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RESEARCH PAPER

Climate change and large-scale human population collapses in the pre-industrial era

David D. Zhang[1]*, Harry F. Lee[1], Cong Wang[2], Baosheng Li[3], Jane Zhang[4], Qing Pei[5] and Jingan Chen[6]

[1]*Department of Geography and International Centre for China Development Study, The University of Hong Kong, Pokfulam Road, Hong Kong, China,* [2]*Department of Finance, Jinan University, Guangzhou 510632, Guangdong, China,* [3]*Department of Geography, South China Normal University, Guangzhou 510631, Guangdong, China,* [4]*WestEast Magazine, Wyndham Street, Central, Hong Kong, China,* [5]*Department of Geography, The University of Hong Kong, Pokfulam Road, Hong Kong, China,* [6]*Institute of Geochemistry, Chinese Academy of Sciences, Guizhou 550002, China*

*Correspondence: David D. Zhang, Department of Geography and International Centre for China Development Study, The University of Hong Kong, Pokfulam Road, Hong Kong, China.
E-mail: zhangd@hkucc.hku.hk

ABSTRACT

Aim It has long been assumed that deteriorating climate (cooling and warming above the norm) could shrink the carrying capacity of agrarian lands, depriving the human population of sufficient food. Population collapses (i.e. negative population growth) follow. However, this human–ecological relationship has rarely been verified scientifically, and evidence of warming-caused disaster has never been found. This research sought to explore quantitatively the temporal pattern, spatial pattern and triggers of population collapses in relation to climate change at the global scale over 1100 years.

Location Various countries/regions in the Northern Hemisphere (NH) during the pre-industrial era.

Methods We performed time-series analysis to examine the association between temperature change and country-wide/region-wide population collapses in different climatic zones. All of the known population collapse incidents in the NH in the period CE 800–1900 were included in our data analysis.

Results Nearly 90% of population collapses in various NH countries/regions occurred during periods of climate deterioration characterized by shrinking carrying capacity of the land. In addition, we found that cooling dampened the human ecosystem and brought about 80% of the collapses in warmer humid, cooler humid and dry zones, while warming adversely affected the ecosystems in dry and tropical humid zones. All of the population collapses and growth declines in periods of warm climate occurred in dry and tropical humid zones. Malthusian checks (famines, wars and epidemics) were the dominant triggers of population collapses, which peaked dramatically when climate deteriorated.

Main conclusions Global demographic catastrophes and most population collapse incidents occurred in periods with great climate change, owing to overpopulation caused by diminished carrying capacity of the land and the resultant outbreak of Malthusian checks. Impacts of cooling or warming on land carrying capacity varied geographically, as a result of the diversified ecosystems in different parts of the Earth. The observed climate–population synchrony challenges Malthusian theory and demonstrates that it is not population growth alone but climate-induced subsistence shortage and population growth working synergistically, that cause large-scale human population collapses on the long-term scale.

Keywords

Climate change, land carrying capacity, Malthusian checks, Northern Hemisphere, population collapses, pre-industrial era.

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INTRODUCTION

The issue of climate change has attracted significant scholarly attention. Scholars have come to realize that social activities are heavily dependent on climate, and that human societies are especially vulnerable to significant and long-term temperature changes. In the 17th century – the coldest period in the last millennium – population collapses occurred in various European regions, including Castile, Germany, Catalonia, the Netherlands, Denmark, Poland, England, France and others (Steensgaard, 1978). Meanwhile, the global synchronistic population expansion in the 18th century remains a puzzle. In a period when land was, and had always been, available for the expansion of population and the global economy was still very fragile, land availability and international trade were unlikely to be responsible for such a general and powerful increase of population. A favourable climate seemed to be the underlying factor in the global expansion of population during the 18th century (Braudel, 1974).

The linkage between climate change and population growth can be seen in fluctuations in agricultural production (Lee *et al.*, 2008, 2009). Cooling shortens the crop growing season and reduces farmland area (Galloway, 1986); warming shortens the duration between sowing and harvesting and increases evapotranspiration (Lobell & Field, 2007). Both are detrimental to agricultural productivity, especially to a primarily agricultural economy characterized by a low level of technology and high dependence on climate. Together with the side effects of climate change, such as shifts in rainfall pattern (Watson & the Core Writing Team, 2001), the carrying capacity of the agro-economy shrinks significantly in a deteriorating climate (cooling or warming). Pre-industrial societies were not able to compensate rapidly for harvest failures when climate deteriorated, which led to more frequent migration in search of food, a lower birth rate and more disastrous population checks, including wars, famines and epidemics. Population collapses (i.e. negative population growth) followed (Zhang *et al.*, 2006, 2007a,b; Lee *et al.*, 2008, 2009; Lee & Zhang, 2010).

Nevertheless, the conceived climate–population linkage remains controversial in academia because most of the related studies about the topic are either qualitative or based on individual countries/regions (e.g. Li, 1999). There is not much compelling evidence to confirm the linkage in a scientific manner. In addition, scholars have insufficient knowledge about the manner in which different ecosystems in various climatic zones would respond to a change in climate. This incomplete knowledge of the climate–human relationship is unfortunate because such knowledge may help us better understand the future prospects for our globe.

Subject to the above deficiency, we used high-resolution palaeoclimatic data in previous research to explore at a macro-scale the effects of climate change on the outbreak of war and population decline in the pre-industrial era (Zhang *et al.*, 2007a). We showed that long-term fluctuations of war frequency and population changes followed the cycles of temperature change in the Northern Hemisphere (NH), Europe, Asia and the arid areas of the NH (i.e. the arid zone from Eurasia to North Africa) in 1400–1900. We also found a significantly positive correlation between NH temperature swings and population growth rates for the world, NH, Asia, North America, Europe and China (Zhang *et al.*, 2007a). In the present study, we move forward to examine empirically the relationship between climate change (warming and cooling) and population collapses in finer geographic units over a longer period. We limited our study area and study period to the NH from 800 to 1900 – the pre-industrial period in which fine-grained palaeoclimatic, demographic and socio-economic records are relatively abundant (see Appendix S1 in Supporting Information) and both long-term warming and cooling events are evident. By adopting a quantitative approach, we aimed to explore how significant the climate–population linkage was in the pre-industrial world; to check whether the linkage would be mediated significantly by geographic factors; and to examine the direct triggers of population collapses in relation to climate change at the global scale.

