The causality analysis of climate change and large-scale human crisis

David D. Zhang[a,b,c,1], Harry F. Lee[a,b], Cong Wang[d], Baosheng Li[e], Qing Pei[a,b], Jane Zhang[f], and Yulun An[c]

[a]Department of Geography and [b]The International Centre of China Development Studies, University of Hong Kong, Hong Kong; [c]School of Geographic and Environmental Sciences, Guizhou Normal University, Guizhou 550001, China; [d]Department of Finance, Jinan University, Guangzhou 510632, China; [e]Department of Geography, South China Normal University, Guangzhou 510631, China; and [f]South China Morning Post, Causeway Bay, Hong Kong

Edited by Charles S. Spencer, American Museum of Natural History, New York, NY, and approved September 6, 2011 (received for review March 17, 2011)

Recent studies have shown strong temporal correlations between past climate changes and societal crises. However, the specific causal mechanisms underlying this relation have not been addressed. We explored quantitative responses of 14 fine-grained agro-ecological, socioeconomic, and demographic variables to climate fluctuations from A.D. 1500–1800 in Europe. Results show that cooling from A.D. 1560–1660 caused successive agro-ecological, socioeconomic, and demographic catastrophes, leading to the General Crisis of the Seventeenth Century. We identified a set of causal linkages between climate change and human crisis. Using temperature data and climate-driven economic variables, we simulated the alternation of defined "golden" and "dark" ages in Europe and the Northern Hemisphere during the past millennium. Our findings indicate that climate change was the ultimate cause, and climate-driven economic downturn was the direct cause, of large-scale human crises in preindustrial Europe and the Northern Hemisphere.

climate-driven economy | Granger Causality Analysis | grain price

Debate about the relation between climate and human crisis has lasted over a century. With recent advances in paleotemperature reconstruction, scholars note that massive social disturbance, societal collapse, and population collapse often coincided with great climate change in America, the Middle East, China, and many other countries in preindustrial times (1–5). Although most of these scientists believe that climate change could cause human catastrophe, their arguments are backed simply by qualitative scrutiny of narrow historic examples. More recent breakthroughs came from research adopting quantitative approaches to all known cases of social crisis. These studies show that, in recent history, climate change was responsible for the outbreak of war, dynastic transition, and population decline in China, Europe, and around the world because of climate-induced shrinkage of agricultural production (6–15). However, the underlying causal linkages from climate change to agricultural production and various human catastrophes in history have not been addressed scientifically. Hence, this climate–crisis relationship remains obscure. Incomplete knowledge of the topic has led to criticism that the notion of climate-induced human crisis neglects historical complexities or relies on weak evidence of causality (16, 17).

To resolve this issue, we examined the climate–crisis causal mechanism in a period that contained both periods of harmony and times of crisis. Given that we addressed whether climate change is a credible cause for large-scale societal crisis from the macrohistoric perspective, macrohistoric and aggregate features are privileged over microhisoric and individual ones; general trends are preferred to particular moments or events; and broad distinctions or geographical uniformities take precedence over localized analyses. Because the General Crisis of the 17th Century (GCSC) in Europe was marked by widespread economic distress, social unrest, and population decline (18–21), we systematically collected and tabulated all available historical data about climate, agro-ecology, economy, society, human ecology, and demography in Europe, A.D. 1500–1800. Sixteen variables were identified (Fig. 1 and *SI Appendix. Materials and Methods* I–XI) that facilitate our exploration of specific causal mechanisms between climate change and large-scale human crisis. We used five criteria to explore the mechanisms scientifically: (*i*) a rational explanation of the relationship can be given; (*ii*) a strong relationship exists between the variables; (*iii*) there is a consistent relation between the causal variable and the effect; (*iv*) the cause precedes the effect; and (*v*) the use of the causal variable results in strong prediction (22). In this study we took the following steps, which are in line with the deductive route for scientific explanation:

i) We examined the response of all variables to climate change at multidecadal to centennial scales. Based on the variable's response time to climate change, together with natural laws and social theories, we identified the relationships among the variables. According to these relationships, we identified a set of causal linkages from climate change to human crisis. Each stage of causal linkage was explained fully (Criterion I).

ii) Correlation and regression tests were run to validate the strength and consistency of the causal linkages (Criteria II and III).

iii) Granger Causality Analysis (GCA) was used to validate the time sequence of the causal linkages (i.e., whether cause precedes the effect at an annual scale) (Criterion IV).

iv) The direct and ultimate causes of human crisis, identified via statistical verification of the causal linkages, were used to simulate the alternation of periods of harmony and crisis in Europe and the Northern Hemisphere (NH) for earlier periods with scant historical records (Criterion V).

Results

Responses to Climate Change in Human Society. Our study period covers both mild and cold phases of the Little Ice Age in the NH. Based on the NH (Fig. 1*A*, red line) and European (Fig. 1*A*, black line) temperature anomaly series, we divided our study period into Mild Phase 1 (A.D. 1500–1559; average temperature = 0.43σ), Cold Phase (A.D. 1560–1660; average temperature = –0.59σ), and Mild Phase 2 (A.D. 1661–1800; average temperature = 0.24σ). The Cold Phase coincided with the GCSC. In Mild Phase 2, there was brief cooling in A.D. 1700 and A.D. 1750. To elicit the real association between climate change and the cyclic pattern of various variables, the variables with obvious long-term trends (agricultural production index, grain price, real wages, body height, and population size) were linearly detrended (23, 24).

