Vol. 59: 229–242, 2014
doi: 10.3354/cr01215

CLIMATE RESEARCH
Clim Res

Published online May 7

Climate-induced agricultural shrinkage and overpopulation in late imperial China

Harry F. Lee*

Department of Geography and the International Centre of China Development Studies, University of Hong Kong, Hong Kong, SAR

ABSTRACT: There is a continuing debate over whether the series of population checks in late imperial China were caused by overpopulation or not. The debate may be rooted in the absence of quantitative estimates of population pressure. In the present study, fine-grained historical socioeconomic and population datasets together with statistical methods were utilized to estimate quantitatively the population pressure in China in the period 1730–1910. The possible paths through which population pressure was translated into demographic catastrophes were also examined. Statistical results show that (1) the frequency of various population checks was positively correlated with subsistence pressure, (2) food strain and its associated demographic catastrophes were driven by the synergistic work of climate-induced agricultural shrinkage and population growth, and (3) the synthesis significantly determined population growth dynamics across China at various geographic levels. To conclude, overpopulation in late imperial China is not a myth, and the series of population checks and eventually population collapse were caused by subsistence pressure during the period. When examining historical Chinese demography, the adverse effect of climatic forcing on human carrying capacity should be considered.

KEY WORDS: Climate change · Human carrying capacity · Population pressure · Overpopulation · Population checks · Demographic catastrophes · China

1. INTRODUCTION

China was marked by a series of population checks in the 19th century. In the 1840s, a succession of famines and warfare broke out. Flooding, drought, and famine were rampant. In 1849, catastrophic flooding in Hebei, Zhejiang, and Hubei provinces alone killed 15 million people (Gao 1997). The Taiping Rebellion, which is believed to be the biggest civilian war in world history, erupted in 1851. In 1855, the Nian Rebellion also broke out. Throughout the 1850s, there were 65 wars in total, and 61 of them were rebellions (Editorial Committee of Chinese Military History 1985). In 1857, large-scale flooding in Hubei and Shandong caused 8 million deaths (Gao 1997). The Taiping and Nian Rebellions ended in 1864 and 1868 respectively, and it is estimated that nearly 100 million people died during the rebellion period (Cao 2000). The 1860s was also a decade characterized by frequent pestilence, with 23 instances breaking out (Sun 2004). And the 3 yr drought famine from 1876 to 1878 led to 13 million deaths (Chen & Gao 1984). Overall, the population size of China dropped from 436.1 to 364.5 million in the period 1851 to 1880 (Cao 2000). Because the population loss was so immense and is of great historical significance, many scholars study it to try to discover the root cause of frequent population checks in late imperial China.

Considering the overwhelmingly agrarian nature of historical Chinese society, in which >90% of the population was involved in agriculture, the most widely accepted explanation for the recurrence of population checks is the periodic overshooting of Malthusian limits on population size. As stated by Malthus (1798), when the population increases be-

*Corresponding author: harrylee@hku.hk

yond the means of subsistence, food prices increase, real wages decline, and per capita consumption drops (especially among the poorer social strata). The ensuing economic distress, often accompanied by famine, plague, and war, leads to lower reproduction and higher mortality rates, resulting in slower population growth (or even decline), which in turn allows the subsistence means to catch up. The restraints on reproduction are loosened and population growth resumes, leading eventually to another subsistence crisis. Periodic mortality crises are regarded as the essential parts of Malthusian dynamics. Subject to the influence of Malthusian theory, contemporary scholars cite a variety of indicators of overpopulation, including ecological destruction, declines in land/human ratios, and erosion of real wages (Ho 1959, Chao 1986). Various characterizations of China's plight — as a 'high level equilibrium trap' (Nelson 1956, Elvin 1973) and an 'involution' (Huang 1990) — enshrine the essential idea of population pressure on resources. Despite some variations in approaches and vocabularies, the root cause of the recurring population checks in the 19th century in China is often traced back to overpopulation triggered by excessive (or unchecked) population growth.

On the other hand, Pomeranz (2000) notes that the presence of civil war and other disasters in China in the mid-19th century cannot by themselves demonstrate the existence of overpopulation in the previous century. Some historical demographers demonstrate that the distinctive influence of mortality on population in China was not through famines or epidemics, but through individual proactive interventions such as infanticide (particularly for daughters)[1], late male marriage and bachelorhood[2], low marital fertility[3], and resort to fictive kinship and adoption[4] (Lee et al. 1994, 2002, Lee & Wang 1999). In China, reproductive decisions are collective and influenced by 2 enduring cultural characteristics: patrilineal ancestor worship and bureaucratic state autocracy. Chinese demographic behavior was shaped not just by biology but also by choice. Given that the above practices were adopted on a significant scale, population never pushed itself to subsistence levels, and hence, the series of demographic catastrophes in late imperial China should not be credited to overpopulation. They were merely incidental events attributable to political and institutional problems. Overpopulation in late imperial China is simply a myth:

> *While* [*there were*] *spectacular mortality spikes, … these crises hardly restrained long-term population growth …* [*They*] *appear to have been the products of political and organizational problems, not excess population per se.* (Lee & Wang 1999, p. 36)

> *… such crises* [*large-scale famines and epidemics*] *were neither a product of overpopulation nor sufficiently frequent and severe to regulate systematically long-term population growth.* (Lee et al. 2002, p. 594)

The above argument is going against received wisdom, and concurred with by other scholars (Lavely & Wong 1998, Pomeranz 2002). Although the intellectual discourse of population studies has somehow been re-shaped, the debate over whether the mortality events in late imperial China were caused by overpopulation continues (Cao 2000, Huang 2002), probably because of a very basic shortcoming—the term overpopulation has never been quantitatively defined. Without a yardstick for measuring overpopulation, the debate is unlikely to be resolved.

In the present study, I estimated quantitatively the population pressure in late imperial China. Based on that estimation, I proceeded to investigate the following issues that are imperative in comprehending historical Chinese demography: Were the series of demographic catastrophes in late imperial China associated with overpopulation? If the answer is affirmative, how did population strain translate into population checks and eventually population collapse? Finally, to what extent was the population growth dynamic in historical China determined by such mechanisms? To answer the above questions, fine-grained paleo-climate and historical socio-economic and population datasets together with 1-way ANOVA and multiple regression analysis were employed. The study period was 1730 to 1910, using the entire span of my available data.

---

[1]In the 18th century, female infanticide was prevalent in China and about 10% of female babies were killed every year. Males were also vulnerable to infanticide

[2]While Chinese men married earlier than their counterparts in Europe, by age 30 nearly one-quarter of Chinese men were still unmarried. By age 45, in both China and the West, between 10 and 15% of men were still bachelors, and the Chinese proportion was slightly higher than in Sweden, Denmark, or Norway

[3]While Western married women in the absence of contraception had on average a total marital fertility rate (the number of children a married woman would bear in her lifetime if she experienced at each age the fertility rates of a given year) of 7.5 to 9, Chinese married women had a total marital fertility rate of 6 or less. This low marital fertility is one of the most distinctive features of the Chinese demographic system

[4]At least 1 of every 100 Chinese children in the past was given up for adoption, which is almost an order of magnitude larger than for any modern Western population

2. THEORETICAL FRAMEWORK

Human carrying capacity is the maximum population that can be supported at a given living standard by the interaction of any given human-ecological system. Environmental and human resources are largely relevant to human population size (Butler 2004). Empirical findings show that human carrying capacity in historical China (Lee et al. 2008, 2009, Lee & Zhang 2010, 2013) and in early modern societies elsewhere (Zhang et al. 2007a, 2011a, 2011b) was primarily determined by food subsistence. In pre-industrial societies, when the means of subsistence increases, population increases. Overpopulation occurs when food supply per capita is below the average subsistence level[5]. Given the above premise, to facilitate our research, I posited a set of simplified pathways for population growth in historical agrarian China (cf. Lee & Zhang 2010, 2013) as follows:

(1) The linkage between temperature change and population growth shows up through fluctuations in agricultural production (Lee et al. 2008, 2009, Lee & Zhang 2010, 2013). Cooling shortens the crop growing season and reduces farmland area (Galloway 1986). Both of these are detrimental to human carrying capacity in terms of agricultural production, especially in a primarily agricultural economy characterized by a low level of technology and high dependence on favorable climate conditions[6].