METHODS

This research is designated to assess whether long-term (i.e. centennial) climate change is a credible factor to drive large-scale human population collapses at hemispheric and large ecosystem scales. Attention has been paid to negative population growth (i.e. population collapses) and secular fluctuation of population size rather than to other demographic variables such as fertility, mortality, nuptiality and age structure. It takes an 'eagle eye' perspective, the purpose being to obtain an approximate overview, with little attention being paid to the details of each population collapse incident. It is believed that this rather broad-brush approach, although not without limitations, is appropriate to the task and also compatible with existing historical population data. We focused on primarily agricultural societies, as opposed to industrial societies, because the economy of agricultural societies is more determined by (or more sensitive to) climate.

We chose to study the NH because most of the historical records (climate, demography and socio-economy) originate from the region and 90% of the world's population lived in this part of the world (McEvedy & Jones, 1978). Nonetheless, we faced a major methodological difficulty, in that early history is much less known than more recent history and the volume of documentary data is considerably reduced for the early period. Subject to this concern, the study period in this research is delimited to 800–1900, which allows the maximum use of documentary evidence, as historical records are more abundant and reliable after 800. On the other hand, when disentangling any complex human phenomenon, a focus on a particular socio-economic formation is necessary in order to make progress. For that reason, we chose 1900 as the end year in order that we can focus mainly on agrarian societies. Finally, according to the assessment of the Intergovernmental Panel on Climate Change, palaeotemperature reconstructions for the period 800–1900 are more well established (Jansen *et al.*, 2007).

We employed time-series analysis to examine the association between temperature change and all of the known country-wide/region-wide population collapse incidents in different climatic zones in the NH from 800 to 1900. The data used in this research and their processing procedures are detailed in the following.

Population collapse incidents and population growth in different climatic zones

Country-wide/region-wide population collapse incidents and population growth data were extracted from McEvedy & Jones' (1978) *Atlas of World Population History* (see Appendix S1). The selection of countries/regions was also made according to the atlas. As our study area was limited to the NH, only those countries/regions with average latitude above 0.00 according to the CIA World Factbook (which can be accessed at https://www.cia.gov/library/publications/the-world-factbook/index.html) were considered. As agro-ecological sensitivity to climate change is determined by regional geographic context, the impact of climate change on various geographic regions around the globe will be different. Thus, the climate–population relationship may vary in different geographic locations (Zhang *et al.*, 2007a; Lee *et al.*, 2008). For this reason, we categorized population collapses according to their associated climatic zones in reference to the modified Köppen classification system used in the *Times Atlas of the World* (London Times, 2007) to explore how geographic factors mediate the climate–population relationship. Four major climatic zones in the NH were identified: tropical humid (TH), warmer humid (WH), cooler humid (CH) and dry (D) zones (Table 1, Fig. 1).

Palaeoclimate in the NH

The centennial climate variability in the NH from 800 to 1900 was elicited by arithmetically averaging the 12 most recent and authoritative palaeo-temperature reconstructions chosen by the Intergovernmental Panel on Climate Change (Jansen *et al.*, 2007) (see Appendix S2), then smoothed by the 100-year Butterworth low-pass filter to remove fluctuations on time-scales less than 100 years. Based on the resultant temperature anomalies series (in °C, from the 1961–90 mean), we established warming and cooling thresholds according to the averaged temperature anomalies of the starting century of the Medieval Warm Period (MWP) and Little Ice Age (LIA), respectively. A period in which the temperature anomaly was higher than –0.3 °C was classified as a warm phase; a period in which the temperature anomaly was lower than –0.42 °C was classified as a

Table 1 Delineation of major climatic zones in the Northern Hemisphere. The delineation is made according to the modified Köppen classification system used in the *Times Atlas of the World* (London Times, 2007).

Climatic zone	Abbreviation	Characteristics
Tropical humid	TH	Rainy climate with no winter: coolest month above 18 °C (64.4 °F)
Warmer humid	WH	Rainy climates with mild winters: coolest month above 0 °C (32 °F), but below 18 °C (64.4 °F); warmest month above 10 °C (50 °F)
Cooler humid	CH	Rainy climates with severe winters: coldest month below 0 °C (32 °F); warmest month above 10 °C (50 °F)
Dry	D	Dry climates; limits are defined by formulae based on rainfall effectiveness

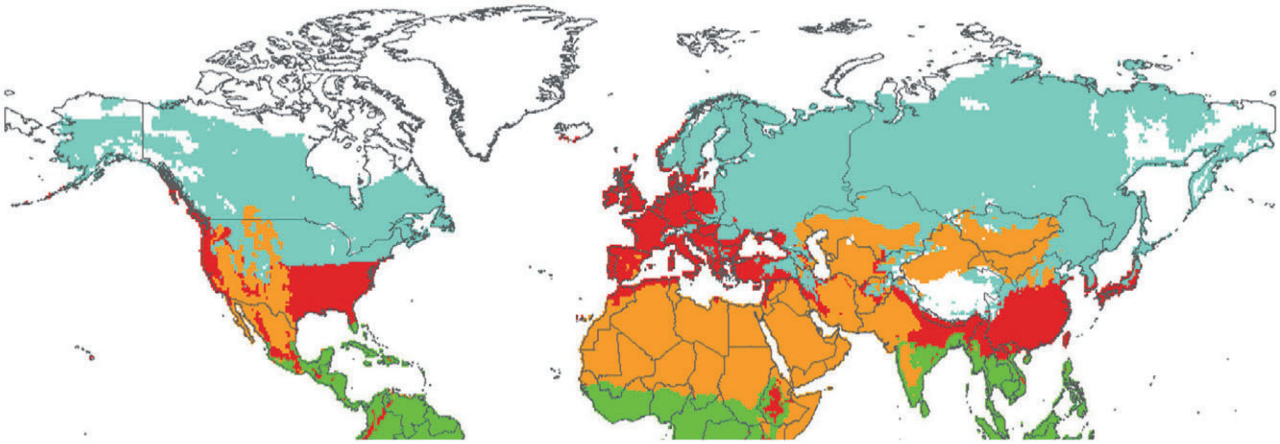

Figure 1 Map of the Northern Hemisphere (map projection Gall Stereographic). The boundary of each major climatic zone is delineated according to the modified Köppen classification system used in the *Times Atlas of the World* (London Times, 2007): red (WH, warmer humid zone); turquoise (CH, cooler humid zone); bright green (TH, tropical humid zone); orange (D, dry zone) (see Table 1 for details). The boundary of each country/region (described by a grey line) is drawn according to the *Atlas of World Population History* (McEvedy & Jones, 1978).

