Temperature, aridity thresholds, and population growth dynamics in China over the last millennium

Harry F. Lee*, David D. Zhang, Lincoln Fok

Department of Geography, University of Hong Kong, Pokfulam Road, Hong Kong, SAR

ABSTRACT: The relationship between climate and population has long been discussed, but rarely has it been quantitatively measured. Hence, the relationship remains ambiguous. In the present study, we employ fine-grained temperature, aridity threshold, and population data, together with logistic models and spatial statistics, to quantitatively explore how far climate change affected population growth dynamics in China from 1000 to 1979. Statistical results confirm that cold climate was associated with below average population growth, mediated by regional geographic contexts. In addition, cold climate triggered a southward shift of populations. In short, the climate–population relationship was evident in historical China, and temperature was more influential than the aridity threshold in explaining the fluctuation of population size and shifts in population distribution. The strong influence of temperature change on northward and southward population shifts and the weak influence of the change in the aridity threshold on population growth dynamics are further discussed. The observed temperature–population relationship may give some indication of future demographic effects from climate warming.

KEY WORDS: Climate change · Temperature · Aridity threshold · Population dynamics · Land carrying capacity · China

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1. INTRODUCTION

Climate has long been suggested as a factor of the utmost importance in determining human population growth, especially in the pre-industrial era when social buffers were rather limited (crude technology and limited interregional trade, for example). Steensgaard (1978) notes that in the 17th century—the coldest period in the last millennium—depopulation occurred in various European regions, including Castile, Germany, Catalonia, Netherlands, Denmark, Poland, England, and France. Meanwhile, Braudel (1974) observes that the global synchronistic population expansion of the 18th century is a puzzle. At the time, space was, and had always been, available for population expansion and the global economy was still very fragile, so land availability and international trade were unlikely to have been responsible for such a general and powerful increase of population. He concludes

that a favorable climate was the underlying factor in the global expansion of population during the 18th century.

In brief, warm periods are associated with above-average population growth, while cool periods are associated with lower than average growth. This is particularly true in middle latitude areas (Galloway 1986). Nevertheless, the suggested climate–population relationship is primarily based on the qualitative scrutiny of narrow historic examples. Therefore, any conclusions about it remain ambiguous. This may explain why some scholars caution against allocating any causal role to climate change as a driver of the long-term changes of population through history (Appleby 1980, DeVries 1980). In fact, the paucity of quantitative evidence has made it difficult to move the discussion of the climate–population relationship from a perceived influence of climate as a driver of population change to a statistically quantifiable one.

*Email: harrylee@hkusua.hku.hk

The problem is further complicated by the fact that most of the demographic studies on this subject are eurocentric. This leads to 2 questions: (1) How far does climate change affect population growth dynamics (in terms of the fluctuation of population size and shifting of population distribution) in non-European settings? and (2) Temperature and aridity threshold are 2 major climatic variables. Which one is more influential in determining population growth dynamics? The present study seeks to answer the above questions using quantitative methods.

The Chinese population composes about 25% of the total world's population. Quantitative analysis of the climate–population association requires a temporal record of population data sampled at sufficiently frequent intervals across a long time frame (500 to 600 yr). With the exception of China, the historical population records of many countries do not fit this requirement (Ho 1959, Zhao & Xie 1988, Jiang 1993). Moreover, for a long period of time, China was a predominantly agrarian society, characterized by a high degree of 'endogeneity' (Zhu 1998, Turchin 2005)—systematic emigration overseas dates back only to the opening of China in the 1840s (Ho 1959, Jiang 1993). These factors provide an ideal setting to examine the climate–popu-

lation relationship using China as the study area (Fig. 1).

The authors encountered one major methodological difficulty: the early history of China is much less known than more recent history, and many pieces of documentary evidence are considerably reduced in the early period. Records from earlier times are more fragmentary than from recent centuries. This issue is particularly pertinent to the earlier Chinese population data as they are often sketchy, sporadic, and were frequently recorded for other purposes (Ho 1959, Jiang 1993). Consequently, the study period has been restricted to the past millennium, 1000 to 1979.

Given that the goal in this research is to consider whether climate is a credible factor to shape demographic history at the macro-historical level, we will focus on the assessment of the relationship between climate change and the concomitant population change, and will pay little attention to other demographic variables, such as fertility, mortality, marriage, age structure and the like. We believe that this rather broad-brush approach, although not without limitations, suits the scope of the present study.

