Global climate change, war, and population decline in recent human history

David D. Zhang*[†], Peter Brecke[‡], Harry F. Lee*, Yuan-Qing He[§], and Jane Zhang[¶]

*Department of Geography, University of Hong Kong, Pokfulam Road, Hong Kong; [‡]Sam Nunn School of International Affairs, Georgia Institute of Technology, Atlanta, GA 30332-0610; [§]Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science, Lanzhou 730000, Gansu, China; and [¶]Department of Anthropology, University College London, London WC1E 6BT, United Kingdom

Although scientists have warned of possible social perils resulting from climate change, the impacts of long-term climate change on social unrest and population collapse have not been quantitatively investigated. In this study, high-resolution paleo-climatic data have been used to explore at a macroscale the effects of climate change on the outbreak of war and population decline in the preindustrial era. We show that long-term fluctuations of war frequency and population changes followed the cycles of temperature change. Further analyses show that cooling impeded agricultural production, which brought about a series of serious social problems, including price inflation, then successively war outbreak, famine, and population decline successively. The findings suggest that worldwide and synchronistic war–peace, population, and price cycles in recent centuries have been driven mainly by long-term climate change. The findings also imply that social mechanisms that might mitigate the impact of climate change were not significantly effective during the study period. Climate change may thus have played a more important role and imposed a wider ranging effect on human civilization than has so far been suggested. Findings of this research may lend an additional dimension to the classic concepts of Malthusianism and Darwinism.

agricultural production | population collapse | price | war–peace cycles | preindustrial era

Scientists have noted that social activities heavily depend on climate. They have also pointed out that temperature probably influences our lives more than any other climatic factor and human society is especially vulnerable to large, long-term temperature changes (1). However, scientific research on the social effects of climate change has tended to focus on the economic costs of current and future climate change and has neglected the study of how societies have historically reacted to long-term climate change. This neglect is unfortunate because a better understanding of how past climatic changes have influenced human society may help us better understand our future prospects.

Recently, important attempts have been made to use high-resolution, reconstructed paleo-climatic data to elucidate individual cases of prehistoric cultural/population collapses caused by agricultural failure in the Middle East, United States, and China (2–4). Webster (5) pointed out that warfare was an adaptive ecological choice in prehistoric societies with limited resources and growing populations, although he was not able to use systematic, scientific data to support his conclusion. The concept of environmental conflict has been suggested by several researchers, but they focus only on conflicts caused by short-term climate variations and meteorological events (6–9). Galloway (10) found that long-term climate change controlled population size in middle-latitude areas. However, his finding lacked quantitative precision because of the absence of high-resolution climate records at the time. We studied a long span of Chinese history and found that the number of war outbreaks and population collapses in China is significantly correlated with Northern Hemisphere (NH) temperature variations and that all

of the periods of nationwide unrest, population collapse, and dynastic change occurred in the cold phases of this period (11–13). As a result of recent scientific breakthroughs in establishing more precise paleo-climatic records [see supporting information (SI) Text], we extend the earlier study to the global and continental levels between A.D. 1400 and A.D. 1900, during the Little Ice Age (LIA; see SI Text).

The hypothesis we propose posits that long-term climate change has significant direct effects on land-carrying capacity (as measured by agricultural production). Fluctuation of the carrying capacity in turn affects the food supply per capita. A shortage of food resources in populated areas increases the likelihood of armed conflicts, famines, and epidemics, events that thus reduce population size. As a feedback mechanism, population decline has a dominant tendency to increase the food supply per capita (seen in decreasing food prices), which results in relative peace and fast population growth. The interactions among these components in a social system create an important rhythm of macrohistory in agricultural societies. The simplified pathways of the above chain reactions and feedback loops are represented in SI Fig. 3.