Table 2 Delineation of climatic phases in the Northern Hemisphere from 800 to 1900. The period in which the Northern Hemisphere temperature anomaly (in °C, from the 1961–90 mean) (Jansen *et al.*, 2007) was higher than −0.3 °C was classified as a warm phase; the period in which the temperature anomaly was lower than −0.42 °C was classified as a cold phase (see Appendix S3).

Period	Average temperature anomaly (°C)*	Climatic phase	Duration (years)
800–953	−0.38	Mild	154
954–1114	−0.22	Warm (MWP)	161
1115–1235	−0.37	Mild	121
1236–1359	−0.44	Cold (C1)	124
1360–1458	−0.35	Mild	99
1459–1510	−0.44	Cold (C2)	52
1511–53	−0.40	Mild	43
1554–1741	−0.51	Cold (C3)	188
1742–1803	−0.38	Mild	62
1804–66	−0.46	Cold (C4)	63
1867–1900	−0.34	Mild	34

*From the 1961–90 mean.

cold phase (see Appendix S3). It should be noted that the average 1961–90 temperature anomaly is 0°C, which is *c.* 0.3°C higher than that of the MWP. In line with these criteria, we identified a warm phase in the MWP (954–1114) and four cold phases in the LIA [C1 (1236–1359), C2 (1459–1510), C3 (1554–1741), C4 (1804–66)]. These represent periods of climate deterioration. The remaining years were classified as mild phases (Table 2, Fig. 2a). Our analyses of climate–population association were conducted according to the above climatic phase delineations.

Direct triggers of population collapses

According to McEvedy & Jones' (1978) *Atlas of World Population History*, five major triggers of population collapses could be identified: famines, wars, epidemics, out-migration and cross-oceanic colonization. The first three are generally referred to as Malthusian checks. Cross-oceanic colonization brought about population collapses through wars, epidemics and the slave trade in the pre-industrial era. Although some population collapse incidents might be induced by a number of causes, we listed only the most important trigger or two for each population collapse incident to facilitate our data analysis in line with McEvedy & Jones' (1978) book. As most historic population collapses were caused by Malthusian checks (i.e. famines, wars and epidemics), we also calculated the total number of famines, wars and epidemics in the NH from 800 to 1900 according to historical records for our quantitative analysis. Our famine time series was derived from Walford's (1970) *The Famines of the World: Past and Present* and Golkin's (1987) *Famine: a Heritage of Hunger*; our war time series was derived from Kohn's (1999) *Dictionary of Wars*; and our epidemics series was derived from Cliff *et al.*'s (1998) *Deciphering Global Epidemics: Analytical Approaches to the Disease Records of World Cities, 1888–1912*, Kohn's (2001) *Encyclopedia of Plague and Pestilence* and Xiao & Liu's (2005) *History of Pestilence* (see Appendix S4).

RESULTS

Climate change and the temporal pattern of population collapses

There were 88 population collapses at the country/regional scale (see Appendix S5), out of which 7, 70 and 11 occurred (the average number of population collapses per century was 4, 16 and 2) in the MWP, C1–C4 and mild phases, respectively. Most of the collapses happened in C1 (41) and C3 (23) – the two long cold phases. Nearly 70% of the collapses clustered in 1040–50 (7), 1340–50 (36) and 1592–1620 (17) – although the three short climate-deteriorating periods spanned less than 2% of the study period (Fig. 2b, grey bar). In contrast, the mild phases spanned over 50% of the study period, but the associated number of population collapse incidents was only 11. Furthermore, the average population growth rate and temperature in the NH moved in the same direction. The long cold phases were associated with population decline; after-cooling mild phases were associated with rapid population growth, while warm phases were associated with diversified population growth rates in different climatic zones (Fig. 2b).

The strong clustering of population collapses in phases of climate deterioration and the fascinating synchronicity in climate change and human population growth were unlikely to be accidental. In the pre-industrial era, climate was the only common factor shared by countries and regions with different patterns of socio-economic development and geographical locations. This implies that only climate change could explain the simultaneity of population collapses at the hemispheric level.

Under conditions of ecological stress, adaptive choices for animal species include the reduction of population size, migration and dietary change. Depopulation typically takes place through starvation and cannibalism. Humans have more pathways and social mechanisms to adapt to climate change and mitigate ecological stress; besides migration, they include economic change, innovation, trade and peaceful resource redistribution. However, we believe that among late agrarian societies, established political boundaries in populated areas limited mass migration; the result of such mass migration, when it occurred, was often war. Economic change was a costly and slow process that involved changing cultures, technologies and habits. When the speed of human innovation and its transfer were not fast enough to keep pace with rapid ecological change, famines and diseases became difficult to avoid. In the face of shrinking resources, trade and redistribution would not help much because the ecological stress of climate change was at a global or very large regional scale. Finally, social organization in the form of international and national institutions was not strong enough to buffer the tensions caused by scarcity of food resources. Therefore, as stated by Malthus (1798), population collapses