Fluctuations of all agro-ecological, socioeconomic, human ecological, and demographic variables corresponded very well with temperature change and were in successive order. The variables of the bio-productivity, agricultural production, and food supply per

Author contributions: D.D.Z. designed research; D.D.Z., H.F.L., and B.L. performed research; D.D.Z., H.F.L., C.W., Q.P., and Y.A. analyzed data; and D.D.Z., H.F.L., and J.Z. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

[1]To whom correspondence should be addressed. E-mail: zhangd@hkucc.hku.hk.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1104268108/-/DCSupplemental.

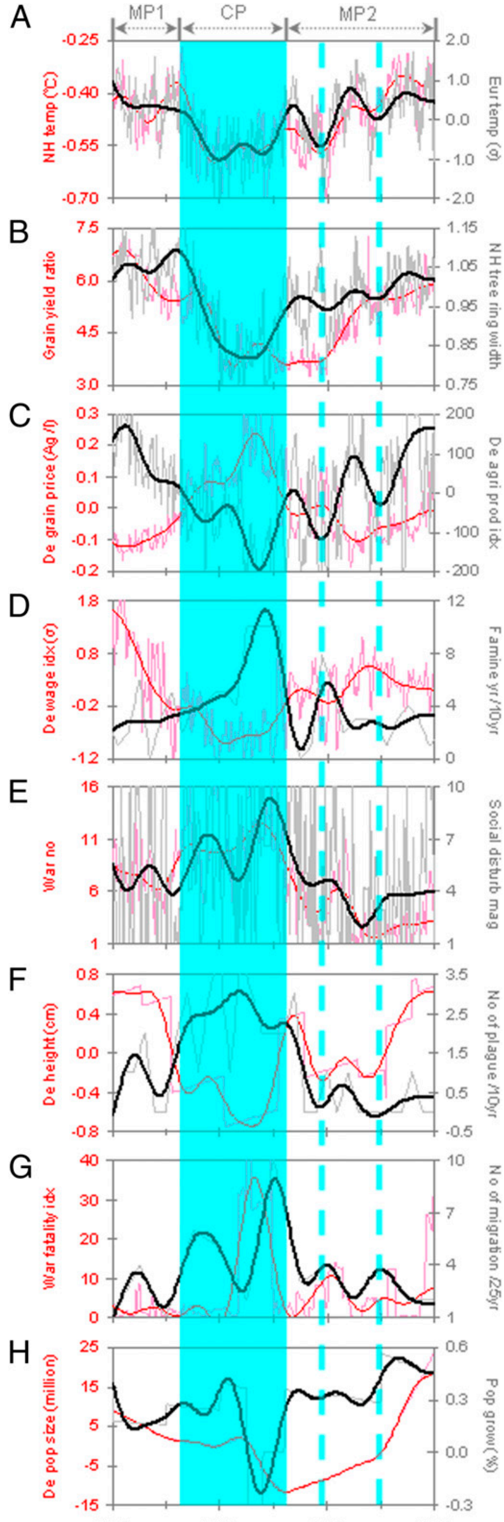

Fig. 1. Responses of different variables in human society to climate change in Europe, A.D. 1500–1800. (*A*) NH temperature anomaly (°C, red line) and Europe temperature anomaly (σ, black line). (*B*) Ratio of grain yield to seed (red line) and NH extratropical tree-ring widths (black line). (*C*) Detrended grain price (Ag/L, red line) and detrended agricultural production index (black line). (*D*) Detrended wage index (σ, red line) and number of famine years per decade (black line). (*E*) Number of wars (red line) and magnitude of social disturbances (black line). (*F*) Detrended human height (in cm, red line) and number of plagues per decade (black line). (*G*) War fatality index (red line) and number of migrations per quarter century (black line). (*H*) Detrended population size (in millions, red line) and population growth rate (%, black line). All data are smoothed by 40-y Butterworth low-pass filter. The blue shading represents the crisis period (Cold Phase), and the blue dashed line represents short-term cooling.

capita (FSPC) sectors responded to temperature change immediately, whereas the social disturbance, war, migration, nutritional status, epidemics, famine, and population sectors responded to the drop in FSPC with a 5- to 30-y time lag. The adverse effect of the two short-term, minor cooling episodes in Mild Phase 2 (Fig. 1, blue dotted lines) also was reflected by the variables' fluctuations in annual and decadal units, such as NH tree-ring width, grain yield, grain price, and agricultural production index.

Cooling in the Cold Phase dampened agro-ecosystem output by shortening plant growing seasons and shrinking the cultivated land area (23). The ratio of grain yield to seed decreased along with temperature decline (Fig. 1*B*, red line). Tree-ring width (a variable of bio-productivity) also varied in response to temperature change, decreasing rapidly in A.D. 1560–1650 (Fig. 1*B*, black line). Grain yield links directly to agricultural production, which is represented by the agricultural production index. Although in the long term the agricultural production index moved upwards with population size, it decreased or stagnated in a cold climate and increased rapidly in a mild climate at the multidecadal time-scale (Fig. 1*C*, black line).