[5]Although subsistence crises can be overcome by high-level human co-operation, it is only applicable to those crises that are below certain 'thresholds' (Butler 2004)

[6]The history of rice cultivation in the middle and lower reaches of the Yangtze River may give a more complete picture of the effect of cooling on settled agricultural areas. Double cropping of rice started there in the Tang Dynasty (618–906), when the climate was similar to that of today. In the Sung Dynasty (960–1279), due to a cooler climate, double cropping of rice cultivation was unfeasible in most of the Jiangnan region. But, in the late 15th century, the cultivation practice was further developed. The practice reached its peak in the warm mid-16th century. The period also overlapped with the 'warm phase' of the Little Ice Age (1400–1900). However, in the 17th century, the coldest period in the Little Ice Age, the double cropping system collapsed (Gong et al. 1996). Coinciding with the warmer phase that started in the early 18th century, double-cropping rice cultivation began to dominate the region again. Nevertheless, by the beginning of the 19th century (demarcated by a cold climate), it once more proved unsustainable despite government promotion. In the Jiangsu region, double-cropping rice cultivation was no longer practiced. Today, double-cropping rice cultivation is again functioning successfully (Gong et al. 1996). In short, the above historical shifting of rice cultivation is basically synchronous with the long-term alternation of warm and cold phases

(2) Population pressure is co-determined by human carrying capacity and population growth. In the pre-industrial era, the speed of human innovation and its diffusion were not rapid enough to accommodate a growing population. Population pressure will naturally accumulate over time, and the Chinese population probably repeatedly reached a state of demographic saturation and equilibrated at the edge of misery, i.e. starvation (Wrigley 1973, Li 1998, Wood 1998, Fagan 2000, Nefedov 2003).

(3) The shrinkage of human carrying capacity brought on by long-term cooling further intensifies population pressure (food shortage). Social buffering mechanisms (technological advancement, inter-regional trade) were ineffective in dissipating the growing population pressure in agrarian societies, resulting in more frequent mortality events, such as famine, epidemics, and civil wars (Zhang et al. 2007a).

(4) Cold periods are often associated with great climatic variability, including extremes of drought and flood, which further disturb agricultural practices already handicapped by a short growing season (Gribbin 1978, Galloway 1986). The synergy of low temperatures and increased population pressure also intensifies reclamation activities on agriculturally marginal lands, which invites more frequent natural calamities such as floods or drought (Ho 1959, Jiang 1993).

(5) The productive potential of the state was weakened by long-term cooling and destroyed by ensuing civil wars, which reduced its ability to resist, and in some cases even encouraged, nomadic invasions. Hence, internal warfare and nomadic invasions can be difficult to separate (Long 1989).

(6) Mass migration driven by population pressure, famine, war, and natural calamities facilitated the spread of epidemics and even pandemics (Zhang et al. 2007a).

(7) Mass migration, especially nomadic migration towards settled agricultural areas, promoted disputes over land and food resources between natives and migrants, resulting in violent conflicts (Fang & Liu 1992, Zhang et al. 2007b).

(8) Because the various mortality factors were often interlinked, their demographic impact was magnified, and demographic collapse followed. The resultant depopulation reduced population pressure, and mortality events subsequently decreased.

(9) This sequence was followed by renewed population growth, setting in motion another population cycle (Zhang et al. 2007a).

The pathways described in the chains of events and feedback loops are represented in Fig. 1. As this

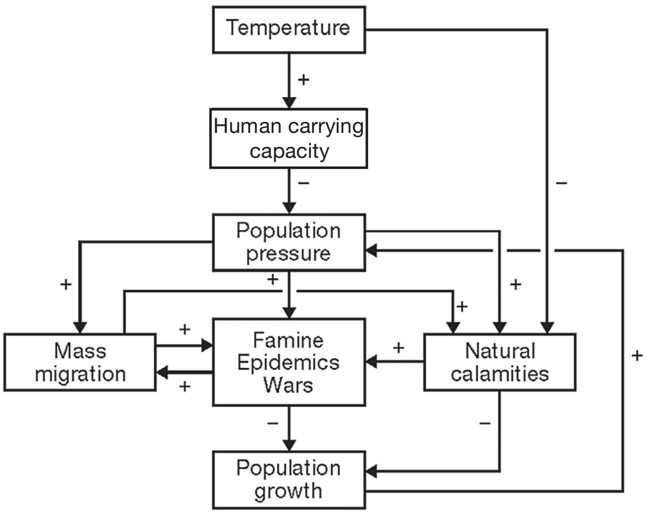

Fig. 1. Simplified pathways for population growth in historical agrarian China. Arrows indicate: 'change in *X* is associated with change in *Y*'. Plus or minus sign indicates whether the association is positive or negative

research sought to investigate the association between population pressure and demographic catastrophes in a broad sense, a macro-historical perspective will be taken, with little attention to individual incidents.

3. MATERIALS AND METHODS

3.1. Temperature

Yang et al.'s (2002) China-wide temperature anomaly series was chosen as the standard paleotemperature record in the present study. The series was reconstructed by combining area-weighted regional multi-proxy data, including ice cores, tree rings, lake sediments, and historical documents (see Fig. 3a). Although there are some recent temperature reconstructions in China (Wang et al. 2001, Tan et al. 2003), their spatial coverage did not cover the entire country.

3.2. Population

Population size data were retrieved from Cao's (2000) estimate of historical Chinese population size (see Fig. 2a). Cao (2000) gives estimates of Chinese population size at irregular time intervals, and 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 distortions of the population growth rate in data interpolation. Population growth rate (see Fig. 3h) and population density was calculated by the following formula:

$$\text{Population growth rate} = (P_t - P_{t-1})/P_{t-1} \times 100 \quad (1)$$

$$\text{Population density} = P/A \quad (2)$$

where P is population size, t is time step (yr), and A is land area (km^2). The land area data were also retrieved from Cao (2000).

Cao (2000) also estimates Chinese population at the province and the county levels[7]. However, the data were only available for the years 1776, 1820, 1851, 1880, and 1910.

3.3. Agricultural production parameters

3.3.1. Cultivated land area. The cultivated land area[8] data used in the present study were compiled by Li (1957). Their data spanned from 1661 to 1933. As they give estimates of cultivated land area 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 rate of land area change in data interpolation.

3.3.2. Harvest indexes. Based on the historical regional harvest reports of 66 stations in China that were kept in the Palace Museum in Beijing, Gong et al. (1996) have constructed the summer and autumn harvest indexes of grain production that spanned from 1730 to 1910. The indexes, ranging from 3.0 to 10.0, represent the grain yield per land unit in terms of full harvest (e.g. the index 5.5 indicates that grain production is only 55% of full harvest). Index values ≥8.0 and ≤6.0 represent good and poor harvest, respectively.

