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Climate Change, Food Shortage and War: A Quantitative Case Study in China during 1500 – 1800

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ABSTRACT

Although global warming and its future possible consequences for human societies have been thoroughly examined in recent years, quantitative studies about the notable effects of climate changes upon human societies in history are almost absent. Recently, the authors scientifically explored the relationship between climate change and wars by comparing high-resolution paleo-climate reconstructions with known war incidences in history. They found that in most of the geographic regions worldwide war frequencies showed a cyclic pattern that closely followed the paleo-temperature changes. In this research, the authors proposed a conceptual model to exemplify how climatic fluctuations are translated into war peace cycles via socio-economic mechanism, with China during 1500 – 1800 to be a case study. The model was quantitatively verified by time series analysis and Pearson's correlation analysis. Statistical results confirmed that, cooling impeded agricultural production brought about a series of social problems including food price inflation, then successively war outbreak, famine and population decline. The findings indicate that war-peace, population and price cycles in agrarian societies in recent centuries have been driven mainly by long-term climate change, which may challenge those socio-economic theories about historical cycles, human demography and wars. The observed temperature-war relationship may give some indication of future societal impacts from climate warming.

Key words: Zhang, Lee, China, Climate Change, Food Shortage, War

INTRODUCTION

There are many studies indicating that climate change will induce a series of human-ecological crises at the global scale. For instance, Lobell *et al.*(2008) suggest that due to climate change, South Africa could lose more than 30% of its main crop (i.e. maize) by 2030. In South Asia losses of many regional staples, such as rice, millet and maize could reach 10%. Burke *et al.* (2009) indicate that warmer years leading to significant increases in the likelihood of war. When combined with climate model projections of future temperature trends, this historical response to temperature suggests a roughly 54% increase in armed conflict incidence by 2030, or an additional 393,000 battle deaths if future wars are as deadly as recent wars. However, most of their research findings are based on estimations according to some biological, economic and social models.

In unison, there are few pieces of quantitative and scientific evidences proving that climate change induced global disasters in the history. This may be a big knowledge gap because the available information is highly pertinent in evaluating the possible human-ecological crises brought by the recent climate change. In recent years, the effects of climate change and the outbreak of war and population decline in the pre-industrial era have been explored quantitatively. It has been found that long-term fluctuation of war frequency and population changes followed the cycles of temperature change (Zhang *et al.*, 2007a). However, the linkage between climate change, war and population is still preliminarily investigated. This research sought to further examine the linkage and the mechanism behind in details.

THEORETICAL FRAMEWORK

Climate change, human and ecosystem are interrelated. Their interaction takes place at a macro-scale, which is materialized via the fluctuation of land carrying capacity. To human societies, land carrying capacity is primarily determined by the amount of agricultural production (Hopfenberg, 2003), which is contingent upon climatic condition (Bryson & Murray, 1977). Briefly, land carrying capacity will shrink significantly in a deteriorating climate, and vice versa. This relationship is particularly true in pre-industrial era when technology was backward (Galloway, 1986; Lee *et al.*, 2008; Lee *et al.*, 2009).

Based upon previous research findings (Zhang *et al.*, 2007a), a simple conceptual model has been established to explain how climate change affects agricultural production, food supply per capita, population and wars (Fig. 1). The model posits that climate change directly affects land carrying capacity. Climate change affects the length of growing seasons, the intensity of average summer warmth and the reliability of rainfall. In addition, a lengthy cooling period will lower the elevation at which crops can be grown, thus decreasing the amount of land available for cultivation and leading either to a decline in total output or to more intensive cultivation but with lower yields. Lower yields may result from the biological inability of certain grains to effectively withstand cooler temperatures and the associated variability in short-term weather patterns (Bryson & Murray, 1977; Galloway, 1986). Unfavorable climate would not only directly hamper agricultural production, but also impede the means of boosting agricultural productivity (Fang, 1993).