With respect to the character of the causal pathways, the relation between climate and agricultural production has been demonstrated by many empirical studies (10, 14). Under ecological stress, adaptive choices for animal species are the reduction of population size, migration, and dietary change. Depopulation typically takes place through starvation and cannibalism. Humans have more pathways, social mechanisms, to adapt to climate change and mitigate ecological stress. Besides migration, they include warfare, economic change, innovation, trade, and peaceful resource redistribution. We believe that in late agrarian society established political boundaries in populated areas limited mass migration; the result of such mass migration, when it occurred, often was war. Economic change was a costly and slow process that involved changing cultures, technologies, and habits. When the speed of human innovation and its transfer were not fast enough to keep pace with rapid ecological change, famine and disease became difficult to avoid. Trade and redistribution under the condition of shrinking resources would not help much because the ecological stress was at a global or very large regional scale. Finally, human social development in the form of international and national institutions was not strong enough to buffer the tensions caused by food resource scarcity. Therefore, war and population decline became common consequences of

climate-induced ecological stress in the late preindustrial era. Recent developments in resource and environmental studies (e.g., refs. 8, 9, 15, and 16) suggest that limited resources and environmental degradation would have caused armed conflicts in human history. However, these perceived climate–war–population decline sequences have never been substantiated with scientific evidence consisting of long-term time series. In the following sections, we verify our hypothesis and evaluate the role of climate change on war outbreak and population decline with empirical data at global and continental scales.

Results and Discussion

We adopted a quantitative and macrohistorical approach to explore the climate–agriculture–war–population relationships depicted in SI Fig. 3 in the preindustrial era. Statistical methods were used to examine the correlations among the various components in the pathways. The various relationships between different factors between the pathways were more thoroughly analyzed with the two regions for which there are more data, Europe and China.

Cyclic Patterns of Wars and Temperature Changes. In the same manner as the NH temperature variations, the incidence of warfare in the NH, Europe, Asia, and the arid areas of the NH (i.e., the arid zone from Eurasia to North Africa; see SI Fig. 4) in A.D. 1400–1900 tends to follow a cyclic pattern with a turbulent period followed by a relatively tranquil one (Fig. 1 *A* and *B*). Two periods plagued by unrest and warfare and three relatively peaceful periods follow the temperature undulation inversely. This pattern not only appears at a continental scale, but also in three war databases with different violence thresholds at a global scale (Fig. 1*C*), except for the late 19th century when the temperature of the Southern Hemisphere (SH) was its coldest in the last millennium (17) and a great number of wars occurred in the southern part of Africa.[||] In short, synchronous periods of relative peace and turbulence during those 500 years were a global phenomenon seemingly linked to temperature change.

To look at the severity of these wars and their impacts on human population, a NH fatality index for A.D. 1400–1900 was calculated from the wars with a known fatality record aggregated into 50-year intervals (see Fig. 1*D* and *SI Text*). The two peaks of the fatality index appear in the cold 17th and the early 19th centuries. Two of the greatest population declines since A.D. 1400 coincided with the two peaks.

We note that the turning points of war/peace cycles in the NH at the ends of the 17th and 18th centuries are different from the turning points of the two longest mild/cold periods in the centuries. The time gaps are 20–30 years in all cases, which is caused by the population feedback, which will be verified in a later section.

We also examined Chinese warfare history back to A.D. 1000 (see *SI Text* and SI Table 2), which shows several war/peace cycles. It can be seen that all war peaks (>25 wars per decade) occurred in a cold climate, and multiple war–peace cycles were followed closely the NH's temperature variations (see SI Fig. 5). The temperature–war correlation is also statistically significant, and population declines followed every high war peak (12, 13). Krus *et al.* (19) also examined frequency of Chinese wars and found that the periods that non-Confucian ethical systems dominated China had more wars. However, the periods often were cold and dry, and such climate drove the northern and western tribal states to enter central China, thus changing original Confucian ethical systems.