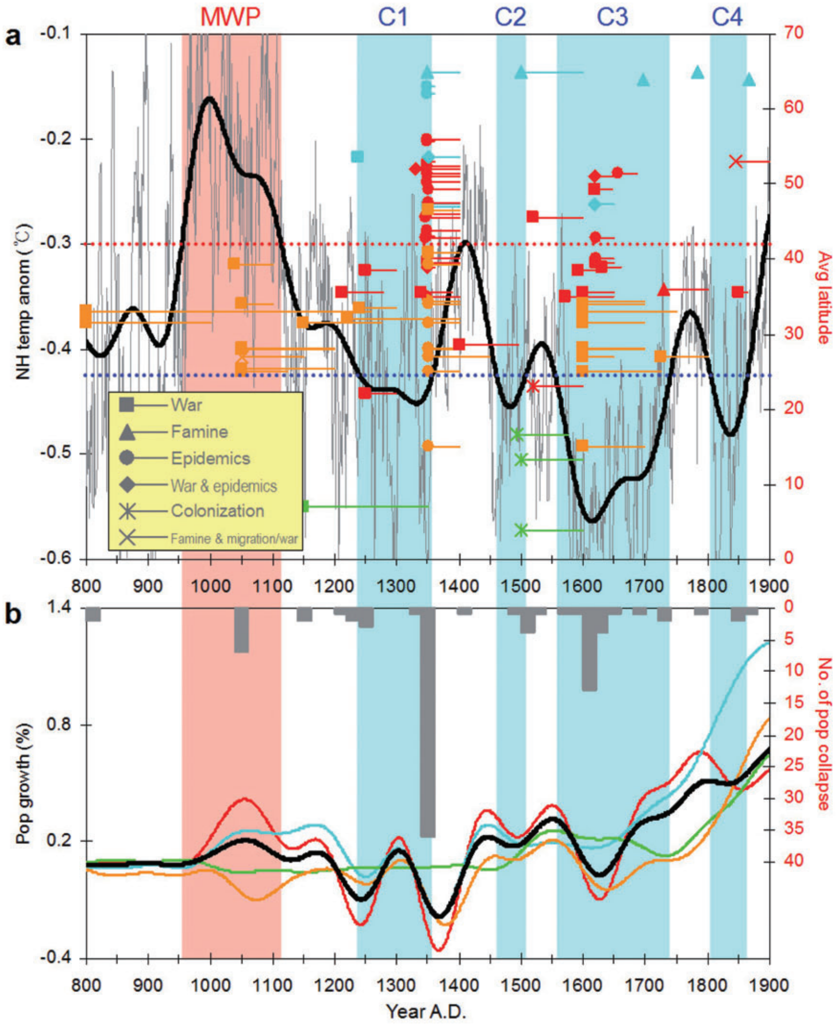

Figure 2 Climate change, population collapse and population growth in the Northern Hemisphere in 800–1900. (a) Northern Hemisphere temperature anomaly (°C) from the 1961–90 mean (Jansen *et al.*, 2007) and population collapse (McEvedy & Jones, 1978). The temperature series (grey line) has been smoothed by the Butterworth 100-year low-pass filter to characterize its centennial variability (bold black line). Red and blue dotted horizontal lines denote the warming threshold (> –0.3 °C) and cooling threshold (< –0.42 °C), respectively. Regarding the details of each population collapse; the average latitude of the relevant country/region corresponds to the right *Y*-axis and the associated climatic zone is identified by colour (red, warmer humid zone; turquoise, cooler humid zone; bright green, tropical humid zone; orange, dry zone); cause is represented by a symbol (see figure legend); and duration is revealed by the length of the line. (b) Population collapse and population growth rate (McEvedy & Jones, 1978). The grey bars represent the number of population collapses in 20-year units, which corresponds to the right *Y*-axis (inverted). Population growth rate in different climatic zones is identified by colour (red, warmer humid zone; turquoise, cooler humid zone; bright green, tropical humid zone; orange, dry zone), and bold black (Northern Hemisphere). The red shaded area represents the warm phase in the Medieval Warm Period (MWP), while the blue shaded area represents the cold phases in the Little Ice Age (C1–C4).

became common consequences of climate-induced ecological stress in the pre-industrial era (Demenocal, 2001; Diamond, 2005; Zhang *et al.*, 2006, 2007a,b; Lee *et al.*, 2008, 2009; Lee & Zhang, 2010).

Climate change and the spatial pattern of population collapses

Although population size in Zone D comprised only 15% of the NH total, 37.5% (33) of the population collapses happened there. The population growth rate in Zone D fluctuated along with temperature change. Every warming/cooling resulted in population decline before 1800 (Fig. 2b, orange line). Twenty-nine population collapses happened in Zone D in the MWP, C1 and C3. Population grew slowly in mild phases. From 1 to 1800, total population increased by only 76.92%, while population in Zones WH and CH increased by 493.14% and 890.57%, respectively. Zone D was the only zone that suffered from population collapses in the MWP. After the population drop of the MWP, the population sizes of some countries there (Egypt, Libya, Tunis and Iraq) did not reach their previous high until 1800 (McEvedy & Jones, 1978). This indicates that the agro-ecosystem in arid and semi-arid regions is highly sensitive to changes in temperature and precipitation (Zhang *et al*., 2007a). Furthermore, most of the countries and regions in Zone D were long-civilized and underwent long-term intensive cultivation. The resultant land degradation might have magnified and prolonged the ecological impact of climate change (i.e. shrinkage of land carrying capacity). This explains why the average population collapse duration in Zone D (102.76 years) was much longer than that in other zones (50.29 years) (Fig. 2a). Although the Muslim agricultural revolution spread to all arid areas in northern Africa and western Asia beginning in the 8th century, it could not help dissipate the demographic impact of climate change. All population collapses in the MWP located in Zone D's major agricultural regions (Algeria, Arabia, Egypt, Libya, Morocco, Tunisia and Turkey) were primarily triggered by nomadic tribal invasions (Issar, 1995). As the zone became hotter and drier in the MWP (von Rad *et al*., 1999; Enzel *et al*., 2003), nomadic tribes in pastoral areas suffered most, forcing them to invade adjacent agricultural regions for subsistence. Subject to further warming, farmlands in those regions were degraded to pastoral land (McEvedy & Jones, 1978; Issar, 1995). In light of these historic changes, many scientists have forecast a similar disastrous outcome of global warming. A recent study, which is based on the contemporary war dataset and temperature change, has shown that warming increases the risk of civil war in sub-Saharan regions (Burke *et al*., 2009). Here we provide the first historical evidence for it.