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Fluctuation of agricultural production will in turn affect the food supply per capita. When the food supply per capita decreases, food shortage occurs. This may increase the number of conflicts over food resources and/or intensify any pre-existing societal conflicts. In history, most of these conflicts were eventually developed into wars. Together with wars, famines and epidemics will become more frequent. All of these Malthusian checks (i.e. wars, famines and epidemics) lead to the reduction of population size at the end. As a feedback, population reduction results in an increase of the food supply per capita. Subsequently, society will become relatively stable, accompanied with rapid population growth. It was hypothesized that the interactions among these components within the human-ecosystem determine the rhythm of war-peace cycles in agricultural societies.

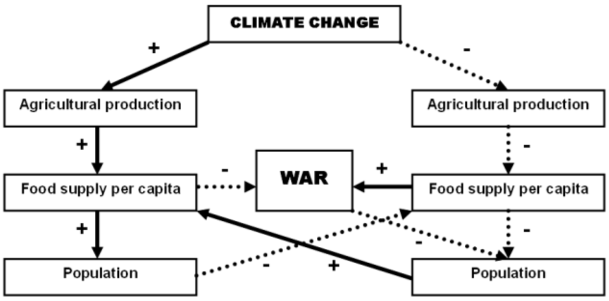

Figure (1): Model for long-term climatic fluctuations and social stability in China in the pre-industrial era. Solid arrow indicates positive linkage; dotted arrow indicates negative linkage.

STUDY AREA AND STUDY PERIOD

In China, climate expresses itself explicitly in landscapes of the country and the modes of human occupancy and livelihood. The effect of climate has had the most far-reaching and persistent historical consequences (Chang, 1946). At the same time, China is characterized by a long history of civilization. There are voluminous documentations in the palaces of different dynasties that systematically record all the major events in China. This valuable documentary compilation contains rich information about the changes in climate, ecology, economy, social stability and population history. Therefore, China was chosen to be the present study area for examining the climate-society relationship.

The study period has been delimited to 1500-1800, the time when China's economic activities were primarily dominated by agricultural production. Besides, there are relatively abundant data for climate, socioeconomic and population changes in this period. The period contains the significant alternation of order and disorder. The time of order is the Kangqian Harmony in the 18th century, which is one of the longest peaceful times in Chinese history. The time of disorder is the transition from Ming to Qing dynasty in the 17th century. Furthermore, the period 1500–1800 is also marked by considerable climate change, as the 17th century was the coldest phase in the Little Ice Age (c. 1400 –1900) (Zhang *et al.*, 2006). This provides an ideal setting for us to verify our conceptual model.

MATERIALS AND METHODS

To verify the linkage between climate change, food shortage and war in the pre-industrial era (Fig. 1), a quantitative approach and macro-historic perspective have been adopted. Besides, Pearson's correlation analysis was employed to examine the cross correlations among the various components in the model. In addition, the documentary evidence from various studies was used to support the quantitative analyses. The data used in this research are described as follows:

Climate change

Research in the past ten years has resulted in a number of high-resolution paleo-climate reconstructions spanned the last millennium, especially for the Northern Hemisphere. The time resolution of those reconstructtions reaches the decadal to annual units, which are useful to reflect the decadal to centennial change of land surface temperature in the past. The climate change data were obtained from Yang *et al.*, (2002) China temperature anomaly series, which is one of the most recent and authoritative works about the paleo-temperature in China (Fig. 2).

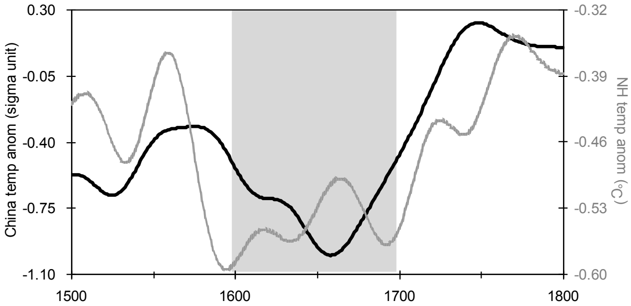

Figure (2): China temperature anomaly (in sigma unit) (bold black line, corresponds to the left Y-axis) and NH temperature anomaly (in °C) (grey line, corresponds to the right Y-axis) during 1500 – 1800. All data were smoothed by 40-year Butterworth low-pass filter. Grey shadow represents a cold climate.