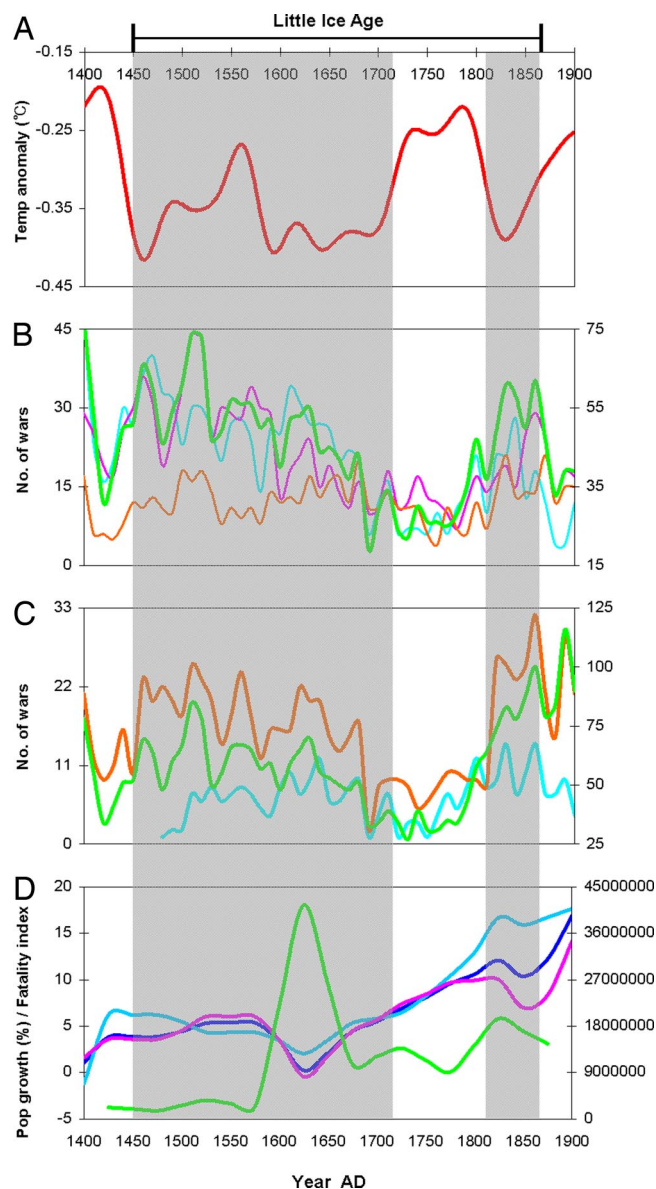At the century timescale, war frequencies and the ratio of wars

[||]Brecke P, Annual Meeting of the Peace Science Society (International), October 8–10, 1999, Ann Arbor, MI.

Fig. 1. Paleo-temperature variation, war frequency, and population growth rate, A.D. 1400–1900. (*A*) Temperature anomaly (°C) in the NH that is smoothed by 40-year Butterworth low pass filter (17). (*B*) Number of wars in the NH (bright green), Asia (pink), Europe (turquoise), and the arid areas in the NH (orange).[||] (*C*) Number of wars worldwide as recorded by Wright (39) (turquoise), Luard (38) (orange), and Brecke[||] (bright green). (*D*) Twenty-year population growth rate in Europe (turquoise), Asia (pink), and the NH (blue)[||] and the NH 50-year fatality index (bright green). Cold phases are shaded as gray stripes. All war time series are in 10-year units, and the data are listed in SI Table 1. The bright green curves correspond to the right *y* axis.

per year in different centuries have been calculated at global and continental geographic scales. Those calculations demonstrate that the number and ratio of wars in the 18th century are the lowest compared with other centuries. The results indicate that the worldwide war ratio during cold centuries was 1.93 times greater than that of the mild 18th century, and 1.77, 1.91, 1.50 and 2.24 times greater for the NH, Asia, the arid areas of the NH, and Europe, respectively. At the country scale, as the incidence of warfare has been too small to permit correlation analysis to be conducted, the number of wars in each century was calculated and the ratios of wars per year were compared. These calculations show that only 27 of 170 countries and areas around the

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world had higher war ratios in the 18th century than in the 15–17th and 19th centuries. Most of the "exceptional cases" are located near the Equator, where there was no obvious LIA, and thus cooling that would have a significant effect on agriculture.

To refine the analysis, a series of correlation analyses were carried out at the much lower scale of an annual level timeframe. Although the SH had no obvious LIA, the temperature anomaly for the SH was used for comparative purposes in the correlation analysis by examining the temperature and war frequency relationship. The results show that the numbers of wars per year, in all war classifications, were significantly negatively correlated with the annual changes of the temperature anomalies at the global level (see SI Table 3). The number of wars in the NH and SH also correlated significantly with their temperature variations. The reliability of the correlation analysis was verified by a cross-examination method that deliberately correlates the war frequency of a particular hemisphere or region with the other hemisphere's temperature anomaly. The results show that all correlation coefficients of these "mismatched" combinations were either insignificant or very low positive. For instance, the correlation coefficients between the SH temperature anomaly and NH war frequency were −0.06 for A.D. 1400–1900 and 0.137 for A.D. 1500–1900, respectively. This finding suggests that the strikingly high coefficients of our correlation analysis are by no means accidental, and the number of wars in each hemisphere is related only to its own temperature variation. Further analysis of the frequency of wars in Europe, Asia, and the arid areas of the NH also shows significant correlations with the NH temperature anomaly for their geographical patterns (see SI Table 3).

