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Changes in climate and secular population cycles in China, 1000 CE to 1911

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ABSTRACT: Many studies of secular population cycles in historical China conclude that when population is large — relative to the land's carrying capacity — further population increase can lead to mortality crises through war, famine and epidemics, resulting in subsequent population decline. In these studies, population cycles are thought to be driven primarily by population growth. Nevertheless, some scholars have noted a strong correlation between deteriorating climate, dynastic change, and population collapse in historical China. They suggest climate forcing as the underlying driver of population cycles, but quantitative evidence has been lacking to date. In the present study, we employed high resolution temperature data, reports on mortality events, and population datasets to quantitatively examine the extent to which climate change was responsible for Chinese population cycles. Results show that there were 5 major population contractions in China between 1000 CE and 1911, and all of them occurred in periods with a cold climate, when mortality crises triggered population collapses. Nevertheless, the climate–population association is non-linear, because it is mediated by population pressure. Although social buffers were increasingly effective in dissipating climate forcing, they could not prevent population collapses from occurring during periods of long-term cooling. Our results challenge classic Malthusian and post-Malthusian interpretations of historical Chinese population cycles.

KEY WORDS: Climate change · Land carrying capacity · Population pressure · Mortality · Human population cycles · China

1. INTRODUCTION

The presence of recurrent secular population cycles (at multi-decadal to centennial scales) in historical agrarian China has long been known. Population declines tended to occur at intervals of 100 to 300 years, and they often occurred in periods of historical downturn marked by internecine wars that had been triggered by famine (Chu & Lee 1994). The Late Yuan and Late Ming dynasties, and the Taiping Rebellions, are typical examples. Given that these cycles are evidence of a system (Hall & Turchin 2007), what cause set in motion the population cycles in historical agrarian China?

Scholars have suggested various explanations: the inability (personal misconduct, mismanagement) of the 'bad-last ruler' of a dynasty (Wright 1965, Zhao 1994); the co-evolution between agricultural and steppe societies along their frontiers (Lattimore 1988); the growth and decline of key economic areas (Chi 1963); the struggle between private interest in land rent and state interest in land tax (Wang 1936); the fiscal distress of internal social institutions (Reischauer 1965, Huang 1988); the random outbreak of exogenous large-scale warfare (Chao 1986). 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 Chinese population cycles is the periodic overshooting of Malthusian limits on population size. As stated by Malthus (1798), when the population increases beyond the means of subsistence, food prices increase, real wages decline, and per capita consumption drops (especially among the poorer social strata). 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)

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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. In line with this theory, many studies of Chinese socio-political and population cycles conclude that when population was large relative to land carrying capacity, further population increase would lead to political instability. At that point, internecine warfare would break out, eventually causing population decline and dynastic collapse. Scholars therefore often conclude that population growth is the primary factor causing population size to oscillate (Chen 1946, Usher 1989, Chu & Lee 1994, Zhou 1997, Turchin 2003, Wu 2003, Turchin 2005, Xiao 2005).

In contrast, several scholars have noted a strong coincidence between historical Chinese climatic, dynastic, and population cycles. In short, the heydays of dynasties and rapid population growth coincided with favorable climate, and vice versa (Long 1989, Liu 1994, Pan 1994, Wang 1996, Li 1999, Zhang 1999, Tang & Tang 2000, 2002, Jiang et al. 2004, Lan & Jiang 2005). Their consensus suggests that instead of population growth, climate change is more imperative in driving population cycles in China. Nevertheless, the perceived climate–population linkage remains controversial, because related studies of the topic are either qualitative or based on individual incidents. To date, there was no compelling scientific evidence to confirm the linkage.

To address this controversy, we quantitatively verified the climate–population relationship described in qualitative studies (Lee et al. 2008, 2009). Using logistic models and spatial statistics, we systematically demonstrated that long-term cooling significantly shrank the carrying capacity of agrarian China, resulting in below average population growth and southward shifts of the population, and that the reverse scenario was also true. Our preliminary results provided strong evidence for the climate–population relationship in historical China, and demonstrated that temperature was more influential than aridity threshold in explaining fluctuations in population size and shifts in population distribution (Lee et al. 2008, 2009). In the present study, we further explore the climate–population relationship via an empirical approach. Our basic premise is: Given that the alternating growth and decline in historical Chinese (Zhao & Xie 1988, Jiang 1993) — and in early modern populations elsewhere (McEvedy & Jones 1978, Goldstone 1991) — was primarily determined by mortality crises, and if the empirically observed mortality factors in historical agrarian China were significantly related to temperature change (i.e. mortality events became more frequent in a cold climate), then we could postulate temperature change to be an important factor in driving historical Chinese population cycles.

Our focus is on the linkage from temperature change to mortality events to population cycles in agrarian China. Because the goal in this research was to consider whether temperature change drives secular population cycles at the macro-historical level, the aforementioned linkage was addressed in a broad sense, with little attention to individual incidents. As this research requires fine-grained temperature, mortality, and population data, we encountered a major methodological difficulty: much less is known about the early history of China than its more recent history, and documentary evidence is considerably reduced for the early period. Furthermore, records from earlier periods are more fragmentary than from recent centuries. Consequently, the study period has been restricted to the past millennium (1000 to 1911).