Although agricultural production decreased or stagnated in a cold climate, population size still grew. Hence, two variables of FSPC—grain price and real wages of labor—changed considerably, and economic crisis followed. Grain price is determined by both demand and supply and is an important indicator of the boom-and-bust cycle in an agrarian economy. The detrended grain price (Fig. 1*C*, red line) was inversely correlated with every fluctuation of the agricultural production index and temperature. Real wages of labor (Fig. 1*D*, red line) varied inversely with grain price and followed agricultural production and temperature change closely. Given the low FSCP, famine became more frequent (Fig. 1*D*, black line), resulting in deteriorating nutritional status and ultimately in reduced human body height (25). The average height of Europeans followed temperature closely (Fig. 1*F* red line) and declined 2 cm in the late 16th century. It increased slowly with rising temperatures only after A.D. 1650.

Inflating grain prices and declining real wages bred unbearable hardship in all walks of life, triggering many social problems and intensifying existing social conflicts. Peaks of social disturbance such as rebellions, revolutions, and political reforms followed every decline of temperature, with a 1- to 15-y time lag (Fig. 1*E*, black line). Many disturbances eventually developed into armed conflicts. The number of wars increased by 41% in the Cold Phase (Fig. 1*E*, red line). Although the number of wars decreased in the interval A.D. 1620–1650, these wars were comparatively more lethal and longer lasting (e.g., the Thirty Years War) (26). Annual war fatalities from 1620–1650 were >12 times those in the period A.D. 1500–1619 (Fig. 1*G*, red line).

More frequent and severe economic chaos, famine, social disturbance, and war pushed people to emigrate. In Europe, migration (Fig. 1*G*, black line) peaked during A.D. 1580–1650, overlapping exactly with the peak of social disturbance. This correlation indicates that social conditions are imperative in driving migration (27). Migration, coupled with individuals' deteriorating health caused by poor nutrition, facilitated the spread of epidemics (7). The number of plagues peaked during A.D. 1550–1670 (Fig. 1, black line), reaching the highest level throughout the study period. Population growth rate, which is codetermined by famine, epidemics, and war, fluctuated complexly. When peaks in war fatalities and famine occurred during A.D.1620–1650, the annual population growth rate (Fig. 1*H*, black line) dropped dramatically from 0.4 to −0.3%. Population collapse occurred (Fig. 1*H*, red line), and the European population dropped to its lowest point (105 million people) in A.D. 1650.

In general, variables in European societies (except population) reacted linearly to temperature change at the multidecadal time scale (Fig. 1 and *SI Appendix*, Table S1). Some variables, however, responded exponentially to cooling in A.D. 1620–1650. We further examined the time-series of those variables and found that, after cooling, population pressure rose after A.D. 1560 (the agricultural production index declined, and annual population growth was ~0.4%) to the point that a significant reduction of population size was necessary to ease food strain in Europe. The triggers of population collapse were war and famine. After A.D. 1618, many large-scale wars and famines occurred in Europe. The war fatality index was 20 times higher than the A.D. 1500–1617 average and persisted at a similar level for the next 32 y (Fig. 1*G*, red line). During A.D. 1618–1649, ~10 million people perished in wars (26).

Humans have served as both producers and consumers in Earth's ecosystem since the Agricultural Revolution. During great wars and famines, death rates exceeded birth rates, causing substantial reduction of the agricultural production workforce. Also, collapse of agricultural production infrastructure caused by wars left behind massive damage to carrying capacity and sustainability (8). Consequently the role of the human population as a producer became less significant. Although the temperature and grain yield in A.D. 1600–1620 and A.D. 1620–1650 were similar, in 1621 the feedback effect of population collapse brought about a 13% reduction in agricultural production, which had stagnated for ~50 y. Such a huge decrease caused an exponential increase in grain price (+200%), famine (+250%), war fatality (+1,350%), social disturbance (+100%), migration (+250%), and other population checks. On the other hand, real wages, body height, and epidemics remained at the same level, and the number of wars dropped slightly (Fig. 1). This complex relationship between agricultural production and population size continued until A.D. 1650, when temperature and thus agricultural production increased.

At the end of the Cold Phase there was an augmentation of agricultural production that, together with a population slump, led to a rise in FSPC and the recuperation of most of European society after A.D. 1660. This date marks the end of the GCSC and the start of the Enlightenment era. The mild climate in the 18th century created human ecological harmony, leading to a speedy economic and population recovery in Europe. Although the short cooling in A.D. 1700 and A.D. 1750 caused minor fluctuations in grain yield, real wages, grain price, famine, war, social disturbance, and migration, its impact was not strong enough to cause general crisis and population collapse (Fig. 1).

Statistical Verification of Causal Linkages Between Climate Change and Large-Scale Human Crisis. Cooling triggered a chain of responses in variables pertaining to European physical and human systems. All 16 of the variables we identified are categorized into 11 sectors according to the response time of variables to cooling, together with natural laws and social theories related to different variables. Five of these sectors contain two variables with the same properties (e.g., the variables "NH temperature" and "European temperature" belong to the climate change sector). We then identified a set of causal linkages among the 11 sectors, demonstrating how climate change brings about general human crisis (Fig. 2 and *SI Appendix*, *Text* section 1).