The values of the coefficients at the annual scale also reflect environmental vulnerability and population density, which could further verify our hypothesis. As arid regions are the most vulnerable to climate change, the highest coefficient should and does appear in the war frequencies for the arid areas of the NH. Values are lower for Asia, probably because much of the continent for which there is conflict data is subject to a wet tropical or subtropical environment, where a fall in temperature would have a smaller effect than elsewhere on agricultural production and would not reduce food resources to the same extent because there is more alternative food. The American continents had a very low population density and a large amount of fertile land during this period, and its values are therefore either insignificant or of very low significance. Europe and Africa have either large cold areas or desert areas relatively vulnerable to cooling, and we find that warfare there is highly correlated with the temperature anomalies. At the global scale, the temperature anomaly is simply an arithmetic mean of the NH and SH temperature anomalies (17). The values of the coefficient for wars at the global scale are thus lower than those of the NH and SH alone.

Population Growth. The ecological stress triggered by climate change induces population shrinkage of most species, including human beings. Johnson and Gould (20) demonstrated that the agricultural production of Mesopotamia (present-day Iraq) closely followed its changing climate, which led to periodic collapses of its population by famine and wars (20). Using the best available world population estimates extending back to A.D. 1000, we compared the NH temperature series with the NH population growth rate. We also included the data series defining the spatial extent of cooling in the NH for reference (21) (see SI Fig. 6). Variations in the population growth rate can be divided into three periods. In A.D. 1000–1400, when agricultural technology and trade flows were at a low level, the population growth rate was also low, and the world population basically stagnated. Because of the gradual temperature drop and the increase in size of the cold area from the "Medieval Warm Period" to the LIA, the growth rate also decreased concomi-

tantly. Every sudden temperature drop would induce a "demographic shock," and the correlation coefficient between the NH temperature and the population growth rate (in 20-year units) is highly significant in this period ($r = 0.84$, $P < 0.001$, $n = 21$) as agriculture largely depended on climate. The growth rate reached its lowest level in the 13–14th centuries, primarily because of epidemics, wars, and famines. In China, the invasion by the Mongols in the 13–14th centuries was related to the ecological stress caused by cooling, which reduced China's total population nearly by half (≈ 55 million decline) (22). In Europe, Black Death spread out during the time, which was accompanied by massive social unrest and economic collapse (23, 24), which wiped out a quarter to one-third of the population in A.D. 1347–1353, the coldest period in the last several hundred years (24). At first glance, a cold climate did nothing to foster plague. However, cooling, according to our model, would cause wars, forced migration, or even famine, which would help to spread out the "vectors." In China, historical statistics also reveal that a cold climate has been accompanied by more epidemics (25).

The second period is A.D. 1400–1700. The first part of this period coincided with a warm phase and the beginning of the "Early Modern Times," and the NH population growth rate rose rapidly. The population growth rate stayed at an elevated level from A.D. 1400 to 1600, despite a short cooling beginning in the middle of the 15th century. This phenomenon can probably be explained by three factors: (*i*) a large portion of the north hemispheric land area was not affected by the cooling (see SI Fig. 6C); (*ii*) improvements in trade in the Renaissance Era; and (*iii*) fewer large magnitude wars during this period (Fig. 1C). However, when the coldest and also lengthiest epoch of the LIA took place (17th century), more wars of great magnitude and the associated population declines in Europe and Asia (especially China) followed (Fig. 1D). The European population was devastated by possibly the worst war in its history in terms of the share of the population killed in A.D. 1618–1648 (24), starvation, and epidemics. In China, the population plummeted 43% (≈ 70 million) because of wars, starvation and epidemics in A.D. 1620–1650 (22). The rapid "postshock" bounce of the population growth rate in the late 17th century was related to the dramatically reduced population size and the coupled increase of food supply per capita. A more efficient resource distribution caused by technological and social advance in Europe might have also played a role.