3.3.3. Maximum grain yield per land unit. Geographically weighted maximum yield per land unit (mu) across the whole of China was provided by Zhao et al. (1995). The maximum yield was 2.3 shi during the Qing Dynasty[9], where 1 shi is equal to 70 kg.

[7]Population data at the county level is only available for 18 provinces, including Jiangsu, Anhui, Zhejiang, Jiangxi, Hunan, Hubei, Fujian, Guangdong, Guangxi, Yunnan, Guizhou, Sichuan, Zhili, Henan, Shandong, Shanxi, Sha'anxi, and Gansu

[8]The original unit of cultivated land area was qing, which was converted to mu by multiplying by 100

3.4. Population check parameters

3.4.1. Natural calamities. This dataset (see Fig. 3d), compiled by Chen & Gao (1984), documents climatic disasters such as typhoons, cold spells, flooding, drought, famines, and epidemics with >10 000 casualties in the years from 180 before the Common Era (BCE) to 1949 in the Common Era (CE). In the present study, only the data for flooding and drought were aggregated as natural calamities.

3.4.2. Famine. My famine dataset (see Fig. 3e) was derived from the chronological table of natural hazards from 205 BCE to 1911 CE compiled by the Institute of History, Chinese Academy of Social Sciences (1988); only those events that were classified as great famines in the original data source have been included in the chronological table.

3.4.3. Epidemics. This dataset (see Fig. 3f) was derived from Sun's (2004) chronological table of pestilence in China. The year of outbreak and magnitude of each epidemic are also provided in the table.

3.4.4. Wars. My war dataset (see Fig. 3g) was derived from a multi-volume compendium compiled by a group of researchers from the Nanjing Academy of Military Sciences, which scrupulously records the wars that took place in China from 800 BCE to 1911 CE (Editorial Committee of Chinese Military History 1985).

3.5. Estimation of population pressure and its thresholds

According to the theoretical framework (Fig. 1), population pressure is the key factor driving population growth dynamics in pre-industrial societies. It can be interpreted as subsistence pressure epitomized by per capita grain output. Based on historical population and agricultural production data (see Sections 3.2 and 3.3), I estimated the annual fluctuation of human carrying capacity and per capita grain output in China from 1730 to 1910 using the following equations:

$$\text{Human carrying capacity} = \text{Total cultivated land area} \times \text{Max yield per land unit} \times \text{Harvest index} \quad (3)$$

$$\text{Per capita grain output} = \text{Human carrying capacity}/\text{Total population size} \quad (4)$$

Perkins (1969) highlighted that Chinese grain consumption habits have not changed significantly over time. In Chinese history, the lower limit of average per capita grain output was around 200 kg, while the upper limit was around 350 kg. The 200 kg limit represents something like a minimum subsistence level. During the Ming (c. 1368–1644) and Qing (1644–1911) dynasties, the average per capita grain output in China fluctuated between 250 and 300 kg. I made use of Perkins' (1969) work to set some thresholds for measuring population pressure. The period is regarded as 'normal' when per capita grain output is >250 kg, 'overpopulated' when per capita grain output is between 200 and 250 kg, and 'extremely overpopulated' when per capita grain output is <200 kg.

3.6. Statistics

One-way ANOVA is used to test for significant differences between the means over a single dependent variable for 2 or more groups divided by an explanatory variable (i.e. independent factor). If *F* is significant, it can be concluded that there are differences in group means and thereby, the explanatory variable is proven to have an effect on the dependent variable (De Vaus 2002). It was employed to test the association between population pressure and the frequency of population checks. The study time span was divided into normal, overpopulated, and extremely overpopulated periods (see Section 3.5) and then entered as the independent ANOVA factor, while the frequency of each type of population check (see Section 3.4) was entered as a dependent ANOVA factor. In addition, Tukey's HSD test was used in conjunction with 1-way ANOVA to identify which pairs of groups show statistically significant mean differences.

Multiple regression analysis is based on linear combinations of interval, dichotomous, or dummy independent variables to account for the variance

[9] Zhao et al. (1995) rely on the historical data from 1750 to 1900 to set this value. The assumption of constant maximum yield per land unit in late imperial China was based on the following reasoning: grain import and export was too small to significantly affect agricultural productivity (Perkins 1969), institutions relevant to agriculture did not evolve significantly after the 14th century (Perkins 1969), while farming technology remained stagnated in late imperial China (Zhao et al. 1995). Human carrying capacity was basically augmented by agricultural intensification, multiple cropping, and the introduction of new crop species. However, their positive effect on human carrying capacity was often constrained by diminishing return and environmental degradation (Zhao et al. 1995). Therefore, the maximum yield per land unit did not change much throughout the study period

in an interval dependent variable. The general purpose of the method is to assess the degree of relationship between one dependent variable and several independent variables, and the proportion of variance in the dependent variable explained by regression, and the relative importance of the various independent variables to the solution (De Vaus 2002). It was employed to examine the mechanism of how subsistence pressure was translated into population checks and eventually population collapse according to the theoretical framework shown in Fig. 1. In the theoretical framework, there is a variable 'mass migration'. However, in the 1750s, Emperor Qianlong successfully conquered Tianshan[10] and put many nomadic tribes under Qing rule. Hence, the political boundary of China was extended to the west, and nomadic migration disappeared as a consequence. Since the variable is irrelevant in examining Chinese population cycles in the study period, it has been excluded from the following statistical analysis. Prior to statistical analysis, all of the time-series data were smoothed by the Butterworth 40 yr low-pass filter to remove noise from the data. In this instance, the 40 yr cycle of the variables could be elicited[11]. Serial correlation of the time-series data prevents the application of standard tests for statistical significance, because assuming all data points to be independent would produce unrealistically high significance levels. Therefore, degrees of freedom of the correlated coefficients were corrected for autocorrelation of the time series using the Prais−Winsten estimation method.

The availability of historical Chinese population data at the province and the county levels (see Section 3.2) provides a unique opportunity to further explore how far population growth dynamics were determined by population pressure in late imperial China. It was also done by multiple regression analysis. It has been demonstrated that the demographic impact produced by subsistence pressure is often characterized by strong regional variation. The impact is more significant in regions with lower human carrying capacity (Zhang et al. 2007a, 2011b, Lee et al. 2008, 2009). Besides, climate and human societies interact over an extensive range of spatial scales. The key explanatory variable of population growth dynamics may change substantially at different spatial scales (Gibson et al. 2000). Taking into account the regional variation of, and the possible influence of spatial scale on, population growth dynamics, spatially disaggregated population panel data and region-specific constraints (fixed-effect) at different geographic levels were used in the multiple regression analysis. In the present study, the study period was determined as the period 1730 to 1910 to make the most of the available data. However, Chinese population data at the province and the county levels were only available for the years 1776, 1820, 1851, 1880, and 1910. Hence, the study period for this part was delimited to the period 1776 to 1910 accordingly.