2. THEORETICAL FRAMEWORK

To facilitate our research, we posit the following:

(1) The linkage between temperature change and population growth shows up through fluctuations in agricultural production (Lee et al. 2008, Lee et al. 2009). Cooling shortens the crop growing season and reduces farmland area (Galloway 1986). Both of these are detrimental to land 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.

(2) Population pressure is co-determined by land carrying capacity and population growth. In the pre-industrial era, the speed of human innovation and its diffusion were not fast 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 land 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). The synergy of low temperatures and increased population pressure also intensifies reclama-

tion activities on agriculturally marginal lands, which invites more frequent natural calamities such as floods or drought (Ho 1959, Jiang 1993).

(5) When the productive potential of the state was weakened by long-term cooling and destroyed by ensuing civil wars, this reduced its resistance to, or 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 or even pandemics (Zhang et al. 2007a).

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

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

(9) This 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. The reciprocal interactions among the variables along the pathways generate the secular cycles, which are embedded within the particular environmental conditions, cultural history, and socio-economic context of historical agrarian China.

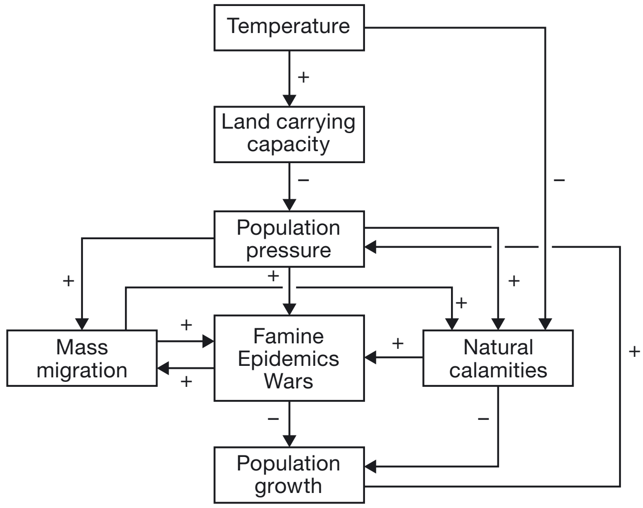

Fig. 1. Simplified pathways for long-term climate change and population growth in historical China. The arrows may be read as follows: 'Change in X are associated with change in Y'. The sign indicates whether the association is positive or negative

3. DATA

The recent advancement in paleoclimate reconstructions and an abundance of historical Chinese documents provided a good foundation for analysing the climate–population relationship. The following data were used:

3.1. Paleotemperature

Briffa & Osborn (2002) chose the 5 representative climate series of the last millennium in the Northern Hemisphere (Jones et al. 1998, Mann et al. 1999, Briffa 2000, Crowley & Lowery 2000, Esper et al. 2002), including the data from China, to discuss differences between the records of various independent paleotemperature studies. These series were reconstructed using multi-proxy data, including tree ring, coral, ice core and borehole studies, as well as historical documents. In addition, each of the series was recalibrated by linear regression against the 1881–1960 mean annual temperature observations averaged over the land area north of 20° N, and smoothed with a 50 yr filter. The 5 recalibrated temperature anomaly series were arithmetically averaged to give the Northern Hemispheric temperature anomaly series (in °C, from the 1961–1990 mean) (Fig. 2a). Although there are some recent China-wide temperature reconstructions with a millennium year length of record (Wang et al. 2001, Yang et al. 2002), they did not reach the annual scale that is required by this research. Given that the major long-term cooling events revealed by the temperature reconstructions of China and the Northern Hemisphere were basically synchronous in the past millennium, Briffa & Osborn's (2002) 'averaged' Northern Hemisphere temperature anomaly series was chosen as the standard paleotemperature record to quantitatively delineate the cold and warm phases in this study.

In reference to Zhang et al. (2005, 2006, 2007b), the boundaries of the warm and cold phases were delineated at the mean temperature point between minimum and maximum values of 2 contiguous phases on Briffa & Osborn's (2002) averaged series. A cold or warm phase would be determined if the average temperature change had an amplitude exceeding 0.14°C, in order to obtain an equal aggregate duration of cold and warm periods. Based on the averaged series, 6 major cycles of warm and cold phases were identified between 1000 and 1911 (Table 1). These phases were also reflected in other climatic reconstructions for

