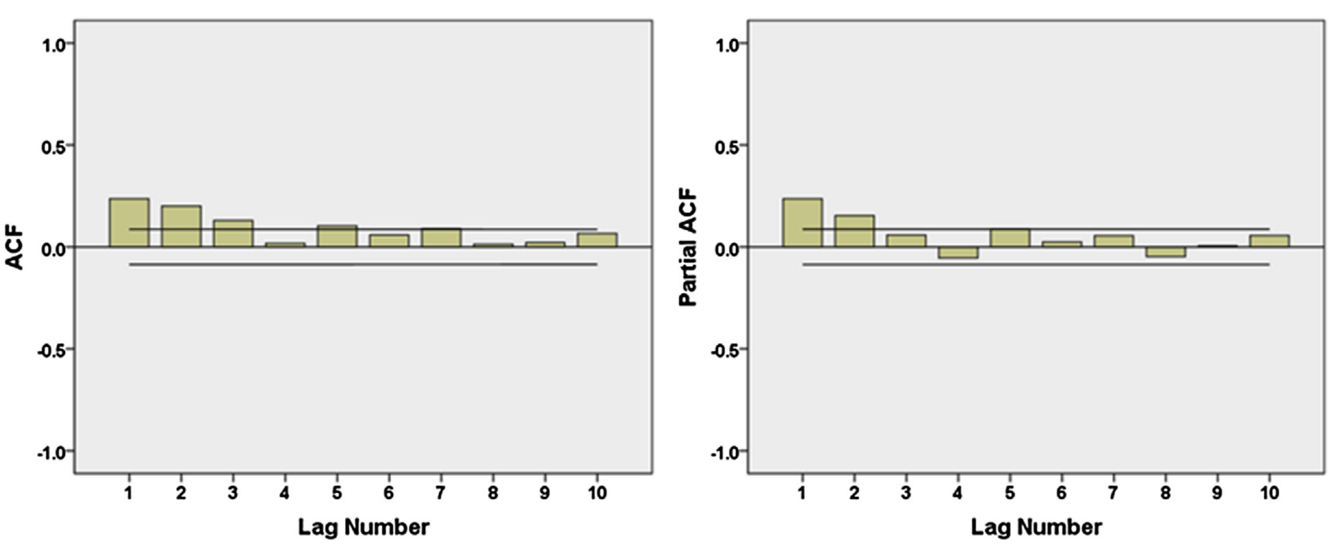

Fig. 3. ACF and PACF test results on epidemics.

Table 4
Coefficients of ARX (2) model.

		Model 1	Model 2	Model 3
Constant		0.894***	−4.125***	−0.531
Epidemics	AR 1	0.153***	0.159***	0.152***
	AR 2	0.107**	0.113***	0.106**
ln(Price)		0.381***	–	0.290*
ln(Population)		–	0.388***	0.112

*** Coefficient is significant at 0.01 level (2-tailed).
** Coefficient is significant at 0.05 level (2-tailed).
* Coefficient is significant at 0.1 level (2-tailed).
Model 1 indicates ARX (2) model: Epidemics−ln(Price).
Model 2 indicates ARX (2) model: Epidemics−ln(Population).
Model 3 indicates ARX (2) model: Epidemics−ln(Price) + ln(Population).

Table 5
Coefficients of Poisson−ARX (2) model.

		Model 1	Model 2	Model 3
Constant		−0.259**	−8.224***	−0.845
Epidemics	AR 1	0.153***	0.164***	0.154***
	AR 2	0.114**	0.125***	0.115**
ln(Price)		0.723***	–	0.804***
ln(Population)		–	0.607***	−0.086

*** Coefficient is significant at 0.01 level (2-tailed).
** Coefficient is significant at 0.05 level (2-tailed).
* Coefficient is significant at 0.1 level (2-tailed).
Model 1 indicates Poisson−ARX (2) model: Epidemics−ln(Price).
Model 2 indicates Poisson−ARX (2) model: Epidemics−ln(Population).
Model 3 indicates Poisson−ARX (2) model: Epidemics−ln(Price) + ln(Population).

particularly sensitive to climatic conditions (McMichael et al., 2006). However, the socio-economic circumstances, such as economic well-being, can promote certain measures that inhibit the transmission of infectious disease (Martens et al., 1999). The spread of epidemics in human communities is co-determined by ecological and socio-economic aspects (Jones et al., 2008).

Based on Tables 1 and 2, economic well-being is only dependent on external system to human society, i.e. climate, in historical China, whereas population change is only correlated with but cannot lead fluctuations in economic well-being. If the impact of climate change exceeds the buffering capacity of the economy, measured by price and consequent food stress, the influence of climate change is transmitted to induce further epidemic occurrence. Agrarian economy is the transitional element between climate change and epidemics. The study justifies that the social buffering capacity could mitigate climatic shocks in the past by combining the quantitative evidence in both historical China and Europe.

Notably, temperature is more influential to economic well-being than precipitation. Precipitation is significantly correlated with rice price, as shown in Table 1. However, precipitation cannot pass the GCA, as shown in Table 2. Precipitation is significantly correlated with price, but the correlation value between price and precipitation is less than that of price and temperature. This reduced importance of precipitation may be attributed to the economic and demographic center in space. Rice is the major staple food of the residents in Southern China, which has more rainfall than other regions in the country (Ren, 1999). It is the reality of China, not only for the past, but also at present (Talhelm et al., 2014). Moreover, Southern China has been the economic and demographic center of China since the Song Dynasty. The bio-productivity of North China is primarily controlled by precipitation (Begzsurena et al., 2004; Sternberg, 2008), whereas that of South China is sustained by temperature (D. D. Zhang et al., 2007). In spite of this, we can still find the importance of precipitation in affecting price of rice according to Table 1. The correlation between precipitation and price of rice is significant at the level of 0.05. Overall, temperature is generally more influential to economic well-being than precipitation in the long term and national studies. However, the current study still recognizes the importance of rainfall both in the short term and at the regional scale.