This paleo-temperature series spanned over the last two millennia. It was derived from recent paleo-climate researches from different research groups. The time resolution of Yang *et al.*, (2002) reconstruction is in 10-year units. Their temperature series closely matches other independent research results about the paleo-temperature in China (Wang *et al.*, 2001; Ge *et al.*, 2003). This indicates a high degree of accuracy with reference to both temperature and timing, which provides a solid ground for this research. The Northern Hemispheric temperature anomaly series was included in this study for comparison (Fig. 2). It was derived from the arithmetical averaging of 12 recent paleo-temperature reconstructions of the Northern Hemisphere (derived from multiple climate proxy records), which were chosen by the experts from the Intergovernmental Panel on Climate Change (IPCC, 2007). The Northern Hemispheric temperature series is in annual units.

Agricultural production and food supply per capita

Rice has been the most important food crop in China since thousands of years ago. Therefore, rice price was taken to be a proxy representing the "food supply per capita" in the provided model. Historical rice price data for the early pre-industrial era are hardly available. It was not until the Ming dynasty (c. 1368–1644) some of the socio-economic records started to be kept systematically. In this research, rice price data (in 10-year units) were elicited from Peng, (1965).

The fluctuations of food price mainly reflect the variations of demand (population size) and supply (agricultural production). When both the population size and food price data are available, the amount of agricultural production can be calculated. In reference to Zhang *et al.*, (2007a), the amount of agricultural production was calculated as follows: as the rice price inflated over time due to increasing circulation of money in the economy, they were linearly detrended to get the "real price". Then, the detrended rice price was converted into positive numbers by adding positive integers. Based on the interrelationship among supply (agricultural production), demand (population size), and price (equilibrium point of supply and demand), the population size was divided by the "positive" rice price to obtain the amount of agricultural production agricultural production index. The index is in annual units, which serves as the proxy of "agricultural production" in the provided model.

Population

Based on Chinese historical materials, several scholars have endeavoured to get the best possible historical estimates of Chinese population size within the current political boundary of China. Although they disagree over the precise population size at high and low points, they are in agreement over the timing and direction of change, which is critically important to this study. Population data were extracted from Jiang, (1993). This set of population data has been used in some previous studies (Zhang *et al.*, 2006; Zhang *et al.*, 2007a). As the population data are at irregular time intervals, the common logarithm of the data points was taken, linearly interpolated and then anti-logged back, to create an annual time series. This method avoids any distortions of the population growth rate resulting from the data interpolation process.

War

A research team of the Nanjing Academy of Military Sciences, based on thousands of historical documents, compiled a multi-volume compendium which exhaustively records information on the wars that took place in China from 800 BC to 1911 (Editorial Committee of Chinese Military History, 1985). War data of the present study was elicited from the appendix of this reference. To avoid bias that might result from the diverse sources of information, only the year of inception, number of the wars and the involved parties from this authoritative treatise are used as reliable data for scientific analysis in the present study. There are five hundred and thirty six wars listed in the book for the period 1500–1800, out of which 229 are rebellions. These data have been converted into war and rebellion time series respectively, which are in annual units. Lee, (1933) compiled a time series of wars in China (in 10-year units) since Qin dynasty (c. 221–206 BC), which included only for comparison because the data sources of Lee's war record are not clearly specified.

Data processing

In order to facilitate data analysis, the time resolution of the above datasets was standardized. Those data which are not in annual resolution (e.g. China temperature, rice price and the number of wars recorded by Lee, 1933) were linearly interpolated into annual units. Given that paleo-temperature is usually examined in terms of its 40-year cycle (Mann & Jones, 2003), all of the time series data were smoothed by the Butterworth 40-year low pass filter to remove the noise from the data. In this instance, the 40-year cycle of the variables could be elicited and then they could be compared among themselves (see Zhang *et al.*, 2007a for details). Furthermore, in order to compare between different variables and assess the "real influence" of one variable on another over time, it is essential to remove the long-term trend (Galloway, 1986; Galloway, 1988). Therefore, those series with obvious trend (e.g. agricultural production index, rice price and population size) were linearly detrended.