Warming and cooling were detrimental to Zone D, but in Zones WH and CH, in middle and high latitudes, only cooling was detrimental. Forty-five out of the total of 51 population collapses in those zones occurred in cold phases, while warming boosted population growth rates by increasing the local land carrying capacity (Galloway, 1986; Lee *et al*., 2008, 2009; Lee & Zhang, 2010) and created a golden age for human societies, such as the High Middle Age in Europe and Northern Song in China during the MWP. Population size in Zones WH and CH made up nearly 70% of the NH total, which largely determined the overall trend of NH population growth (Fig. 2b). A disparity of agro-ecological sensitivity between the two zones might be revealed by their respective population growth rates. Zone CH had a gentle fluctuation of population growth (Fig. 2b, turquoise line), while the rate in Zone WH oscillated more (Fig. 2b, red line). As agricultural production in the southern part of Zone WH (i.e. southern Europe and China) involves multiple-cropping that is only sustainable in a warm climate, the land carrying capacity in Zone WH was more vulnerable to cooling relative to other zones, resulting in greater fluctuations in population growth.

The demographic impact of deteriorating climate was not great in Zone TH. The zone had steady population growth and only four population collapses, owing to the rich biodiversity and large land carrying capacity there. There were two slight drops in population growth (Fig. 2b, green line): one in the MWP because of the hot-drought climate in India (Walford, 1970) and one from 1550 to 1750, caused by the colonization-induced disasters in the New World (McEvedy & Jones, 1978).

Eighty-four out of the 88 (95.45%) population collapses in the NH took place in the Old World. In the late agricultural era, most of the Old World's countries and regions were marked by demographic saturation, while the New World was characterized by abundant farmland. Spare land carrying capacity was shown to be imperative in dissipating the demographic impact of climate deterioration upon human societies. In contrast, demographic saturation was an essential prerequisite for population collapses.

Given the significant association between temperature change and population collapses, regressions were run to estimate the relative sensitivity of population growth in the NH and various climatic zones to climate change. The independent variables are time and temperature anomalies in the NH. Time (t) presumably represents technology and/or capital accumulation. An attempt is made to eliminate the trend from the population, using parabolic (t and t^2), squared (t^2) and cubic (t^3) terms (see Galloway, 1986). The regressions were corrected for autoregressive disturbances using the Prais–Winsten estimation method. Results show that the various detrending procedures did not affect the significance of temperature (Table 3). For the NH, temperature was positive and highly significant in the regressions in which a 10% increase in temperature produced on average a 3.1% increase in population growth rate. At the regional level, Zone WH was shown to be the region most sensitive to temperature change, in which a 10% increase in temperature produced on average a 2.9% increase in population growth rate. This is consistent with the above findings regarding temperature change and population collapses in Zone WH. In Zones TH, CH and D, even though temperature positively correlated with population growth, their association (elasticity) was relatively weak compared with that of Zone WH. This might be attributable either to their relatively low population density (McEvedy & Jones, 1978) or to favourable geographic context, which leaves some spare land carrying capacity to buffer climate-induced subsistence shortage and its demographic impact (Zhang *et al*., 2007a). Zone D is the only region in which population collapses occurred in both warm and cold phases. Such a non-stationary relationship may dampen the regression results.

Climate change and the direct triggers of population collapses

In answer to questions of how population collapses were brought about, historical data showed that 38 were caused by war, 33 by epidemics, 6 by famine, 5 by war–epidemic synthesis, 4 by cross-oceanic colonization, 1 by famine–migration synthesis and 1 by famine-war synthesis (Fig. 2a; see Appendix S5).

A period of deteriorating climate, with its attendant decrease in agricultural yield, can lead to relative over-population and food shortage. Such a subsistence crisis can lead to elevated mortality in a number of ways. The most obvious is through catastrophic famines. When human food intake falls chronically

Table 3 Regressions of the population growth rates in various climate zones on time and Northern Hemisphere temperature anomalies from 800 to 1900. Population growth and temperature anomaly data have been smoothed by the 100-year Butterworth low-pass filter prior to regression analysis. The regressions are corrected for autoregressive disturbances using the Prais–Winsten estimation method. Elasticity can be interpreted as the percentage of population growth in response to a 1% increase in temperature.

		Independent variable					
Dependent variable	Constant	t	t^2	t^3	Temp.	Elasticity	R^2_{adj}
Northern Hemisphere	1.175	−1.799***	0.845***		0.499***	0.301	0.781
Northern Hemisphere	0.087		0.209***		0.516***	0.312	0.611
Northern Hemisphere	0.153			0.101***	0.505***	0.305	0.677
Warmer humid	0.606	−0.516	0.325		0.833***	0.288	0.561
Warmer humid	0.293		0.141**		0.838***	0.290	0.468
Warmer humid	0.362			0.063**	0.832***	0.288	0.507
Cooler humid	2.159	−4.068***	1.890***		0.110*	0.063	0.783
Cooler humid	−0.290		0.456***		0.147**	0.084	0.609
Cooler humid	−0.173			0.227***	0.121*	0.069	0.682
Tropical humid	1.422	−2.446***	1.084***		0.154***	0.200	0.784
Tropical humid	−0.051		0.222***		0.176***	0.229	0.579
Tropical humid	−0.005			0.112***	0.163***	0.210	0.647
Dry	2.242	−4.077***	1.766***		0.130**	0.083	0.606
Dry	−0.214		0.328***		0.168***	0.107	0.407
Dry	−0.160			0.169***	0.147***	0.093	0.470

t = calendar year divided by 10^3. R^2_{adj} = adjusted R^2 calculated for the untransformed variables.
***$P < 0.001$; **$P < 0.01$; *$P < 0.05$.