[10]Tianshan lies to the north and west of the Taklamakan Desert in the border region of Kazakhstan, Kyrgyzstan, and the Xinjiang Uyghur Autonomous Region of western China

[11]The climate−human relationship, which represents the interaction between physical systems and human societies, is a multi-decadal process. It is usually examined in terms of its 40 yr cycle (Zhang et al. 2007a, 2011a, Lee & Zhang 2013)

4. RESULTS

4.1. Population pressure and its association with population checks

The estimated human carrying capacity (in terms of grain output) and per capita grain output are shown in Fig. 2 (see Section 3.5). The human carrying capacity changed in an oscillating manner (Fig. 2a). Total grain output increased from the 1730s to the 1770s, dropped till the 1870s, and then increased again. Gong et al. (1996) estimated that in the cold period of 1840 to 1890, agricultural yields in China were reduced by 10 to 25% compared with the relatively warm period of 1730 to 1770. I found that the total grain output between the periods 1730−1770 and 1840−1890 was reduced by 11.4%, which is close to the lower end of Gong et al.'s (1996) estimation. Besides, the human carrying capacity fluctuated more deeply than population size did, and the drop of human carrying capacity preceded population collapse, implying a possible cause-and-effect relationship between the 2 variables (Zhang et al. 2011b). Per capita grain output (Fig. 2b) shot over 400 kg in individual years in the 1730s. After that, it trended downward. In the period 1730 to 1797, per capita grain output still remained above 300 kg, which is regarded as above average conditions in historical China (see Section 3.5). This coincided with the Kang−Qian Golden Age. Per capita grain output dropped continuously from 300 to 250 kg in 1812 and then 200 kg in 1845. In the period 1812 to 1845, China became overpopulated. In the period 1846 to 1868, per capita grain output dropped below 200 kg, which is the minimum subsistence level indicated by Perkins (1969). Per

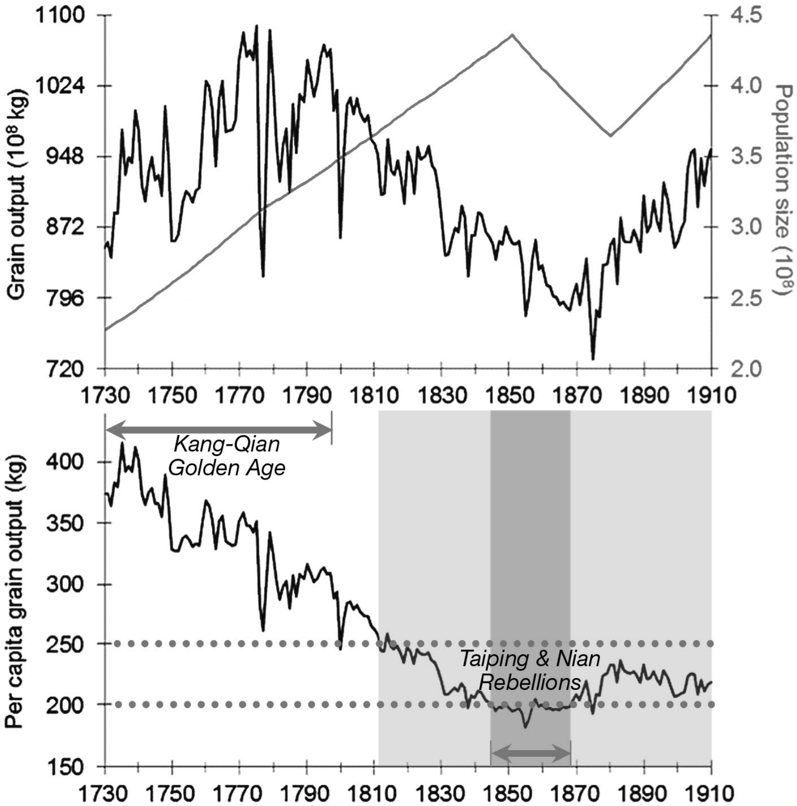

Fig. 2. (a) Grain output (black line) and population size (gray line) and (b) per capita grain output in China, 1730 to 1910. Light gray areas represent overpopulated periods (per capita grain output = 200–250 kg; marked by horizontal dotted lines); the dark gray stripe represents an extremely overpopulated period (per capita grain output < 200 kg), coincident with Taiping & Nian Rebellions (see Section 1). Kang-Qian Golden Age period coincided with per capita grain output >300 kg

capita grain output was reduced by >50 % when compared with the 1730s. China became extremely overpopulated during time. The Taiping Rebellion (1851–1864) and Nian Rebellion (1855–1868) — the 2 incidents with the most catastrophic demographic impacts — occurred in this period. After 1868, population pressure was slightly reduced. Yet, China still remained overpopulated, as per capita grain output only fluctuated within the range 200 to 250 kg.

The association between population pressure and the frequency of population checks was tested by 1-way ANOVA. Table 1 shows that there were significant mean differences of various population checks among the periods with different population pressure ($p < 0.01$ in all cases). To be more specific, when compared with the normal period, the overpopulated and the extremely overpopulated periods were associated with more frequent famine, epidemics, and natural calamities in a statistically significant manner. Yet, the mean differences of the above population checks between the overpopulated and the extremely overpopulated periods were not statistically significant. On the other hand, wars became more frequent only in the extremely overpopulated period in comparison with the normal and the overpopulated periods. The above results indicate that when there was overpopulation in historical China, famine, epidemics, and natural calamities became more frequent immediately. Wars followed only if the population pressure in China had reached an extremely high level.

4.2. Translation of population pressure into population checks and population collapse

Although population checks were found to be inversely correlated with per capita grain output, the relationship is a dynamic one. Fig. 3 shows that when per capita grain output is low (i.e. population pressure is

Table 1. One-way ANOVA of various population checks in China, 1730 to 1910. Annual means are mean number of incidents per period. ***$p < 0.01$

Population check	*F*	df[a]	df[b]	Annual means of population checks: Normal period	Overpopulated period	Extremely overpopulated period
Famine***	12.986	2	178	0.15	0.41[c]	0.61[c]
Epidemics***	6.587	2	178	0.41	0.96[c]	1.26[c]
Wars***	57.386	2	178	0.74	1.09	4.96[c,d]
Natural calamities***	5.908	2	178	0.00	0.13[c]	0.17[c]

[a]Between groups; [b]within groups; [c]significantly higher than that for the group 'normal' (per capita grain output >250 kg) (Tukey's HSD, $p < 0.05$); [d]significantly higher than that for the group 'overpopulated' (per capita grain output: 200 to 250 kg) (Tukey's HSD, $p < 0.05$)