RESULTS

Temperature change and food shortage

The temperature series of China shows that there were two mild phases (16th and 18th centuries) separated by a cold phase (17th century) during 1500–1800. When compared with the Northern Hemispheric temperature series, China's cold phase was shown to be relatively shorter (Fig. 2). Rapid drop of China's temperature started from 1580 and ended in 1660. The temperature rose from 1660 afterwards till 1740, followed by a slight temperature drop. It should be noted that the temperature anomaly of the 17th century was below -0.5 sigma unit, which can be considered as a cold century. The total amount of agricultural production and rice price increased in the long-run. The upward trend of agricultural production represents the advancement of technology and agricultural productivity, while the upward trend of rice price reveals the increasing circulation of money in the economy. This suggests that the above components were determined by factors other than climate change in the long-term. Yet, their association with climate change were apparent in the shorter-term. A considerable drop of agricultural production and the skyrocketing of rice price started in 1610 when the temperature anomaly dropped to -0.65 sigma unit (Figs. 3 and 4). The agricultural production reached its lowest point and the rice price reached its highest point in 1650–1660 (i.e. the coldest decade during the study period). The starting time for the recovery of agricultural production and the drop of rice price was around 1650, which was almost the same time for the rapid increase of temperature. At the beginning of the 18th century, the agricultural production had reached a moderate level. Despite a small agricultural decline at the end of 17th century, the agricultural production increased afterwards till 1740. The rice price was basically kept at a low level during 1660–1740. The temperature stopped rising in 1740, with a small drop till the end of the 18th century. The agricultural production dropped around 1740 and then bounced back. In the same period, the rice price rose fast first and then stabilized after 1760.

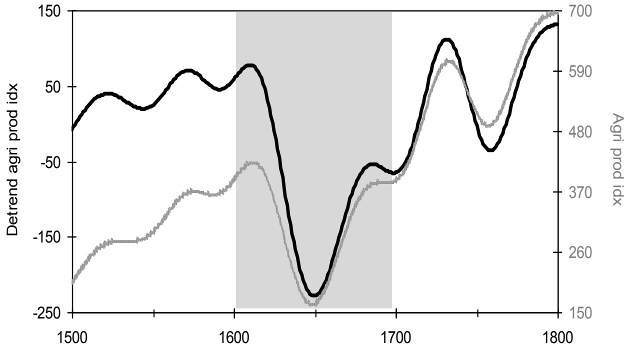

Figure (3): Agricultural production index (grey line, corresponds to the right Y-axis) and detrended agricultural production index (bold black line, corresponds to the left Y-axis) in China during 1500 – 1800. All data were smoothed by 40-year Butterworth low-pass filter. Grey shadow represents a cold climate.

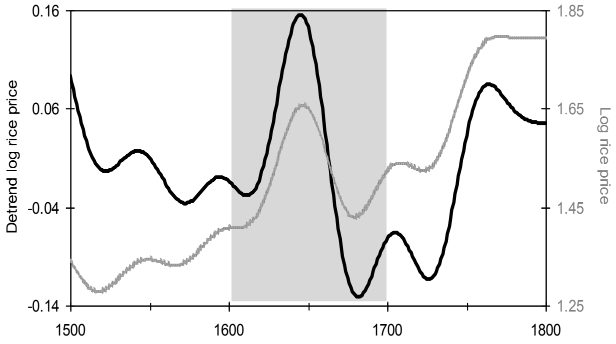

Figure (4): Logged rice price (in grams of silver per hectoliter) (grey line, corresponds to the right Y-axis) and detrended logged rice price (bold black line, corresponds to the left Y-axis) in China during 1500 – 1800. All data were smoothed by 40-year Butterworth low-pass filter. Grey shadow represents a cold climate.