2. WORKING HYPOTHESES

The association between climate change and population growth is materialized through fluctuations in the food supply. Climate change affects the length of growing seasons, the intensity of average summer warmth, and the reliability of rainfall. In addition, a lengthy cooling period will lower the elevation at which crops can be grown, thus decreasing the amount of land available for cultivation and leading either to a decline in total output or to more intensive cultivation but with lower yields. Lower yields may also result from the biological inability of certain grains to effectively withstand cooler temperatures and the associated variability in short-term weather patterns (Bryson & Murray 1977, Gallo-way 1986). Unfavorable climate would not only directly hamper agricultural production, but also impede the means of boosting agricultural productivity (Fang 1993). Human societies were not able to compensate rapidly for harvest failures when climate deteriorated, which led to more frequent migration in search of food, a lower birth rate, and

Fig. 1. Map of China. Delineation of geographic regions is based on Chinese traditions (see Zhao 1986). However, principles of climatic zoning have been adopted in this research and, hence, North China and Northeast China are merged into the 'North' zone; South and Southwest China, into the 'South' zone; Northwest arid China and the Tibetan Plateau form the 'Marginal' zone; and central China is the 'Central' zone. Stars indicate locations of various capital cities in the past millennium. The gray-shaded line stretching from the northeast to the southwest is the 'Aihui-Tengchong Line' (known internationally as the 'Hu Line'). Nowadays, <6% of China's total population resides west of the line

more disastrous population checks, including war, famine, and epidemics (Zhang et al. 2006, 2007a,b, Lee et al. 2008).

We hypothesized that deteriorating climate (cooler or drier) in agrarian China¹, coupled with a low level of technology, will significantly shrink the land's carrying capacity as measured by agricultural production. The reduction in carrying capacity affects the food supply per capita. A shortage of food resources results in below-average population growth or even population collapses.

Subject to the dependence on agricultural production, we also hypothesized that in a deteriorating climate, people in the north migrated to the south to take advantage of the relatively favorable climate. The population became more clustered and unevenly distributed. In contrast, during favorable climate conditions (warmer or wetter), there was significant expansion of arable land and an increase in land productivity in the north. Some pastoral steppe land or wasteland was converted to farmland. Lured by the rich agricultural prospects there, many people in the south went north to avail themselves of the increase in arable land in formerly marginal farming areas. During these periods, the population became more dispersed and evenly distributed.

3. DATA

3.1. Temperature

Recently, paleo-climatologists worldwide have employed ingenious methods to reconstruct the paleo-temperature of the Northern Hemisphere (NH) for the past millennium (Mann et al. 1999, Briffa & Osborn 2002). Progress in paleo-climatic research in China has resulted in several high-resolution temperature reconstructions in recent years. However, these temperature series are constructed from different non-instrumental proxies and calibrating methods. Besides, their spatial coverage

within China differs (Zheng & Wang 2005). Therefore, in order to better characterize climate changes in China over the past millennium, a composite temperature series has been derived that is composed of 7 individual temperature reconstructions, most of which are publicly available from the World Data Center for Paleoclimatology (www.ncdc.noaa.gov/paleo/recons.html).

Of the 7 chosen climate reconstructions, 4 are located inside the national boundaries of China (Wang et al. 2001, Yang et al. 2002, Ge et al. 2003, Tan et al. 2003). These temperature anomaly series are believed to be the most authoritative Chinese paleo-climatic reconstructions, covering 1000 yr. As mentioned above, each individual series has its own spatial coverage. Except for the reconstruction done by Tan et al. (2003), their data resolution cannot reach the annual level. Consequently, the annual temperature variability reconstruction of Mongolia carried out by D'Arrigo et al. (2001) has been incorporated into the temperature composite. In addition, 2 recent and influential annual NH proxy records (Mann & Jones 2003, Moberg et al. 2005) have also been included. As China is spatially nested within the NH, inclusion of the NH series helps to average out the spatial differences among the Chinese temperature series. Details of the chosen temperature series are listed in Table 1.

As the chosen time resolution for the temperature series is not homogeneous, the data were transformed into identical decadal units. In the cases of records with a coarser time resolution (Wang et al. 2001, Ge et al. 2003), decadal resolution was obtained by linear interpolation between existing data points. In the cases of records with a finer resolution (D'Arrigo et al. 2001, Mann & Jones 2003, Tan et al. 2003, Moberg et al. 2005), decadal resolution was obtained by averaging the data within a decade. Another problem is that the chosen series are derived from different proxies. Therefore, each series has been normalized to homogenize the original variability of all series. This transformation cannot preserve the numerical values of temperature variation, but will provide the relative amplitude of temperature change. Finally, all of the normalized series were arithmetically averaged to generate the temperature composite shown in Fig. 2a.