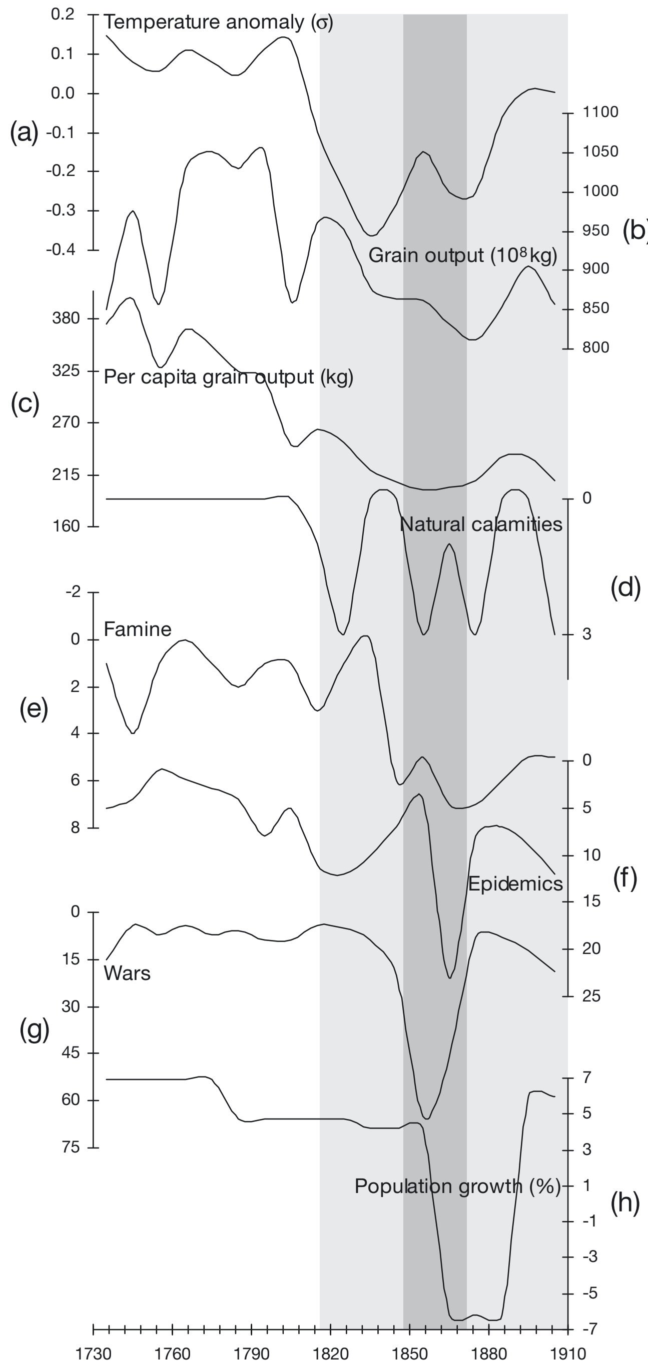

Fig. 3. Comparison of temperature, human carrying capacity, population pressure, population checks, and population growth in China, 1730 to 1910. (a) Temperature anomaly (in σ), (b) grain output, (c) per capita grain output (as a measure of population pressure), (d) number of natural calamities, (e) number of famines, (f) number of epidemics, (g) number of wars, and (h) population growth rate. All time series are in decadal units. The *y*-axes of panels (d) to (g) are inverted so that their negative association with population pressure can be visualized easily. Light gray areas represent overpopulated periods (per capita grain output: 200–250 kg); dark gray area represents an extremely overpopulated period (per capita grain output: <200 kg)

high), population checks become more frequent. Nevertheless, despite the prevalence of population checks, total births outnumber total deaths caused by mortality events at this stage. Hence, population growth rate still remains positive, population size increases, and population pressure accumulates further. When population pressure reaches an extremely high level in which per capita grain output drops below the minimum subsistence level, population checks cause a mortality crisis. In this stage, the number of deaths surpasses the number of births, resulting in a marked reduction in population size. This is a chaotic period. Since population pressure has been largely eliminated by the mortality crisis, population checks decrease afterwards.

I proceeded to examine the mechanism of how subsistence pressure was translated into population checks and eventually population collapse according to the theoretical framework (Fig. 1). The theoretical framework was boiled down to 15 individual causal linkages, and 5 of them were linked to population pressure, which is represented by per capita grain output (Table 2). Their consistency and predictability was verified by multiple regression analysis. Seven regression models were run in total[12]. Statistical results show that the coefficients of determination (R^2) of all regression models were statistically significant ($p < 0.01$ in all cases, see Appendix), while the standardized coefficients (β) of 11 out of the 15 individual causal linkages were statistically significant ($p < 0.5$) and in the expected direction (Table 2). Based on these significant causal linkages, the possible paths through which population pressure was translated into demographic catastrophes were further specified as follows: Temperature and human carrying capacity were strongly and positively correlated. When temperature decreased, human carry capacity shrank accordingly. Apart from increasing population size, climate-induced agricultural shrinkage also elevated population pressure, resulting in more frequent famine, epidemics, and wars. Although the association between natural calamities and population pressure was shown in Section 4.1, when temperature was taken in account, the correlation was no longer significant. As the natural calamities studied here are extreme ones (see Section 3.4.1), climatic factors might be more important than human factors in explaining

[12]In regression models, the independent variables were causal variables, and the dependent variable was the 'effect' variable. For example, in the relationship of temperature → human carrying capacity, temperature is a causal variable, and human carrying capacity is the effect variable. This principle also applies to the relation in which an effect variable is determined by multiple causal variables

Table 2. Standardized coefficient (β) for each of the linkages shown in Fig. 1. The coefficient is derived from the regression models given in the Appendix. A β of 0.046 means that holding all the control variables at their mean, a 10% increase in mean temperature increased human carrying capacity by 4.26%. $^{***}p < 0.01$, $^{**}p < 0.05$

Causal linkage	β
Temperature → Human carrying capacity	0.426***
Human carrying capacity → Population pressure (per capita grain output)	0.393***
Population pressure (per capita grain output) → Famine	–0.180**
Population pressure (per capita grain output) → Epidemics	–0.099**
Population pressure (per capita grain output) → War	–0.200**
Population pressure (per capita grain output) → Natural calamities	0.003
Temperature → Natural calamities	–0.669***
Natural calamities → Famine	0.056
Natural calamities → Epidemics	0.793***
Natural calamities → War	0.057
Famine → Population growth	–0.322***
Epidemics → Population growth	–0.176
War → Population growth	–0.354***
Natural calamities → Population growth	–0.383***
Population size → Per capita grain output	–0.956***

their occurrence. Epidemics were triggered by natural calamities, while famine, wars, and natural calamities were found to be more important than epidemics in checking population growth in late imperial China.

For those nonsignificant causal linkages, the common feature is that the effect variable concerned is determined by multiple factors. For the linkage of population pressure → natural calamities, natural calamities were co-determined by temperature change and population pressure. For the linkages of natural calamities → famine and natural calamities → wars, both famine and wars were co-determined by population pressure and natural calamities. For the linkage of epidemics → population growth, population growth was co-determined by 4 variables: famine, epidemics, wars, and natural calamities. The importance of the causal variable concerned might simply be outweighed by other causal variables in the same regression model (see Appendix).

4.3. Population pressure and population growth dynamics across China at various geographic levels

It has been demonstrated in the previous sections that demographic catastrophes in late imperial China were driven by population pressure. The pressure represents the interaction between physical systems and human societies. Because population pressure is co-determined by exogenous climate-induced agricultural shrinkage and endogenous population growth, I used periodic temperature average[13] and lagged population density[14] as independent variables to further explore how their synergistic work determines population growth dynamics across China at various geographic levels.

Table 3 shows the results from a number of regression models, with province or county as analytical units. I regressed our panel data of provincial population growth percentage on temperature together with lagged population density (Model 1a), and detected a significant positive correlation between temperature and population growth, and a significant negative correlation between lagged population density and population growth. When temperature increased and/or population density decreased, population growth increased. Both relationships move in the expected direction. To control for the effect of spatially varying human carrying capacity on population growth, region-specific constants were added, with estimated standard errors clustered by physiographic zones[15] (Model 1b). The correlation persisted. In addition, the effect of social development on population growth was also controlled by adding calendar year as a time trend (Model 1c), and the correlation persisted.