A dramatic increase in human population occurred in the last two centuries of the LIA because of the Industrial and Agricultural revolutions, especially in Europe. However, a cooling period that covered a relatively larger area in the mid-19th century still caused a worldwide demographic shock, in part because of the prevalence of warfare in different continents (Fig. 1).

Annual-scale analysis for the period A.D. 1400–1900, which has higher-resolution population data, could help verify the above hypothesis. Correlation analysis showed a very significant relationship between the NH temperature swings and population growth rates for the world, NH, Asia, North America, and Europe, as well as China (see SI Table 4). As expected, the correlation coefficients for Europe and North America are lower than the others. The reason is that Europeans and Americans lived in an ecologically open system since the Industrial Revolution in which European population pressure could be relieved by cross-continental colonization and migration. When the 19th century (the age of Great Migration in Europe) population data were not included in the analysis, the correlations for Europe and North America were almost as high as those for Asia and the whole NH. Similarly, the large-scale trans-Atlantic migration from Europe to North America in A.D. 1700–1900, which is supposed to be driven by cooling, can also be substantiated by the significant negative correlation between the NH temperature

anomaly and North America's population growth ($r = -0.341$, $P < 0.001$, $n = 201$).

European and Chinese Cases. The above results have shown significant correlations and coincident timing between temperature change, war frequency, and population growth rate in different temporal and spatial scales. The analyses also indicate that cooling may have contributed to widely separated human disasters during the cold periods. The paths to those disasters operated through a reduction in agricultural production. The reduction is mainly because the cooling brought about a shortening of the growing season and a reduction of available land for cultivation. Shortages of food resources (reflected in price rises) instigated conflicts and demographic declines. To illustrate the relationship between temperature change and other factors in our pathways, we present figures that show successive fluctuations of those factors in Europe and China in A.D. 1500–1800 (Fig. 2). Only those two regions have relatively long-span historical records of the factors, and both shared ≈60% of the total world population during that time. China here refers to current territories of the People's Republic of China, including so-called China proper, part of Outer China, and some tribal states of China. Regarding the time span, Europe before A.D. 1500 did not have any effective market-pricing mechanisms (26), whereas the Industrial Revolution in Europe spread out after A.D. 1800. To see the real influence of nature, the upward trends in agricultural production, population size, cereal prices, and war frequency, which were caused by technological development during the period, have been detrended in Fig. 2.