Warm temperatures characterize the period from the 1000s to the 1400s. Around 1400 there is a sharp decrease in temperature that lasted several decades. Cool temperatures dominate from the 1450s to 1900s, when the long-term trend of temperature shifted downward. This corresponds to the gradual transition from the Medieval Warm Period to the Little Ice Age. Since the 1900s, China has been subjected to consistent warming. These rises and falls match closely with the alternation of cold and warm phases in China delineated by Zhang et al. (2005, 2006, 2007b).

¹By definition, in agrarian societies, 80 to 90 % of the population is engaged in subsistence agriculture. There are many stages of human societies, ranging from bands of hunter-gatherers to the modern post-industrial states. The main disadvantage of studying hunter-gatherer societies is the crucial dependence on archaeological data, while the disadvantages of studying industrial and post-industrial societies are that the pace of change has become quite rapid and the societies have become very complex. Agrarian societies appear to suffer the least from these 2 disadvantages: throughout most of their history they changed at a reasonably slow pace, and there are reliable historical records for them, as well. Most importantly, >95 % of recorded history is the history of agrarian societies, which justifies the significance of the research focus.

Table 1. Details of the chosen temperature reconstructions

No.	Geographic region	Proxy type	Interpretation	First to last year	Resolution	Source
1	Whole of China	Historical disaster records related to temperature anomalies	Annual temperature	AD 800–2000	50 yr	Wang et al. (2001)
2	Whole of China	Peat, lake sediment, ice core, tree-ring, and historical documents	Annual temperature	AD 1–1990	10 yr	Yang et al. (2002)
3	Shihua Cave, Beijing, China	Stalagmite	May–Aug temperature	665 BC–AD 1985	Annual	Tan et al. (2003)
4	Middle & lower reaches of the Yellow River and Yangtze River, China	Cold/warm events recorded in historical documents	Oct–Apr temperature	AD 1–1999	30 yr for AD 1–959 and 1110–1499; 10 yr for AD 960–1109 and 1500–1999	Ge et al. (2003)
5	Solongotyn, Davaa, Mongolia	Tree-ring	Aug–Jul temperature	AD 262–1999	Annual	D'Arrigo et al. (2001)
6	Northern Hemisphere	Document, lake sediment, tree-ring, ice core, fossil shells, etc.	Annual temperature	AD 200–1980	Annual	Mann & Jones (2003)
7	Northern Hemisphere	Document, lake sediment, tree-ring, ice core, fossil shells, etc.	Annual temperature	AD 1–1979	Annual	Moberg et al. (2005)

3.2. Aridity threshold

Ancient Chinese societies were keenly aware of the relationship between climate and agricultural production. As a consequence, China has a rich legacy of documents describing climatic and agricultural conditions in historical times, which makes possible the reconstruction of various aridity threshold proxies (Gong & Hameed 1991, Zheng et al. 2002). Just like the temperature composite, our aridity threshold composite is composed of 7 individual aridity threshold reconstructions, over a period of 1000 yr (GKJW 1990, Fang 1993, Yan et al. 1993, Yao et al. 1996, Zhang et al. 1997, Kang et al. 2003, Jiang et al. 2005). All of the chosen aridity threshold reconstructions are located inside the national boundaries of China, and 5 of them are derived from ancient Chinese documents. Their details are listed in Table 2. As the time resolution of the reconstructions is not homogeneous, they were transformed into identical decadal units. Each series was normalized to homogenize the original variability of all series. Following this, all of the normalized series were arithmetically averaged to generate the aridity threshold composite shown in Fig. 2b.

In historical China, 3 significant drought periods were demarcated, namely: 1120s–1240s, 1580s–1640s, and 1900s onwards. In comparing the temperature and aridity threshold composites (Fig. 2a,b), no obvious relationship between the 2 could be discerned ($r = 0.053$, $p > 0.05$, $n = 98$)². Besides, the amplitude of fluctuation for the aridity threshold composite is relatively smaller ($\pm 1\delta$), while that for the temperature composite is nearly double ($\pm 2\delta$). Furthermore, more frequent short-term perturbations (i.e. decadal variability) could be spotted along the aridity threshold composite.