I replicated the above analysis by using county as analytical units, with estimated standard errors clustered by provinces (Models 2a to 2c). The correlation

[13]To explain population growth in 1851, the temperature average over the period 1820 to 1851 was used

[14]Malthus posited an inevitable cycle of population growth, resource depletion, and rising mortality (positive checks) unless there were effective mechanisms to limit fertility (preventive checks). Population-resource dynamics is envisioned as a self-governing system with feedback loops. However, when population check frequencies reach a certain level, they will lead to an immediate and rapid decline of population size (and also population pressure). Hence, there will be some periods of high frequency of population checks while population pressure is dropping. This leads to a 'paradoxical situation' that disrupts the positive linkage between population size and population checks (Korotayev et al. 2006). To resolve the paradoxical situation, lagged population density (i.e. population density in a previous period) was chosen as an independent variable. For instance, to explain the population growth in 1851, population density in 1820 would be used (see Section 3.2)

[15]According to biophysical characteristics, China is divided into 4 physiographic regions, namely: marginal area, North China, Central China, and South China (cf. Zhang et al. 2005, 2006, Lee et al. 2008, 2009)

Table 3. Synergistic work of temperature and population growth on population growth percentage in China, 1776 to 1910. Results of regression models with province or county as analytical unit are shown. Standard errors of regression coefficients in parentheses. Time trend: calendar year. A β of 0.446 means that holding all the control variables at their mean, a 10% increase in mean temperature increased population growth by 4.46%. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Model	Constant	Temperature	Lagged population density	Fixed effect	Time trend	n	R^2	*F*	β (temperature)	β (lagged population density)
Province										
1a	25.256*** (3.975)	70.648*** (16.233)	−0.061** (0.026)	No	No	72	0.289	13.999***	0.446	−0.242
1b	16.089** (7.136)	68.864*** (16.280)	−0.080*** (0.029)	Yes	No	72	0.319	6.193***	0.435	−0.322
1c	280.554** (113.817)	68.896*** (15.761)	−0.077*** (0.028)	Yes	Yes	72	0.372	6.410***	0.435	−0.308
County										
2a	29.800*** (2.345)	78.975*** (10.704)	−0.055*** (0.012)	No	No	1064	0.074	42.440***	0.219	−0.140
2b	11.704* (6.893)	76.663*** (10.679)	−0.080*** (0.018)	Yes	No	1064	0.106	6.495***	0.213	−0.202
2c	281.489*** (76.916)	76.694*** (10.621)	−0.076*** (0.017)	Yes	Yes	1064	0.116	6.857***	0.213	−0.193

persisted in the expected direction. This shows that the effect of temperature and lagged population density on population growth was robust to various analytical units and region-specific constants in regression analysis. The relationship held no matter whether the analytic units were provinces or counties, and no matter whether the fixed effect was controlled at the physiographic zone or province levels.

Given that population growth can be interpreted in relative (i.e. percentage change) or absolute (i.e. absolute change) terms, the dependent variable 'population growth percentage' was replaced with 'absolute population change', and regression analysis was replicated as shown in Table 3. I continued to find an association between temperature and population change and between lagged population density and population change in the expected direction (Table 4).

The R^2 of all regression models in Tables 3 & 4 was statistically significant ($p < 0.01$ in all cases), indicating that the synergistic work of temperature change and population growth were significant in determining population growth dynamics across China at the province and the county levels. In 10 out of the 12 regression models (i.e. Models 1a to 4a), the β value of temperature was stronger than that of lagged population density. The opposite was only found in the remaining 2 models (i.e. Models 4b and 4c). This shows temperature to be more imperative than lagged population density in driving population growth dynamics.

5. DISCUSSION

Some scholars emphasize that the demographic catastrophes in late imperial China were caused by overpopulation (Ho 1959, Elvin 1973, Chao 1986, Huang 1990), while others disagree (Lee et al. 1994, 2002, Lee & Wang 1999) (see Section 1 in the present paper). Even though the views of the 2 camps are diametrically opposed, they share the same belief with Malthus (1798) in assuming human carrying capacity to be monotonically increasing. At most, only the dampening effect of human-induced ecological degradation on human carrying capacity has been considered, while the adverse effect of climate-induced agricultural shrinkage on human carrying capacity is totally ignored. Most importantly, the verdict of overpopulation (and population checks) is largely based on the fertility regimen of population (low fertility or the prevalence of fertility control measures implies the non-existence of overpopulation).

The fundamental hypothesis of the present study is that population is limited by subsistence, and population checks will come into operation when population size exceeds the subsistence level (i.e. per capita grain output drops below average subsistence level) (see Section 2).

Table 4. Synergistic work of temperature and population growth on absolute population change in China, 1776–1910. Results of regression models with province or county as analytical unit are shown. Standard errors of regression coefficients in parentheses. Time trend: calendar year. A β of 0.362 means that holding all the control variables at their mean, a 10% increase in mean temperature increased population size by 3.62%. ***p < 0.01, **p < 0.05, *p < 0.1

Model	Constant	Temperature	Lagged population density	Fixed effect	Time trend	n	R^2	*F*	β (temperature)	β (lagged population density)
Province										
3a	411.843*** (95.998)	1289.849*** (392.002)	−1.033* (0.619)	No	No	72	0.183	7.737***	0.362	−0.183
3b	119.475 (168.395)	1233.979*** (384.191)	−1.655** (0.684)	Yes	No	72	0.254	4.487***	0.346	−0.294
3c	4968.763* (2729.915)	1234.570*** (378.035)	−1.590** (0.674)	Yes	Yes	72	0.288	4.390***	0.346	−0.282
County										
4a	27.781*** (2.341)	87.433*** (10.689)	−0.064*** (0.012)	No	No	1064	0.092	53.855***	0.241	−0.162
4b	−2.172 (6.650)	80.782*** (10.302)	−0.134*** (0.017)	Yes	No	1064	0.182	12.188***	0.222	−0.338
4c	317.815*** (73.979)	80.820*** (10.215)	−0.130*** (0.017)	Yes	Yes	1064	0.196	12.720***	0.222	−0.328

This notion has a Malthusian flavor. However, the present study has shown that, given the technological limitations of agricultural production in historical China, long-term climate change has a significant impact on food supplies, and that a monotonic increase in human carrying capacity was not the case, at least in the pre-industrial era. It can be seen in Fig. 2a that human carrying capacity changed in an oscillating manner in late imperial China (see Section 4.1). The upward trend of human carrying capacity is, in fact, characterized by shorter-term recurring oscillations, in accordance with the alternation of cold and warm climate (Zhang et al. 2007a, 2011a, 2011b, Lee et al. 2008, 2009, Lee & Zhang 2010, 2013). On the other hand, in agrarian societies, population expands to the human carrying capacity (demographic saturation). Population pressure will aggregate, and the population will proceed to the state of 'hungry homeostasis' over time (Wrigley 1973, Li 1998, Wood 1998, Fagan 2000, Nefedov 2003). This also reduces the natural buffering capacity that would provide for societal resilience (e.g. tracts of non-cultivated arable land) and renders the population vulnerable to any shocks in food supplies. Such circumstances interact with the climate-induced decline of human carrying capacity to produce a demographic collapse via famine, epidemics, wars, and natural calamities (see Section 4.2). Briefly, overpopulation and the associated population checks were driven by the synthesis of climate change and population growth. The synthesis also determined the population growth dynamics across China at both the province and the county levels (see Section 4.3).

Ever since Malthus (1798), it has been conventional wisdom to cast the Chinese and European pre-industrial demographic systems as opposing archetypes—Europe as a model of demographic restraint and China as demographic profligate. Europe's moderate population growth, fertility control keyed to economic conditions, and favorable living standards are contrasted with China's rapid growth, periodic mortality crises, and precarious balance of population and resources (Lavely & Wong 1998). The work of some historical demographers (Lee et al. 1994, 2002, Lee & Wang 1999) has been reshaping our thinking about demographic behavior in late imperial China. They systematically demonstrate that the demographic behavior in historical China and Europe was not in a simple binary opposition as depicted by Malthus (1798). I agree with this point. Nonetheless, their mythology of overpopulation in historical China should be treated with caution. It is worth mentioning that overpopulation is a relative concept concomitantly determined by population size and human carrying capacity. It results not from the absolute numbers being too large, but from too-high population density in relation to carrying capacity. Even if Chinese families were found to constantly adjust their demographic behavior according to their economic and social circumstances and expectations, the possibility of overpopulation still cannot be refuted with certainty because the fluctuating human carrying capacity caused by long-term climate change, which is emphasized in the present study, might have offset the deliberate societal effort in preventing the precarious balance of population and resources[16]. In fact, Malthus (1798) is insightful in pointing out that the root cause of demographic tragedies is the ecological imbalance between population size and human carrying capacity, which is attributable to divergent rates of population growth and subsistence increase. Although his work does not address the details of demographic behavior in historical China 200 yr ago, this does not imply that overpopulation did not happen in late imperial China.