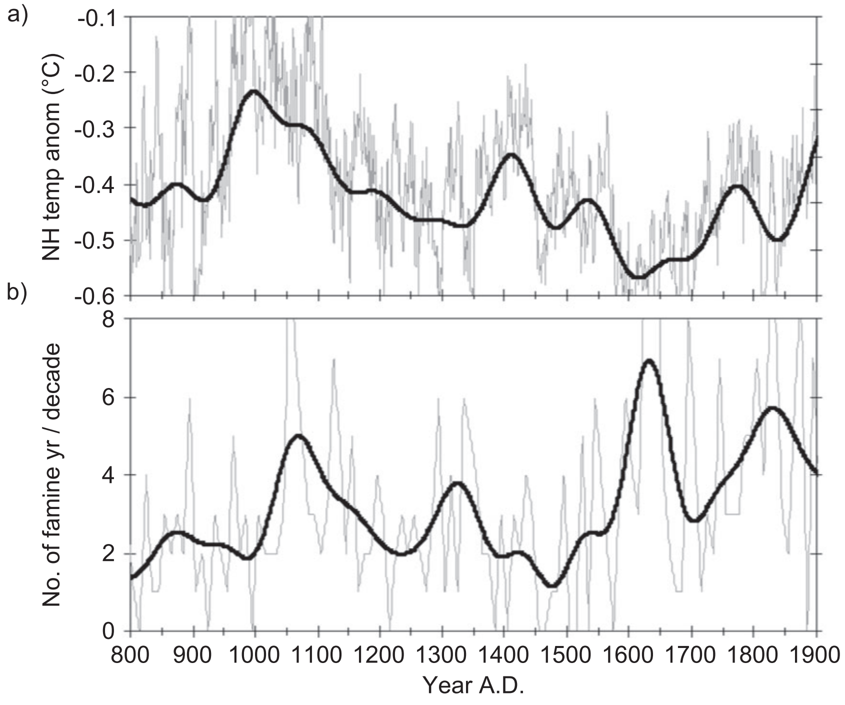

Figure 3 Climate change and famines in the Northern Hemisphere in 800–1900. (a) Northern Hemisphere temperature anomaly (°C) from the 1961–90 mean (Jansen *et al.*, 2007). (b) Years with famine per decade (Walford, 1970; Golkin, 1987). Both series have been smoothed by the Butterworth 100-year low-pass filter (described by the bold curve).

below the amount required for physiological energy balance, tissue wasting is inevitable and, eventually, death must ensue (Scrimshaw, 1983). We found that all of the peaks of famine years in the NH coincided with climate-deteriorating phases (MWP, C1, C3 and C4) (Fig. 3). During the famine peak in the MWP, most famines occurred in Zones D and TH, which reconfirms the catastrophic impact of warming in our above findings.

War is an adaptive ecological choice during periods of resource shortage and population pressure (Webster, 1975). Such resource scarcity directly induces resource-oriented wars

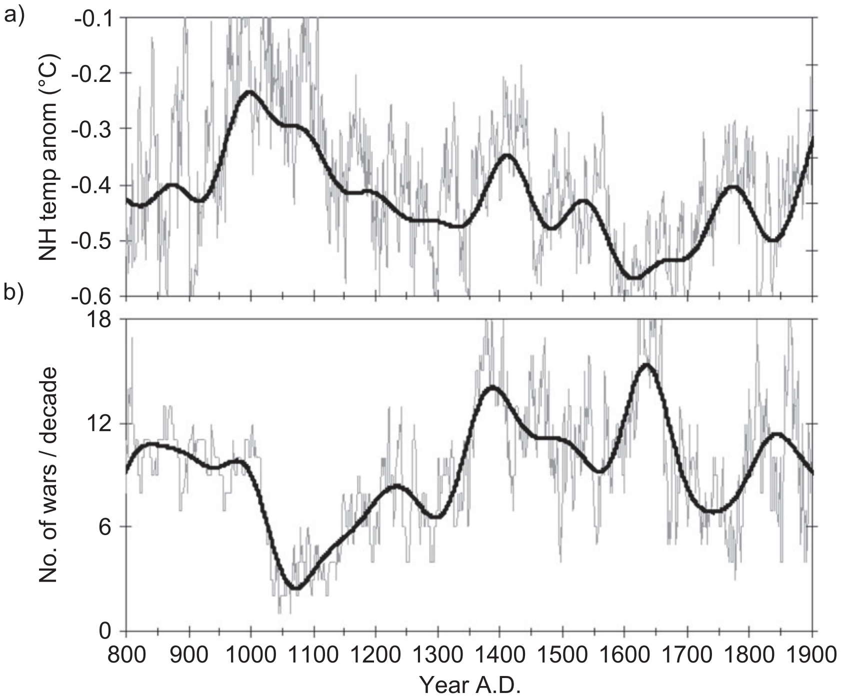

Figure 4 Climate change and number of wars in the Northern Hemisphere in 800–1900. (a) Northern Hemisphere temperature anomaly (°C) from the 1961–90 mean (Jansen *et al.*, 2007). (b) Number of wars per year (Kohn, 1999). Both series have been smoothed by the Butterworth 100-year low-pass filter (described by the bold curve).

as most of the world's population struggles to satisfy the lower levels of Maslow's (1970) hierarchy of needs, or intensifies different social contradictions which increases the likelihood of outbreak of war. Historical data showed that peaks of war in the NH occurred in C1, C3 and C4 – the three long cold phases (Fig. 4). We also noted the time lags between climate deterioration and peaks of war before 1500. The lags were caused by the lengthy duration of wars before the 16th century, when military organization and technology were underdeveloped (Diamond, 1997) (see Appendix S6).

Climate-induced agricultural shrinkage had the potential to lead to a general decline in nutrition. Chronic undernourishment drastically increases the body's susceptibility to infections of all kinds, so that diseases of whatever degree of severity which are normally endemic among the population may suddenly find themselves endowed with increased virulence and rampancy, which results in high mortality (Dunstan, 1975; Demenocal, 2001). In addition, more frequent famine- and war-driven migrations in a cold climate facilitated the outbreak of epidemics (Galloway, 1986; Lee & Zhang, 2010). We found that with increasing population density over time the six most deadly epidemics increased in the NH, namely malaria, plague, typhus, measles, smallpox and dysentery (Fig. 5). Despite this trend, those epidemics also peaked in C1, C3 and C4 when climate deteriorated.

C2 did not generate any peaks of Malthusian checks and the MWP did not lead to peaks in wars and epidemics. This is because the temperature change in C2 and the MWP was comparatively mild (Fig. 2a), and not strong enough to induce widespread socio-ecological crises across the NH.

Regressions were run to estimate the relative sensitivity of various Malthusian checks (i.e. wars, famines and epidemics) to temperature change in the NH. Again, the independent variables are time and temperature anomalies in the NH. An attempt was made to eliminate the long-term trend from the Malthusian checks and to correct autoregressive disturbances for regressions (see the previous section). Results show that the various detrending procedures do not affect the significance of temperature. Temperature was negative and highly significant in all regressions (Table 4). A 10% decrease in temperature produces on average 2.2%, 1.2%, and 1.1% increases in famines, wars and epidemics, respectively, in the NH. Although warming and cooling can shrink the land carrying capacity, the regression results in the previous section and here indicate that cooling was generally more detrimental to human societies at the hemispheric and global scales in history.

