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

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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

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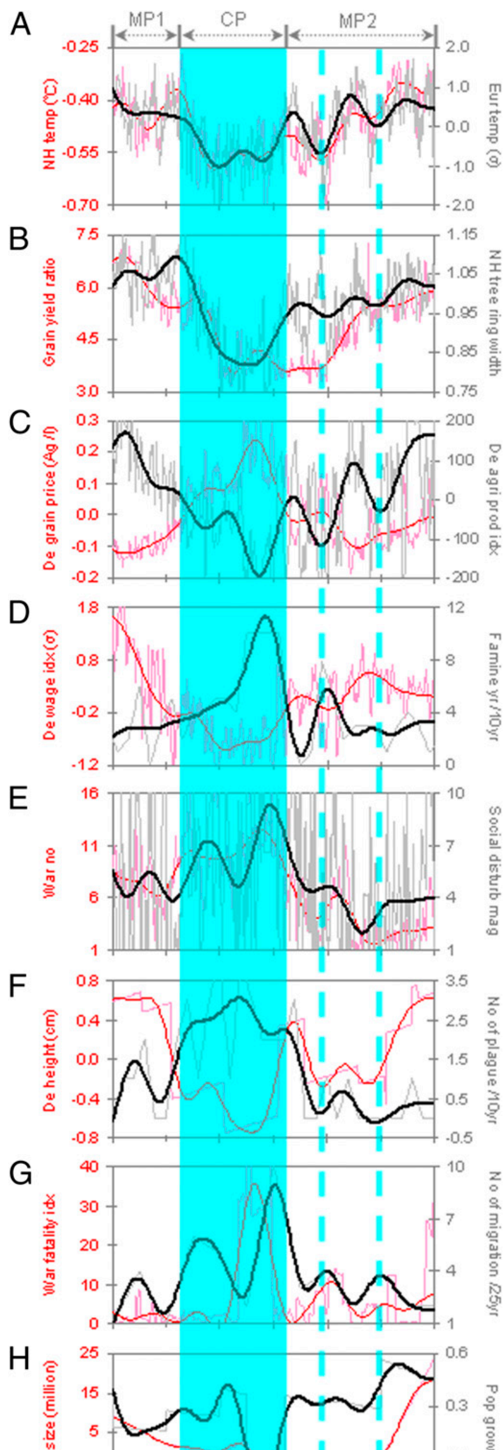

Fig. 1. Responses of different variables in human society to climate change in Europe, A.D. 1500–1800. (*A*) NH temperature anomaly (°C, red line) and Europe temperature anomaly (σ, black line). (*B*) Ratio of grain yield to seed (red line) and NH extratropical tree-ring widths (black line). (*C*) Detrended 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.

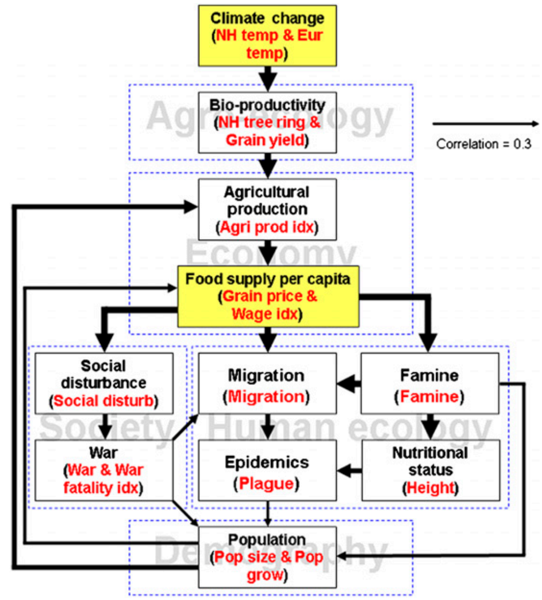

Fig. 2. Set of causal linkages from climate change to large-scale human crisis in preindustrial Europe. The terms in bold black type are sectors, and terms in red type within parentheses are variables that represent the sector. The thickness of the arrow indicates the degree of average correlation, which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

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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,

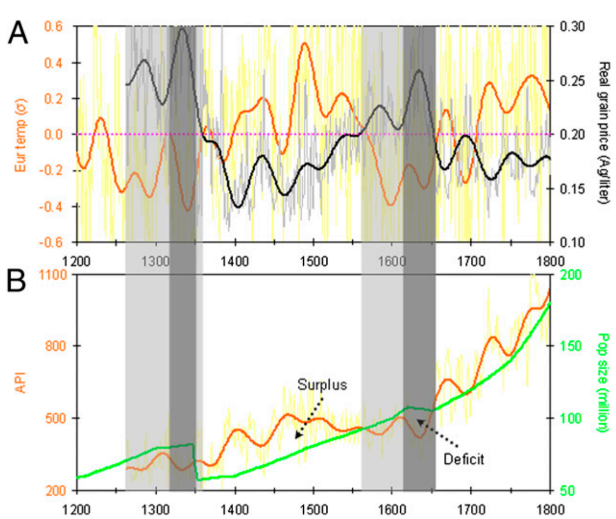

Fig. 3. Real grain prices and the alternation of periods of harmony and crisis in Europe, A.D. 1200–1800. (*A*) European temperature anomaly (σ, orange line), real grain price (Ag/L, bold black line), and the threshold of general crisis (real grain price = 0.2, pink dotted line). (*B*) Agricultural production 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.

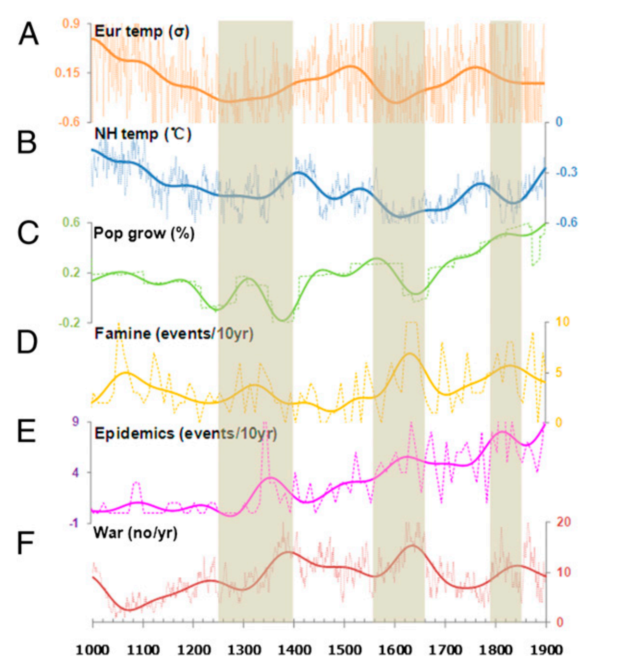

Fig. 4. Temperature change and the alternation of periods of harmony and crisis in the NH during the past millennium. (*A*) European temperature anomaly (σ). (*B*) NH temperature anomaly (°C). (*C*) NH annual population growth rate (%). (*D*) Famine years in the NH (number of famine years per decade). (*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).

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SI Appendix for

Climate change is the ultimate cause of large-scale human crisis

This file includes:

MATERIAL AND METHODS

I. Climate change

1. Northern Hemisphere temperature anomaly (NH temp)
2. Europe temperature anomaly (Eur temp)

II. Bio-productivity

1. Northern Hemisphere extra-tropical tree-ring widths (NH tree ring)
2. Grain yield ratio in relation to seed (Grain yield)

III. Agricultural production

1. Agricultural production index (Agri prod idx)

IV. Food supply per capita

1. Grain price (Grain price)
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V. Famine

1. Famine years (Famine)

VI. Nutritional status

1. Average height (Height)

VII. Social disturbance

1. Magnitude of social disturbances (Social disturb)

VIII. War

1. Number of wars (War)
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IX. Migration

1. Number of migration incidents (Migration)

X. Epidemics

1. Number of plagues (Plague)

XI. Population

1. Population size (Pop size)
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TEXT

SUPPLEMENTARY TABLES

SUPPLEMENTARY REFERENCES

MATERIAL AND METHODS

I. Climate change

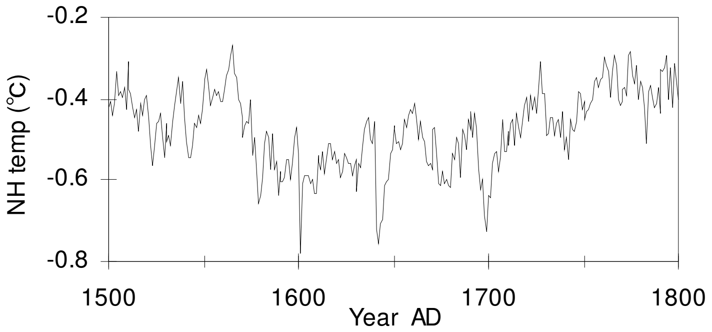
Misconceptions of climate are always around. The first and foremost misconception is the ignorance of scale in interpreting climate. The climate that looks normal, the 30-year period that weather agencies define as ‘normal’, indeed looks quite abnormal in the perspective of the last 1,000 years. By comparison with longer periods, back to a million years ago, it looks very abnormal (1). Another related misconception is about the presumed fixity of climate. Until the last few decades it was a common belief that climate was stable throughout recorded history (2, 3). But, thanks to recent work in paleo-climatology. It has come to light that climate is characterized by significant long-term fluctuations.

In order to understand climate change and how it might vary in the future, it is first necessary to appreciate how climate has fluctuated in the past. The most ‘direct’ record revealing climate change is instrumental measurement. Nonetheless, the thermometer, rain gauge and barometer were invented in the seventeenth century. Besides, only for a handful of places do quantitative meteorological data go back more than 200 years. While Manley’s (4) temperature series for Central England beginning in 1659 is the longest continuous run of instrumental records, a much longer perspective is needed to identify and understand the full range of climatic variation that has occurred.

For many parts of the world, qualitative records of climatic conditions and climate-related phenomena – such as droughts, floods, the freezing of rivers and lakes, the flowering of trees and the ripening of grapes – provide information about past climates which is less precise than instrumental records but is more abundant and sometimes extends several centuries further back in time. Ships’ logs, for example, contain a good deal of information on climatic conditions. Medieval manorial records are a useful source of information on weather events such as droughts, severe snowfalls and storms, as well as providing information on the impact of such events on society. However, historical records may be biased and cannot reveal climatic information very far though (5).

Fortunately a wide range of natural phenomena is climate-dependent and become sealed into stratified deposits containing built-in proxy measures of past climate. A wide range of proxy data is now available relating to environment in different parts of the world. An important aspect of such indicators is the quality of their time resolution. Sources that provide data on a seasonal or annual basis such as tree rings and ice cores allow climatic fluctuations to be dated accurately (5).

1. Northern Hemisphere temperature anomaly (NH temp)



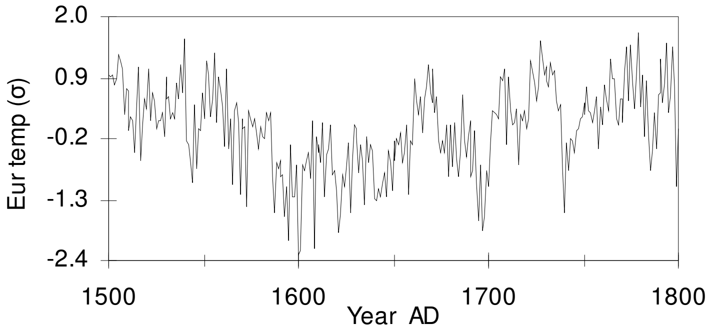
In the past few years, a number of long, high-resolution (annual or decadal) temperature proxy reconstructions of Northern Hemisphere with reliable millennial-scale variability have been produced. Despite their diversified sources of data and the associated methods of reconstructions, the strikingly high congruence among the reconstructed records warranted their validity and reliability. Although the amplitudes vary, due in part to the different scales used, the turning points appear to occur at about the same time, with three pronounced climatic fluctuations in the Northern Hemisphere in the past millennium affirmed, namely: the Medieval Warm Period, the Little Ice Age, and the post nineteenth-century sustained warming.

Recently, experts from the Intergovernmental Panel on Climate Change chose 12 recent paleo-temperature reconstructions of the Northern Hemisphere (derived from multiple climate proxy records) to assess how the climate system changes during the last 1,300 years (6). Details of each reconstruction are listed as follows:

Paleo-temperature reconstruction	Period	Reconstructed season	Region
Jones et al., 1998 (7) ; calibrated by Jones et al., 2001 (8)	1000–1991	Summer	Land, 20°N–90°N
Mann et al., 1999 (9)	1000–1980	Annual	Land + marine, 0–90°N
Briffa et al., 2001 (10)	1402–1960	Summer	Land, 20°N–90°N
Esper et al., 2002 (11); recalibrated by Cook et al., 2004 (12)	831–1992	Annual	Land, 20°N–90°N
Briffa, 2000 (13); calibrated by Briffa et al., 2004 (14)	1–1993	Summer	Land, 20°N–90°N
Mann and Jones, 2003 (15)	200–1980	Annual	Land + marine, 0–90°N
Rutherford et al., 2005 (16)	1400–1960	Annual	Land + marine, 0–90°N
Moberg et al., 2005 (17)	1–1979	Annual	Land + marine, 0–90°N
D'Arrigo et al., 2006 (18)	713–1995	Annual	Land, 20°N–90°N
Hegerl et al., 2006 (19)	558–1960	Annual	Land, 20°N–90°N
Pollack and Smerdon, 2004 (20); reference level adjusted following Moberg et al., 2005 (17)	1500–2000	Annual	Land, 0–90°N
Oerlemans, 2005 (21)	1600–1990	Summer	Global land

All of the above reconstructions are in yearly resolution, which represent anomalies (°C) from the 1961–1990 mean. In this study, we arithmetically averaged those reconstructions to generate a temperature composite, which characterizes the climate change in the Northern Hemisphere. We took the Northern Hemisphere temperature composite as a control variable to verify whether the climate change in Europe is significant in affecting the pre-industrial European societies.

2. Europe temperature anomaly (Eur temp)



Regarding the temperature anomaly series in Europe, it was derived from two authoritative temperature reconstructions at the annual scale. This first one is Luterbacher et al's (22) annual temperature reconstruction for European land areas (25^{o}W to 40^{o}E and 35^{o}N to 70^{o}N) spanned 1500–2003. This reconstruction is based on a comprehensive dataset that includes a large number of homogenized and quality-checked instrumental data series, a number of reconstructed sea-ice and temperature indices derived from documentary records for earlier centuries, and a few seasonally resolved proxy temperature reconstructions from Greenland ice cores and tree rings from Scandinavia and Siberia. The second temperature reconstruction is associated with Osborn and Briffa's (23) annual temperature dataset spanned 800–1995, which contains 14 temperature-related proxy records in the following regions: Western USA (regional), Southwest Canada (Icefields), Western USA (Boreal/Upperwright), Northeastern Canada (Quebec), Eastern USA (Chesapeake Bay), Western Greenland (regional), Netherlands/Belgium (regional), Austria (Tirol), Northern Sweden (Tornetrask), Northwestern Russia (Yamal), Northwestern Russia (Mangazeja), Northern Russia (Taimyr), Mongolia (regional), and Eastern Asia (regional). However, only those regional temperature series nested within Europe were combined to show the temperature change in Europe over time, namely: Western Greenland, Netherlands/Belgium, Austria, Northern Sweden, Northwestern Russia, Northwestern Russia, and Northern Russia. It was done by normalizing each of the above series and then taking their arithmetical average.