Food shortage and social stability

Both the numbers of wars and rebellions peaked in China during 1610–1660 (Fig. 5). It is not only the coldest phase in our study period, but the coldest time in the last millennium (Jones & Mann, 2004). Besides, the trough of the agricultural production and the peak of the rice price coincided in this period. There was 5 to 10 years time lag between the Nanjing Academy of Military Sciences' war and rebellion data (Editorial Committee of Chinese Military History, 1985) and Lee, (1933) war record owing to the low resolution (10-year units) of Lee, (1933) record. However, the shape and amplitude of fluctuations of the both series are the same. Here a successive consequence from climate deterioration to the outbreak of wars can be envisaged from the changes of China's temperature, agricultural production, rice price and war time series (Figs. 2 to 5). A small war peak in the mid-16th century – the period without any great temperature change and agricultural production failure – from the total number of wars has been observed (Fig. 5). This seemed to be contradictory with our model. However, by examining historical records, it was found that this war peak was primarily caused by the repeated attacks from Wokou (Japanese pirates) along the coastal regions. This can be interpreted as an "external random factor", which is out of the scope of our model.

Population change and its feedback effect

The variation of population growth and population size basically followed the war-peace cycles in China (Fig. 6). In the 16th century the population growth rate was steady (~0.5%). When war peak occurred in 1610, the growth rate sharply declined to a negative value (the lowest rate was < -2.0%). The population size, therefore, dropped to 90 million from 1610 to 1650, which are 70 million people less than the previous population peak. When the peak of war finished, the growth rate bounced back to 1.4% in 1700 and maintained at 1.0 – 1.3% for the whole of the 18th century. The 18th century is the century with the fastest population growth in Chinese history, and that the population size increased from 130 million to 310 million in 100 years. Such a rapid population growth coincided with a mild climate and the socio-economic harmony in the 18th century.

Fluctuation of population size would affect the food supply per capita according to our model, causing feedback effects in the human-ecosystem (Fig. 1). For instance, the war peak during 1610 – 1650 had led to 70 million population losses, which in turn increased the food supply per capita (i.e. drop of rice price) after 1650. Such an increase in the food supply per capita caused a sharp decline of the frequency of wars. Although the temperature anomaly continually dropped to -1.0 sigma unit by 1660 – the lowest point throughout the last millennium, the war number in 1660 was only one-third of that in 1650. Another example of the population feedback mechanism is the rice price variation in the second half of the 18th century. During that period the rice price inflated to a very high level because of the fast increase of population size. As the population size had not overshot food subsistence during the time, such a high price did not generate any war peaks. However, the population size had caught up food subsistence in the late 18th century. When another cooling occurred during 1820–1870, the rice price skyrocketed, followed by war peak and disastrous population collapse in 1840–1860 (Zhang *et al.*, 2006; Lee *et al.*, 2008; Lee *et al.*, 2009).

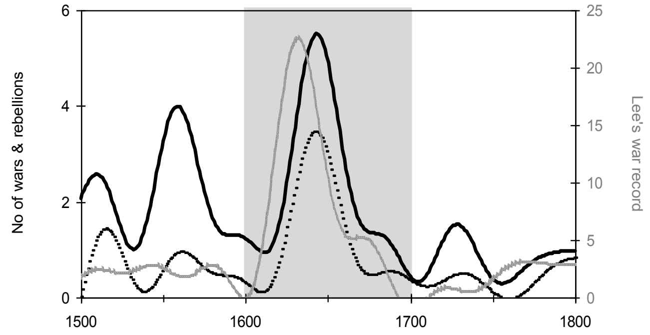

Figure (5): Number of wars (bold black line, corresponds to the left Y-axis), rebellions (bar-dotted line, corresponds to the left Y-axis), and wars recorded by Lee (grey line, corresponds to the right Y-axis) in China during 1500 – 1800. All data were smoothed by 40-year Butterworth low-pass filter. Grey shadow represents a cold climate.

Cross correlations of the various components in the model

By using time-series analysis, the linkages from climate change to agricultural production, food supply per capita, population and war can be envisaged (Figs. 2 to 6). Pearson's correlation analysis was used to further examine how strong these linkages were in a statistical sense. Table 1, showed the cross correlations among the variables used in this research. Almost all correlation coefficients were highly significant (i.e. $p < 0.001$). Besides, those variables which are determined by one factor (i.e. linked by a single pathway likes climate change → agricultural production → food supply per capita → war → population) as shown in the conceptual model were generally associated with stronger correlation coefficients. For those variables which are determined by two factors, they were associated with weaker correlation coefficients. For instance, food supply per capita was determined by population size and agricultural production. Even though the correlation coefficient between population size and food supply per capita and that between agricultural production and food supply per capita were statistically significant, they were relatively weaker when compared with the others in Table 1. Among all of the variables, population size did not correlate strongly with the other variables used in this research. This is primarily attributable to human life expectancy. Unlike animals, it takes a longer time for human to reduce their population size in face of shrinking land carrying capacity. This inflexibility creates time gaps between the population size and other variables. Hence, the population size associated with weaker correlation coefficients.