In the set of causal linkages, climate change and associated bio-productivity fluctuation are revealed as the ultimate cause of economic, social, human ecological, and demographic problems. If the climate change and bio-productivity sectors are disregarded, various linkages within the human system seem to be driven endogenously by population growth. The concept of a population-driven human system is prevalent among social scientists, demographers, and economists (28, 29), but ignoring the impact of climate forces on human systems may lead to false conclusions. Although the causal linkages in Fig. 2 are theoretically reasonable, the strength, consistency, predictability, and time sequence of the linkages should be verified statistically before any definite conclusions are drawn.

We cross-correlated the 16 variables (*Materials and Methods*) to validate the strength of the set of causal linkages in Fig. 2. All 120 cross-correlations were statistically significant ($P < 0.05$), and 116 of them were highly significant ($P < 0.001$) (*SI Appendix*, Table S2). Patterns of the correlations reveal the following:

i) Correlation between temperature data and a variable in another sector became weaker as the sector's distance from climate change increased. For instance, the sector's distance for climate change → bio-productivity vs. climate change → population showed a distance decay effect indicating that the impact of climatic forcing was partially offset by human adaptation or natural factors.

ii) Compared with the NH temperature variable, the European temperature variable was better correlated with other variables, because, aside from NH temperature and NH tree ring variables, all other variables are for Europe only.

iii) The causal linkage from the climate change sector to the bio-productivity sector (e.g., European temperature and grain yield variables) was comparatively stronger.

iv) The variables Population size and Population growth rate had weaker correlations with other variables because they were determined by multiple variables. The strength of association among different sectors is shown in Fig. 2.

We also used multiple regression analysis to validate the consistency and predictability of the causal linkages shown in Fig. 2 (*Materials and Methods*). In regression models, the independent variables were time and causal variables, and the dependent variable was the "effect" variable. For example, in the relation European temperature → grain yield, European temperature is a causal variable, and grain yield is the effect variable. Time (t) presumably represents technology and/or capital accumulation. An attempt was made to eliminate the trend from the dependent variable (effect variable) using parabolic (t and t^2), squared (t^2), and cubic (t^3) terms (23). The various detrending procedures did not affect the regression results significantly, and all the elasticity of the effect variable in response to the change in the causal variable was statistically significant (*SI Appendix*, Table S3). The causal relationship between variables/sectors was statistically valid when the effect of societal development was controlled.

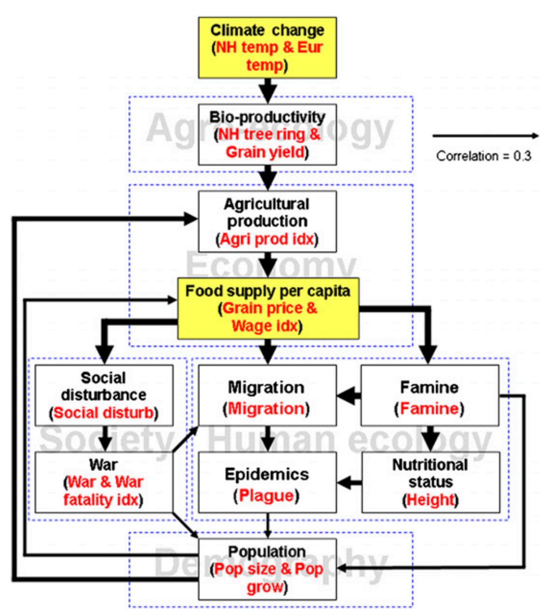

Fig. 2. Set of causal linkages from climate change to large-scale human crisis in preindustrial Europe. The terms in bold black type are sectors, and terms in red type within parentheses are variables that represent the sector. The thickness of the arrow indicates the degree of average correlation, which is calculated from *SI Appendix*, Table S2.

We further validated the time sequence and predictability of the causal linkages in Fig. 2 by using GCA (*SI Appendix, Text* section 2). Via GCA, the causal relationship between variables is confirmed only if the cause precedes the effect in time and the causal series contains special information that could better explain and forecast the series being caused (30). The causal linkages in Fig. 2 boiled down to these relationships: Climate change → bio-productivity → agricultural production → FSPC; FSPC → social disturbance → war; FSPC → famine → nutritional status; FSPC, social disturbance, war, and famine → migration; nutritional status and migration → epidemics; war, famine, and epidemics → population; population → agricultural production; and population → FSPC. Our GCA results show that all null hypotheses of these linkages were rejected (13 linkages with $P < 0.01$ and 4 linkages with $P < 0.05$), implying that causal relationships between climate change and human crisis are statistically valid (Table 1 and *SI Appendix, Text* section 2.1).

Because the alternation of periods of harmony and crisis in Europe followed variations in FSPC (Figs. 1 and 2), we suggest that FSPC is a key sector bridging climate change and human systems. Because FSPC is codetermined by agricultural production (supply) and population size (demand), it can be epitomized by grain price (the ratio of supply to demand). We used GCA to test whether grain price is the direct cause of all social and human ecological crises. Grain price was the *Granger-cause* of social disturbance, war, migration, epidemics, famine, and nutritional status (five linkages with $P < 0.01$ and one linkage with $P < 0.05$) (Table 2 and *SI Appendix, Text* section 2.2). Hence, grain price could be taken as an indicator and direct cause of conditions of harmony or crisis in preindustrial Europe.