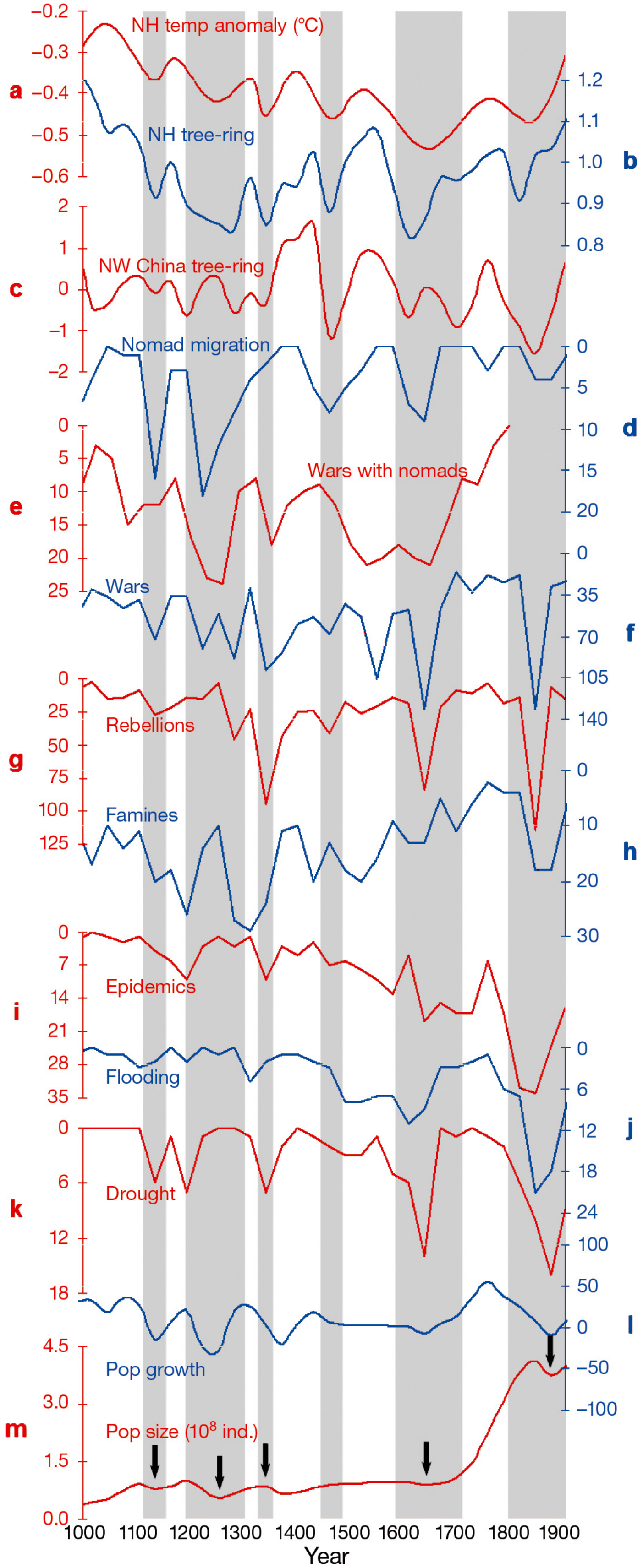

Fig. 2. Comparisons of temperature change, tree-ring width, nomad migration, mortality factors, and population growth dynamics in China, 1000–1911. Gray: cold phases; arrows: population collapses. (a) Phase average of the temperature anomaly (°C) over the land area north of 20° N (Briffa & Osborn 2002). (b) Regional Curve Standardization Chronology of the Northern Hemisphere extra-tropical tree-ring widths (Esper et al. 2002). (c) Arithmetically averaged series of ring width in *Sabina przewalskii* on Qilian Mountain (Liu et al. 2004) and *Pinus sibirica* at Solongotyn Davaa in Mongolia (D'Arrigo et al. 2001); (b) and (c) are taken as a proxies for agricultural production in China. (d) Number of years (per 30 yr period) with records of nomad migration (Ge et al. 1997). (e) Frequency of wars between Chinese and nomad polities along 110° E longitude (Fang & Liu 1992). (f) Total number of wars (Zhongguo Junshishi Bianxiezu 1985). (g) Total number of rebellions (Zhongguo Junshishi Bianxiezu 1985). (h) Number of years with great famines (Zhongguo Shehui Kexueyuan Lishi Yanjiusuo Ziliao Bianzuanzu 1988). (i) Number of great epidemics (Sun 2004). (j) Number of flooding incidents with >1000 fatalities (Gao 1997). (k) Number of drought incidents with >1000 fatalities (Gao 1997). (l) Population growth rate (%) in China (Zhao & Xie 1988). (m) Population size (in 100 million) in China (Zhao & Xie 1988). Time series are with 30 yr resolution, except for the phase average of the Northern Hemisphere temperature anomaly (Panel a), the resolution of which is irregular because the data are based on phase averages (see Table 1); *y*-axes of panels (d) to (k) are inverted to visualize their negative association with temperature change

China and the Northern Hemisphere (e.g. Ge et al. 2003, Mann & Jones 2003). The aggregate duration of the cold phases was 459 yr and that of the warm phases was 453 yr.