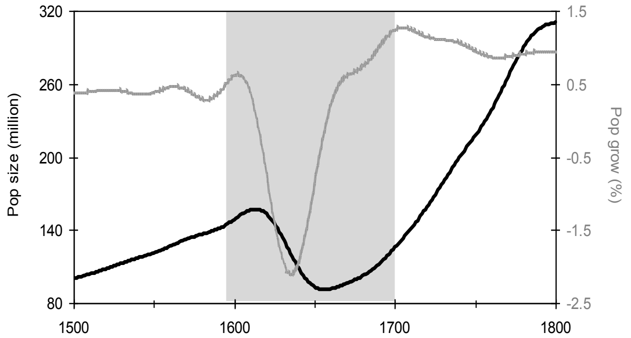

Figure (6): Population size (in million) (bold black line, corresponds to the left Y-axis) and population growth rate (in %) (grey line, corresponds to the right Y-axis) in China during 1500 – 1800. All data were smoothed by 40-year Butterworth low-pass filter. Grey shadow represents a cold climate.

DISCUSSION AND CONCLUSION

The association between climate change and agricultural production can be seen from the history of rice cultivation in the middle and lower reaches of the Yangtze River. Double cropping of rice started in Tang dynasty (c. 618–906), as an innovation in agricultural technology, and was further developed in the late 15th century in Ming dynasty. The double cropping, however, failed in 1620–1720 because of the cold climate, and thereafter during 1720–1800 it recovered and dominated the region again. In the 19th century, double cropping in the region failed again despite the government's promotion of the techniques. At present the double cropping is functioning well (Yin *et al.*, 2003). It should be noted that in the middle and lower reaches of the Yangtze River, the periods of double cropping successes coincided with a warm climate.

The linkage between climate change and agricultural production is evident in the long-term. Besides, the results showed the interrelationship between climate change, agricultural production, food supply per capita, population and war. But, what does the history tell us about the climate-war relationship in China during 1500 – 1800? In China from the late 16th century to the mid-17th century, due to cooling and its associated climatic hazards, the growing season in northern China was two weeks shorter than it is now (Jiang, 1993). This resulted in significant reduction of agricultural production and food supply per capita. Here a list of the climate disasters and famine events at the provincial scale is provided For instance, there was drought in the Beijing region in the autumn and winter of 1584 and famine in Huguang during the late summer of 1585. At various points during 1587, drought and famine were reported in areas north of the Yellow River. By early months of 1588, the areas experiencing severe food shortages had widened to include parts of Sha'anxi, Shanxi, Shandong, Henan, Zhejiang, and Jiangnan. In 1589, an extended period of severe drought began in southeastern China, with parts of Zhejiang, Huguang, Jiangxi, and Jiangnan being particularly hard hit. After a brief respite in 1590, the next few years saw heavy rains and floods damage agricultural production in many regions of the country. By 1594, in some parts of China, people had to eat the bark of trees, the seeds of grass, or even the excrement of wild geese. Although the epicenter of the 1594 famine is usually considered to have been in north-central China, there also were very poor harvests that year in the southeastern provinces of Fujian and Guangdong. In 1601, there was extended drought in northern China, followed by summer floods in both the north and the southeast of the country. In 1609, the Ming Empire was hit by an extended drought in Huguang, Sichuan, Henan, Sha'anxi, and Shanxi and by heavy rains and floods in Fujian, Zhejiang, and Jiangxi. By the late spring of 1610, famine conditions were reported in parts of Bei Zhili, Shandong, Shanxi, Henan, Sha'anxi, Fujian, and Sichuan (Atwell, 2001 and 2002). Since 1620, both the lakes of the middle Yangtze and the Huai River froze over in winter (Wakeman, 1986). Unusually severe weather struck China during 1620–1640, when the earth's climate fell to the lowest temperatures since 1000. Extreme droughts were followed by major floods. Frequent famines, accompanied by plagues of locusts and smallpox, produced starvation and mass death during that period (Zhang *et al*., 2007b). Throughout the past five centuries, the five worst years of consecutive drought in China as a whole occurred during 1637–1641 (Wakeman, 1986). From the Huai Valley to the Northern Metropolitan Region, all the bark had been stripped from the trees and people even dug up corpses for food. However, there were much fewer climatic hazards and famine incidents in the late 17th century as shown by historical documents.