Simulation of Periods of Harmony and Crisis in Europe and the NH.
Grain price. Based on the above findings, we used a longer grain price series to simulate the alternation of conditions of harmony and crisis in Europe further back in time. To eliminate the effect of long-term inflation upon the market price of grains, real grain price was used (*SI Appendix, Text* section 3). We found that real grain price followed temperature change inversely (Fig. 3*A*).

When the GCSC began in A.D. 1560, real grain price was 0.2. Therefore, we set a real grain price = 0.2 as the general crisis threshold. The periods in which real grain price was >0.2 or <0.2 represent periods of crisis or harmony, respectively. With that threshold, our simulated crisis periods were A.D. 1264–1359 and A.D. 1559–1652, consistent with the time spans of the Crisis of the Late Middle Ages and the GCSC, as delimited by historians. In both crisis periods, real grain price was driven up by population pressure (i.e., steady population growth over a long period), bringing about demographic collapses at later stages. Each demographic collapse lasted for ∼30 y. The collapse of the 14th century started in A.D. 1315 when the Great Famine began. Our simulated periods of harmony (A.D. 1360–1558 and A.D. 1653–1800) coincided with the prosperous Renaissance and Enlightenment eras (*SI Appendix, Text* section 4.2) (21, 31, 32).

The complex relationship among temperature, real grain price, agricultural production, population size, and social conditions during the period is illustrated clearly in Fig. 3*B*. The finding echoes the key notion of Malthusian theory (33): When population size overshoots agricultural production, human misery follows. Malthus (33) argued that rapid population growth was the cause of human misery. Our findings, however, indicate that the misery in fact was triggered by climate-induced agricultural decline. Malthusian theory emphasizes increasing demand for food as the cause, whereas we found the cause to be shrinking food supply.

Temperature. Although the alternation of harmony and crisis tracked fluctuations in the real grain price in preindustrial Europe, GCA results show that temperature change was the *Granger-cause* of real grain price (*SI Appendix, Text* section 2.3), because agricultural production was climate dependent at the time. Indeed, temperature change is the ultimate cause of human catastrophes, in that it affects first agro-economy and then people's livelihood.

We used a European temperature series as another indicator of conditions of harmony or crisis to simulate the "golden" and "dark" ages in Europe over the past millennium. We set temperature = −0.1σ (according to the 100-y smoothed European temperature series) as the general crisis threshold. The periods in which temperature was lower than −0.1σ or greater than −0.1σ represent dark ages and golden ages, respectively. With that threshold, the dark ages we calculated were A.D. 1212–1381 (the Crisis of Late Middle Ages) and A.D.1568–1665 (the GCSC), whereas the golden ages were the 10th to 12th centuries (the High Middle Ages), the late-14th to early 16th centuries (the Renaissance), and the late-17th to 18th centuries (the Enlightenment) (*SI Appendix, Text* section 4.1), largely in agreement with time intervals delimited by historians (*SI Appendix, Text* section 4.2). The mild cooling in Europe in the late 18th and 19th centuries brought about an upsurge in prices, social disturbance, war, and migration, but not demographic crisis, because of social buffers such as cross-continental migration, trade, and industriali-

Table 1. GCA for each of the linkages shown in Fig. 2 (*SI Appendix, Text* section 2.1)

Causal linkage (null hypothesis)	*F*	*P*
Climate change does not *Granger-cause* bio-productivity	207.485	0.000*
Bio-productivity does not *Granger-cause* agricultural production	7.440	0.007†
Agricultural production does not *Granger-cause* FSPC	9.834	0.002†
War does not *Granger-cause* population	391.805	0.000*
Epidemics does not *Granger-cause* population	103.054	0.000*
Famine does not *Granger-cause* population	155.736	0.000*
Population does not *Granger-cause* agricultural production	5.731	0.017‡
Population does not *Granger-cause* FSPC	67.664	0.000*
FSPC does not *Granger-cause* famine	10.307	0.000*
Famine does not *Granger-cause* nutritional status	2.139	0.009†
Nutritional status does not *Granger-cause* epidemics	2.345	0.004†
FSPC does not *Granger-cause* social disturbance	1.971	0.024‡
Social disturbance does not *Granger-cause* war	3.256	0.000*
Social disturbance does not *Granger-cause* migration	1.786	0.037‡
War does not *Granger-cause* migration	2.250	0.006†
FSPC does not *Granger-cause* migration	2.164	0.008†
Migration does not *Granger-cause* epidemics	1.835	0.031‡

*Significant at 0.001 level (2-tailed) ($P < 0.001$).
†Significant at 0.01 level (2-tailed) ($P < 0.01$).
‡Significant at 0.05 level (2-tailed) ($P < 0.05$).