The above two temperature reconstructions were derived from different proxies and reconstructed by different methods. In order to combine the two reconstructions together, each of them was normalized to homogenize the original variability of all series. It should be noted that this transformation cannot preserve the numerical values of temperature variation, but will provide the relative amplitude of temperature change. Then, the two normalized series were arithmetically averaged to generate the Europe temperature composite used in this study.

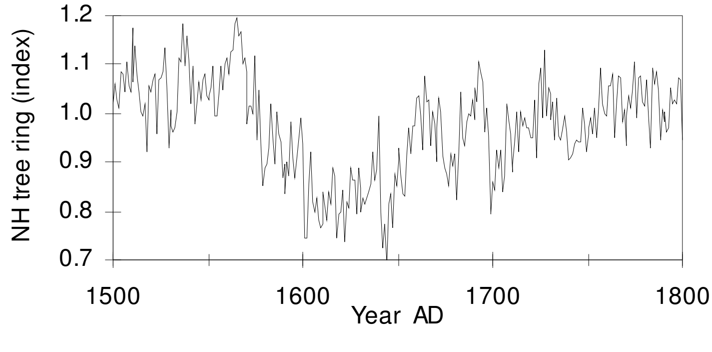
II. Bio-productivity

According to biological principles, warm climate makes possible the augmentation of agricultural production, while cooling can directly impede agricultural production or even lead to crop failure. Given the limited technology in pre-industrial Europe, the relationship is more clear-cut especially over the long run.

Temperature change influences agricultural production by affecting the length of growing seasons, intensity of summer warmth on the average, and reliability of rainfall, which can bring serious problems for food production sequentially, especially in the high and middle latitudes (1, 2). Besides, cooling will also restrict the spatial extent of possible farming areas. The obvious impact of a long period of cooling is to lower the elevation where crops can be effectively grown, in effect decreasing the amount of land available for cultivation and leading to a decline in total output or more intense cultivation but lower yields. For instance, a fall of 1°C reduces the growing season for plants by three or four weeks, lowers the maximum altitude at which crops will ripen by about 150 meters, and diminishes crop yields in northerly latitudes by up to 15%. Whereas most Western European farmers expect eight or even nine months in which to grow crops, their northern counterparts have only four (around Novgorod), five (around Moscow), or six months (around Kiev). Given the shorter growing seasons and less advanced agricultural methods, a cooler climate would have had greater impacts in those northern regions (24). A modest fall in mean summer temperature may take certain parts of Northern Europe which were previously cultivable if marginal into the category of grazing land or rough pasture. The impact of climate change upon bio-productivity is apparent.

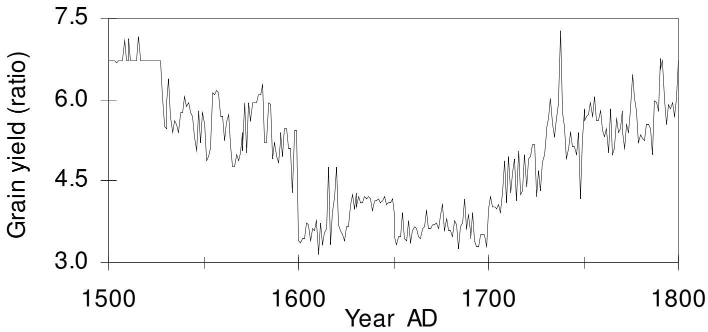
There are two parameters which can reflect the change of bio-productivity in pre-industrial Europe over time, namely: Northern Hemisphere extra-tropical tree-ring widths and grain yield ratio in relation to seed.

1. Northern Hemisphere extra-tropical tree-ring widths (NH tree ring)



The Northern Hemisphere extra-tropical tree-ring widths series spanned 831–1992, which was derived from the selected tree-ring chronologies of 14 sites in the Northern Hemisphere extra-tropics (11). This series is in annual resolution and not scaled to any observational record (index values only). As tree growth is independent of human activities, it may be more satisfactory in measuring the fluctuation of bio-productivity brought by climate change.

2. Grain yield ratio in relation to seed (Grain yield)



Our grain yield series represents crop yield ratio in relation to seed, which was derived from Slicher van Bath's (25) dataset spanned 810–1820. Slicher van Bath (25) assembled nearly 11,500 yield ratios of the following countries in Europe, including: England, Ireland, France, Italy, Spain, Germany, Switzerland, Denmark, Sweden, Norway, Poland, Lithuania, Latvia, Estonia, and Russia. Besides, four types of grains are covered, namely: wheat, rye, barley, and oats ('small grain' crops). His dataset is compiled from various kinds of sources. The medieval English yield ratios are taken from accounts of manors held by the clergy or by monasteries that administered their manors themselves. In the fourteenth and fifteenth centuries this system gave way to leasehold so that later accounts omit reference to amounts of seed and crop yields. The German, Danish, Polish and Russian yield ratios are taken from the accounts of the great landowners or controllers of the royal domains.

Regarding the construction of the grain yield time-series, firstly the yield ratio series (the aggregate of wheat, rye, barley, and oats) of each country in Europe was compiled. Any missing data were linearly interpolated to give an annual time series. Then the annual yield ratio series of all of the countries in Europe were arithmetically averaged to give the grain yield time-series used in this study.

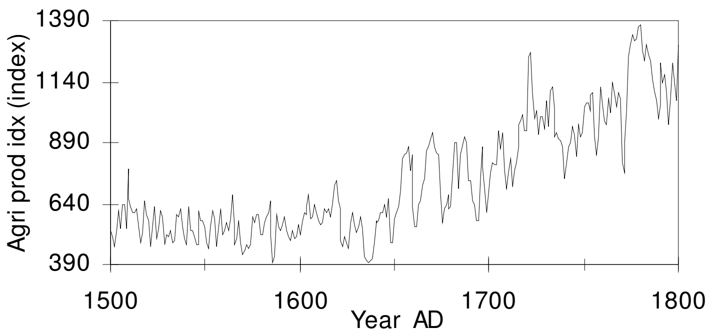
III. Agricultural production

Agriculture occupied an important place in pre-industrial Europe. The larger the amount of agricultural production is, the larger the number of people can be supported, and *vice versa*. Given that agricultural production is still an important factor determining human population growth and that human beings will increase their number until approaching the limit of food availability in the present days, which has been repeatedly evidenced by empirical studies (26), historical agrarian societies are unlikely to be immune from such a limitation (27).

Regarding agricultural production, on one hand, it is determined by the climate-induced fluctuation of bio-productivity. On the other hand, it is also determined by the feedback effect of population growth. Yet, the later relationship remains a controversial issue over which two hardened points of view oppose one another. The first sees demographic growth as an essentially negative force, which strains the relationship between fixed or limited resources (land, minerals) and population, leading in the long run to increased poverty (28). According to the second, demographic growth instead stimulates human ingenuity so as to cancel and reverse the disadvantages imposed by limited resources. A larger population generates economies of scale and more product and surplus, and these in turn support worked as the major dynamic engine of agricultural change, stimulating, in particular, the adoption of improvements in land use and technology. Other things being equal, the larger a population is, the larger will be the number of farmers, and therefore the greater will be the chance that someone will discover a new and more productive way of cultivating the available supply of land (29, 30).

In pre-industrial Europe, there were three ways for raising agricultural production: by increasing the acreage of cultivable land, by increase number of harvest seasons in warmer climate and by increasing the yield from the same area. In practice both methods were generally adopted. However, the difficulty in increasing the acreage of cultivable land was that the pace of technological progress is fairly slow or basically stagnated during the time. Furthermore, land productivity was also constrained by the traditional methods of crop rotation and long follow periods (31). Regarding the feasibility of increasing the amount of cultivable land, the difficulty was that the best lands had long been permanently under cultivation; developing poor lands (e.g., swamps, marshlands, and moors) only gave temporary relief, since although fairly good results were obtained at first their yield ratios subsequently declined (32). The synthesis of relatively stable land productivity and fixed amount of arable land implies that even though population growth and agricultural production might be positively correlated, their strength of association would be relatively weak. Instead of population growth, the climate-induced fluctuation of bio-productivity was more important in determining agricultural production.

1. Agricultural production index (Agri prod idx)



Data on the total amount of agricultural production for Europe are unavailable in our study's time span. As a remedy, we compiled the agricultural production index for Europe. Based on our previous study (33), the agricultural production index was calculated by using two parameters, namely: population size (34) and grain price (International Institute of Social History). Detail descriptions of the population size and grain price data are listed in later paragraphs. As the nominal grain price inflated over time, they were transformed into "real grain price" by the following formula:

$$RP_t = \frac{CPI_{BaseYear}}{CPI_t} \times P_t$$

Where RP represents real grain price, P represents nominal grain price, CPI stands for Consumer Price Index, and t is the time step. The base year is 1500. Our CPI data were downloaded from the web-page of the International Institute of Social History (http://www.iisg.nl/hpw/data.php#europe). Based on the interrelationship among supply (i.e., agricultural production), demand (i.e., population size), and price (i.e., equilibrium point of supply and demand), our annual agricultural production index (API) was calculated by the following formula:

$$API_t = \frac{PS_t}{RP_t}$$

Where PS stands for population size.

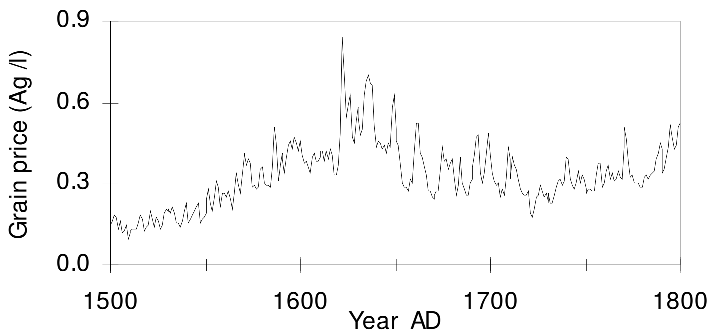
IV. Food supply per capita

Until the start of the Industrial Revolution, it is estimated that three-fourths to four-fifths of the workforce in Europe were engaged in farming. In Sweden and Finland, Russia, Austria and Hungary, Spain, Portugal, and Ireland – countries that industrialized late – censuses from the second half of the nineteenth century reveal proportions of nearly this size, between two-thirds and four-fifths. For earlier periods, estimates are even higher: 80 percent in France at the start of the eighteenth century and in Sweden by the middle of that same century; 75 percent in Austria in 1790; 78 percent in Bohemia in 1756. In Europe as a whole less than 6 percent of all people lived in cities bigger than 10,000 inhabitants in 1500, and in 1700 still fewer than 9 percent did. Those who lived in small villages or in the countryside were mostly peasants, share-croppers, and small landowners. This population was bound to the land, and its survival and progress relied upon developments in farming (31). From the economic viewpoint, any rise or fall in agricultural production resulting from higher or lower yield ratios affected the economic life of the entire region. In particularly every European country the farmers' output long continued to represent most of the entire national production (32). Furthermore, at least half of the expenditure of ordinary families is directed towards grain-based food and drink. As the pre-industrial social economy was highly dependent on agricultural activities, we might reasonable expect that a significant fraction of the population, with the least financial resources, would have experienced substantial changes in the amount of food available in face of the climate-induced agricultural shrinkage (35).

In the pre-industrial time, wherever improved yields are achieved, whether through better methods or increased area of cultivation, the growing population will soon swallow up the surplus produced. There is little capital accumulation, therefore little increase in the supply of daily bread. Under this circumstance, increasing food demand driven by population growth would reduce the amount of food available to each individual. As the speed of human innovation and its diffusion is not fast enough to accommodate growing population, population pressure will be "autonomously" piled up over time, and that the population probably live at the subsistence level and reach the recurring state of demographic saturation and equilibrate at the edge of misery (i.e., starvation) (27, 36-39).

In this study, food supply per capita is represented by grain price and wage index. Prices and wages have long been central concerns of economic historians, for they bear on such fundamental issues as the pace of economic development, economic leadership, and the standard of living.

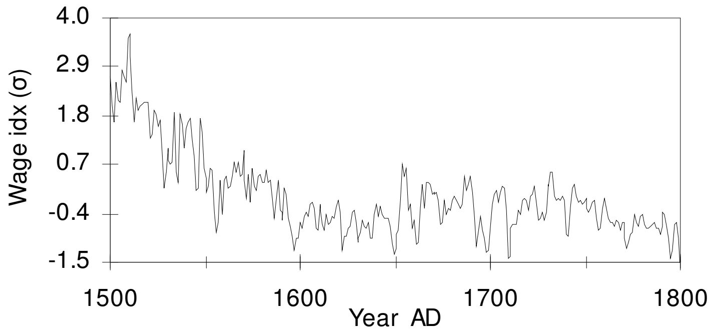
1. Grain price (Grain price)



Our grain price series was derived from the European commodity price data downloaded from the website of the International Institute of Social History (http://www.iisg.nl/hpw/data.php#europe). The price data spanned 1260–1914 covering four types of grains (i.e., wheat, rye, barley, and oats) in 16 major European regions, namely: Amsterdam & Holland, Antwerp & Belgium, Augsburg, Gdansk, Krakow, Leipzig, London & Southern England, Lwow, Madrid & New Castile, Munich, Naples, Northern Italy, Paris, Strasbourg, Vienna, and Warsaw. The grain price is expressed in terms of grams of silver per liter.

Regarding the construction of the grain price series, firstly the prices of wheat, rye, barley, and oats were calculated, respectively. It was done by arithmetically averaging the price data of, say wheat, in the 16 major European countries. Any missing data were linearly interpolated to give an annual time series. Then the annual price series of the four types of grains were arithmetically averaged to give the grain price series used in this study. As stated by some scholars (40), the only cause which can reasonably account for the characteristic peaks of grain prices is a fluctuation in the yield of harvests. That this was, in fact, the cause can be shown a posteriori practically in all cases by historical records; the main peaks and the minor elevations alike are almost all identified with well-known years of famine or harvest failure, generally attributed to inclement weather.

2. Wage index (Wage idx)



Nevertheless, movement in prices does not tell us much about changes in the availability of food over the long run. We also need to take into account changes in wages, which will influence the ability of households to afford the prices charged in the market. Our wage index, which represents the amount of food that can be purchased with the current level of wages, was derived from two datasets.