In the late 16th century, the rapid drop of temperature led to a great reduction of agricultural production and a huge increase of rice price. Consequently, food shortage problem occurred in China at the beginning of the 17th century. Food shortage could trigger famines, tax revolts and a weakening of state power. The deficit in livelihood resources was aggravated by the population expansion accumulated in the previous favorable climate. Thus, state wars and rebellions were likely to erupt in a deteriorating climate (Zhang *et al*., 2005; Zhang *et al*., 2006; Zhang *et al*., 2007b). Starting from the beginning of the 17th century, the social stability of China worsened as the climate was getting colder. Drought and famine continued to plague northern China the following years. At the time, the Ming Empire had to fight a protracted two-front war against the peasant guerrillas and the Manchu cavalrymen. In the 1620s, peasant rebellions occurred in most of the provinces of China and many of them started after serve climate hazards. They did not only fight the Ming Empire, but also fight each other. Economic conditions remained terrible in 1641. Not only did unusually heavy snowfalls and food shortages cause serious problems in southeastern China during the early months of the year, it remained very dry in much of the north with infestations of locusts being reported in many areas. As grain prices rose to extraordinary levels, local people organized bandit gangs and even resorted to cannibalism to stay alive (Jiang, 1993).

Table (1): Pearson's correlation coefficients (r) of the various variables employed in this research. n = 301 (i.e. 1500 – 1800). All data were smoothed by 40-year Butterworth low pass filter prior to statistical analysis. r values ≥ 0.23 are significant at P < 0.001. NH temp = Northern hemisphere temperature anomaly; Chi temp = China temperature anomaly; De agri prod = Detrended agricultural production index; De rice price = Detrended rice price; War = Total number of wars; Rebel = Total number of rebellions; Lee's war = Total number of wars recorded by Lee; De pop size = Detrended population size; Pop grow = population growth rate.

	Chi temp	De agri prod	De rice price	War	Rebel	Lee's war	De pop size	Pop grow
NH temp	0.65	0.41	0.23	-0.12	-0.26	-0.35	0.57	0.41
Chi temp		0.63	-0.03	-0.53	-0.52	-0.44	0.57	0.57
De agri prod			-0.33	-0.50	-0.63	-0.48	0.75	0.50
De rice price				0.46	0.55	0.50	0.35	-0.57
War					0.86	0.60	-0.24	-0.77
Rebel						0.75	-0.31	-0.83
Lee's war							-0.16	-0.94
De pop size								0.14

The final collapse of Ming Empire happened in 1644 when the strongest rebellion force led by Li Zicheng entered Beijing, the capital city of Ming, the last Ming Emperor Chongzhen hanged himself in the back garden of the Forbidden City and Ming finally collapsed. With the help from the General Wu Sangui of Ming Empire, Manchu forces went across the Great Wall and beaten the rebellion forces from all provinces in Chinese continent and successfully controlled all China. To what extent the Manchus were experiencing climatic disasters of their own remains to be thoroughly studied, but, as was the case during the late 16th century, there is considerable evidence to suggest that their attacks on China during the 1630s had been inspired, at least in part, by serious economic problems in the Manchu homeland (Hsü, 1995; Atwell, 2001 and 2002). Climate cooling in northeastern China (Manchu) was one of major reasons causing the economic problems because after the Manchu conquest, nearly all of the Manchus abandoned their homeland and move southward (Ge *et al.*, 1997). The above historical ups and downs in China closely match the climate change during the period.