The European grain yield ratio followed temperature change very closely (Fig. 2 A and B). As this data series is only in 50-year intervals, we estimated the annual agricultural production index by using cereal prices and population sizes. The estimated values matched closely with the temperature and real grain yield trajectories, which imply that temperature change definitely controlled agricultural production during that period. The most surprising finding is that the fluctuations of all of the components are the same in terms of macrotrends, turning points, and oscillation magnitude for both Europe and China at a time when both regions were detached, economically, politically, and geographically (Fig. 2 B–E). The most important aspect of this finding is that the fluctuations of all of the factors were in a successive order and corresponded to the temperature change. When agricultural production went down, wheat prices went up in both Europe and China. When prices reached a certain level, more wars erupted. Population growth rates were influenced by both war frequency and food supply per capita (reflected in cereal prices) and dramatically dropped to negative values when agricultural production was at its lowest levels, cereal prices reached their highest level, and peaks in war frequency occurred. Such a human ecological and social disaster reduced population sizes and even caused catastrophic population collapses in both Europe and China in the 17th century. The period is then called the General Crisis of the 17th Century. Research on biological living standards of ancient Europeans also support our data and analysis; the average height of Europeans in the 17th century is the shortest during the last two millennia and was 2 cm shorter than those in 16th and 18th centuries (27). After the slump in population size, food supply per capita increased (as reflected in decreased prices), and the incidence of war in the late 17th century declined even as the climate was cold and agriculture production was still low. Such a feedback effect can also be seen in Europe in the late 18th century. Although the climate was mild and agricultural production was high, the rapid increase in population dampened the food supply per capita (prices increased), and then the number of wars started to go up. The feedback mechanism explains why there were time gaps between the turning points of temperature variation and the war–peace
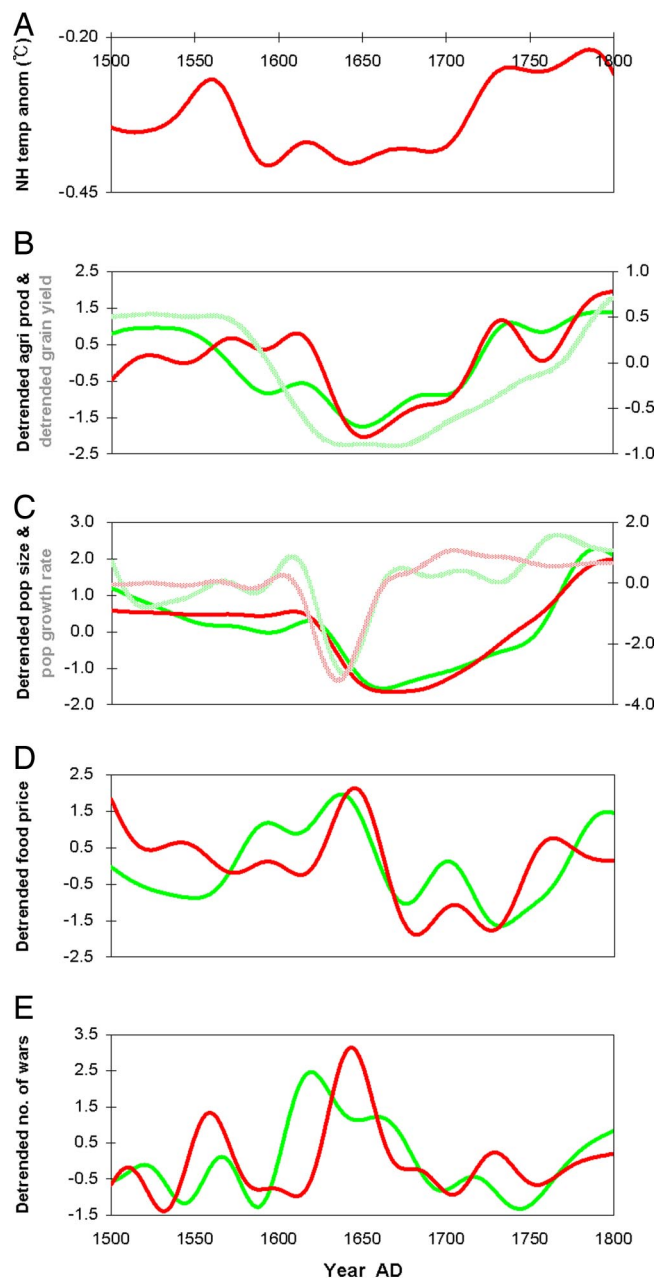

Fig. 2. Paleo-temperature variation and its impact on Europe and China, A.D. 1500–1800. (*A*) Temperature anomaly (°C) in the NH (17). (*B–E*) European data are in green and Chinese data are in red. The data are in normalized units that indicate the relative amplitude of change only. (*B*) Detrended estimated values of agricultural production (solid lines) and detrended grain yield ratio in Europe (green-dotted curve) (18). The estimated values of agricultural production are calculated by dividing population size by food price. (*C*) Detrended population size (solid lines) and population growth rate (dotted curves) (22, 24). (*D*) Detrended wheat price index in Europe and detrended rice price in China (41, 42). (*E*) Detrended total war frequency (‖ and ref. 40). All data are smoothed by 40-year Butterworth low pass filter. All of the dotted curves correspond to the right *y* axis.

cycles in various NH continents in the late 17th and late 18th centuries (Fig. 1*B*). The correlation coefficients between the factors listed in Fig. 2 have been calculated, and all of the coefficients for both regions are above the 0.001 significance level (see SI Table 5). The level of average correlation is shown by the thickness of the lines in SI Fig. 3. Population size is

correlated with cereal prices, and the population growth rate is correlated with war frequency and agricultural production.

Theoretical and Social Implications

The very significant correlations between temperature change, war frequencies, and population declines at the global and continental scales have been verified by different quantitative methods. The coincidence of multiple war–peace cycles and population decreases worldwide at various temporal scales is unlikely to be accidental. It has been shown that elevated levels of war outbreak and population decline in populated areas occurred during a cold climate in the past millennium. Europe and China are strong cases to illustrate that the links and feedback effects between temperature change and social events, long-term cycles of war outbreak and population decline, originate in large part from a fundamental driver, climate change. All of the above analytical results indicate that war and depopulation have been the important adaptive choices in preindustrial society. The results also have implications for the following outstanding issues.