3.2. Agricultural production

The effect of cooling on population growth is based on the change in agricultural production (Fig. 1). Historical agricultural production data are sketchy, however, and restricted to recent time spans; therefore, the linkage of temperature–agriculture–population in earlier periods cannot be assessed directly. Given the limited technology in agrarian China, climate change will have had a substantial impact on agricultural production, and differences between agricultural productivity and natural biological productivity will not have been very great. Therefore, tree-ring growth can serve as a proxy for agricultural production. We chose 2 tree-ring series: (1) Regional Curve Standardization Chronology of the Northern Hemisphere extra-tropical tree-ring widths, derived from selected tree-ring chronologies at 14 sites (including China) in the Northern Hemisphere extra-tropics (Esper et al. 2002) (Fig. 2b). (2) The arithmetically averaged series of *Sabina przewalskii* in Qilian Mountain (Liu et al. 2004) and *Pinus sibirica* Du Tour at Solongotyn Davaa in Mongolia (D'Arrigo et al. 2001), both normalized prior to averaging (Fig. 2c).

Table 1. Climate phases in China, 1000–1911. Anomaly: deviation of mean temperature from the 1961–1990 mean

Phase	Years (CE)	Duration (yr)	Anomaly (°C)
Warm	1000–1109	110	–0.252
Cold	1110–1152	43	–0.368
Warm	1153–1193	41	–0.315
Cold	1194–1302	109	–0.419
Warm	1303–1333	31	–0.362
Cold	1334–1359	26	–0.454
Warm	1360–1447	88	–0.345
Cold	1448–1487	40	–0.461
Warm	1488–1582	95	–0.392
Cold	1583–1717	135	–0.534
Warm	1718–1805	88	–0.413
Cold	1806–1911	106	–0.456

3.3. Nomad migrations

These data were obtained from the chronological table of migrations in China compiled by Ge et al. (1997). The chronological table records important migration events in China over the period 2000 BCE–1949 CE. Over the period 1000–1911, there were 121 years with records of nomad migration (Fig. 2d).

3.4. Mortality factors

Wars, rebellions, and nomad invasions: A group of researchers from the Nanjing Academy of Military Sciences has compiled a multi-volume compendium which scrupulously records the wars that took place in China from 800 BCE to 1911 CE (Zhongguo Junshishi Bianxiezu 1985). There were 1679 wars during the period 1000–1911 (Fig. 2f), including 682 rebellions (Fig. 2g) and 438 nomad invasions. In addition, data on wars with nomads (i.e. wars between Chinese and nomad polities along the 110° E longitude) (Fig. 2e), compiled by Fang & Liu (1992), were used to supplement the data on nomad invasions. However, Fang & Liu's (1992) data are presented only in 30 yr units.

Famine: Data were obtained from the chronological table of natural hazards from 205 BCE to 1911 CE compiled by Zhongguo Shehui Kexueyuan Lishi Yanjiusuo Ziliao Bianzuanzu (1988); only those events that were classified as great famines in the original data source have been included in the chronological table. There were 437 famine years during 1000–1911 (Fig. 2h).

Epidemics: This dataset 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. There were 298 epidemics over 1000–1911 (Fig. 2i).

Flood and drought disasters: Gao (1997) documents flood and drought disasters in China from 180 BCE to 1983 CE with >1000 casualties, stating the date, location, and loss of life for each incident. In the present study, those data were transformed to number of provinces affected by flooding/drought disasters in a year. There were 143 flooding (Fig. 2j) and 104 drought incidents (Fig. 2k), respectively, in the period 1000–1911.

3.5. Population size and growth rate

Population size data were retrieved from Zhao & Xie's (1988) estimate of historical Chinese population size (Fig. 2m). Their estimate is judged to be the most reliable, and it has been used by other scholars (Chu & Lee 1994, Zhang & Li 1999, Turchin 2003, 2005, 2006). Zhao & Xie (1988) give 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 (Fig. 2l) was calculated by the following formula:

$$\frac{P_t - P_{t-1}}{P_{t-1}} \times 100 \qquad (1)$$

where P is population size, and t represents time step (yr).

4. RESULTS

Fluctuations in the various time series were basically synchronous (Fig. 2; note inverted y-axes in Fig. 2e–k). Mortality events peaked during cold phases (shaded). The linkage is likely to be as follows (see Fig. 1): climate cooling affected agricultural production (see Zhang et al. 2006, 2007b, Lee et al. 2008, 2009 for empirical examples), and various mortality events ensued; 5 of the 6 cold phases were correlated with population contractions, with a reduction ranging from 11.4 to 49.4 % of the total population size.

4.1. Mortality events in cold and warm phases

The association between climate change and mortality events was analyzed by 2 methods: (1) Calculation of the ratios of the annual mean of mortality crises between cold and warm periods (cold phase mean divided by warm phase mean of mortality events per factor); a ratio >1 means that the mortality factor is more prevalent in a cold climate. (2) We applied 1-way

ANOVA to test the association between climate change and the frequency of mortality events. Values of −1 and +1 were assigned to cold and warm phases, respectively (see Section 3.1 for the delineation of cold and warm phases). Then, the climatic phase was chosen as independent ANOVA factor, while the frequency of each type of mortality event was entered as a dependent ANOVA factor (Table 2).