Agricultural production was the dominant economic activity in Europe and farm workers constituted over half the entire working populace. Therefore, the first dataset to be included is the real day wages of farm laborers in England for calculating the wage index. The wage history of pre-industrial England is unusually well documented for a pre-industrial economy. The relative stability of English institutions after 1066, and the early development of markets, allowed a large number of documents with wages and prices to survive in the records of churches, monasteries, colleges, charities and government. Using manuscript and secondary sources, Clark (41) calculated real day wages (index values only) for male farm laborers in England by decade from the 1200s to 1840s. For farm work, it includes tasks such as hedging, ditching, making faggots, threshing, spreading dung, plowing and carting. The real farm wages are interpreted as the purchasing power (i.e., the amount of things can be consumed) the farm labors have, which is set to 100 in the 1770s. Although the farm wage dataset is for England, it is the only Europe-related farm wage dataset we could find in our study's time span. As the wages are in decadal units, the data points were linearly interpolated to create an annual time series.

The purpose of calculating a real wage index is to track changes in the ability to purchase food over time. Since conditions of employment and remuneration are likely to have varied widely between different occupations, the level of the farm workers' real wage cannot be expected to apply to everyone in Europe. Therefore, we included the second dataset to calculate the wage index, that is the real day wages of building craftsmen and laborers in 19 major European cities (Antwerp, Amsterdam, London, Oxford, Paris, Strasbourg, Florence, Milan, Naples, Valencia, Madrid, Augsburg, Leipzig, Munich, Vienna, Gdansk, Krakow, Warsaw, and Lwow) spanned 1264–1913. The dataset is compiled by Allen (42). Building craftsmen and laborers are the workers whose wages are the most frequently reported in the price histories. When comparing their wages to the earnings of other workers in the same area, it is found that they move in harmony (42). A more substantial test is provided by the British industrial revolution. Lindert and Williamson (43) and Feinstein (44, 45) have both estimated annual earnings is for the British working class by using shifting weights to combine the history of wages and hours for many occupations. There is little disagreement between them in this regard. This indicates that the wages of building craftsmen and laborers are indicative of trends in average earnings of non-farm population. The real wages of building craftsmen and laborers equal the nominal wages divided by the relative consumer price levels, which show proportional changes and relative levels only.

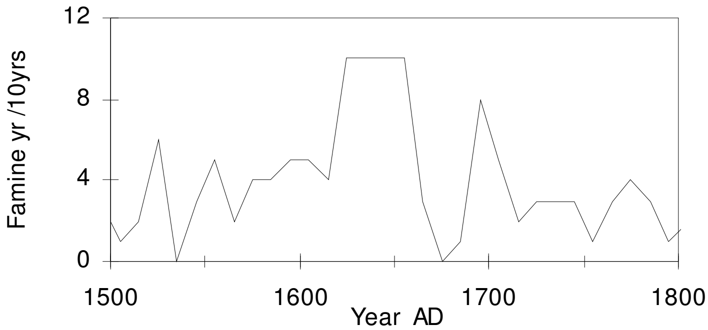
By combining the real wages of farm labors and building craftsmen and laborers, it is hoped that the overall standard of living of Europeans could be revealed. It should be noted that the farm labors' real wages are in decadal units, while the building craftsmen and laborers' ones are in annual units. Therefore, they were transformed into identical decadal units. For the building craftsmen and laborers' real wage series, decadal resolution was obtained by averaging the data within a decade. Furthermore, the two series are also in different measurement units. Thereby, each real wage series has been normalized to homogenize the original variability of all series. Finally, the two normalized series were arithmetically averaged and then linearly interpolated to create an annual wage index series.

V. Famine

In pre-industrial societies, around 75% of daily caloric intake came from cereals (bread, porridges, gruels), supplemented by legumes (peas and beans), small quantity of dairy products, occasional fruits and vegetables, honey as a major sweetening agent, some fish and meat (very seldom, ~200g per week, mostly lamb and pork). At the same time, majority of population routinely was living on the verge of starvation (46). A crop failure was a disaster for a large part of the population. Famine stalked in the background and there was also the threat of unemployment. There was less corn to thresh in the winter, the earnings of farm workers and hired laborers went down, and cereal prices went up as a result of the bad harvest. Industries such as breweries and distilleries that depended on the processing of cereals suffered from the consequent decline in their trade (32). The consequences of a single bad harvest could often be borne by the population, but it often happened that such years rapidly succeeded each other and broke down all resistance, sending cereal prices up to unprecedented heights. The population was scourged with starvation (32).

At the same time, the transition of agricultural production from a lower to a higher stage was generally accompanied by an increase in population. Therefore, a succession of crop failures could be really disastrous. The increased population is obliged to live on harvests that have fallen to the level of an earlier stage of development corresponding to a much smaller population. A long series of crop failures without imports from areas not affected by bad harvests ought in theory to cause a reduction in the population to 50% to 60% of the original number before the disasters began (32).

1. Famine years (Famine)



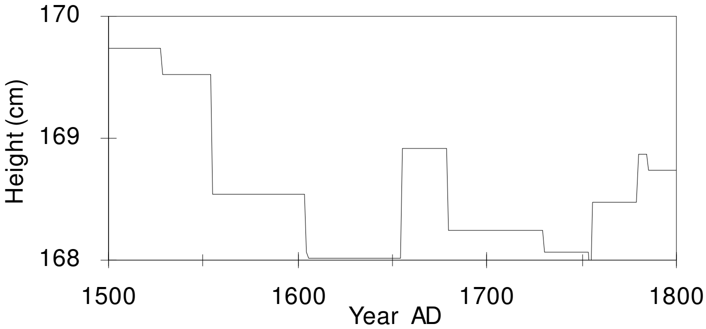
A famine as defined in the chronicles of sages was a protracted total shortage of food in a restricted geographical area, causing widespread disease and death from starvation. This definition is also adopted in this study. Our famine data was elicited from Walford's (47) chronology of famines in world history (which includes in the whole over 350 famines in various parts of the world), which is believed to be the first list of the major famines which had occurred in the history of the world. Episodes of famine have occurred throughout history in many parts of the world. In this research, only those famines occurred in Europe would be considered. Besides, the chronology has also been crosschecked with and supplemented by other materials such as Golkin's (48) chronology of famines printed in *Famine: A Heritage of Hunger*, the "Famine" section in *The Cambridge World History of Food* (49), and the list of known major famines in Wikipedia. We felt that our famine dataset must necessarily be incomplete despite our great effort in fine-tuning it. However, it could somehow show the long-term trend of famine occurrence in Europe. The above figure should be interpreted as the number of famine years per decade. As the data points of which are in 10-year units, they were linearly interpolated to create an annual time series for statistical analysis.

VI. Nutritional status

For the data of nutritional status of population, ideally we should like to know the calorie and protein value of the food that people could command in the past, and how this varied over time and place. In practice, the evidence that we have on past diets is sparse and largely confined to aristocratic households and to institutions. We simply do not know in any detail the quantity and quality of the food of the people, how it varied over time, or what scope there was for substituting other foods in time of harvest deficiency.

In this research, adult stature was used as a proxy for the nutritional status of population. Although genes are important determinants of individual height, studies of genetically similar and dissimilar populations under various environmental conditions suggest that differences in average height across most populations are largely attributable to environmental factors and their nutritional status (50). Besides, stature is a function of proximate determinants such as diet, disease and work intensity during the growing years, and as such it is a measure of the consumption of basic necessities that incorporates demands placed on one's biological system (50).

1. Average height (Height)



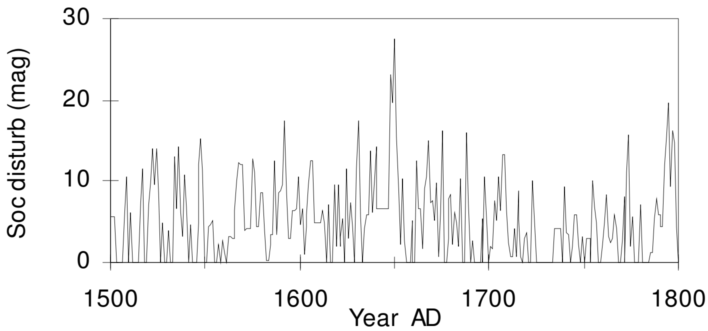
Our time-series of average height was derived from the following historical adult height reconstructions: adult male heights in the Netherlands in 1070–1858 (51); adult male and female heights in Sweden in 900–1699 (52); adult male heights in northern Europe in 800–1930 (53); and adult male and female heights in Europe in 1–1799 (54). The above reconstructions are reconstructed from femur lengths. The length of femur can be regarded as a roughly constant proportion of full body height. Subjects were in all cases assumed to have reached mature height. As the above series are reconstructed from human skeletal remains, for reasons of comparability, we have subtracted 45 years (approximately the average age at death of adults) from the burial time periods as suggested by de Beer (51). Besides, we also included the series of adult male heights in Europe in 1750–1950 (50). All of the five series were arithmetically averaged to give the European height.

VII. Social disturbance

Because man's life activity consists of receiving, transforming, and expending energy, the behavior of the people depends to a great extent upon the type and quantity of energy received by the organism. Like the work of a medicine, which depends upon the quality and the quantity of fuel, the work (behavior) of a man-machine depends directly or indirectly upon the quantity and quality of energy received from without. Deductively, it is possible to foresee that the behavior of a human being represents to a certain degree 'a function' of the quantity and of the quality of energy received, as an 'independent variable'. As long as every social process in the final result consists of the totality of human behavior-acts and the action of the people, it becomes obvious that social processes also are conditioned by this independent variable (55). Here is a sequence: The quantity and the quality of energy received by people (event A) condition their life activity (behavior, event B). The character of human behavior (B) determines surroundings (event C). Therefore, C (social processes) is in functional relationship with event A. This means that the variation and fluctuation of A must cause changes and variations in sphere B (human behavior), and through B also in sphere C (the area of social processes) (55).

In face of famines, social buffering mechanism is an essential factor in determining how far their impact has on human societies. A community's buffering capacity may be seen as a parallel of ecological resilience (56) – a system's ability to withstand environmental perturbations without a change in its dynamic equilibrium. Pre-industrial populations are not expected to evolve spontaneously to a state in which they are well buffered against environmental perturbations. The primitive transport and communication systems typical of pre-industrial times are the most important factors limiting the tempo and spatial extent of social development (27). Even if institutional and social arrangements may have become increasingly efficient and effective over time, those arrangements will be ultimately exhausted by the recurrent subsistence crises caused by long-term cooling, which has been evidenced by historical examples (57). The associated outcomes of famines are more frequent social disturbances, wars, epidemics, and migrations. As revealed by human history, a significant portion of the social disturbances were ultimately developed into wars.

1. Magnitude of social disturbances (Social disturb)



Data about the number of social disturbances were obtained from Sorokin's (58) *Social and Cultural Dynamics Volume III*, which include most of the recorded internal disturbances of importance that have taken place in the life history of Greece, Rome, France, Germany (Central Europe), England, Italy, Spain, the Netherlands, Byzantium, Poland, Lithuania, and Russia. The book documents a total of 205 social disturbances (excluding wars) in Europe in 1500–1800. Those internal disturbances can be further categorized as:

- Predominantly political disturbances, the main objective of which is a change of the existing political regime
- Predominantly socioeconomic disturbances, directed toward a modification of the existing social and economic order

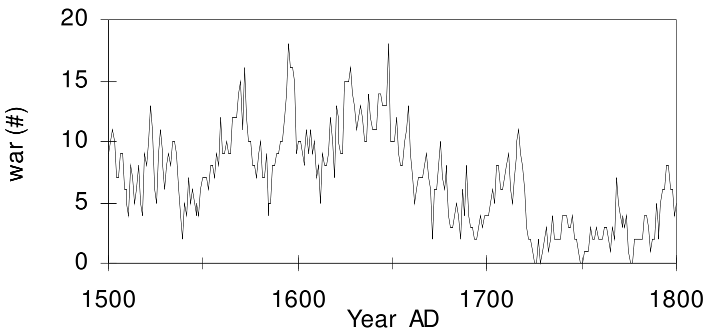
- National and separatistic disturbances, the main objective of which is national independence, or autonomy, or the elimination of disfranchisements, or the achievement of some other privileges and advantages
- Religious disturbances
- Others

The magnitude of each social disturbance (as defined by social area, duration, size of the masses involved, intensity, etc.) is also provided in the book. Based on this information, we compiled our social disturbance time-series as follows: Firstly, the magnitude of each social disturbance was divided by its duration (in terms of the number of years). Secondly, we summed up the annual magnitude of all of the social disturbances in Europe on a yearly basis. Lastly, the yearly sum was divided by the number of countries in Europe.

VIII. War

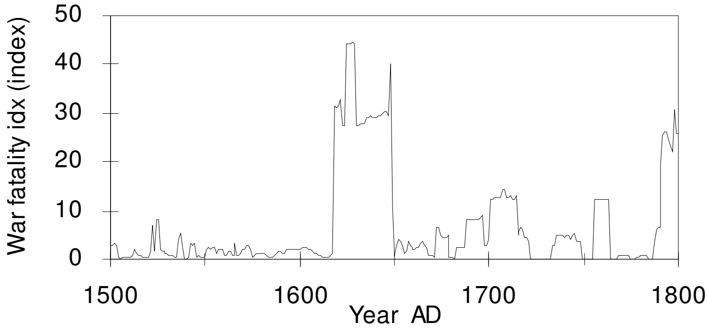
When an animal population faces a situation of insufficient resources, its members often fight and kill each other until the meager resources available are enough for the smaller group of survivors to be in equilibrium with supply. Human beings are not significantly different from animals in this aspect (59, 60). In pre-historic societies, warfare is evidenced to be an adaptive ecological choice under the conditions of population growth and resource limitations (61). Recent empirical studies also confirm that an ever-growing imbalance between population size and the human carrying capacity of the land may have caused armed conflicts in recent human history (33, 62-64) and the present days (65-68). The role of food shortage in provoking wars is generally ascertained. On the one hand, it directly fuels food riots. On the other hand, it serves as a backdrop intensifying a series of social bifurcations and ideological conflicts, which increases the likelihood of war outbreaks.

1. Number of wars (War)



We obtained the total number of wars from the most inclusive global war series so far, the *Conflict Catalogue*, which was compiled by Prof. Peter Brecke (69) from the Sam Nunn School of International Affairs, Georgia Institute of Technology. The catalogue documents a total of 582 wars fought in Europe in 1500–1800, which includes all recorded violent conflicts that meet Richardson's magnitude 1.5 or higher criterion (32 or more deaths). The starting year and end year of each war are also provided in the catalogue. Based on this information, we compiled our war series in terms of the number of wars happening in Europe in a particular year.