Table 2. GCA of the relationship between grain price and various social and human ecological crises (*SI Appendix Text* section 2.2)

Causal linkage (null hypothesis)	*F*	*P*
Grain price does not *Granger-cause* social disturbance	1.971	0.024*
Grain price does not *Granger-cause* war	5.060	0.000†
Grain price does not *Granger-cause* migration	2.164	0.008‡
Grain price does not *Granger-cause* epidemics	5.113	0.000†
Grain price does not *Granger-cause* famine	10.307	0.000†
Grain price does not *Granger-cause* nutritional status	3.970	0.000†

*Significant at 0.05 level (2-tailed) ($P < 0.05$).
†Significant at 0.001 level (2-tailed) ($P < 0.001$).
‡Significant at 0.01 level (2-tailed) ($P < 0.01$).

zation. Hence, the crisis that occurred in the early 19th century (the Age of Revolution) was not a general one.

Periods of harmony and crisis in the NH are reflected by fluctuations in population growth and the frequency of famine, epidemics, and war (*SI Appendix*, *Text* section 5). The NH temperature and European temperature was highly correlated (Fig. 4 *A* and *B*). The troughs of population growth (Fig. 4*C*) and the peaks of various mortality factors (Fig. 4 *D–F*) in the NH coincided with a cold climate. In fact, the alternation of periods of harmony and crisis in the NH corresponded to the alternation of such periods in Europe. In addition, regression results indicate that all the aforementioned variables were determined significantly by temperature change (*SI Appendix*, Table S4). Just as in Europe, temperature could be taken as the indicator of conditions of harmony or crisis in the NH in historical time. However, in the NH warming also caused widespread famine between the 11th and 12th centuries (the Medieval Warm Period), because high temperature caused drought in North Africa and Western Asia (34, 35). However, the warmth was not severe enough to engender global crises.

Discussion

In this study, all criteria for confirming the causal mechanisms between climate change and human crisis were met. The alternation of historical golden and dark ages in Europe and the NH, which often was attributable to sociopolitical factors (20, 21), was indeed rooted in climate change. Climate change determined the fate of agrarian societies via the economy (the ratio between resources and population). Because the economy also interacts with numerous social factors, scholars tend to rely on social factors to explain human crisis. Although many individual, short-term human crises are triggered by social problems, this effect does not necessarily contradict our findings if we take differing temporal and spatial scales into account. The crucial issue linking scale to explanation is whether the variables used to explain a phenomenon are themselves located at the same scale. Causal explanation and generalization relevant to one scale regime are unlikely to be appropriate at others (36). Although social factors may explain some short-term crises in history, they cannot explain the synchronous occurrence of long-term crises in different countries (in different stages of civilization, culture, economic development, and resources) across different climatic zones in the NH, nor can they simulate the alternation of historical golden and dark ages. In fact,

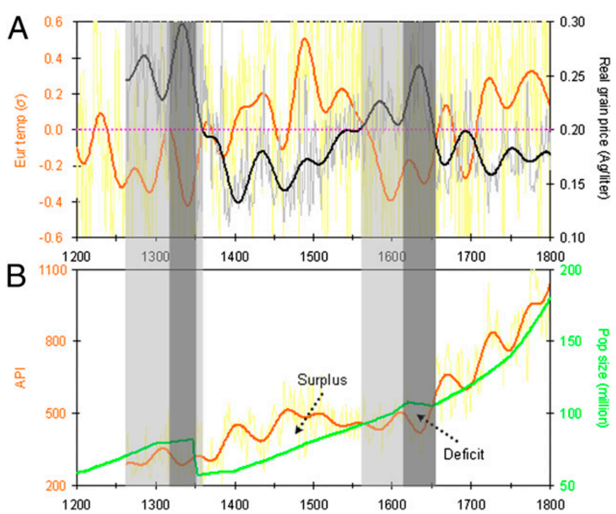

Fig. 3. Real grain prices and the alternation of periods of harmony and crisis in Europe, A.D. 1200–1800. (*A*) European temperature anomaly (σ, orange line), real grain price (Ag/L, bold black line), and the threshold of general crisis (real grain price = 0.2, pink dotted line). (*B*) Agricultural production index (orange line) and population size (in millions, green line). European temperature, real grain prices, and agricultural production index were smoothed by 40-y Butterworth low-pass filter. The light gray stripe represents a period of general crisis (real grain price >0.2); the dark gray stripe represents a period of demographic collapse.

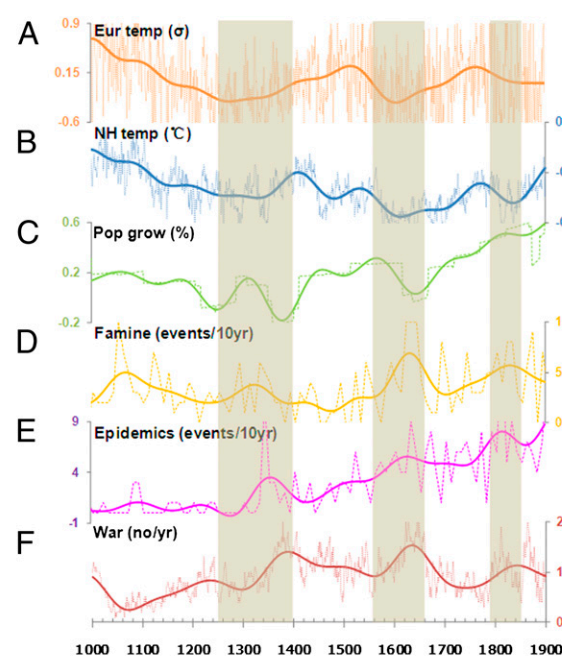

Fig. 4. Temperature change and the alternation of periods of harmony and crisis in the NH during the past millennium. (*A*) European temperature anomaly (σ). (*B*) NH temperature anomaly (°C). (*C*) NH annual population growth rate (%). (*D*) Famine years in the NH (number of famine years per decade). (*E*) Number of deadly epidemic events (malaria, plague, typhus, measles, smallpox, and dysentery) per decade in the NH. (*F*) Number of wars per year in the NH. All data were smoothed by a 100-y Butterworth low-pass filter. Gray stripes represent periods of crisis in Europe as delimitated by historians (*SI Appendix*, *Text* section 4.2).