All of the cold/warm ratios of the various mortality factors were >1, which means there were more mortality events in a period of cold climate than in a warm climate. The cold/warm ratios of rebellions, epidemics, and flooding were >2. For nomad migrations, the ratio was 4.2, and for drought 5.5, which suggests that their occurrence was strongly related to cooling. Cooling was significantly associated with more nomad migration and more frequent occurrence of mortality events, such as war with nomads, rebellions, total number of wars, epidemics, flooding, and drought ($p \leq 0.01$ in all cases). However, nomad invasions and famine were not significantly related to cooling, even though their cold/warm ratios were >1.

Historical records are usually incomplete for earlier periods, and in the present study this may distort the accuracy of the statistical results. To verify this issue, 1-way ANOVA was carried out for 2 sub-periods of roughly equal length, namely 1000–1459 (460 yr) and 1460–1911 (452 yr). Cold/warm ratios of all mortality factors were >1, except for nomad invasions in 1460–1911. Again, the ratios were the highest for nomad migrations and drought. ANOVA results for both sub-periods were basically the same as for the overall period, but some of the findings are worth noting in greater detail.

Nomad invasions were not significant in ANOVA results for the overall period. However, when the study period was divided, invasions were more frequent in phases of cold climate in 1000–1449, and of warm cli-

Table 2. 1-way ANOVA of nomad migrations and mortality factors in China. Data are annual means for the corresponding period. Factors are defined in Fig. 2 caption. Significant p-values in **bold**

Period Factor	Overall	Cold period	Warm period	Cold/warm ratio	F	df[a]	df[b]	p
Overall (1000–1911)								
Nomad migrations	0.133	0.214	0.051	4.20	55.550	1	910	**<0.001**
War with nomads	12.9	16.2	10.1	1.60	7.814	1	26	**0.010**
Nomad invasions	0.48	0.51	0.45	1.15	1.450	1	910	0.229
Rebellions	0.75	1.03	0.46	2.25	35.414	1	910	**<0.001**
Wars	1.84	2.18	1.50	1.45	26.863	1	910	**<0.001**
Famine	0.48	0.50	0.46	1.08	1.141	1	910	0.286
Epidemics	0.327	0.455	0.196	2.32	27.296	1	910	**<0.001**
Floods	0.157	0.224	0.088	2.55	19.181	1	910	**<0.001**
Drought	0.114	0.192	0.035	5.49	22.599	1	910	**<0.001**
Early (1000–1459)								
Nomad migrations	0.167	0.321	0.059	5.44	61.993	1	458	**<0.001**
War with nomads	12.3	16.6	8.9	1.86	11.432	1	14	**0.010**
Nomad invasions	0.60	0.87	0.41	2.11	24.895	1	458	**<0.001**
Rebellions	1.88	2.45	1.48	1.66	34.837	1	458	**<0.001**
Wars	0.64	0.97	0.41	2.36	20.571	1	458	**<0.001**
Famine	0.57	0.61	0.55	1.10	1.484	1	458	0.224
Epidemics	0.120	0.158	0.093	1.70	3.893	1	458	**0.049**
Floods	0.046	0.053	0.041	1.29	0.301	1	458	0.584
Drought	0.057	0.105	0.022	4.77	9.849	1	458	**0.002**
Late (1460–1911)								
Nomad migrations	0.097	0.138	0.038	3.63	12.504	1	450	**<0.001**
War with nomads	13.8	15.7	11.8	1.32	0.816	1	10	0.388
Nomad invasions	0.36	0.26	0.50	0.53	13.162	1	450	**<0.001**
Rebellions	1.80	1.99	1.53	1.30	4.761	1	450	**0.030**
Wars	0.86	1.08	0.53	2.03	12.766	1	450	**<0.001**
Famine	0.39	0.42	0.33	1.26	3.472	1	450	0.063
Epidemics	0.538	0.665	0.350	1.90	11.699	1	450	**<0.001**
Floods	0.270	0.346	0.158	2.19	10.399	1	450	**0.001**
Drought	0.173	0.253	0.055	4.60	10.330	1	450	**0.001**

[a]Between groups; [b]within groups

mate in 1450–1911. This is also reflected by the statistical results of wars with nomads, which were significantly related to cooling in the early, but unrelated to cold climate in the later period. The lack of significance in the association between cooling and invasions in 1450–1911 was most probably caused by 2 incidents: (1) A peak in nomadic invasions in the warm mid-16th century, led by the Mongol leader Altan Khan (Zhongguo Junshishi Bianxiezu 1985); this reveals the influence of factors other than climate change in provoking invasions. (2) The conquest of Tianshan by Emperor Qianlong in the 1750s, which placed many nomadic tribes under Chinese rule (Jiang 1993); thus, the political boundary of China was extended to the west and nomad migrations and wars against nomads disappeared.

Famine was not significantly related to cooling over the whole period, nor for the early period; it was almost significant at the 0.05 level in the later period. In contrast, flooding was significantly related to cooling over the whole period, but in terms of the 2 sub-periods, the relationship was not significant in 1000–1449 and significant in 1450–1911. Population size may mediate in the relationship between climate change and mortality crises. When population size is large, it reduces natural buffering capacity that would provide for societal resilience (e.g. tracts of non-cultivated arable land). When there is a lack of arable land, more flood-prone areas will be occupied, rendering the population vulnerable to flooding and famine (Ho 1959, Jiang 1993). As population size increased over time, cooling affected these mortality factors more strongly. Still, the above phenomena may also be attributable to the incompleteness of historical data. Further examination is required.