2. War fatality index (War fatality idx)

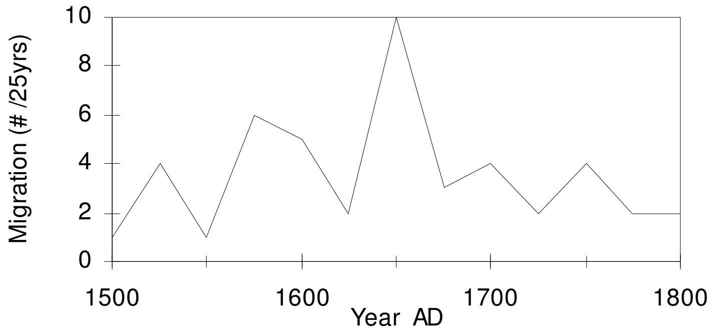


Not all wars come with precise fatality records. As a remedy, based on Brecke's (69) *Conflict Catalogue*, we composed a war fatality index (in annual units) to estimate annual war fatalities. It was done by the following steps: Firstly, the fatality of each war (with known fatality record) was divided by its duration (in terms of the number of years). Secondly, we summed up the annual fatality of all of the wars on a yearly basis. Finally, the resultant figure was divided by 10,000 to give the annual war fatality index.

IX. Migration

Though the people of Europe were essentially bound to the land, they were not an entirely immobile people. An important demographic feature of famines, social disturbances, and wars is migration, which in traditional societies has historically been one of the most important ways that people have coped with those human miseries. Decrease in agricultural yields and more frequent social disorder as a result of a cold climate will lead to profound changes in agrarian economy and society, and consequently an increase in mass migration from poorer to richer areas. A cold climate and its associated deepening economic misery would have its greatest effects in marginal areas. It is likely that those areas would experience significant out-migration.

1. Number of migration incidents (Migration)



Migration can take many forms: newlyweds; domestics and apprentices moving between families; those engaged in seasonal work, transhumance, or agriculture. In addition to these short-range and periodic migrations, there were long-range and definitive ones between states or large regional areas. The latter ones are more important in affecting the operation of socio-economic and demographic systems. In keeping with the scale of our analysis thus far, only those long-range and definitive migrations would be considered in this study.

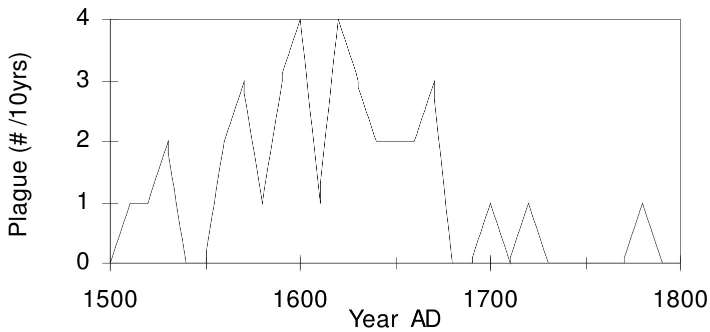
Our data of the starting year of long-range and definitive migrations in pre-industrial Europe was primarily elicited form the website about European migration movement (http://www.let.leidenuniv.nl/history/migration/index.html) under the Leiden University, Netherlands. The aim of that website is to help researchers and students who want to study European migration movements by providing them with a framework and with documents and information about sources on migration. In the website, the following details of every single migration incident are given, such as the description of the migration movement, causes of migration, consequences of migration, and reactions on migration. Besides, our migration data was crosschecked with and supplemented by the following materials: Segal and Marston's (70) *Maps and keys – World involuntary migration*, Moch's (71) *Moving Europeans: Migration in Western Europe since 1650*, and Livi Bacci's (72) *The Population of Europe: A History*. Since the data are in 25-year units, the data points were linearly interpolated to create annual time series for statistical analysis.

X. Epidemics

Epidemics and famines have been consistently linked in historical records. The reasons for their synthesis appear to be both physiological and social. The decrease in agricultural yields brought by cooling, along with an increase in the frequency of famines, probably leads to a general decline in the nutritional status of population. Apart from the deficiency diseases and the various gastro-enteritic disorders, such a chronic undernourishment increases the body's susceptibility drastically to infections of all kinds and a reduced capacity to recover from them, so that what diseases of whatever degree of severity there are normally endemic among the population may suddenly find themselves endowed with increased virulence and rampancy, which results in high mortality (49, 73, 74). In most famines, mortality from epidemic disease has greatly exceeded that from actual starvation (49).

On the other hand, migration elevates epidemics by increasing the frequency of interaction among different groups of the population, which in turn increases the frequency of virulent diseases and the probability of contracting virulent diseases (2). Further, migration has the effect of spreading disease to areas not directly affected by hunger. During times of famine, personal hygiene also tends to be neglected. Debilitated people may fail to wash, and they may drink filthy or contaminated water. They may consume ‘famine foods’ (unripe grain, grass, or roots) in an attempt to suppress hunger; this sometimes causes diarrhea and vomiting, which results in a further weakening of the body and a greater risk of spreading disease. The high level of famine mortality, in other words, is partially a consequence of the nature of the expedients people adopt to try to escape from hunger and partly one of the disruption created by famine in customary patterns of social behavior (49).

1. Number of plagues (Plague)



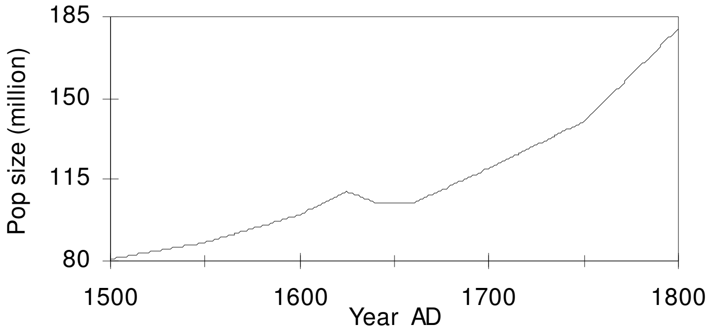
Plague was the most devastating disease out of various types of epidemics. It’s bubonic form was fatal to 60–80% infected, pneumonic – 100% fatal (46). Thereby, we focused on plague in this study because it is more pertinent in checking population size in pre-industrial Europe when compared with other epidemics. The number of plague in Europe was retrieved from Kohn’s (75) *The Encyclopedia of Plague and Pestilence*, which is a compendium of geo-historical information about major, outstanding, and unusual epidemics in regions of the world from ancient times to the present. The encyclopedia provides concise descriptions of more than 700 epidemics. Each detailed entry includes when and where a particular epidemic began, how and why it happened, whom it affected, how it spread and ran its course, and its outcome and significance. In this research, only the plague incidents in Europe were considered. The above figure should be interpreted as the number of plagues per decade. As the data points of which are in 10-year units, they were linearly interpolated to create an annual time series for statistical analysis.

XI. Population

It is frequently claimed that the human species is equipped with 'self-regulating' mechanisms that allow for the speedy re-establishment of the balance between numbers and resources. However, this is only partially true, as these mechanisms – when they do work – are imperfect (and of varying efficiency from population to population and from one age to another), so much so that entire populations have disappeared – a clear sign of the failure of all attempts at regulation (76).

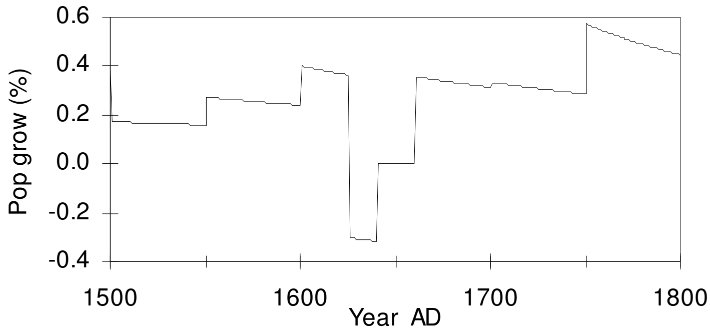
Subject to widespread mortality crises, population size is considerably reduced and the population pressure is unleashed in consequence. During the period of population decline, population losses due to famines, social disturbances, wars, epidemics, and migrations are not made up by sustained population growth. In retrospect, the reduction of population may be viewed as a blessing in disguise, for it gives Europe a breathing space in which to adjust her population to her land carrying capacity. However, due to the carry-over effect of mortality crises such as the destruction of infrastructure (e.g., irrigation, flood control), reduction of agrarian workforce, and also abandonment of exposed lands, the agricultural productive capacity of the society will remain at a low level for some time (63). The restraints on population growth will be loosened only if the climate turns warm and agricultural production is back to normal again. Then, per capita production and consumption considerably increases, mortality crises decrease, the population growth resumes, and a new demographic cycle starts.

1. Population size (Pop size)



It is only from the end of the Middle Ages that estimates of European population growth begin to be based on something more than guesswork (31). In this study, population size of Europe was extracted from McEvedy and Jones' (34) *Atlas of World Population History*. This is a remarkably accurate work, which have been used by other scholars repeatedly. 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.

2. Population growth rate (Pop grow)



Based upon McEvedy and Jones' (34) population size data, population growth rate was calculated by the following formula:

$$\frac{PS_t - PS_{t-1}}{PS_{t-1}} \text{x} 100,$$

where PS is the population size, *t* represents time step.

TEXT

1. Notes for Figure 2

In pre-industrial Europe, long-term cooling dampens bio-productivity by shortening the growing season and reducing available land for cultivation, which significantly shrinks agricultural production. Even though agricultural production can be driven by population growth, subject to the synthesis of relatively stagnated land productivity and fixed amount of arable land, such association will not be significant. Given that agriculture is climate-dependent in pre-industrial period, instead of population growth, climate-induced fluctuation of bio-productivity is more imperative in determining agricultural production during the time. As pre-industrial social economy is highly dependent on agricultural activities, any climate-induced agricultural shrinkage will put a sizeable proportion of population into food strain. In the pre-industrial time, wherever improved yields are achieved, whether through better methods or increased area of cultivation, the growing population will soon swallow up the surplus produced. There is little capital accumulation, therefore little increase in the supply of daily bread. Under this circumstance, increasing food demand driven by population growth would reduce the amount of food available to each individual. Famine stalked in the background. Given the ineffective social mechanisms in buffering subsistence shortage, more frequent social and human ecological crises such as famines, social disturbances, wars and mass migration follow. Poor nutritional status of population caused by famines, together with the mass migration driven by famines and wars, instigate more epidemics. As the various crises are often interlinked, their demographic impact is magnified, resulting in population decline. It is emphasized that the above interactions are embedded within the socio-economic context of pre-industrial Europe. This set of causal linkages does not rule out the operation of other factors, but posits deteriorating climate as a very important driver of socio-economic and demographic instability. There may be alternative explanations concerning some of the causal linkages. However, when we consider the set of linkages in aggregate, we can obtain a holistic view of how climate change causes large-scale human crisis in pre-industrial Europe.

In Fig. 2, thickness of arrow indicates the degree of 'average correlation', which is calculated from Table S2. Here are two examples:

Example 1
[Climate change → Bio-productivity] involves six pairs of correlation, namely: NH temp & Eur temp, NH temp & NH tree ring, NH temp & Grain yield, Eur temp & NH tree ring, Eur temp & Grain yield, and NH tree ring & Grain yield. Therefore, the associated 'average correlation' will be:
(0.862 + 0.811 + 0.705 + 0.811 + 0.625 + 0.731) / 6 = 0.756

Example 2
[Agricultural production → Food supply per capita] involves three pairs of correlation,

namely: De agri prod idx & De grain price, De agri prod idx & De wage idx, and De grain price & De wage idx. Therefore, the associated 'average correlation' will be:
(-0.779 + 0.729 + -0.840) / 3

However, in Fig. 2, we want to show the strength of association instead of the direction of association. Therefore, -0.779 and -0.840 will be treated as 0.779 and 0.840 respectively, and the 'average correlation' will be:
(0.779 + 0.729 + 0.840) / 3 = 0.783

Calculation of the 'average correlation' of each causal linkage in Fig. 2 is shown below:

Causal linkage	**Associated pairs of variables and their correlation**		**Average correlation**
Climate change → Bio-productivity	NH temp & Eur temp NH temp & NH tree ring NH temp & Grain yield Eur temp & NH tree ring Eur temp & Grain yield NH tree ring & Grain yield	*0.862* *0.811* *0.705* *0.811* *0.625* *0.731*	0.756
Bio-productivity → Agricultural production	NH tree ring & Grain yield NH tree ring & Agri prod idx Grain yield & Agri prod idx	*0.731* *0.737* *0.745*	0.738
Agricultural production → Food supply per capita	Agri prod idx & Grain price Agri prod idx & Wage idx Grain price & Wage idx	*(-0.779)* *0.729* *(-0.840)*	0.783
Food supply per capita → Social disturbance	Grain price & Wage idx Grain price & Social disturb Wage idx & Social disturb	*(-0.840)* *0.686* *(-0.545)*	0.690
Food supply per capita → Migration	Grain price & Wage idx Grain price & Migration Wage idx & Migration	*(-0.840)* *0.545* *(-0.464)*	0.616
Food supply per capita → Famine	Grain price & Wage idx Grain price & Famine Wage idx & Famine	*(-0.840)* *0.831* *(-0.631)*	0.767
Social disturbance → War	Social disturb & War Social disturb & War fatality idx War & War fatality idx	*0.786* *0.392* *0.432*	0.537
War → Migration	War & War fatality idx War & Migration War fatality idx & Migration	*0.432* *0.560* *0.230*	0.407
Migration → Epidemics	Migration & Plague	*0.577*	0.577
Famine → Migration	Famine & Migration	*0.634*	0.634
Famine → Nutritional status	Famine & Height	*(-0.635)*	0.635
Nutritional status → Epidemics	Height & Plague	*(-0.557)*	0.557
War → Population	War & War fatality idx War & Pop size War & Pop grow War fatality idx & Pop size War fatality idx & Pop grow Pop size & Pop grow	*0.432* *(-0.174)* *(-0.712)* *(-0.134)* *(-0.616)* *0.317*	0.398
Epidemics → Population	Plague & Pop size Plague & Pop grow Pop size & Pop grow	*(-0.175)* *(-0.490)* *0.317*	0.327
Famine → Population	Famine & Pop size	*(-0.260)*	0.435

	Famine & Pop grow Pop size & Pop grow	*(-0.727)* *0.317*	
Population → Agricultural production	Pop size & Pop grow Pop size & Agri prod idx Pop grow & Agri prod idx	*0.317* *0.665* *0.520*	0.501
Population → Food supply per capita	Pop size & Pop grow Pop size & Grain price Pop size & Wage idx Pop grow & Grain price Pop grow & Wage idx Grain price & Wage idx	*0.317* *(-0.203)* *0.273* *(-0.495)* *0.279* *(-0.840)*	0.401

Key: NH temp = Northern Hemisphere temperature anomaly; Eur temp = Europe temperature anomaly; NH tree ring = Northern Hemisphere extra-tropical tree-ring widths; Grain yield = Grain yield ratio in relation to seed; Agri prod idx = Detrended agricultural production index; Grain price = Detrended grain price; Wage idx = Detrended wage index; Height = Detrended average height; Famine = Number of famine years per decade; Plague = Number of plagues per decade; War = Number of wars happening in a year; Social disturb = Magnitude of social disturbances; Migration = Number of migration per quarter century; War fatality idx = War fatality index; Pop grow = Population growth rate; Pop size = Detrended population size.