Other Pathways for Human Adaptation. Our quantitative results also show the importance of the roles of some other human adaptive choices in mitigating war outbreak and population decline. At the country and local scales, these social mechanisms might have lessened, postponed, or even eliminated on occasion war outbreak and population declines during bouts of mild or short cooling. For instance, before A.D. 1400, war outbreaks and population decreases in China immediately followed every decline of temperature (see SI Fig. 5). After then, the short cooling in the 15th century did not generate a period of war outbreak and population decline, and the times of war outbreak and population decrease in response to great temperature declines were postponed by ≈30 years in the 17th and 19th centuries, possibly because of the work of institutions and technological development. After A.D. 1700, the base level of war frequency in China decreased because the Qing emperors had united all troublesome tribal states in the western and northern marginal areas (see SI Fig. 5B).

In the long run and at a global scale, technological and social development raised the population growth rate by 30% for A.D. 1400–1700 and 310% during A.D. 1700–1900, compared with the A.D. 1000–1400 period (Fig. 1D). It also reduced climate dependence of growth rate of population (after A.D. 1400), postponed the time of population decrease, and accelerated subsequent population recovery. For instance, the demographic shocks in the NH before A.D. 1400 have no time delays between the population growth rate drops and the temperature drops, but afterward the shocks are delayed by 20 and 40 years, respectively, in the 17th and 19th centuries (see SI Fig. 6). The gradual increase in time delays for NH population declines as we moved into the modern era may reflect that at least some social mechanisms may becoming more effective over time at the macroscale. We cannot evaluate quantitatively the relative importance of these mechanisms because measurement of these parameters is not feasible with current data sources. However, these adaptive choices that are positive to humanity have not let the human race escape from social calamities such as population collapse caused by severe cooling at both the global and continental scales as shown in the history of the past millennium. For armed conflict, the positive social mechanisms could neither reduce the number of wars nor indefinitely postpone the times of war outbreak in any cooling periods. However, the change of economy after A.D. 1900 (the change of basic resources in industrial society) had made that the great conflicts and demographic shocks were to only a limited extent affected by agricultural production at a global scale.

Cycle Theories. Many social scientists have noted cycles of social order and disorder in history, in which downturn periods were characterized by inflation, a fall in real wages, political crisis, war, and state breakdown (SI Text and refs. 28 and 29). There are many theories and hypotheses that attempt to explain this type of crisis and the dynamics behind the cyclical pattern of history (24). They have told us much about the dynamics behind the cycles. However, those models cannot explain parallel occurrence of these crises in widely separated regions that were in different stages of civilization, culture, and resource endowment, nor predict the timing of such crises. The agrarian and environmental models are similar to our model. But because there were no high-resolution paleo-temperature reconstructions at the time these models were proposed, and the explanations in these models lack population feedback, the models are not entirely convincing.

Demographic Theories. Malthus, as well as Darwin and many other ecologists, who state that ''positive checks'' occur when population growth overshoots the level of livelihood resources based on the assumption that the level of resources needed for basic livelihood is essentially constant or possibly monotonically increasing, is only partly correct (see SI Text). However, our results show that the level of those livelihood resources (food) will, at best, increase in an oscillating, not always positive, manner because the impact of climate change, and population growth was not. An anti-Malthusian, Boserup (30), claimed that population pressure would lead to the growth of agricultural production. She is correct with respect to limited scale regions and short-term timeframes if the land still has potential for intensive cultivation or for a very long-term trend concerning human history. However, such intensive cultivation could not keep pace with the needs of a growing population during periods when the climate cooled in Europe and China, as can be seen in various European economic records and the evidence from this study.