DISCUSSION

The world-wide extent and synchronicity of large-scale population collapses reveals that a very basic and deep-seated influence was at work at the global scale – the deterioration of climate. The proposed climate–population linkage is largely applicable in the pre-industrial world and was mediated by regional geographic context, which concurs with our previous research findings (Zhang *et al.*, 2007a). Geographically, global cooling drove large-scale population collapses in Zones D, WH and CH. Most population collapse incidents in our study occurred in these zones, largely because 70% of the world's population lived there in the pre-industrial era. Warmer climate (0.3 °C lower than the average temperature for 1961–90) brought about population collapses in Zone D, a slight decline in the growth rate in Zone TH and rapid population growth in Zones WH and CH. The direct triggers of the collapses were more frequent Malthusian

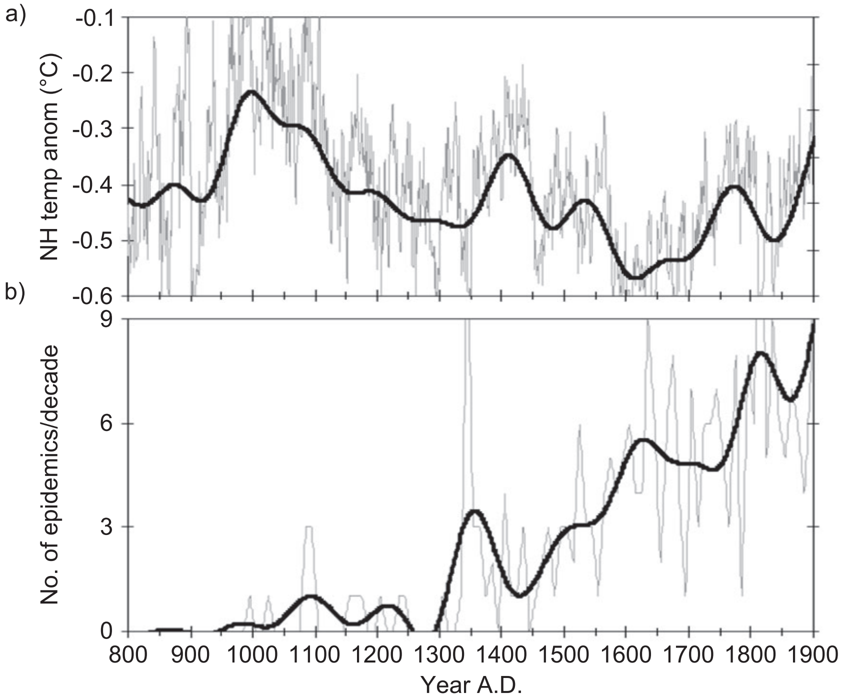

Figure 5 Climate change and epidemics in the Northern Hemisphere in 800–1900. (a) Northern Hemisphere temperature anomaly (°C) from the 1961–90 mean (Jansen *et al.*, 2007). (b) Number of deadly epidemic events of six diseases (malaria, plague, typhus, measles, smallpox, dysentery) per decade (Cliff *et al.*, 1998; Kohn, 2001; Xiao & Liu, 2005). Both series have been smoothed by the Butterworth 100-year low-pass filter (described by the bold curve).

Table 4 Regressions of various population checks in the Northern Hemisphere on time and Northern Hemisphere temperature anomalies from 800 to 1900. Population checks and temperature anomaly data have been smoothed by the 100-year Butterworth low-pass filter prior to regression analysis. The regressions are corrected for autoregressive disturbances using the Prais–Winsten estimation method. Elasticity can be interpreted as the percentage of population check changes in response to a 1% increase in temperature.

		Independent variable					
Dependent variable	Constant	t	t^2	t^3	Temp.	Elasticity	R^2_{adj}
Famine	−4.445	6.713***	−1.441***		−3.493***	−0.212	0.309
Famine	−0.383		0.936**		−3.555***	−0.216	0.279
Famine	0.205			0.386**	−3.580***	−0.217	0.298
War	9.333	−2.783	1.164		−3.678***	−0.119	0.226
War	7.651		0.180		−3.653***	−0.118	0.218
War	7.774			0.071	−3.657***	−0.118	0.218
Epidemics	7.643	−18.248***	9.772***		−1.680***	−0.113	0.927
Epidemics	−3.398		3.328***		−1.514***	−0.103	0.886
Epidemics	−2.120			1.559***	−1.670***	−0.113	0.914

t = calendar year divided by 10^3. R^2_{adj} = adjusted R^2 calculated for the untransformed variables.
***$P < 0.001$; **$P < 0.01$.

checks that resulted from the reduction in the land's carrying capacity in a specific zone. The results also have implications for the following issues.

Challenge to demographic theories

Scholars emphasize a range of socio-economic factors, including real wages (Wrigley & Schofield, 1981; Lee, 1985, 1987, 1993; Wrigley *et al.*, 1997; Lee & Anderson, 2002), grain prices (Duncan *et al.*, 2001; Duncan & Scott, 2004), price movements (Fischer, 1996), the level of adaptive specialization of economic development (Chu & Tai, 2001) and combinations thereof as the major determinants for historical population growth. Yet they cannot explain why population collapses, or the outbreaks of Malthusian checks, and population growth occurred simultaneously in various NH countries and regions which are characterized by different socio-economic settings. Our previous research has already shown that the price movement in an agro-economy is mainly controlled by grain production, which is determined by climate in the pre-industrial era (Zhang *et al.*, 2007a). Here, our findings satisfactorily resolve questions of when, where and why population collapses occurred in history.