Note: n = 301 (i.e., 1500–1800). All data have been transformed into annual units (via linear interpolation if necessary).

2. Granger Causality Analysis (GCA)

Granger's notion of causality is that '… Y_t is causing X_t if we are better able to predict X_t using all available information than if the information apart from Y_t had been used' (77). His definition of probabilistic causality is based on two important principles: (1) the cause must precede the effect in time; and (2) the causal series should contain special information to the series being caused (78). Granger (77) also put forward a two-variable causal model (i.e., Granger Causality Analysis) for two stationary time-series X_t and Y_t with zero means:

$$X_t = \sum_{j=1}^{m} a_j X_{t-j} + \sum_{j=1}^{m} b_j Y_{t-j} + \varepsilon_t$$

The stationarity of time-series will be checked by Augmented Dickey-Fuller (ADF) test prior to implementing GCA. If necessary, differencing will be used to transform the time-series into stationary ones (79, 80). For ADF test, the lagged difference terms of the dependent variable Y are added to the right-hand side of the regression so as to control higher-order correlation, which can be expressed in the following equation (81):

$$DY_t = \mu + \delta Y_{t-1} + \beta_1 DY_{t-1} + \beta_2 DY_{t-2} + \ldots + \beta_p DY_{t-p} + \varepsilon_t$$

Where

$$DY_t = Y_t - Y_{t-1}$$

The null hypothesis of the time-series has a unit root, which will be the same as above, that is:

H_0: $\delta = 0$.

In ADF test, the upper bound of the lag length will be specified according to the following equation (82):

$$Lag_{Max} = \mathrm{int}\left[12 \times (\frac{T}{100})^{0.25}\right]$$

Because our data are not with zero-mean (for non-difference data), in this study, ADF test was carried out with the intercept option by EViews.

After ADF test, lag length for GCA will be set. The lag length will be determined according to: (1) the theoretical and empirical knowledge of the relationships under examination (apparently instantaneously causal); or (2) statistical criterion (83). When the lag length for

GCA is set according to the theoretical and empirical knowledge, theory, belief and other common senses (extra knowledge) about the hypothesized causal relationship should be taken into account. On the other hand, when the lag length for GCA is set according to statistical criterion, Akaike's information criterion (AIC) (84) will be adopted to give the appropriate lag length. The equation for AIC is shown below:

$$AIC = -2\ln(L) + 2k$$

Where k is the number of independently adjusted parameters within the model and L is the maximized value of the likelihood function for the estimated model. In GCA, the likelihood function is as follows:

$$L = \prod_{i=1}^{n} (\frac{1}{2\pi\sigma^2})^{1/2} \exp\left(-\sum_{i=1}^{n} \frac{(x_t - \sum_{j=1}^{m} a_j X_{t-j} - \sum_{j=1}^{m} b_j Y_{t-j})^2}{2\sigma^2} \right)$$

Where n is the sample size and σ is the variance. Therefore, the AIC is given by:

$$AIC = \ln\left(\prod_{i=1}^{n} (\frac{1}{2\pi\sigma^2})^{1/2} \right) \times \left(-\frac{1}{2} \sum_{i=1}^{n} \frac{(x_t - \sum_{j=1}^{m} a_j X_{t-j} - \sum_{j=1}^{m} b_j Y_{t-j})^2}{\sigma^2} \right) + 2k$$

a. GCA of the causal linkages in Fig. 2

GCA has been applied in other study examining the economy in pre-industrial Europe (85). Here we employed GCA to verify all of the causal linkages as shown in Fig. 2. To start with, we transformed the entire set of causal linkages into 17 null hypotheses. We categorized the causal linkages (null hypotheses) into two groups as shown in Table 2.1:

Table 2.1. Causal linkages (null hypotheses) boiled down from Fig. 2

	Causal linkage (null hypothesis)
[Group 1]	
(1)	**Temperature** (Eur temp) does not *Granger-cause* **Bio-productivity** (Grain yield)
(2)	**Bio-productivity** (Grain yield) does not *Granger-cause* **Agricultural production** (Agri prod idx)
(3)	**Agricultural production** (Agri prod idx) does not *Granger-cause* **Food supply per capita** (Grain price)
(4)	**War** (War) does not *Granger-cause* **Population** (Pop size)
(5)	**Epidemics** (Plague) does not *Granger-cause* **Population** (Pop size)
(6)	**Famine** (Famine) does not *Granger-cause* **Population** (Pop size)
(7)	**Population** (Pop size) does not *Granger-cause* **Agricultural production** (Agri prod idx)
(8)	**Population** (Pop size) does not *Granger-cause* **Food supply per capita** (Grain price)
[Group 2]	
(9)	**Food supply per capita** (Grain price) does not *Granger-cause* **Famine** (Famine)
(10)	**Famine** (Famine) does not *Granger-cause* **Nutritional status** (Height)
(11)	**Nutritional status** (Height) does not *Granger-cause* **Epidemics** (Plague)
(12)	**Food supply per capita** (Grain price) does not *Granger-cause* **Social disturbance** (Social disturb)
(13)	**Social disturbance** (Social disturb) does not *Granger-cause* **War** (War)
(14)	**Social disturbance** (Social disturb) does not *Granger-cause* **Migration** (Migration)
(15)	**War** (War) does not *Granger-cause* **Migration** (Migration)
(16)	**Food supply per capita** (Grain price) does not *Granger-cause* **Migration** (Migration)
(17)	**Migration** (Migration) does not *Granger-cause* **Epidemics** (Plague)

Key: Eur temp = Europe temperature anomaly; Grain yield = Grain yield ratio in relation to seed; Agri prod idx = Detrended agricultural production index; Grain price = Detrended grain price; Pop size = Detrended population size; War = Number of wars happening in a year; Plague = Number of plagues per decade; Famine = Number of famine years per decade; Height = Detrended average height; Social disturb = Magnitude of social disturbances; Migration = Number of migration per quarter century.

Note: The terms in bold black stand for sectors, while the terms in red and brackets stand for variables.

The stationarity of each pair of variables under the same causal linkage was checked via ADF test prior to implementing GCA. If both of the variables under the same causal linkage are stationary at the 0.1 level ($P < 0.1$) without differencing, GCA will be conducted without differencing. However, if a variable is stationary without differencing while the other is not, then both variables will be subjected to the first- or second-level differencing until all of the variables under the same causal linkage are stationary at the 0.1 level. The ADF test results are shown in Table 2.2.

Table 2.2. ADF test results.

Variable	*P*		
	No differencing	1st level differencing	2nd level differencing
[Group 1]			
Eur temp	0.000***	---	---
Grain yield	0.000***	---	---
Agri prod idx	0.000***	---	---
Grain price	0.000***	---	---
Pop size	0.000***	---	---
War	0.000***	---	---
Plague	0.000***	---	---
Famine	0.000***	---	---
[Group 2]			
Grain price	0.016*	0.682	0.000***
Famine	0.435	0.171	0.000***
Height	---	0.820	0.000***
Plague	0.071#	0.716	0.000***
Social disturb	---	0.563	0.000***
War	0.938	0.112	0.000***
Migration	---	0.542	0.000***

Key: Eur temp = Europe temperature anomaly; Grain yield = Grain yield ratio in relation to seed; Agri prod idx = Detrended agricultural production index; Grain price = Detrended grain price; Pop size = Detrended population size; War = Number of wars happening in a year; Plague = Number of plagues per decade; Famine = Number of famine years per decade; Height = Detrended average height; Social disturb = Magnitude of social disturbances; Migration = Number of migration per quarter century.

Note: n = 301 (i.e., 1500–1800). All data have been transformed into annual units (via linear interpolation if necessary). # = Significant at 0.1 level (2-tailed) ($P < 0.1$); * = Significant at 0.05 level (2-tailed) ($P < 0.05$); ** = Significant at 0.01 level (2-tailed) ($P < 0.01$); *** = Significant at 0.001 level (2-tailed) ($P < 0.001$).

For those linkages in Group 1, their causal relationship is apparently instantaneously materialized (say within a year). Thereby, the time lag for GCA for the linkages in Group 1 was set to be 1. On the other hand, for those linkages in Group 2, their causal relationship is marked by a time gap. We used AIC to set the time lag for GCA for the linkages in Group 2 (Table 2.3).

In this study, the aforementioned null hypotheses will be rejected at the 0.05 level ($P < 0.05$). Our GCA results show that all of the null hypotheses were rejected (Table 2.4). It should be noted that our GCA results also concur with Fig. 1 and Table S2. This implies that all of the causal linkages in Fig. 2 were not only statistically valid, but also conceptually correct.

Table 2.3. Time lag for GCA for the linkages in Group 2.

Variable	Time lag for GCA		
	No differencing	1st level differencing	2nd level differencing
Grain price	15	---	15
Famine	---	---	15
Height	---	---	15
Plague	15	---	15
Social disturb	---	---	13
War	---	---	15
Migration	---	---	15

Key: Grain price = Detrended grain price; Famine = Number of famine years per decade; Height = Detrended average height; Plague = Number of plagues per decade; Social disturb = Magnitude of social disturbances; War = Number of wars happening in a year; Migration = Number of migration per quarter century.

Note: n = 301 (i.e., 1500–1800). All data have been transformed into annual units (via linear interpolation if necessary).

Table 2.4. GCA results for each of the causal linkages as shown in Fig. 2.

	Causal linkage (null hypothesis)	*F*	*P*
[Group 1]			
(1)	**Temperature** (Eur temp) does not *Granger-cause* **Bio-productivity** (Grain yield)△	207.485	0.000***
(2)	**Bio-productivity** (Grain yield) does not *Granger-cause* **Agricultural production** (Agri prod idx)△	7.440	0.007**
(3)	**Agricultural production** (Agri prod idx) does not *Granger-cause* **Food supply per capita** (Grain price)△	9.834	0.002**
(4)	**War** (War) does not *Granger-cause* **Population** (Pop size)△	391.805	0.000***
(5)	**Epidemics** (Plague) does not *Granger-cause* **Population** (Pop size)△	103.054	0.000***
(6)	**Famine** (Famine) does not *Granger-cause* **Population** (Pop size)△	155.736	0.000***
(7)	**Population** (Pop size) does not *Granger-cause* **Agricultural production** (Agri prod idx)△	5.731	0.017*
(8)	**Population** (Pop size) does not *Granger-cause* **Food supply per capita** (Grain price)△	67.664	0.000***
[Group 2]			
(9)	**Food supply per capita** (Grain price) does not *Granger-cause* **Famine** (Famine)#	10.307	0.000***
(10)	**Famine** (Famine) does not *Granger-cause* **Nutritional status** (Height)#	2.139	0.009**
(11)	**Nutritional status** (Height) does not *Granger-cause* **Epidemics** (Plague)#	2.345	0.004**
(12)	**Food supply per capita** (Grain price) does not *Granger-cause* **Social disturbance** (Social disturb)#	1.971	0.024*
(13)	**Social disturbance** (Social disturb) does not *Granger-cause* **War** (War)#	3.256	0.000***
(14)	**Social disturbance** (Social disturb) does not *Granger-cause* **Migration** (Migration)#	1.786	0.037*
(15)	**War** (War) does not *Granger-cause* **Migration** (Migration)#	2.250	0.006**
(16)	**Food supply per capita** (Grain price) does not *Granger-cause* **Migration** (Migration)#	2.164	0.008**
(17)	**Migration** (Migration) does not *Granger-cause* **Epidemics** (Plague)#	1.835	0.031*

Key: Eur temp = Europe temperature anomaly; Grain yield = Grain yield ratio in relation to seed; Agri prod idx = Detrended agricultural production index; Grain price = Detrended grain price; Pop size = Detrended population size; War = Number of wars happening in a year; Plague = Number of plagues per decade; Famine = Number of famine years per decade; Height = Detrended average height; Social disturb = Magnitude of social disturbances; Migration = Number of migration per quarter century.

Note: The terms in bold black stand for sectors, while the terms in red and brackets stand for variables. n = 301 (i.e., 1500–1800). All data have been transformed into annual units (via linear interpolation if necessary). △ = No differencing; # = 2nd level differencing; * = Significant at 0.05 level (2-tailed) ($P < 0.05$); ** = Significant at 0.01 level (2-tailed) ($P < 0.01$); *** = Significant at 0.001 level (2-tailed) ($P < 0.001$).

b. GCA of the causal relationship between grain price and various social/human ecological catastrophes

We employed GCA to examine whether grain price is the direct cause of various social and human ecological catastrophes such as migration, war, social disturbance, famine, nutritional status, and epidemics. Some null hypotheses were generated (Table 2.5). As the causal relationship between food supply per capita and the above catastrophes is marked by a time gap, we used AIC to set the time lag for GCA for the null hypotheses. For the stationarity check of the variables used, please refer to Table 2.2. For the time lag set for GCA, please refer to Table 2.3. Our GCA results (Table 2.5) show that grain price is the *Granger-cause* of social disturbance, war, migration, epidemics, famine, and nutritional status.

Table 2.5. GCA results for the causal relationship between grain price and various social/human ecological catastrophes.

	Causal linkage (null hypothesis)	*F*	*P*
(1)	Grain price does not *Granger-cause* **Social disturbance** (Social disturb)#	1.971	0.024*
(2)	Grain price does not *Granger-cause* **War** (War)#	5.060	0.000***
(3)	Grain price does not *Granger-cause* **Migration** (Migration)#	2.164	0.008**
(4)	Grain price does not *Granger-cause* **Epidemics** (Plague)△	5.113	0.000***
(5)	Grain price does not *Granger-cause* **Famine** (Famine)#	10.307	0.000***
(6)	Grain price does not *Granger-cause* **Nutritional status** (Height)#	3.970	0.000***

Key: Grain price = Detrended grain price; Social disturb = Magnitude of social disturbances; War = Number of wars happening in a year; Migration = Number of migration per quarter century; Plague = Number of plagues per decade; Famine = Number of famine years per decade; Height = Detrended average height.

Note: The terms in bold black stand for sectors, while the terms in red and brackets stand for variables. n = 301 (i.e., 1500–1800). All data have been transformed into annual units (via linear interpolation if necessary). △ = No differencing; # = 2nd level difference; * = Significant at 0.05 level (2-tailed) ($P < 0.05$); ** = Significant at 0.01 level (2-tailed) ($P < 0.01$); *** = Significant at 0.001 level (2-tailed) ($P < 0.001$).

c. GCA of the causal relationship between temperature and real grain price in 1264–1800

Our GCA results reveal grain price – a proxy of food supply per capita – to be the direct cause in alternating harmony and crisis condition in Europe in 1500–1800 (Table 2.5). We used a longer grain price time-series – real grain price series spanned 1264–1800 – to simulate the alternation of harmony and crisis condition in pre-industrial Europe back in time. We sought to prove that European temperature change is the ultimate cause of grain price fluctuation. As the linkage from Climate change → Bio-productivity → Agricultural production → Food supply per capita is apparently instantaneously causal, we set the time lag for GCA to be 1. The stationarity check of the variables used is shown in Table 2.6. Our GCA results (Table 2.7) show that European temperature is the *Granger-cause* of real grain price between 1264 and 1800.