4.2. Effect of population pressure

Mortality events were more frequent during periods of cold climate. Consequently, there were 5 population collapses in 6 cold phases. The analysis may lead to the conclusion that population growth was low during cold periods. However, the climate–population relationship is not linear, because of a feedback loop between population growth and population pressure (Fig. 1). The key concept in that relationship is population pressure. On one hand, population pressure results from the decrease in agricultural production caused by cooling. On the other hand, population pressure is also created by population growth. Thus, whether a climate–population relationship holds is contingent on another variable — population pressure.

The manner in which climate drives historical Chinese population cycles can be classified in 4 stages, in which the effect of climatic forcing on population growth rate is different:

(1) Rapid population growth during a warm period. This stage spans the entire warm phase, as acceleration of population growth is facilitated by good agricultural production and fewer mortality events in a favorable climate.

(2) Deceleration in the population growth rate during the early part of a cold phase. This stage spans the period from the final year of a warm phase to the year when the population peaks. In this period, mounting population pressure is engendered by the increased population size from the previous warm phase and decreased agricultural production due to cooling, and this results in a higher frequency of mortality events. Nevertheless, despite the prevalence of mortality factors, total births outnumber total deaths caused by mortality events at this stage. Hence, the population growth rate still remains positive, population size increases, and population pressure accumulates further.

(3) Population collapse in the middle of a cold period. This stage spans the years from the population peak to the population trough. Mortality events cause a mortality crisis in response to the previous increase in population size and the continuous decrease in agricultural production. At this stage, the number of deaths surpasses the number of births, resulting in a marked reduction in population size. This is a chaotic period.

(4) Post-collapse population recovery. This stage spans the period from the year of the population trough to the end of the cold phase. Since population pressure has been largely eliminated by the mortality crisis, population begins to increase in spite of the cold climate.

The historical Chinese population time series in the past millennium can be divided into 6 cycles, 2 of which are incomplete (Cycles 3 and 4) (see Table 3 & Fig. 3). Cycle 3 (1303–1368) is disrupted due to the fact that the year of the population trough (1368) is 9 yr after the end of a cold phase. Moreover, there is no population collapse in Cycle 4 (1369–1487). The data show that the annual population growth rate in Stage 1 was relatively high for all 6 cycles. The growth rate decreased from Stage 1 to Stage 2, but remained positive. Proceeding to Stage 3, population growth rate declined to a negative level, i.e. reduction of population size. In Stage 4, population pressure had been eliminated by population collapse, and population growth resumed in spite of a cold climate (i.e. population feedback effect, cf. Section 2). Although there were 2 incomplete cycles, their associated 'truncated' annual growth rate time series also conformed to the above pattern. For instance, although Stage 4 of Cycle 3 was absent, its population trough was only a short time (i.e. 9 years) behind a cold phase (Fig. 3c). Furthermore, population collapse occurred in the midst of the cold phase, similar to the other cycles.

In Cycle 4, even though there was no population collapse, the annual growth rate in the Stage 2 (0.14 %) was much smaller than that in Stage 1 (0.39 %) (Fig. 3d). The good match among annual growth rate series in the various cycles supports the hypothesis of an interaction among climate change, population pressure, and population cycles.

4.3. Climate–population relationship and social buffers

There were 5 periods of population reduction in the past millennium (Table 4) which occurred during a cold climate phase. Except for the 66 yr population collapse (1210–1275) during the Southern Sung dynasty, all of the mortality crises were short in duration, lasting for only about 20 years. When we examined the associated population loss in terms of absolute numbers, no distinct pattern of population loss was identified. However, the relative magnitude of population loss decreased over time. For instance, for the first 3 population collapses, population size declined by >27 % (49 % for the Southern Sung collapse). But, for the last 2 population collapses, population size shrank by <20 % in each incident. Moreover, the time lag between the start of a cold phase and the subsequent collapse became longer over time. For the first 3 population collapses, the time lag was 15–20 yr. For the last 2 collapses the lag was ~45 years. This may reveal an increasing effectiveness of social buffers (e.g. economic change, innovation, trade, and peaceful resource redistribution) in attenuating the impact of climatic forcing on society. Nevertheless, the data also reveal that social buffers might only be effective in delaying, but not in preventing population collapse. As pointed out by Nefedov (2003), most complex agrarian systems had considerable reserves to provide stability against harvest shortages. However, if the shortages lasted for 50 years or longer, these reserves were