War Theories. War is, no doubt, an extremely complicated social phenomenon, and many scholars have investigated the problem of the causes of war since the days of Thucydides (SI Text and ref. 31). Sadly, scholars have made at best modest progress on the problem even though members of all of the social sciences have addressed it (32). Some of these theories may explain certain wars, and some of the theories may even explain sizable classes of wars, but none of them can explain the temporal and spatial patterns of warfare presented above. Our approach has not been to examine causes of individual wars, but to investigate the frequency of all wars during a specific period of human history and find out when, where, and why the war–peace cycles occurred. Our results not only answered when and where most of wars occurred, but also imply that relative food scarcity was a fundamental cause of war outbreaks according to our quantitative analysis on various physical and social components and in different geographical regions. Such a resource scarcity manifested itself in two causal pathways: a direct cause, in which resource-oriented wars erupted as most of the world's population still struggled to satisfy the lower levels of Maslow's Hierarchy of Needs (33), and an indirect cause, as constrained food resources and economic difficulties stemming from that intensified different social contradictions, that increased the likelihood of war outbreaks.

Implications for the Future. The findings from our study are germane to current situations even though they pertain to the consequences of climate cooling. We are now in the warmest climatic phase of the past two millennia, another climatic extreme like the 17th century in LIA, which was the coldest period of the past two millennia (17). Both higher and lower temperatures would lead to change of the human ecosystem. The

important direct impact of the change from the climate cooling was on agricultural production that dominated the economy of agricultural societies. Global warming could also create an impact on agriculture. Although rising of temperature will, at least for a while, increase total bio-productivity according to biological principles, recent research suggests that the negative effects of global warming on agriculture seems greater than the positive effects (34, 35). Significantly, most of the world's population will continue to rely on small-scale agriculture, which remains as vulnerable to climatic fluctuations as it was in the historical period covered in this study. Other direct impacts of global warming, such as sea level rising, spread of tropical diseases, increase of extreme weather events and glacial retreat, would also add costs on the current economy that is supported by cheap energy. In severe cases, the economic burden would cause conflict for resources and intensify social contradictions and unrest as we have seen in the past. However, we believe that the greater threat from global warming comes from the uncertainty of the ecosystem change, because the current high global average temperature (which has never been experienced in the last two millennia) is continuing to rise at an accelerated speed. Perhaps we are reaching the point at which it might break the balance of a human ecosystem that has been long established at a lower temperature, and in addition, many secondary and tertiary effects of global warming cannot be predicted based on current knowledge. A change of one key component in the ecosystem under global warming would likely cause disastrous results in human societies dependent on the existing human ecosystem. Is the changed ecosystem sufficiently adaptable or are the adaptation choices affordable for all of us?

Although we have more robust social institutions at both international and national levels, and much more advanced social and technological developments at present, a much larger population size, higher standard of living, and more strictly controlled political boundaries will limit some adaptive choices to climate change. We hope that positive social mechanisms that are conducive to human adaptability will play an ever more effective role in meeting the challenges of the future.

Methods

Paleo-Climate Data. Research in the past 10 years has led to significant improvements in high-resolution paleo-climate reconstructions (see *SI Text*). Our temperature data come from the most comprehensive and latest published records of the NH annual temperature trajectory, supplemented by the SH and global temperature trajectories (17). Besides, it has been confirmed that a cold period (LIA) existed globally during the last millennium (36, 37) (see *SI Text*).

Historical Socioeconomic and Demographic Data. Historical socioeconomic and demographic data for the early preindustrial era are scarce. It was not until the Late Middle Ages ($\approx$A.D. 1400) that some of the desired records started to be kept. For war data, three of the most representative worldwide warfare series (‖, 38, 39) were used to measure war frequency. Besides, a comprehensive China warfare dataset (40) that documents 1,664 armed-conflicts fought in A.D. 1000–1900 was also used in this research (see *SI Text*). For population data, they were extracted from the *Atlas of World Population History* (24) and *Recent History of Chinese Population* (22) (see *SI Text*). For food supply per capita, it is represented by historical cereal prices because it is determined by supply (agricultural production) and demand (population size). Nevertheless, only the cereal price data for Europe (41) and China (42) are long enough time series for our data analysis (see *SI Text*). For agricultural production, it is a perceived wisdom that a cold climate would lead to harvest failure, especially in the past. Although the data on agricultural production for many parts of the world are unavailable in our study's time span, we could use two parameters to represent agricultural production in our quantitative analysis. The first one is the grain yield ratio in relation to seed for Western and Central Europe (18), but the data are in 50-year intervals. The second one is the estimated annual values of agricultural production for Europe and China, which are calculated by population size over cereal price (see *SI Text*).

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