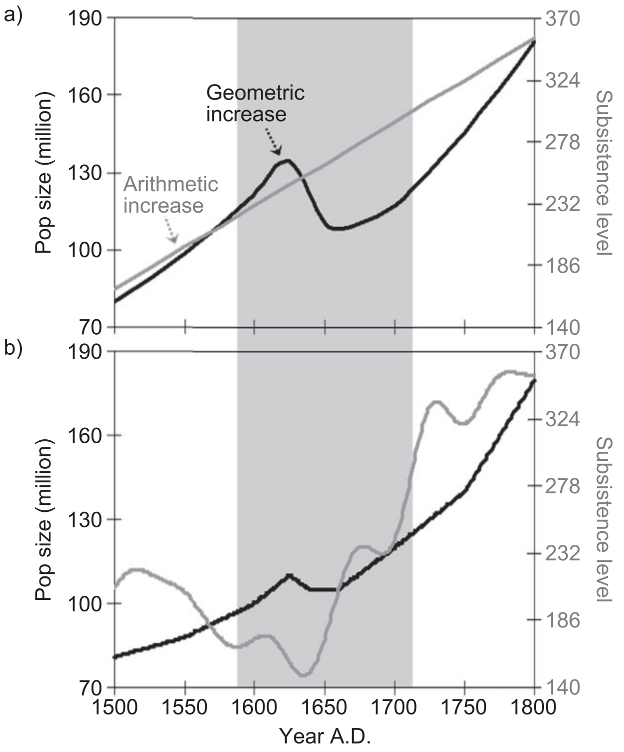

Figure 6 Comparison of population size and subsistence level in Europe in 1500–1800. (a) Malthusian scenario, in which population size and subsistence level are purely hypothetical. (b) Real world situation, in which population data come from McEvedy & Jones' (1978) study, while subsistence level is characterized by the agricultural production index (see Zhang *et al.*, 2007a). The black line represents population size (in millions, corresponds to the left *Y*-axis), while the grey line denotes subsistence level (corresponds to the right *Y*-axis). The grey shaded area represents a cold period with the Northern Hemisphere temperature anomaly below –0.5 °C.

Our work indicates that climate change is one of the most important determinants for historical population growth in a broad sense.

Our findings also challenge a widely accepted basic concept of Malthusian theory in ecological and population research, which states that subsistence level increases arithmetically while population increases geometrically (Malthus, 1798) (Fig. 6a). According to the theory, land carrying capacity is assumed to be essentially constant or possibly increasing monotonically. Malthusian checks (i.e. famines, wars and epidemics) and the associated population collapses occur when faster population growth overshoots the subsistence level. Since the land carrying capacity was understood as relatively fixed, the root of historical demographic tragedies has been attributed simply to excessive population growth. In fact, Malthus (1798) is insightful in pointing out that the root cause of demographic tragedies is the ecological imbalance between population size and land carrying capacity, which is attributable to divergent rates of population growth and subsistence increase. However, this study emphasizes that, given the technological limitations of agricultural production during the time in question, long-term climate changes would have a significant impact on food supplies, and that the constant or possibly monotonic increase in land carrying capacity (assumed by Malthus, 1798, and many other scholars) may not be true, at least in the pre-industrial era. The upward trend of land carrying capacity is, in fact, characterized by shorter-term recurring oscillations (ascending wave pattern) in accordance with the alternation of cold and warm climate (Zhang *et al.*, 2007a; Lee *et al.*, 2008, 2009; Lee & Zhang, 2010). On the other hand, in agrarian societies, population expands to the land carrying capacity (demographic saturation), which reduces the natural buffering capacity that would provide for societal resilience (e.g. tracts of non-cultivated arable land) (Wood, 1998; Fagan, 2000). This renders the population vulnerable to any shocks in food supplies. Such circumstances interact with the climate-induced decline of land carrying capacity to produce a demographic collapse via the increase in various mortality crises, including wars, famines and epidemics.

By examining the fluctuations of agricultural production and population size in Europe from 1500 to 1800, we found that the subsistence level in Europe increased in an ascending but oscillating manner, and its ups and downs matched closely with the alternation of warm and cold climate (Fig. 6b). We also discovered that the subsistence level fluctuated more deeply than population size did, and that agricultural shrinkage brought by cooling since the late 16th century preceded the population collapse in the mid-17th century (Zhang *et al.*, 2007a). Such a sequential relationship (or cause-and-effect relationship) further supports our thesis.

Possible demographic consequences of global warming

The observed demographic crisis in Zones D and TH in the MWP is worth mentioning. The average temperature anomaly since 1960 is higher than that of the MWP and it is rising continuously (Mann *et al.*, 2008). It may cause wholesale disruption of the ecosystem, resulting in widespread damage to sustenance and forced flight (Richter *et al.*, 2007). In addition, nearly all countries located in Zones D and TH are underdeveloped or developing (except those with fossil fuel resources and advanced technology). They may not be able to reverse the effects of warming. Actually, what happened during the MWP (internal wars between pastoralists and agriculturalists) in the northern Sahara (Algeria, Arabia, Egypt, Libya, Morocco, Tunisia and Turkey) is the ecological parallel to what is happening in southern Sahara (Darfur and Rwanda) today. Since the population size in these zones has reached half of the world total and local land carrying capacity in many of these countries has been overshot, the threat to humans of warming in these zones should be seriously regarded. The extent of the associated human disaster will be largely contingent upon the degree of climate change and the effectiveness of advancing social buffering mechanisms, including social institutions at both international and national levels and social and technological developments. These buffering mechanisms may have been working since the warming started. In Zones WH and CH, land carrying capacity increased in a warm climate in historical times because higher temperature produces longer growing seasons and more arable land. However, if the temperature increases further, the associated human–ecological impact remains uncertain. Therefore, the diversified geographic impact of global warming upon regional land carrying capacity deserves our further investigation.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Details of population data.
Appendix S2 Climate data.
Appendix S3 Setting of cooling and warming thresholds.
Appendix S4 Data concerning the direct triggers of population collapses.
Appendix S5 Details of population collapse incidents in the Northern Hemisphere, 800–1900.
Appendix S6 The average duration of war in the Northern Hemisphere.

BIOSKETCHES

D.D.Z. is a professor in the Department of Geography, The University of Hong Kong. His research interests includes physical geography and the climate–human relationship in history. He conceived the concept and designed the research. D.D.Z., H.F.L. and B.L. compiled the dataset and performed the research; D.D.Z., H.F.L., C.W., Q.P. and J.C. analysed the data, and D.D.Z., H.F.L. and J.Z. wrote the paper.

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