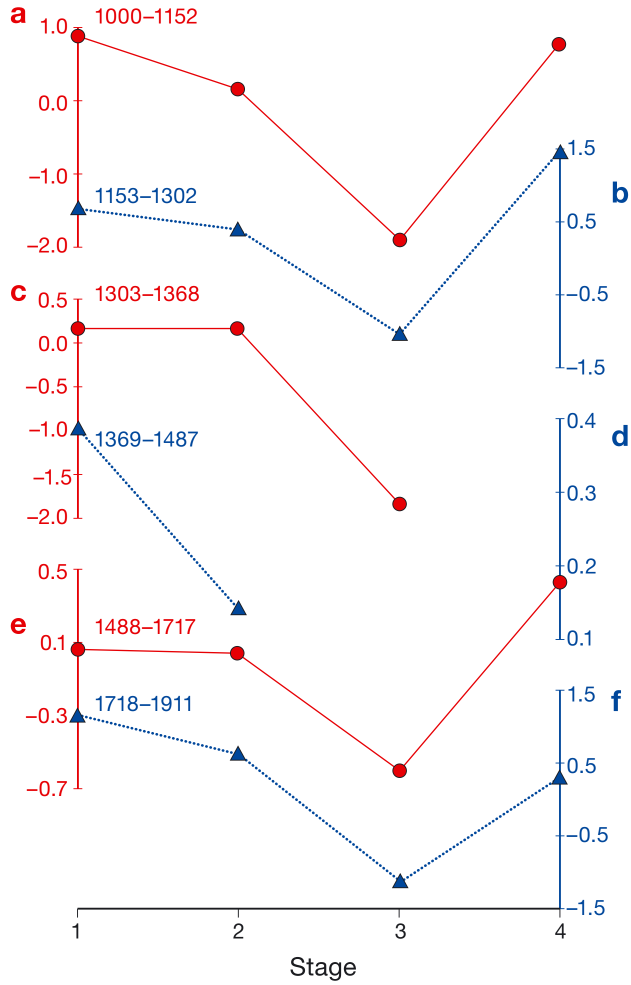

Fig. 3. Relationship between climate change and annual population growth rates in the 6 population cycles (*y*-axes a–f = Cycle 1 to 6, respectively) in China from 1000 to 1911. Stage 1: rapid population growth in a warm phase; Stage 2: deceleration of population growth in the early cold phase; Stage 3: population collapse in the middle of the cold phase; Stage 4: post-collapse population recovery in the late cold phase. Red circles and solid lines correspond to the left *y*-axis; blue triangles and dotted lines correspond to the right *y*-axis

Table 3. Climate fluctuations and change in population (mean annual growth rates in %) during the 6 population cycles in China, 1000–1911. Stage 1: expansion during warm phase; Stage 2: deceleration during early cold phase; Stage 3: collapse in middle of cold phase; Stage 4: recovery during late cold phase

Cycle		Stage 1		Stage 2		Stage 3		Stage 4	
		Period	Change	Period	Change	Period	Change	Period	Change
1	1000–1152	1000–1109	0.88	1110–1124	0.15	1125–1141	−1.91	1142–1152	0.78
2	1153–1302	1153–1193	0.67	1194–1210	0.38	1211–1275	−1.04	1276–1302	1.46
3[a]	1303–1368	1303–1333	0.17	1334–1351	0.15	1352–1368	−1.84	–	–
4[a]	1369–1487	1369–1447	0.39	1448–1487	0.14	–	–	–	–
5	1488–1717	1488–1582	0.07	1583–1626	0.05	1627–1646	−0.60	1647–1717	0.43
6	1718–1911	1718–1805	1.15	1806–1852	0.62	1853–1870	−1.14	1871–1911	0.31

[a]Incomplete population cycle

Table 4. Summary of the major population collapses in China, 1000–1911

Cold phase	Population collapse	Dynasty	Duration (yr)	Lag (yr)[a]	Population (10^6 ind.)			Loss (%)
					Peak	Trough	Loss	
1110–1152	1124–1141	Northern Sung	18	15	98.3	70.8	27.5	28.0
1194–1302	1210–1275	Southern Sung	66	17	108.2	54.7	53.5	49.4
1334–1359	1351–1368	Yuan	18	18	87.6	63.8	23.8	27.2
1583–1717	1626–1646	Ming	21	44	99.9	88.5	11.4	11.4
1806–1911	1852–1870	Qing	19	47	439.6	357.7	81.9	18.6

[a]Time lag between the start of a cold phase and the population collapse

exhausted and the system experienced demographic collapse. Worldwide empirical studies also have revealed that in the face of persistent agricultural shortages induced by long-term cooling, social buffers ultimately became ineffective and were unable to prevent population decline (Zhang et al. 2007a).

5. DISCUSSION

Although other studies have discussed the way in which climatic forcing drove secular population cycles in historical China, relevant scientific evidence was inadequate (cf. Section 1). The present study used an empirical approach to establish such a relationship. We employed high-resolution historical data and statistical methods were employed to substantiate the linkage from temperature change to mortality crises, and then to population cycles. Over the past millennium, the peaks of various mortality crises in China coincided with periods of cold climate; 5 of 6 cold phases are associated with population collapses. Temperature change was thus an important factor driving historical Chinese population cycles. The climate–population relationship is not linear, as it is mediated by population pressure. Although social buffers were increasingly effective in attenuating climatic forcing, they could not prevent population collapses from happening during long-term cooling.