Human beings are not the inanimate recipients of food strain. It is not doubted that innumerable factors of a social, cultural, and political nature intervene in many situations to surmount or overcome the strain. Nevertheless, as demonstrated in this and my previous studies (Lee & Zhang 2010, 2013), even though historical China was one of the most complex agrarian societies in the world, there was still profound demographic impact caused by the food strain which was generated by the synthesis of climate change and population growth in the long term. The same also happened to many other pre-industrial societies in Europe and the Northern Hemisphere (Zhang et al. 2011a, 2011b). This suggests the need to reconsider the role of food strain in determining the course of demographic history.

It is generally believed that global warming is a threat to human societies in many ways (IPCC 2007), while the present study shows that agricultural production in late imperial China was dampened by a cold climate, which concurs with Zhang et al. (2010). People may think that the results of the present study are a plea to accelerate and welcome global warming, similar to scholars such as Hsu (1998), who indicates that global warming has been on the whole a blessing to humankind. However, it must be emphasized that the warmth, especially after the late 20th century, is an anomalous and unprecedented event in the last millennia (Mann & Jones 2003, Moberg et al. 2005). Since both natural and anthropogenic forcing has been engaged, global temperature is expected to rise faster and faster in the foreseeable future (Andronova et al. 2004). Its impacts will be rather unpredictable. On the other hand, the possibility of a cold climate cannot be totally ignored (Engvild 2003). Climatic cooling might have been the driving force in causing high frequencies of meteorological and agricultural disasters and then wars in historical China (Zhang et al. 2009, 2010). Whether contemporary societies have sufficient buffering mechanisms to cope with climate-induced agricultural and demographic consequences should be systematically investigated.

6. CONCLUSIONS

There exists a limitation in this study. In China, cold temperature is often associated with monsoon failure. In cold phases, cold and arid winter monsoon is more influential; in mild phases, China is dominated by warm and humid summer monsoon (An 2000). Consequently, climate in China alternates between cold–dry and warm–wet. Precipitation may overwhelm temperature in affecting human carrying capacity in regional settings. However, the regional variability of precipitation is much more variable and complex than that of temperature. To date, there is not any published high-resolution China-wide paleo-precipitation record. Hence, the effect of precipitation change upon human carrying capacity for the whole of China and its associated demographic impact cannot be estimated at present.

To conclude, overpopulation in late imperial China is not a myth, and the series of population checks and eventually population collapse were caused by subsistence pressure during the period. This is the first study utilizing empirical data and statistical methods to estimate population pressure quantitatively and prove its association with demographic catastrophes in historical China. It does not imply that every population check is caused by subsistence pressure. But, taking the whole of China as an aggregate, subsistence pressure has been verified as a significant factor in increasing the overall probability of population check outbreak in the pre-industrial period. The concept of a population-driven human system is prevalent among social scientists, demographers, and economists (Lee & Anderson 2002, Turchin 2003), but ignoring

[16] Based on empirical data, we found that the subsistence level fluctuated more rapidly and deeply than population size did in pre-industrial Europe, and that subsistence shrinkage brought by cooling since the late 16th century preceded the population collapse in the mid-17th century (Zhang et al. 2007a, 2011a). This implies that humans could not adjust their population size to the changing human carrying capacity efficiently and effectively in the pre-industrial era

the impact of climate forces on human systems may lead to false conclusions. It is suggested that the adverse effect of climate-induced agricultural shrinkage on human carrying capacity should not be overlooked when explaining historical Chinese demography.

Acknowledgements. This research was supported by the Hui Oi-Chow Trust Fund (201205172003 and 201302172003), HKU Seed Funding Programme for Basic Research (201109159014), and Research Grants Council of The Government of the Hong Kong Special Administrative Region of the People's Republic of China (HKU745113H and HKU758712H). Last but not least, a special thanks to Prof. Mauricio Lima and the reviewers for their valuable comments on the manuscript.

LITERATURE CITED

An ZS (2000) The history and variability of the East Asian paleomonsoon climate. Quat Sci Rev 19:171–187

Andronova NG, Schlesinger ME, Mann ME (2004) Are reconstructed pre-instrumental hemispheric temperatures consistent with instrumental hemispheric temperatures? Geophys Res Lett 31:L12202, doi: 10.1029/2004GL019658

Butler CD (2004) Human carrying capacity and human health. PLoS Med 1:e55

Cao S (2000) History of Chinese population — Qing period. Fudan University Press, Shanghai

Chao K (1986) Man and land in Chinese history: an economic analysis. Stanford University Press, Stanford, CA

Chen Y, Gao J (1984) Time characteristics of great climatic disasters of died people over ten thousand in Chinese history. Discovery of Nature:157–166

De Vaus DA (2002) Analyzing social science data. SAGE, London

Editorial Committee of Chinese Military History (1985) Zhongguo Junshishi, Vol II. Jiefangjun Chubanshe, Beijing

Elvin M (1973) The pattern of the Chinese past. Eyre Methuen, London

Engvild KC (2003) A review of the risks of sudden global cooling and its effects on agriculture. Agric For Meteorol 115:127–137

Fagan B (2000) The Little Ice Age: how climate made history 1300-1850. Basic Books, New York, NY

Fang JQ, Liu G (1992) Relationship between climatic change and the nomadic southward migrations in eastern Asia during historical times. Clim Change 22:151–169

Galloway PR (1986) Long-term fluctuations in climate and population in the preindustrial era. Popul Dev Rev 12: 1–24

Gao W (1997) Zhongguo Ziran Zaihaishi (Zonglun). Dizhen Chubanshe, Beijing (in Chinese)

Gibson CC, Ostrom E, Ahn TK (2000) The concept of scale and the human dimensions of global change: a survey. Ecol Econ 32:217–239

Gong G, Ge Q, Xu K (1996) Qihou bianhua dui nongye de yingxiang. In: Zhang P (ed) Zhongguo Lishi Qihou Bianhua. Shandong Kexue Jishu Chubanshe, Jinan, p 406–425 (in Chinese)

Gribbin J (1978) Climatic change. Cambridge University Press, Cambridge

Ho PT (1959) Studies on the population of China, 1368-1953. Harvard University Press, Cambridge, MA

Hsu KJ (1998) Sun, climate, hunger, and mass migration. Sci China D Earth Sci 41:449–472

Huang PCC (1990) The peasant family and rural development in the Yangzi Delta, 1350-1988. Stanford University Press, Stanford, CA

Huang PCC (2002) Development or involution in eighteenth-century Britain and China? A review of Kenneth Pomeranz's "The great divergence: China, Europe, and the making of the modern world economy". J Asian Stud 61:501–538

Institute of History, Chinese Academy of Social Sciences (1988) Zhongguo Lidai Ziran Zaihai ji Lidai Shengshi Nongye Zhengce Ziliao. Nongye, Beijing

IPCC (Intergovernmental Panel on Climate Change) (2007) Climate change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Jiang T (1993) Zhongguo Jindai Renkou Shi. Hangzhou University Press, Hangzhou