Table 2.6. ADF test for the variables used.

Variable	*P*
	No differencing
Eur temp	0.000***
Real grain price	0.000***

Key: Eur temp = European temperature anomaly

Note: n = 301 (i.e., 1500–1800). * = Significant at 0.05 level (2-tailed) ($P < 0.05$); *** = Significant at 0.001 level (2-tailed) ($P < 0.001$).

Table 2.7. GCA results for the causal relationship between temperature and real grain price.

Causal linkage (null hypothesis)	*F*	*P*
Eur temp does not *Granger-cause* Real grain price$^{\triangle}$	80.833	0.000***

Key: Eur temp = European temperature anomaly

Note: n = 301 (i.e., 1500–1800). $^{\triangle}$ = No differencing; *** = Significant at 0.001 level (2-tailed) ($P < 0.001$).

3. Notes for the calculation of real grain price in 1264–1800

In economics, nominal value refers to a value expressed in money terms (that is, in units of a currency) in a given year or series of years. By contrast, real value adjusts nominal value to remove effects of inflation (i.e., a general increase in price over time). In this study, two datasets were used to construct our real grain price time-series, namely: nominal grain price and consumer price index (CPI). Our grain price series was derived from the European commodity price data (cf. *SI Materials and Methods IV.1*). Our CPI data spanned 1264–1913, which was derived from the arithmetic averaging of the CPI of 18 major cities in Europe, namely: Antwerp, Amsterdam, London, Paris, Strasbourg, Florence, Naples, Valencia, Madrid, Augsburg, Leipzig, Munich, Vienna, Gdansk, Krakow, Warsaw, Lwow and Hamburg. Both of the nominal grain price and CPI datasets can be downloaded from the website of the International Institute of Social History (http://www.iisg.nl/hpw/data.php#europe).

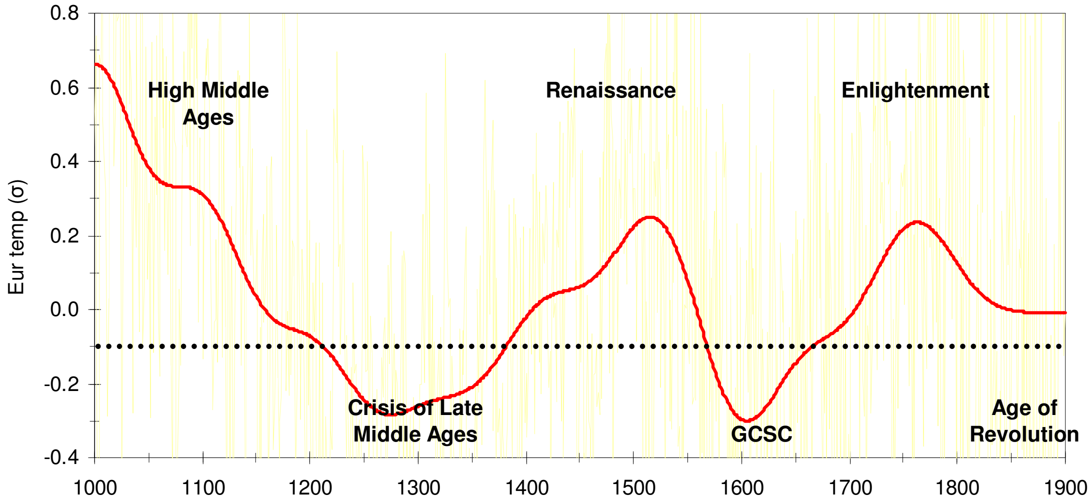
The relationship between nominal grain price and real grain price can be expressed by the following equation:

$$RP_t = \frac{CPI_{BaseYear}}{CPI_t} \times P_t$$

Where *RP* represents real grain price, *CPI* stands for Consumer Price Index, *P* represents nominal grain price, and *t* is the time step. As the first data point of CPI starts from 1264, to maximize the use of our data, we set the base year to be 1264 accordingly.

4. Golden and dark ages in Europe in 1000–1900

a. Simulation of the 'golden' and 'dark' ages in Europe by using temperature data



The above figure shows the European temperature anomaly series (σ) in 1000–1900. The temperature series has been smoothed by 100-year Butterworth low-pass filter. Horizontal dotted line represents the threshold in defining crisis periods (i.e., temperature $\leq$ -0.1σ). The periods in which temperature $\geq$ -0.1σ stand for golden ages, while the periods in which temperature $\leq$ -0.1σ stand for dark ages. Based on the threshold, the golden ages we got were 10th to 12th centuries (High Middle Ages), late-14th to early-16th centuries (Renaissance) and late-17th to 18th centuries (Enlightenment), while the dark ages we got were 1212–1381 (Crisis of Late Middle Ages) and 1568–1665 (GCSC). However, the Age of Revolution in early 19th century – one of the dark ages in European history – could not be simulated. This is because the crisis during the time was comparatively small. Even though there was upsurge of grain price, social disturbance, war and migration, demographic crisis did not happen. This matches with the fact that the cooling during the time was mild.

b. Historians' delimitation of the 'golden' and 'dark' ages in Europe

In reference to Lyon et al. (86) and Roberts (87), the ages and periods in Europe were delineated as follows:

High Middle Ages (11th to 13th centuries)

In the 1000s, Europe began to slowly recover from its artistic darkness. The lost knowledge of the ancient Greeks and Romans was found again. There was a new interest in learning, and the richer life of the Middle Ages began. The revival of trade in the tenth, eleventh, and twelfth centuries sparked the revival of urban life with its middle-class inhabitants and the social, economic, legal, and political privileges they required for engaging in trade and industry. The key historical trend of the High Middle Ages was the rapidly increasing population of Europe, which brought about great social and political change from the preceding era. By 1250 the robust population increase greatly benefited the economy, reaching levels it would not see again in some areas until the nineteenth century. Under these conditions, art, literature and even science were developing apace and we see the height of medieval civilization.

Crisis of Late Middle Ages (14th century)

Around 1300, centuries of European prosperity and growth was checked by a series of calamities, notably the Great Famine (1315–1317), Black Death (1346–1351) and the Hundred Year's War (1337–1453) and also numerous revolts, wars and economic stagnation. The Great Famine of 1315–1317 (occasionally dated 1315–1322) was the first of a series of large scale crises that struck Europe early in the fourteenth century, causing millions of deaths over an extended number of years and marking a clear end to an earlier period of growth and prosperity during the eleventh to thirteenth centuries. The Black Death is estimated to have killed 30% to 60% of Europe's population, reducing the world's population from an estimated 450 million to between 350 and 375 million in 1400. Hundred Year's War is often viewed as one of the most significant conflicts in the history of medieval warfare. In France, the English invasion, civil wars, deadly epidemics, famines and marauding mercenary armies (turned to banditry) reduced the population by two-thirds.

Renaissance (15th to mid-16th centuries)

The Renaissance was a cultural movement that profoundly affected European intellectual life in the early modern period. Beginning in Italy, and spreading to the rest of Europe by the sixteenth century, its influence affected literature, philosophy, art, politics, science, religion, and other aspects of intellectual inquiry. Renaissance scholars employed the humanist method in study, and searched for realism and human emotion in art. The Renaissance also witnessed the discovery and exploration of new continents, the substitution of the Copernican for the Ptolemaic system of astronomy, the decline of the feudal system and the growth of commerce, and the invention or application of such potentially powerful innovations as paper, printing, the mariner's compass, and gunpowder. The economic development in this era was marked by a slow, hesitant, and painful recovery from disasters in the mid-fourteenth century that shattered medieval prosperity. Many historians now prefer to use the term "Early Modern" for this period, a more neutral designation that highlights the period as a transitional one between the Middle Ages and the modern era.

General Crisis of the Seventeenth Century (mid-16th to mid-17th centuries)

Widespread conflict and instability occurred from the late sixteenth century to the mid-seventeenth century in Europe. The middle years of the seventeenth century in Western Europe saw a widespread break-down in politics, economics and society caused by a complex series of demographic, religious, economic and political problems. In this 'general crisis', various events such as the English Civil War, the Fronde in France, the climax of the Thirty Years War in Germany and revolts against the Spanish Crown in Portugal, Naples and Catalonia were all manifestations of the same problem. Population collapses followed. Germany's population was reduced by approximately 30% in the Thirty Years War. The Polish-Lithuanian Commonwealth also lost about a third of its population.

Enlightenment (mid-17th to late 18th centuries)

The Enlightenment is a term used to describe a time in Western philosophy and cultural life, centered upon the eighteenth century, in which reason was advocated as the primary source and legitimacy for authority. There were three great currents of change during the time – commercialization, cultural reorientation, and the rise of the nation-state. Each strand, in fact, produced new ramifications that furthered the overall transformation of the West. Toward the middle of the eighteenth century a new and rapid growth in population began. Where Europe had counted about 120 million people at the beginning of the century, it had grown to about 190 million by its end.

Age of Revolution (late 18th to mid-19th centuries)

During the decades of economic and social transformation, Western Europe also experienced massive political change. The central event throughout much of the continent was the French Revolution (1789–1799). This was followed by a number of significant revolutionary movements occurred in Europe. In 1819 there was a brief, liberal revolution in Spain; another occurred in Italy in 1820. Then there was the Greek revolution for independence from Turkey in 1821, an activity that inspired the English poet Lord Byron to participate. Russia endured a short and confused revolt in 1825 when liberal, aristocratic factions attempted to influence the succession to the throne. And then in July 1830, France underwent another revolution, this one joined in the same year by a revolution in Holland. Finally, in 1848, a series of revolutions erupted throughout all of Western Europe with the notable exception of Great Britain. Moreover, the period also sees the drastic social, political and economic changes initiated by the Industrial Revolution and the Napoleonic Wars, following the re-organization of the political map of Europe at the Congress of Vienna in 1815. There was hyper-inflation during 1790–1820.

5. Data of population growth, famine, epidemics and war in the NH

Population

Population data at different geographical scales were extracted from McEvedy and Jones' (34) Atlas of World Population History. The authors provide figures for the population of each region/country through historical time. There are six parts: Europe, Asia, Africa, the Americas, Oceania, and a global overview. Each of the first five sections has a general review, and then its countries are taken in turn, with a general account of demographic progress illustrated with graphs and maps, a discussion of primary sources for population data, and a bibliography. This is a remarkably accurate work, which have been used by other scholars repeatedly.

As McEvedy and Jones' (34) population size 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. Then, population growth rate for the Northern Hemisphere and different climatic zones was calculated by the following formula:

$$\frac{P_t - P_{t-1}}{P_{t-1}} \text{x}\,100 ,$$

where P is the population size, t represents time step.

Famine

A famine as defined in the chronicles of sages was a protracted total shortage of food in a restricted geographical area, causing widespread disease and death from starvation. This definition is also adopted in this study. Our famine data was elicited from Walford's (47) chronology of famines in world history (which includes in the whole over 350 famine incidents in various parts of the world) printed in The Famines of the World: Past and Present, which is believed to be the first list of the major famines which had occurred in the history of the world. Episodes of famine have occurred throughout history in many parts of the world. In this research, only those famines occurred in the Northern Hemisphere would be considered. Besides, the chronology has also been crosschecked with and supplemented by other materials such as Golkin's (48) chronology of famines printed in Famine: A Heritage of Hunger and the list of known major famines in Wikipedia. We felt that our famine dataset must necessarily be incomplete despite our great effort in fine-tuning it. However, it could somehow show the long-term trend of famine occurrence in the Northern Hemisphere (Fig. 4d in the main text). Fig. 4d in the main text should be interpreted as the number of famine years per decade. As the data points of which are in 10-year units, they were linearly interpolated to create an annual time series for smoothing such that the centennial variability of famine could be retrieved.

Epidemics

Our epidemic data were mainly retrieved from Kohn's (75) The Encyclopedia of Plague and Pestilence, which is a compendium of geo-historical information about major, outstanding, and unusual epidemics in regions of the world from ancient times to the present. The encyclopedia provides concise descriptions of more than 700 epidemics. Each detailed entry includes when and where a particular epidemic began, how and why it happened, whom it affected, how it spread and ran its course, and its outcome and significance. The above data was also supplemented by Cliff et al.'s (88) list of major epidemic outbreaks in world history printed in Deciphering Global Epidemics: Analytical Approaches to the Disease Records of World Cities, 1888–1912 and also Xiao and Liu's (89) epidemic chronology printed in History of Pestilence.

Here we only considered six most deadly epidemics in the Northern Hemisphere, namely: malaria, plague, typhus, measles, smallpox, and dysentery (Fig. 4e in the main text). This is because only those epidemics did have significant demographic impacts in pre-industrial era. Figure 4e in the main text should be interpreted as the number of epidemics per decade. As the data points of which are in 10-year units, they were linearly interpolated to create an annual time series for smoothing such that the centennial variability of epidemic outbreak could be retrieved.

War

Our war data come from Kohn's (90) Dictionary of Wars, which contains detailed summaries of all notable wars from earliest recorded history to the present day, spanning more than 4,000 years (2000BC–present). In the dictionary, war is broadly defined to mean 'an overt, armed conflict carried on between nations or states (international war) or between parties, factions, or people in the same state (civil war)'. More than 1,800 entries are extensively cross-referenced. Each entry gives the name of the conflict, its dates and duration, what caused it, a summary of the military events, and its outcome and significance. It is an authoritative source of information on the global conflicts, civil wars, mutinies, punitive expeditions, undeclared wars, rebellions, and revolutions that have occurred throughout the world.

In this research, we based on the 'duration of war' (in terms of year) to count the number of war fighting in the Northern Hemisphere on a yearly basis (Fig. 4f in the main text). Suppose there are only three wars in the Northern Hemisphere, the first one in 1500–1505, second one in 1503–1506 and third one in 1505–1507, the counting of the number of war will be:

1500	1
1501	1
1502	1

1503	2
1504	2
1505	3
1506	2
1507	1

SUPPLEMENTARY TABLES

Table S1. Phase average of various variables employed in this research. Their percentage change relative to the previous climate phase is italicized and in brackets.