In the discussion of population pressure upon food supplies, Malthus (1798) assumed land carrying capacity to be essentially constant or possibly monotonically increasing. Mortality events due to various factors (famine, epidemics, and wars) and associated population collapses were thought to occur when population growth overshot the level of livelihood resources. In the classic Malthusian view, population is the active factor, while land carrying capacity is understood as relatively fixed, and historical demographic tragedies can be attributed to massive shortages brought on by excessive population growth. Malthus (1798) understood population cycles as autonomous self-generating processes. His approach remains heuristically useful in many ways. Nevertheless, when the classic Malthusian view is mapped onto empirically observed patterns in historical societies, the immediate deficiency is clear: population growth alone cannot predict *when* there will be population contractions and *how long* each contraction will last. Malthusian explanations may account for the recurrence of cycles, but differences or irregularities among cycles (e.g. timing, duration, magnitude, velocity, and momentum) cannot be answered satisfactorily, at least in the case of China.

Post-Malthusian scholars have developed more sophisticated models of the recurrent long-term oscillations in population size through early modern history. They emphasize that population growth causes demographic tragedies indirectly, by affecting social institutions (economic, political, and social structures), which in turn affect socio-political stability. In the context of relatively inflexible economic and social structures, population increase in excess of the productive capacity of the land accelerates inequities in the distribution of resources among different sectors of society (e.g. via price increases), a situation with which agrarian-bureaucratic states cannot cope. The established social fabric is stressed in several ways at once. The result is a protracted period of political disorder, social conflict, and economic disruption, followed by more frequent mortality events and demographic contractions (Goldstone 1991, Turchin 2003, Turchin & Nefedov 2009). Post-Malthusian scholars attribute the differences/irregularities between cycles to various exogenous factors that are not an explicit part of the models. Climate is merely one of them.

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. This notion has a Malthusian flavor. However, our study has shown that, given the technological limitations of agricultural production during the last millenium, long-term climate change has a significant impact on food supplies, and that constant or monotonic increase in land carrying capacity (assumed by Malthus and many other scholars) is not true, at least in the pre-industrial era. The increase in land carrying capacity is characterized by short-term oscillations (ascending wave pattern) in synchrony with the alternation of cold and warm periods. Pre-industrial populations always grow to the land carrying capacity and subsist at the minimum consumption level. 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). Such hungry homeostasis interacts with the climate-induced decline of land carrying capacity to produce a demographic (or even socio-political) collapse via increased frequency of mortality events. This mechanism determined the socio-economic and demographic cycles in pre-industrial China. The classic Malthusian view does not take climate into account, and post-Malthusian views consider climate change to be only an incidental cause of misery; our study, however, shows that deteriorating climate is fundamental, not incidental, in causing human misery and the resultant demographic tragedies in Chinese history. Furthermore, the mechanism is not population growth alone, but population growth and climate fluctuations working synergistically to drive secular population cycles in historical agrarian China.

It may be suggested that political, economic, and social issues are more pertinent factors that account for secular population cycles in historical agrarian China (cf. Introduction). Nonetheless, these are not independent factors, but related aspects of an underlying causal pattern. A decline in the resource base caused by climate change makes human societies exceedingly vulnerable to social and economic changes, and these effects may impinge upon the societies' viability. Without a secular decline in the resource base, those 'more pertinent' (political or socioeconomic) factors would have promoted a less significant social effect (Parry 1981).

Boserup (1965, 1981) argued that population growth often worked as the major dynamic engine of agricultural change, stimulating, in particular, improvements in land use and technology. Moreover, this basically anti-Malthusian perspective can be further developed to argue that — other things being equal — the larger a population is, the larger will be the number of farmers, and therefore the greater will be the chance that someone will discover a new and more productive way of cultivating the available land. In short, land carrying capacity will increase with population growth, so that population growth will not exceed the subsistence level. This notion seems to refute the fundamental hypothesis of the present study. Nevertheless, Boserup's (1965, 1981) concept is valid only with respect to limited regions and short-term time frames — when there is still a potential for intensification of cultivation, or for a very long-term trend in human history (Zhang et al. 2007a). On the other hand, it has been suggested that increasing carrying capacity through agricultural expansion and technology is a culturally driven endeavor, not a foregone conclusion. Population driving agricultural production is, in effect, a cultural construct (Hopfenberg 2009). Therefore, the positive association between population growth and land carrying capacity may not be relevant to the above analysis.

6. CONCLUSIONS

Human societies are not closed systems; they are affected by the physical world (Turchin 2003). Our results suggest that in addition to population growth, climate fluctuation was an important driving force behind the fluctuations of population size in historical China. Population changes can exert an independent force on the historic landscape, but population size can also be affected by changes in land carrying capacity, which is contingent upon climate change. China provides a good example of the effects of climate on fluctuations in population growth. Instead of adopting classic Malthusian or post-Malthusian views, the impact of climatic forcing upon land carrying capacity must be considered when interpreting the secular population cycles in Chinese history.

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