climate-induced societal change can be measured at different scales, whereas the magnitude of change depends upon the economic impact of climate deterioration. Here we established the underlying causal mechanisms between climate change and human crisis at continental and hemispheric scales. We conclude that climate change was the ultimate cause of human crisis in preindustrial societies. In addition, we identified climate-driven economic downturn as the direct cause of human crisis. This result explains why some countries did not undergo serious human crisis in the Little Ice Age: Wet tropical countries with high land-carrying capacity or countries with trading economies did not suffer a considerable shrinkage in food supply, nor did some countries, such as New World countries with vast arable land and sparse populations, experience substantial supply shortage.

Our findings have important implications for industrial and postindustrial societies. Any natural or social factor that causes large resource (supply) depletion, such as climate and environmental change, overpopulation, overconsumption, or nonequitable distribution of resources, may lead to a general crisis, according to the set of causal linkages in Fig. 2. The scale of the crisis depends on the temporal and spatial extent of resource depletion.

Materials and Methods

Data. We collected historic data on climate change, agro-ecology, economy, society, human ecology, and demography in Europe to explore the specific causal mechanisms that translate climate change into large-scale human crisis (*SI Appendix, Materials and Methods* I–XI) and the NH (*SI Appendix, Text* section 5). The data were extracted from the most recent and fine-grained data archives according to our best knowledge. Our NH temperature series was generated by arithmetically averaging the 12 most recent and authoritative NH paleo-temperature reconstructions chosen by the Intergovernmental Panel on Climate Change (37) (in °C, from the A.D. 1961–1990 mean). Our European temperature series (in σ) was given by arithmetically averaging two authoritative European temperature reconstructions (38, 39). Because the two reconstructions were derived from different proxies and were reconstructed by different methods, they were normalized to homogenize the original variability of the series before taking their arithmetic average (*SI Appendix, Materials and Methods* I).

Verification of Strength, Consistency, and Predictability of Causal Linkages. We used 16 fine-grained variables in this study (*SI Appendix, Materials and Methods* I–XI). Using the variables' response time to cooling (at multidecadal to centennial scales), together with natural laws and social theories, we identified a set of causal linkages from climate change to general crisis (Fig. 2). The strength of the linkages was examined by cross-correlation analysis, and the consistency and predictability of the linkages were validated by multiple regression analysis. In accordance with the procedure described by Zhang et al. (7), all our variables were smoothed by a 40-y Butterworth low-pass filter before correlation and regression analysis. This smoothing makes our findings more appropriate within the context of climate–human studies.

Verification of Time Sequence and Predictability of Causal Linkages. We adopted GCA to verify the time sequence and predictability of the causal linkages at an annual scale. GCA has been used widely in business, economics, sociology, psychology, politics, biology, and medicine. It also is regarded as an effective method to verify causal relationships in the social sciences (40, 41). Before GCA, an Augmented Dickey–Fuller test was adopted to check the stationarity of data. Any nonstationary data were subjected to first- or second-level differencing. Then regressions were run (by controlling the number of lags) to identify the causal relation (*SI Appendix, Text* section 2).

ACKNOWLEDGMENTS. We thank our colleagues Profs. C. Y. Jim, G. C. S. Lin, S. X. Zhao, and M. R. Peart, and two anonymous referees for their valuable comments on the manuscript. We thank Dr. G. D. Li (Department of Statistics and Actuarial Science, University of Hong Kong) for his close scrutiny of GCA. We are grateful for the support provided by the University of Hong Kong Seed Funding for Basic Research (Grant 10400340), the Hui Oi Chow Trust Fund, and the Research Grants Council of the Government of the Hong Kong Special Administrative Region (Grant HKU7055/08H).