Climate phase	Mild Phase 1 (1500–1559)	Cold Phase (1560–1660)	Mild Phase 2 (1661–1800)
NH temp (^oC)	-0.43	-0.53	-0.45
- % change	---	*(-22.98%)*	*(14.61%)*
Eur temp (σ)	0.43	-0.59	0.24
- % change	---	*(-238.27%)*	*(141.15%)*
NH tree ring (index)	1.05	0.90	0.99
- % change	---	*(-14.11%)*	*(9.03%)*
Grain yield (ratio)	6.18	4.44	4.84
- % change	---	*(-28.18%)*	*(9.03%)*
Agri prod idx (index)	552.33	568.55	934.72
- % change	---	*(2.94%)*	*(64.04%)*
Grain price (Ag /liter)	0.18	0.42	0.33
- % change	---	*(133.29%)*	*(-19.57%)*
Wage idx (σ)	1.39	-0.29	-0.39
- % change	---	*(-120.73%)*	*(34.56%)*
Height (cm)	169.54	168.30	168.42
- % change	---	*(-0.73%)*	*(0.07%)*
Famine (# of yr /decade)	2.80	6.34	2.91
- % change	---	*(126.31%)*	*(-54.07%)*
Social disturb (magnitude)	4.33	6.55	4.44
- % change	---	*(51.35%)*	*(-32.25%)*
War (#)	7.28	10.66	4.06
- % change	---	*(46.41%)*	*(-61.95%)*
War fatality idx (index)	1.72	11.10	5.91
- % change	---	*(546.42%)*	*(-46.74%)*
Migration (# /25yrs)	2.40	5.28	3.12
- % change	---	*(120.13%)*	*(-41.00%)*
Plague (# /decade)	0.82	2.50	0.49
- % change	---	*(205.52%)*	*(-80.25%)*
Pop size (million)	85.21	101.42	135.98
- % change	---	*(19.03%)*	*(34.08%)*
Pop grow (%)	0.19	0.15	0.39
- % change	---	*(-18.40%)*	*(155.07%)*

Key: NH temp = Northern Hemisphere temperature anomaly; Eur temp = Europe temperature anomaly; NH tree ring = Northern Hemisphere extra-tropical tree-ring widths; Grain yield = Grain yield ratio in relation to seed; Agri prod idx = Agricultural production index; Grain price = Grain price; Wage idx = Wage index; Height = Average height; Famine = Number of famine years per decade; Plague = Number of plagues per decade; War = Number of wars happening in a year; Social disturb = Magnitude of social disturbances; Migration = Number of migration per quarter century; War fatality idx = War fatality index; Pop grow = Population growth rate; Pop size = Population size.

Note: All data have been transformed into annual units (via linear interpolation if necessary).

Table S2. Cross-correlation coefficients of the 16 variables employed in this research. The value in brackets indicates the statistical significance of correlation.

	Eur temp	Grain yield	NH tree ring	Grain price	Agri prod idx	Wage idx	Famine	Height	Plague	War	Social disturb	War fatality idx	Migration	Pop size	Pop grow
NH temp	**0.862** (0.000)	**0.705** (0.000)	**0.811** (0.000)	**-0.657** (0.000)	**0.777** (0.000)	**0.599** (0.000)	**-0.544** (0.000)	**0.626** (0.000)	**-0.613** (0.000)	**-0.554** (0.000)	**-0.596** (0.000)	-0.397 (0.000)	**-0.540** (0.000)	**0.589** (0.000)	0.468 (0.000)
Eur temp		**0.625** (0.000)	**0.811** (0.000)	**-0.819** (0.000)	**0.841** (0.000)	**0.757** (0.000)	**-0.682** (0.000)	**0.759** (0.000)	**-0.670** (0.000)	**-0.602** (0.000)	**-0.628** (0.000)	-0.470 (0.000)	**-0.583** (0.000)	0.379 (0.000)	0.443 (0.000)
Grain yield			**0.731** (0.000)	**-0.621** (0.000)	**0.745** (0.000)	**0.697** (0.000)	-0.494 (0.000)	**0.613** (0.000)	-0.419 (0.000)	-0.278 (0.000)	-0.385 (0.000)	-0.419 (0.000)	-0.449 (0.000)	**0.723** (0.000)	0.175 (0.002)
NH tree ring				**-0.830** (0.000)	**0.737** (0.000)	**0.685** (0.000)	**-0.720** (0.000)	**0.743** (0.000)	**-0.615** (0.000)	-0.483 (0.000)	**-0.522** (0.000)	**-0.654** (0.000)	-0.483 (0.000)	0.401 (0.000)	0.370 (0.000)
Grain price					**-0.779** (0.000)	**-0.840** (0.000)	**0.831** (0.000)	**-0.750** (0.000)	**0.755** (0.000)	**0.677** (0.000)	**0.686** (0.000)	**0.753** (0.000)	**0.545** (0.000)	-0.203 (0.000)	-0.495 (0.000)
Agri prod idx						**0.729** (0.000)	**-0.695** (0.000)	**0.834** (0.000)	**-0.518** (0.000)	**-0.518** (0.000)	**-0.580** (0.000)	**-0.599** (0.000)	**-0.620** (0.000)	**0.665** (0.000)	**0.520** (0.000)
Wage idx							**-0.631** (0.000)	**0.719** (0.000)	**-0.689** (0.000)	**-0.550** (0.000)	**-0.545** (0.000)	-0.454 (0.000)	-0.464 (0.000)	0.273 (0.000)	0.279 (0.000)
Famine								**-0.635** (0.000)	**0.563** (0.000)	**0.672** (0.000)	**0.723** (0.000)	**0.819** (0.000)	**0.634** (0.000)	-0.260 (0.000)	**-0.727** (0.000)
Height									**-0.557** (0.000)	-0.494 (0.000)	-0.317 (0.000)	**-0.552** (0.000)	-0.450 (0.000)	0.489 (0.000)	0.372 (0.000)
Plague										**0.886** (0.000)	**0.709** (0.000)	0.346 (0.000)	**0.577** (0.000)	-0.175 (0.002)	-0.490 (0.000)
War											**0.786** (0.000)	0.432 (0.000)	**0.560** (0.000)	-0.174 (0.002)	**-0.712** (0.000)
Social disturb												0.392 (0.000)	**0.827** (0.000)	-0.278 (0.000)	**-0.644** (0.000)
War fatality idx													0.230 (0.000)	-0.134 (0.020)	**-0.616** (0.000)
Migration														**-0.545** (0.000)	**-0.521** (0.000)
Pop size															0.317 (0.000)

Key: NH temp = Northern Hemisphere temperature anomaly; Eur temp = Europe temperature anomaly; NH tree ring = Northern Hemisphere extra-tropical tree-ring widths; Grain yield = Grain yield ratio in relation to seed; Agri prod idx = Detrended agricultural production index; Grain price = Detrended grain price; Wage idx = Detrended wage index; Height = Detrended average height; Famine = Number of famine years per decade; Plague = Number of plagues per decade; War = Number of wars happening in a year; Social disturb = Magnitude of social disturbances; Migration = Number of migration per quarter century; War fatality idx = War fatality index; Pop grow = Population growth rate; Pop size = Detrended population size.

Note: n = 301 (i.e., 1500–1800). All data have been transformed into annual units (via linear interpolation if necessary) and smoothed by 40-year Butterworth low pass filter prior to statistical analysis. Those strong correlation coefficients (i.e., ≥ 0.5 or ≤ –0.5) are presented in bold red.

Table S3. Verification of the consistency and predictability of the set of causal linkages (Fig. 2) via multiple regression analysis. Regression coefficients on and the p value of independent variable and constant (in brackets) of each causal linkage are shown below:

[Climate change → Bio-productivity]

- *NH temp → NH tree ring*
- *NH temp → Grain yield*

Dependent variable	Constant	Independent variable				Elasticity	R^2_{adj}	Sig.
		t	t^2	t^3	NH temp			
NH tree ring	3.617 (0.017)	-2.452 (0.191)	0.665 (0.245)		0.876 (0.000)	0.834	0.741	0.000
NH tree ring	1.636 (0.000)		-0.082 (0.000)		0.932 (0.000)	0.887	0.740	0.000
NH tree ring	1.565 (0.000)			-0.033 (0.000)	0.938 (0.000)	0.892	0.740	0.000
Grain yield	308.098 (0.000)	-363.836 (0.000)	109.305 (0.000)		2.541 (0.000)	0.190	0.854	0.000
Grain yield	14.006 (0.000)		-1.428 (0.000)		10.823 (0.000)	0.808	0.653	0.000
Grain yield	12.724 (0.000)			-0.569 (0.000)	10.906 (0.000)	0.814	0.647	0.000

- *Eur temp → NH tree ring*
- *Eur temp → Grain yield*

Dependent variable	Constant	Independent variable				Elasticity	R^2_{adj}	Sig.
		t	t^2	t^3	Eur temp			
NH tree ring	8.017 (0.000)	-8.352 (0.000)	2.467 (0.000)		0.103 (0.000)	0.709	0.745	0.000
NH tree ring	1.167 (0.000)		-0.072 (0.000)		0.126 (0.000)	0.868	0.722	0.000
NH tree ring	1.101 (0.000)			-0.029 (0.000)	0.126 (0.000)	0.872	0.721	0.000
Grain yield	336.320 (0.000)	-399.874 (0.000)	120.306 (0.000)		0.194 (0.001)	0.105	0.847	0.000
Grain yield	8.381 (0.000)		-1.249 (0.000)		1.298 (0.000)	0.703	0.510	0.000
Grain yield	7.194 (0.000)			-0.491 (0.000)	1.304 (0.000)	0.706	0.503	0.000

[Bio-productivity → Agricultural production]

- *NH tree ring → Agri prod idx*

Dependent variable	Constant	Independent variable: t	t^2	t^3	NH tree ring	Elasticity	R^2_{adj}	Sig.
Agri prod idx	22140.873 (0.000)	-28794.765 (0.000)	9444.674 (0.000)		334.134 (0.000)	0.116	0.961	0.000
Agri prod idx	-2115.116 (0.000)		734.963 (0.000)		872.513 (0.000)	0.303	0.927	0.000
Agri prod idx	-1409.888 (0.000)			296.799 (0.000)	828.116 (0.000)	0.288	0.932	0.000

- *Grain yield → Agri prod idx*

Dependent variable	Constant	Independent variable: t	t^2	t^3	Grain yield	Elasticity	R^2_{adj}	Sig.
Agri prod idx	---	---	---		---	---	---	---
Agri prod idx	-1718.123 (0.000)		768.797 (0.000)		71.932 (0.000)	0.318	0.933	0.000
Agri prod idx	-994.936 (0.000)			308.951 (0.000)	67.159 (0.000)	0.297	0.935	0.000

[Agricultural production → Food supply per capita]

- *Agri prod idx → Grain price*
- *Agri prod idx → Wage idx*

Dependent variable	Constant	Independent variable: t	t^2	t^3	Agri prod idx*	Elasticity	R^2_{adj}	Sig.
Grain price	5.915 (0.033)	-7.298 (0.030)	2.366 (0.021)		-0.001 (0.000)	-0.861	0.668	0.000
Grain price	-0.082 (0.013)		0.152 (0.000)		-0.001 (0.000)	-0.734	0.663	0.000
Grain price	0.054 (0.016)			0.061 (0.000)	-0.001 (0.000)	-0.743	0.664	0.000
Wage idx	88.931 (0.000)	-100.761 (0.000)	28.320 (0.000)		0.003 (0.000)	0.302	0.799	0.000
Wage idx	6.131 (0.000)		-2.251 (0.000)		0.005 (0.000)	0.515	0.785	0.000
Wage idx	4.096 (0.000)			-0.908 (0.000)	0.005 (0.000)	0.531	0.783	0.000

[Food supply per capita → Social disturbance]

- *Grain price → Social disturb*

Dependent variable	Constant	Independent variable t	t^2	t^3	Grain price*	Elasticity	R^2_{adj}	Sig.
Social disturb	-20.028 (0.530)	37.351 (0.336)	-13.400 (0.255)		11.334 (0.000)	0.644	0.596	0.000
Social disturb	10.702 (0.000)		-2.081 (0.000)		11.846 (0.000)	0.673	0.596	0.000
Social disturb	8.828 (0.000)			-0.841 (0.000)	11.754 (0.000)	0.668	0.596	0.000

- *Wage idx → Social disturb*

Dependent variable	Constant	Independent variable t	t^2	t^3	Wage idx*	Elasticity	R^2_{adj}	Sig.
Social disturb	-77.215 (0.063)	107.245 (0.033)	-34.701 (0.023)		-1.319 (0.000)	-0.451	0.446	0.000
Social disturb	11.064 (0.000)		-2.220 (0.000)		-1.595 (0.000)	-0.545	0.439	0.000
Social disturb	9.072 (0.000)			-0.899 (0.000)	-1.576 (0.000)	-o.539	0.440	0.000

[Food supply per capita → Migration]

- *Grain price → Migration*

Dependent variable	Constant	Independent variable t	t^2	t^3	Grain price*	Elasticity	R^2_{adj}	Sig.
Migration	-300.764 (0.000)	372.410 (0.000)	-113.554 (0.000)		4.964 (0.000)	0.266	0.415	0.000
Migration	5.633 (0.000)		-0.704 (0.018)		10.070 (0.000)	0.540	0.305	0.000
Migration	5.066 (0.000)			-0.299 (0.000)	10.033 (0.013)	0.538	0.306	0.000

- *Wage idx → Migration*

Dependent variable	Constant	Independent variable t	t^2	t^3	Wage idx*	Elasticity	R^2_{adj}	Sig.
Migration	-384.667 (0.000)	474.524 (0.000)	-144.539 (0.000)		-0.219 (0.280)	-0.071	0.375	0.000
Migration	5.941 (0.000)		-0.822 (0.009)		-1.438 (0.000)	-0.464	0.228	0.000
Migration	5.269 (0.000)			-0.347 (0.006)	-1.431 (0.000)	-0.462	0.230	0.000

[Food supply per capita → Famine]

- *Grain price → Famine*

Dependent variable	Constant	Independent variable: t	t^2	t^3	Grain price*	Elasticity	R^2_{adj}	Sig.
Famine	21.992 (0.579)	-19.975 (0.678)	5.535 (0.704)		21.046 (0.000)	0.840	0.692	0.000
Famine	5.557 (0.000)		-0.518 (0.051)		20.772 (0.000)	0.829	0.693	0.000
Famine	5.087 (0.000)			-0.209 (0.052)	20.749 (0.000)	0.828	0.693	0.000

- *Wage idx → Famine*

Dependent variable	Constant	Independent variable: t	t^2	t^3	Wage idx*	Elasticity	R^2_{adj}	Sig.
Famine	-118.357 (0.052)	151.308 (0.041)	-46.588 (0.038)		-2.241 (0.000)	-0.538	0.410	0.000
Famine	6.194 (0.000)		-0.762 (0.040)		-2.630 (0.000)	-0.631	0.403	0.000
Famine	5.529 (0.000)			-0.313 (0.036)	-2.623 (0.000)	-0.630	0.403	0.000

[Social disturbance → War]

- *Social disturb → War*
- *Social disturb → War fatality idx*

Dependent variable	Constant	Independent variable: t	t^2	t^3	Social disturb	Elasticity	R^2_{adj}	Sig.
War	-258.943 (0.000)	335.790 (0.000)	-107.350 (0.000)		0.964 (0.000)	0.498	0.830	0.000
War	15.044 (0.000)		-5.165 (0.000)		1.183 (0.000)	0.611	0.796	0.000
War	10.575 (0.000)			-2.111 (0.000)	1.169 (0.000)	0.604	0.799	0.000
War fatality idx	-716.520 (0.000)	843.086 (0.000)	-248.352 (0.001)		1.970 (0.000)	0.390	0.244	0.000
War fatality idx	-28.605 (0.000)		8.209 (0.000)		2.520 (0.000)	0.499	0.215	0.000
War fatality idx	-21.056 (0.000)			3.272 (0.000)	2.529 (0.000)	0.500	0.213	0.000