4.2. Epidemics, economic well-being, and population pressure in Ming and Qing China

In addition to the attention on the link between epidemic mechanisms and climate change (from external systems in nature), the link between epidemic mechanisms and social systems is discussed in this section. In Table 3, pairwise GCA is performed to systematically verify the relationship of economic well-being and epidemics. The null hypothesis that economic well-being does not Granger cause epidemics is rejected at the significance level of 0.01, but the hypothesis that epidemics does not Granger cause economic well-being cannot be rejected. Therefore, economic well-being is the Granger cause of epidemics, but the opposite is not true. The economic fluctuations lead to the dynamic changes in the mechanism of epidemics. Again, GCA is only used as a method to show the statistical closeness among each link, as shown in Fig. 1. Finally, the study has proposed and statistically verified the mechanism 'climate change → economy → epidemics' which has never been proven in historical China, particularly in a quantitative way.

Furthermore, the study also evaluates the role of economic well-being and population in affecting plague in historical China. Population is consistently considered critical in triggering epidemics and other demographic crises (Malthus, 1798). Based on the results of Tables 1 and 3, the importance of both economic well-being and population pressure in inducing the occurrence of epidemics has been proven. Notably, the results of ARX and Poisson−ARX modeling also indicate the importance of economic well-being and population pressure in Tables 4 and 5, but the modeling results justify that economic well-being is more essential than population in the occurrence of epidemics.

As shown in Models 1 and 2 of Tables 4 and 5, if either price or population is included, the coefficients of these two variables are significant at the 0.01 level. However, if both price and population are included in the ARX and Poisson−ARX modeling, as shown in Model 3 of Tables 4 and 5, only price is significant at the level of 0.1 but population is not. Certainly, we should not neglect the high correlated relationship between price and population, as shown in Table 1 ($r = 0.882$). The high correlation value always leads to mulicollinearity in statistical modeling (Hayashi, 2000). Despite that, based on the statistical results, we can conclude that if both price and population are included in the models, epidemics are mainly explained by price but not population.

In fact, multicollinearity between price and population is also grounded in theory, in addition to statistical data structures. The agrarian market in the past was mainly determined by climatic conditions, though population could also affect the price mechanism as both producer and consumer (Pei et al., 2014). The high price in the past society implied poorer economic well-being (Pei et al., 2013) and would negatively affect population increase, because economic well-being has been proven to contribute to population increase in pre-industrial era (D. D. Zhang et al., 2011). Such relation between economic well-being and population change is also true in modern societies (Haines et al., 2006). Thus, the economic well-being chiefly contributes to epidemics. However, the increase in population size still raises the social vulnerabilities of the occurrence of epidemics under climate change but has less importance than economic well-being. We note that our study does not refute other theories about the importance of population pressures that lead to epidemics within differentiated temporal and spatial scales.

5. Conclusion

This study is the first to raise and quantitatively verify the mechanism 'climate change → economy → epidemics' in historical China. The analysis provides the evidences that climate change could only fundamentally lead to the epidemics spread and occurrence, but the worse economic well-being is the direct trigger of epidemics spread and occurrence at the national and long term scale in historical China. Moreover, our statistical modeling shows that economic well-being is more important than population pressure in the array of factors influence epidemic frequency. Nevertheless, the increase in the population size raises the social vulnerabilities of the occurrence of epidemics under climate change. Each of these results pertains to the national scale, and may or may not transfer to the situation at different temporal and spatial scales Furthermore, the potential role of population movement in triggering epidemics deserves further investigation despite the reluctance of citizens in China to migrate.

The study on economic mechanism 'climate change → economy → epidemics' in historical China has both theoretical and practical implications. First, the findings of large-scale study provide quantitative evidence on epidemics in historical China, which can be a basis of research in other regions or countries. Furthermore, the study can help re-interpret the relationships of climate–human and economy–epidemics in historical China, particularly with statistical evidence to solve the uncertainties in the research on epidemics due to the absence of long-term and high-quality datasets (Patz et al., 2005).

Second, the study also provides quantitative evidence from historical China to support the theory of historical adaptation to climate change. Adaptive capacity is closely linked to social and economic development (Adger et al., 2007). If economic development is adequate, sufficient buffering capacity to tackle climate change is more likely to be available.

Third, the findings can revisit the key notion of Malthusian theory, which assumes that increased population pressure caused human misery and diminished socio-economic well-being (Malthus, 1798). Malthus and some scholars following in his footsteps neglect the effect of climate change. According to our quantitative study, the fluctuations in economic well-being are triggered by climate change, especially in long term. Besides, although population pressure remains essential in determining the social vulnerability of the occurrence of epidemics under climate change, our study proves that economic well-being is more important than demographic pressure.

Analysis of the Chinese records not only supports the theories of adaptation but also enhances our confidence that one means of addressing the climatic impacts is to steadily promote economic buffering capacity. This is important because we face uncertainly about changes in climatic conditions. Certain countries and regions of the world may still share agricultural and socio-economic circumstances similar to those of historical China. Our study suggests that climate change will not induce the increase in epidemics directly if the local economy has sufficient buffering capacity. Therefore, economic buffering capacity should be the first aim in these countries or regions, which decreases the possibility of the spread of epidemics. Verified linkage of 'climate change → economy → epidemics' in historical China can be used by scientists and policymakers as basis for addressing global and regional environmental challenges.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.socscimed.2015.05.010.

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