1. Atwell WS (2001) Volcanism and short-term climatic change in East Asian and world history, c. 1200-1699. *J World Hist* 12:29–98.
2. Atwell WS (2002) Time, money, and the weather: Ming China and the 'great depression' of the mid-fifteenth century. *J Asian Stud* 61:83–113.
3. deMenocal PB (2001) Cultural responses to climate change during the late Holocene. *Science* 292:667–673.
4. Weiss H, Bradley RS (2001) Archaeology. What drives societal collapse? *Science* 291: 609–610.
5. Bryson RA, Murray TJ (1977) *Climates of Hunger: Mankind and the World's Changing Weather* (Univ of Wisconsin Press, Madison, WI).
6. Zhang D, Jim CY, Lin CS, He YQ, Lee F (2005) Climate change, social unrest and dynastic transition in ancient China. *Chin Sci Bull* 50:137–144.
7. Zhang DD, Brecke P, Lee HF, He YQ, Zhang J (2007) Global climate change, war, and population decline in recent human history. *Proc Natl Acad Sci USA* 104:19214–19219.
8. Zhang DD, et al. (2006) Climatic change, wars and dynastic cycles in China over the last millennium. *Clim Change* 76:459–477.
9. Zhang DD, Zhang J, Lee HF, He YQ (2007) Climate change and war frequency in Eastern China over the last millennium. *Hum Ecol* 35:403–414.
10. Lee HF, Fok L, Zhang DD (2008) Climatic change and Chinese population growth dynamics over the last millennium. *Clim Change* 88:131–156.
11. Lee HF, Zhang DD, Fok L (2009) Temperature, aridity thresholds, and population growth dynamics in China over the last millennium. *Clim Res* 39:131–147.
12. Lee HF, Zhang DD (2010) Changes in climate and secular population cycles in China, 1000 CE to 1911. *Clim Res* 42:235–246.
13. Zhang Z, et al. (2010) Periodic climate cooling enhanced natural disasters and wars in China during AD 10-1900. *Proc Biol Sci* 277:3745–3753 10.1098/rspb.2010.0890.
14. Tol RSJ, Wagner S (2010) Climate change and violent conflict in Europe over the last millennium. *Clim Change* 99:65–79.
15. Zhang DD, et al. (2011) Climate change and large scale human population collapses in the pre-industrial era. *Glob Ecol Biogeogr* 20:520–531.
16. Salehyan I (2008) From climate change to conflict? No consensus yet. *J Peace Res* 45: 315–326.
17. Butler D (2007) Darfur's climate roots challenged. *Nature* 447:1038.
18. Aston TH (1966) *Crisis in Europe: 1560 - 1660* (Routledge & Kegan Paul, London).
19. Parker G, Smith LM (1978) Introduction. *The General Crisis of the Seventeenth Century*, eds Parker G, Smith LM (Routledge & Kegan Paul, London), pp 1–25.
20. Fischer DH (1996) *The Great Wave: Price Revolutions and the Rhythm of History* (Oxford Univ Press, New York).
21. Goldstone JA (1991) *Revolution and Rebellion in the Early Modern World* (Univ of California Press, Berkeley, CA).
22. Schumm SA (1991) *To Interpret the Earth: Ten Ways to be Wrong* (Cambridge Univ Press, Cambridge, UK).
23. Galloway PR (1986) Long-term fluctuations in climate and population in the preindustrial era. *Popul Dev Rev* 12:1–24.
24. Chu CYC, Lee RD (1994) Famine, revolt, and the dynastic cycle: Population dynamics in historic China. *J Popul Econ* 7:351–378.
25. Koepke N, Baten J (2005) The biological standard of living in Europe during the last two millennia. *Eur Rev Econ Hist* 9:61–95.
26. Brecke P (1999) Violent conflicts 1400 A.D. to the present in different regions of the world. *1999 Meeting of the Peace Science Society* (Georgia Institute of Technology, Atlanta). Available at http://www.inta.gatech.edu/peter/PSS99_paper.html.
27. Wrigley EA, Schofield RS (1981) *The Population History of England, 1541-1871: A Reconstruction* (Arnold, London).
28. Lee R, Anderson M (2002) Malthus in state space: Macro economic-demographic relations in English history, 1540 to 1870. *J Popul Econ* 15:195–220.
29. Turchin P (2003) *Historical Dynamics* (Princeton Univ Press, Princeton).
30. Granger CWJ (1988) Some recent development in a concept of causality. *J Econom* 39: 199–211.
31. Lyon B, Rowen HH, Hamerow TS (1969) *A History of the Western World* (Rand McNally, Chicago).
32. Roberts JM (1996) *A History of Europe* (Helicon, Oxford).
33. Malthus TR (1993) *An Essay on the Principle of Population* (Oxford University Press, Oxford, UK).
34. von Rad U, et al. (1999) A 5000-yr record of climate change in varved sediments from the oxygen minimum zone off Pakistan, Northeastern Arabian Sea. *Quat Res* 51:39–53.
35. Enzel Y, et al. (2003) Late Holocene climates of the Near East deduced from Dead Sea level variations and modern regional winter rainfall. *Q Res* 60:263–273.
36. Gibson CC, Ostrom E, Ahn TK (2000) The concept of scale and the human dimensions of global change: A survey. *Ecol Econ* 32:217–239.
37. Jansen E, et al. (2007) Palaeoclimate. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK), pp 433–498.
38. Osborn TJ, Briffa KR (2006) The spatial extent of 20th-century warmth in the context of the past 1200 years. *Science* 311:841–844.
39. Luterbacher J, Dietrich D, Xoplaki E, Grosjean M, Wanner H (2004) European seasonal and annual temperature variability, trends, and extremes since 1500. *Science* 303: 1499–1503.
40. Russo F (2009) *Causality and Causal Modelling in the Social Sciences: Measuring Variations* (Springer, Dordrecht, The Netherlands).
41. Sobel ME (2000) Causal inference in the social sciences. *J Am Stat Assoc* 95:647–651.