[Social disturbance → Migration]

- *Social disturb → Migration*

Dependent variable	Constant	Independent variable: t	t^2	t^3	Social disturb	Elasticity	R^2_{adj}	Sig.
Migration	-179.249 (0.000)	213.926 (0.000)	-63.788 (0.000)		0.822 (0.000)	0.776	0.766	0.000
Migration	-4.696 (0.000)		1.312 (0.000)		0.961 (0.000)	0.908	0.720	0.000
Migration	-3.462 (0.000)			0.518 (0.000)	0.962 (0.000)	0.909	0.718	0.000

[War → Migration]

- *War → Migration*

Dependent variable	Constant	Independent variable: t	t^2	t^3	War	Elasticity	R^2_{adj}	Sig.
Migration	-237.386 (0.000)	284.049 (0.000)	-84.217 (0.000)		0.338 (0.000)	0.619	0.499	0.000
Migration	-7.822 (0.000)		2.989 (0.000)		0.489 (0.000)	0.895	0.432	0.000
Migration	-5.088 (0.000)			1.196 (0.000)	0.491 (0.000)	0.898	0.427	0.000

- *War fatality idx → Migration*

Dependent variable	Constant	Independent variable: t	t^2	t^3	War fatality idx	Elasticity	R^2_{adj}	Sig.
Migration	-416.505 (0.000)	513.205 (0.000)	-156.263 (0.000)		0.003 (0.759)	0.015	0.372	0.000
Migration	5.984 (0.000)		-0.958 (0.006)		0.051 (0.000)	0.244	0.071	0.000
Migration	5.250 (0.000)			-0.415 (0.003)	0.051 (0.000)	0.244	0.075	0.000

[Migration → Epidemics]

- *Migration → Plague*

Dependent variable	Constant	Independent variable: t	t^2	t^3	Migration	Elasticity	R^2_{adj}	Sig.
Plague	-146.822 (0.000)	184.306 (0.000)	-57.392 (0.000)		0.173 (0.000)	0.297	0.580	0.000
Plague	4.117 (0.000)		-1.465 (0.000)		0.303 (0.000)	0.522	0.495	0.000
Plague	2.845 (0.000)			-0.599 (0.000)	0.299 (0.000)	0.516	0.499	0.000

[Famine → Migration]

- *Famine → Migration*

Dependent variable	Constant	Independent variable t	t^2	t^3	Famine	Elasticity	R^2_{adj}	Sig.
Migration	-265.019 (0.000)	326.762 (0.000)	-99.543 (0.000)		0.320 (0.000)	0.430	0.508	0.000
Migration	3.053 (0.000)		-0.467 (0.091)		0.466 (0.000)	0.627	0.404	0.000
Migration	2.710 (0.000)			-0.205 (0.066)	0.465 (0.000)	0.626	0.405	0.000

[Famine → Nutritional status]

- *Famine → Height*

Dependent variable	Constant	Independent variable t	t^2	t^3	Famine	Elasticity	R^2_{adj}	Sig.
Height	284.331 (0.000)	-136.582 (0.000)	40.244 (0.000)		-0.058 (0.000)	-0.254	0.794	0.000
Height	172.280 (0.000)		-1.168 (0.000)		-0.119 (0.000)	-0.523	0.597	0.000
Height	171.201 (0.000)			-0.465 (0.000)	-0.120 (0.000)	-0.530	0.586	0.000

[Famine → Population]

- *Famine → Pop size*
- *Famine → Pop grow*

Dependent variable	Constant	Independent variable t	t^2	t^3	Famine	Elasticity	R^2_{adj}	Sig.
Pop size	2504.619 (0.000)	-3191.752 (0.000)	1052.313 (0.000)		0.732 (0.000)	0.069	0.979	0.000
Pop size	-113.860 (0.000)		84.556 (0.000)		-0.698 (0.000)	-0.065	0.930	0.000
Pop size	-38.793 (0.000)			34.275 (0.000)	-0.570 (0.000)	-0.053	0.938	0.000
Pop grow	1.189 (0.623)	-1.763 (0.549)	0.802 (0.369)		-0.049 (0.000)	-0.675	0.727	0.000
Pop grow	-0.258 (0.000)		0.268 (0.000)		-0.049 (0.000)	-0.686	0.728	0.000
Pop grow	-0.018 (0.606)			0.108 (0.000)	-0.049 (0.000)	-0.680	0.728	0.000

[War → Population]

- *War → Pop size*
- *War → Pop grow*

Dependent variable	Constant	Independent variable t	t^2	t^3	War	Elasticity	R^2_{adj}	Sig.
Pop size	2862.047 (0.000)	-3665.435 (0.000)	1205.471 (0.000)		1.316 (0.000)	0.168	0.984	0.000
Pop size	-100.300 (0.000)		80.136 (0.000)		-0.636 (0.000)	-0.081	0.929	0.000
Pop size	-32.425 (0.000)			33.036 (0.000)	-0.451 (0.005)	-0.058	0.937	0.000
Pop grow	7.807 (0.024)	-9.099 (0.033)	2.817 (0.031)		-0.031 (0.000)	-0.593	0.510	0.000
Pop grow	0.454 (0.000)		0.024 (0.480)		-0.036 (0.000)	-0.684	0.504	0.000
Pop grow	0.470 (0.000)			0.011 (0.443)	-0.036 (0.000)	-0.681	0.505	0.000

- *War fatality idx → Pop size*
- *War fatality idx → Pop grow*

Dependent variable	Constant	Independent variable t	t^2	t^3	War fatality idx	Elasticity	R^2_{adj}	Sig.
Pop size	2395.515 (0.000)	-3053.526 (0.000)	1009.392 (0.000)		0.191 (0.000)	0.063	0.979	0.000
Pop size	-118.258 (0.000)		85.337 (0.000)		-0.094 (0.047)	-0.031	0.926	0.000
Pop size	-41.891 (0.000)			34.540 (0.000)	-0.069 (0.117)	-0.023	0.936	0.000
Pop grow	8.648 (0.000)	-11.201 (0.000)	3.730 (0.000)		-0.012 (0.000)	-0.615	0.717	0.000
Pop grow	-0.573 (0.000)		0.341 (0.000)		-0.014 (0.000)	-0.667	0.703	0.000
Pop grow	-0.268 (0.000)			0.138 (0.000)	-0.013 (0.000)	-0.662	0.706	0.000

[Epidemics → Population]

- *Plague → Pop size*
- *Plague → Pop grow*

Dependent variable	Constant	Independent variable t	t^2	t^3	Plague	Elasticity	R^2_{adj}	Sig.
Pop size	3087.078 (0.000)	-3924.571 (0.000)	1281.032 (0.000)		4.277 (0.000)	0.173	0.989	0.000
Pop size	-110.606 (0.000)		82.893 (0.000)		-1.281 (0.004)	-0.052	0.928	0.000
Pop size	-38.333 (0.000)			33.883 (0.000)	-0.833 (0.045)	-0.034	0.936	0.000
Pop grow	21.513 (0.000)	-26.712 (0.000)	8.370 (0.000)		-0.015 (0.171)	-0.090	0.397	0.000
Pop grow	-0.252 (0.007)		0.215 (0.000)		-0.053 (0.000)	-0.317	0.336	0.000
Pop grow	-0.069 (0.293)			0.089 (0.000)	-0.051 (0.000)	-0.308	0.340	0.000

[Nutritional status → Epidemics]

- *Height → Plague*

Dependent variable	Constant	Independent variable t	t^2	t^3	Height*	Elasticity	R^2_{adj}	Sig.
Plague	-116.322 (0.000)	148.456 (0.000)	-46.664 (0.000)		-0.751 (0.000)	-0.319	0.564	0.000
Plague	5.855 (0.000)		-1.692 (0.000)		-1.299 (0.000)	-0.551	0.531	0.000
Plague	4.341 (0.000)			-0.686 (0.000)	-1.278 (0.000)	-0.543	0.533	0.000

[Population → Food supply per capita]

- *Pop size → Grain price*
- *Pop size → Wage idx*

Dependent variable	Constant	Independent variable t	t^2	t^3	Pop size*	Elasticity	R^2_{adj}	Sig.
Grain price	-61.435 (0.000)	74.605 (0.000)	-22.465 (0.000)		0.014 (0.000)	1.060	0.813	0.000
Grain price	-0.023 (0.663)		0.129 (0.000)		-0.003 (0.000)	-0.198	0.165	0.000
Grain price	0.100 (0.004)			0.051 (0.000)	-0.003 (0.000)	-0.205	0.158	0.000
Wage idx	396.773 (0.000)	-474.974 (0.000)	141.729 (0.000)		-0.086 (0.000)	-0.771	0.950	0.000
Wage idx	5.785 (0.000)		-2.118 (0.000)		0.023 (0.000)	0.204	0.561	0.000
Wage idx	3.829 (0.000)			-0.845 (0.000)	0.024 (0.000)	0.218	0.551	0.000

- *Pop grow → Grain price*
- *Pop grow → Wage idx*

Dependent variable	Constant	Independent variable t	t^2	t^3	Pop grow	Elasticity	R^2_{adj}	Sig.
Grain price	-19.123 (0.000)	23.051 (0.000)	-6.784 (0.000)		-0.224 (0.000)	-0.374	0.569	0.000
Grain price	-0.227 (0.000)		0.240 (0.000)		-0.362 (0.000)	-0.605	0.396	0.000
Grain price	-0.005 (0.880)			0.095 (0.000)	-0.363 (0.000)	-0.606	0.385	0.000
Wage idx	175.159 (0.000)	-205.709 (0.000)	60.160 (0.000)		0.072 (0.677)	0.015	0.777	0.000
Wage idx	6.522 (0.000)		-2.519 (0.000)		1.307 (0.000)	0.265	0.572	0.000
Wage idx	4.199 (0.000)			-1.006 (0.000)	1.323 (0.000)	0.269	0.556	0.000

[Population → Agricultural production]

- *Pop size → Agri prod idx*

Dependent variable	Constant	Independent variable t	t^2	t^3	Pop size*	Elasticity	R^2_{adj}	Sig.
Agri prod idx	37545.164 (0.000)	-47091.094 (0.000)	14978.891 (0.000)		-2.984 (0.000)	-0.100	0.957	0.000
Agri prod idx	-1219.184 (0.000)		717.278 (0.000)		7.831 (0.000)	0.262	0.904	0.000
Agri prod idx	-574.567 (0.000)			289.996 (0.000)	7.279 (0.000)	0.243	0.909	0.000

- *Pop grow → Agri prod idx*

Dependent variable	Constant	Independent variable: t	t^2	t^3	Pop grow	Elasticity	R^2_{adj}	Sig.
Agri prod idx	26240.385 (0.000)	-33255.620 (0.000)	10743.131 (0.000)		149.438 (0.000)	0.113	0.962	0.000
Agri prod idx	-1022.080 (0.000)		610.260 (0.000)		349.088 (0.000)	0.265	0.887	0.000
Agri prod idx	-483.125 (0.000)			249.860 (0.000)	331.860 (0.000)	0.252	0.896	0.000

Key: t = Calendar year divided by 10^3; R^2adj = adjusted R^2 calculated for the untransformed variables; NH temp = Northern Hemisphere temperature anomaly; Eur temp = Europe temperature anomaly; NH tree ring = Northern Hemisphere extra-tropical tree-ring widths; Grain yield = Grain yield ratio in relation to seed; Agri prod idx = Agricultural production index; Grain price = Grain price; Wage idx = Wage index; Height = Average height; Famine = Number of famine years per decade; Plague = Number of plagues per decade; War = Number of wars happening in a year; Social disturb = Magnitude of social disturbances; Migration = Number of migration per quarter century; War fatality idx = War fatality index; Pop grow = Population growth rate; Pop size = Population size.

Note: n = 301 (i.e., 1500–1800). * = detrended data. All data have been transformed into annual units (via linear interpolation if necessary) and smoothed by 40-year Butterworth low-pass filter prior to multiple regression analysis. Elasticity can be interpreted as the percentage of change in dependent variable in response to a one percent change in independent variable.

Table S4. Regression coefficients of population growth rate, famine, epidemics and war on time and temperature in the NH in 1000–1900. The value in brackets indicates the p value of independent variable and constant.

Dependent variable	Constant	Independent variable: t	t^2	t^3	NH temp	Elasticity	R^2_{adj}	Sig.
NH pop grow	0.914 (0.047)	-1.390 (0.035)	0.710 (0.002)		0.608 (0.000)	0.324	0.783	0.000
NH pop grow	-0.024 (0.853)		0.244 (0.000)		0.657 (0.000)	0.350	0.717	0.000
NH pop grow	0.110 (0.308)			0.109 (0.000)	0.633 (0.000)	0.337	0.743	0.000
Famine	5.648 (0.250)	-7.588 (0.277)	3.207 (0.176)		-4.601 (0.000)	-0.249	0.512	0.000
Famine	0.528 (0.725)		0.663 (0.068)		-4.337 (0.000)	-0.235	0.165	0.000
Famine	0.831 (0.538)			0.310 (0.046)	-4.405 (0.000)	-0.238	0.192	0.000
Epidemics	19.629 (0.000)	-35.192 (0.000)	15.255 (0.000)		-3.227 (0.000)	-0.192	0.913	0.000
Epidemics	-4.111 (0.004)		3.469 (0.000)		-2.003 (0.000)	-0.120	0.889	0.000
Epidemics	-2.419 (0.014)			1.576 (0.000)	-2.338 (0.000)	-0.139	0.902	0.000
War	24.661 (0.010)	-24.929 (0.061)	8.423 (0.062)		-5.671 (0.000)	-0.165	0.528	0.000
War	7.852 (0.015)		0.073 (0.917)		-4.805 (0.000)	-0.139	0.352	0.000
War	7.768 (0.009)			0.063 (0.834)	-4.818 (0.000)	-0.140	0.339	0.000

Key: t = Calendar year divided by 10^3; NH temp = NH temperature anomaly (°C); R^2adj = Adjusted R^2 calculated for the untransformed variables; NH pop grow = Annual population growth rate in the NH (%); Famine = Number of famine years per decade in the NH; Epidemics = Number of deadly epidemic events (malaria, plague, typhus, measles, smallpox and dysentery) per decade in the NH; War = Number of wars per year in the NH.

Note: n = 901 (i.e., 1000–1900). All data have been transformed into annual units (via linear interpolation if necessary) and smoothed by 100-year Butterworth low-pass filter prior to multiple regression analysis. Elasticity can be interpreted as the percentage of dependent variable in response to a one percent increase in independent variable (i.e., temperature).

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