The impact of the alternation of war-peace cycles upon population in China during 1500–1800 can be boiled down as follows: From the early to mid-16th century, China was relatively peaceful, except the repeated attacks along the coastal areas by Japanese pirates. In the late 16th century, climate was getting cooler. Famines and rebellions became more frequent in some areas. As temperature dropped continuously and reached a certain level, the agricultural production shrank considerably and rice price went up immediately in China. Subsequently, a series of wars broke out from 1610. Chinese population growth rate largely followed the fluctuations of the agricultural production. The growth rate dramatically became negative when the number of wars peaked and the amount of agricultural production dropped to its trough. Such a tragic synthesis caused a catastrophic population collapse in China in the mid-17th century, which largely reduced her total population size. After the slump of population size, the food supply per capita increased (i.e. rice price decreased) and the incidents of war reduced significantly in the late 17th century even though the climate was still cold and the agriculture production was still below the 1610's level during the time.

From the end of the 17th century till the end of the 18th century, the rise of temperature created favorable agricultural condition in the first half of the 18th century, which sustained a higher level of agricultural production in China. China experienced a long peaceful time and economic harmony. This period is coined to be the "Kangqian Harmony". During this period the three Qing emperors namely Kangxi, Yongzheng and Qianglong enlarged Chinese territory, built up many palaces, and formed the largest kingdom in the world at the time. All these were primarily attributable to the sound agricultural economy in China during the time. However, in the late 18th century, too rapid population expansion brought about the skyrocketing of rice price, which accrued societal stress and population pressure to fuel the war peak in the mid-19th century.

The linkage from temperature change to food shortage and war has been quantitatively verified by times series analysis and Pearson's correlation analysis, supplemented by qualitative historical documentary evidences. Besides, the mechanism behind the linkage has also been revealed. The results so far concur with the causal linkages as hypothesized in the model. The strong coincidence between temperature change and war outbreak is unlikely to be accidental. It is also impossible to explain the temperature-war coincidence by using any socio-economic theories because it happened not only in China, but also in other countries and regions worldwide simultaneously. For instance, in Europe in 1500-1800, three social development phases can be identified, namely: the Renaissance in the 16th century, General Crisis in the 17th century and Enlightenment in the 18th century. These three phases represent the order-disorder-order (mild-cold-mild) alternation. This exactly matches with the Chinese war-peace cycles in the same period of time. Please note that China and Europe were geographically and politically detached and characterized by different stages of civilization, culture, socio-economic development and resource endowment during the time (Zhang *et al.*, 2007a). The temperature-war coincidence indicates that climate change has played a decisive role in driving the war-peace cycles in different countries and regions in the Northern Hemisphere. Webster (1975) points out that warfare is an adaptive ecological choice in prehistoric societies with limited resources and growing populations. he has not substantiated his viewpoint by any quantitative evidence. Besides, he has not noted that resource shortage periods are often the times of deteriorating climate. Despite the above drawbacks, his view point is still valid in comprehending the situation in China during 1500–1800.

Nowadays, although a lot of countries and regions in the world have been transformed into industrial or even post-industrial societies, there are still many developing and underdeveloped countries and regions depending on agricultural production to support their populations. According to biological principles, higher temperature is good for plant growth within a certain threshold. Yet, recent research confirms that the detrimental impact of increasing warmth on agricultural production appears to be overriding its beneficial effect (Brown, 2004; Lobell & Field, 2007). Thereby, the recent rapid increase of global temperature may be another climate deterioration that will shrink agricultural production considerably and induce human-ecological disaster in some agricultural societies, just like the historical Chinese societies studied here. In fact, the greatest threat from global warming comes from the uncertainty of ecosystem change; perhaps we are reaching the point at which it might break the balance of agro-ecosystems that have been long established at a lower temperature.

In addition, many secondary and tertiary effects of global warming cannot be predicted based on current knowledge (Zhang *et al.*, 2007b). How big the associated human-ecological impact will be is largely contingent upon the effectiveness of existing social buffering mechanisms, including social institutions at both international and national levels and social and technological developments. This topic deserves our further investigation.

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