Korotayev AV, Malkov AS, Khaltourina DA (2006) Secular cycles and millennial trends. In: Korotayev AV, Malkov AS, Khaltourina DA (eds) Introduction to social macrodynamics: secular cycles and millennial trends. Editorial URSS, Moscow, p 95–133

Lavely W, Wong RB (1998) Revising the Malthusian narrative: the comparative study of population dynamics in late imperial China. J Asian Stud 57:714–748

Lee R, Anderson M (2002) Malthus in state space: macro economic-demographic relations in English history, 1540 to 1870. J Popul Econ 15:195–220

Lee JZ, Wang F (1999) One quarter of humanity: Malthusian mythology and Chinese realities, 1700-2000. Harvard University Press, Cambridge, MA

Lee HF, Zhang DD (2010) Changes in climate and secular population cycles in China, 1000 CE to 1911. Clim Res 42:235–246

Lee HF, Zhang DD (2013) A tale of two population crises in recent Chinese history. Clim Change 116:285–308

Lee J, Wang F, Cameron C (1994) Infant and child-mortality among the Qing nobility: implications for 2 types of positive check. Popul Stud 48:395–411

Lee J, Cameron C, Wang F (2002) Positive check or Chinese checks? J Asian Stud 61:591–607

Lee HF, Fok L, Zhang DD (2008) Climatic change and Chinese population growth dynamics over the last millennium. Clim Change 88:131–156

Lee HF, Zhang DD, Fok L (2009) Temperature, aridity thresholds, and population growth dynamics in China over the last millennium. Clim Res 39:131–147

Li W (1957) Zhongguo Jindai Nongyeshi Ziliao, Vol 1. Sanlian Shudian, Beijing (in Chinese)

Li X (1998) Renkou dongtai pingheng de lishi fenxi. J Hist Sci:110–117 (in Chinese)

Long G (1989) Neiyou waihuan yu qihou bianqian. Geographical Knowledge:24–25 (in Chinese)

Malthus TR (1798) An essay on the principle of population. J. Johnson, London

Mann ME, Jones PD (2003) Global surface temperatures over the past two millennia. Geophys Res Lett 30:1820, doi:10.1029/2003GL017814

Moberg A, Sonechkin DM, Holmgren K, Datsenko NM, Karlén W (2005) Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433:613–617

Nefedov SA (2003) A theory of demographic cycles and the social evolution of ancient and medieval oriental societies. Vostok-Oriens 3:5–22

Nelson RR (1956) A theory of the low-level equilibrium trap in underdeveloped economies. Am Econ Rev 46: 894–908

Perkins DH (1969) Agricultural development in China, 1368-1968. Aldine, Chicago, IL

Pomeranz K (2000) The great divergence: Europe, China, and the making of the modern world economy. Princeton University Press, Princeton, NJ

Pomeranz K (2002) Beyond the east-west binary: resituating development paths in the eighteenth-century world. J Asian Stud 61:539–590

Sun G (2004) Research of dispersed in time and space untal regularity of Chinese historical big pestilence. Areal Res Dev 23:123–128 (in Chinese; English abstract)

Tan M, Liu TS, Hou JZ, Qin XG, Zhang HC, Li TY (2003) Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature. Geophys Res Lett 30:1617

Turchin P (2003) Historical dynamics. Princeton University Press, Princeton, NJ

Wang SW, Gong DY, Zhu JH (2001) Twentieth-century climatic warming in China in the context of the Holocene. Holocene 11:313–321

Wood JW (1998) A theory of preindustrial population dynamics: demography, economy, and well-being in Malthusian systems. Curr Anthropol 39:99–135

Wrigley EA (1973) Population and history. Weidenfeld and Nicolson, London

Yang B, Braeuning A, Johnson KR, Shi Y (2002) General characteristics of temperature variation in China during the last two millennia. Geophys Res Lett 29:1324, doi:10.1029/2003GL017352

Zhang D, Jim CY, Lin CS, He YQ, Lee F (2005) Climate change, social unrest and dynastic transition in ancient China. Chin Sci Bull 50:137–144

Zhang DD, Jim CY, Lin GCS, He YQ, Wang JJ, Lee HF (2006) Climatic change, wars and dynastic cycles in China over the last millennium. Clim Change 76:459–477

Zhang DD, Brecke P, Lee HF, He YQ, Zhang J (2007a) Global climate change, war, and population decline in recent human history. Proc Natl Acad Sci USA 104: 19214–19219

Zhang DD, Zhang J, Lee HF, He YQ (2007b) Climate change and war frequency in Eastern China over the last millennium. Hum Ecol 35:403–414

Zhang Z, Cazelles B, Tian H, Stige LC, Bräuning A, Stenseth NC (2009) Periodic temperature-associated drought/flood drives locust plagues in China. Proc R Soc Lond B Biol Sci 276:823–831

Zhang Z, Tian H, Cazelles B, Kausrud KL, Bräuning A, Guo F, Stenseth NC (2010) Periodic climate cooling enhanced natural disasters and wars in China during AD 10-1900. Proc R Soc Lond B Biol Sci 277: 3745–3753

Zhang DD, Lee HF, Wang C, Li B, Pei Q, Zhang J, An Y (2011a) The causality analysis of climate change and large-scale human crisis. Proc Natl Acad Sci USA 108: 17296–17301

Zhang DD, Lee HF, Wang C, Li B, Zhang J, Pei Q, Chen J (2011b) Climate change and large scale human population collapses in the pre-industrial era. Glob Ecol Biogeogr 20:520–531

Zhao G, Liu Y, Wu W, Chu J, Chen C, Chen Q (1995) Qingdai Liangshi Muchanliang Yanjiu. Zhongguo Nongye Chubanshe, Beijing (in Chinese)

Appendix. Regression of dependent on independent variables (n = 181 in all cases). Population pressure here means per capita grain output. Regressions are corrected for the first-order autoregressive disturbances using the Prais–Winsten estimation method. R^2 is calculated for the untransformed variables. Standard errors in parentheses. –: not applicable. ***$p < 0.01$, **$p < 0.05$

Model no.	Dependent variable	Constant	Temperature	Human carrying capacity	Population size	Population pressure	Natural calamities	Famine	Epidemics	Wars	R^2	*F*
A1	Human carrying capacity	870.990*** (39.959)	145.484*** (23.175)	–	–	–	–	–	–	–	0.361	100.947***
A2	Population pressure	364.744*** (10.454)	–	0.208*** (0.011)	−79.640*** (1.683)	–		–	–	–	0.992	11630.082***
A3	Natural calamities	0.069 (0.069)	−0.389*** (0.036)	–	–	0.000 (0.000)		–	–	–	0.745	259.625***
A4	Famine	0.679*** (0.183)	–	–	–	−0.001** (0.001)	0.132 (0.179)	–	–	–	0.478	81.598***
A5	Epidemics	0.735*** (0.182)	–	–	–	−0.001** (0.001)	3.590*** (0.200)	–	–	–	0.888	703.870***
A6	Wars	4.883*** (1.402)	–	–	–	−0.012** (0.005)	1.353 (1.843)	–	–	–	0.250	29.687***
A7	Population growth	11.371*** (0.745)	–	–	–	–	−20.678*** (5.585)	−7.233*** (1.561)	−2.091 (1.428)	−0.802*** (0.106)	0.781	157.288***

Editorial responsibility: Mauricio Lima, Santiago, Chile

Submitted: September 19, 2013; Accepted: December 13, 2014
Proofs received from author(s): April 9, 2014