3.3. Long- and short-term climate change

The temperature and aridity threshold composites can be further interpreted in terms of their long-term trend (i.e. centennial variability) and short-term variation (i.e. decadal variability). In order to disentangle the contribution of the long-term trend and short-term variability of the various climatic elements on the historical Chinese population growth dynamics, 6th-order polynomials were fitted to the temperature and aridity threshold composites. The fitted curves are also shown in Fig. 2a,b. Following this, each of the composites was then decoupled into 2. Taking the temperature composite to be an example, the first decoupled temperature record comprised the fitted polynomials alone, representing the long-term trend of temperature change; the second one was formed by subtracting the fitted curve from the original temperature composite, with the resulting residual series representing the short-term variability of temperature change. Including the original 'complete' temperature composite, temperature is characterized by 3 different composites in total.

3.4. Population

Based on Chinese historical materials, several studies (Zhao & Xie 1988, Jiang 1993, Cao 2002) have endeavored to obtain the best possible historical estimates of the Chinese population size within the current political

²Degrees of freedom of the correlated coefficient have been corrected for autocorrelation of the time series by using the Cochrane-Orcutt iterative procedure.

Fig. 2. Comparisons of temperature, aridity threshold, and population. (a) Temperature composite (data points) derived from the combined data on temperature anomaly series by D'Arrigo et al. (2001), Wang et al. (2001), Yang et al. (2002), Ge et al. (2003), Mann & Jones (2003), Tan et al. (2003) and Moberg et al. (2005). Positive values indicate higher temperatures; negative values indicate lower temperatures. (b) Aridity threshold composite (data points) derived from the combined data on aridity threshold reconstructions by GKJW (1990), Fang (1993), Yan et al. (1993), Yao et al. (1996), Zhang et al. (1997), Kang et al. (2003), and Jiang et al. (2005). Positive values indicate wetter conditions; negative values indicate more arid conditions. In (a) and (b) solid black lines are the long-term trends (6th-order polynomial fit) of the associated composites. (c) Population size in historical China (millions) (Zhao & Xie 1988). Arrows indicate population collapses. All time series are in decadal units

boundaries of China³. Although these studies disagree over the precise population size at high and low points, they are in agreement over the timing and direction of change, which is critically important to the present study. We used Zhao & Xie's (1988) population estimate because it is believed to be the most detailed estimate and has been repeatedly used by other authors (Chu & Lee 1994, Zhang & Li 1999, Turchin 2003). As Zhao & Xie (1988) give estimates of the Chinese population size at irregular time intervals, the common logarithm of the data

points were taken, linearly interpolated and then anti-logged back, to create an annual time series. This method avoids any distortions of population growth rate in data interpolation. The interpolated annual population series has been expressed as a 10 yr average—the basic time step for measuring population growth.

Zhao & Xie (1988) also give historical population estimates at the provincial level based on the current provincial political boundaries of China. With reference to the climatic conditions of various physical regions in China (Zhao 1986), the country is divided into 4 macro-regions, namely northern China, central China, southern China, and marginal areas. The geographic coverage and description of each region are shown in Fig. 1 and Table 3, respectively. Zhao & Xie's (1988) provincial population data were grouped into the above 4 regions, with the aforementioned data interpolation procedure applied.

In Fig. 2c, we can see that the Chinese population expanded during periods of political stability and declined (sometimes precipitously) during periods of unrest, often coinciding with dynastic change. Population surplus in any given population growth period, which might have taken 100s of years to amass, vanished in 10 to 20 yr. There were 5 demographic collapses in the past millennium, each with population losses ranging from 30 to 80 million.

4. METHODS

4.1. Climate change and population size

In order to scrutinize the relationship between climate change and the fluctuation of population size, we: (1) detrended the population data prior to data analysis and (2) applied the logistic model to bridge climate change and population growth.

4.1.1. Detrending the population data

Population size in a number of places is characterized by hyper-exponential growth⁴, which is supposed to be related to technological improvement over time (Varfolomeyev & Gurevich 2001). This common growth kinetic is also noticeable in China. However, this general average trend in human demography may hinder the scrutiny of population growth dynamics,

³Throughout China's history, the country's political boundaries were subject to change. If population reconstructions are not based on a fixed boundary, then the population data in different periods cannot be compared.

⁴Exponential growth means that the larger a number gets, the faster it grows. All biological populations grow according to exponential law, whereas the human population grows according to hyper-exponential law, a rate of increase that is even faster than the exponential one.

Table 2. Details of the chosen aridity reconstructions

No.	Geographic region	Proxy type	Interpretation	First to last year	Resolution	Source
1	Whole of China	Historical flood and drought records	Flood/drought ratio	AD 950–1988	Annual	GKJW (1990)
2	Whole of China	Historical records relating to lake surface areas and their variations	Lake level	1000 BC–AD 1989	100 yr for 1000–801 BC; 30 yr for 800 BC–AD 1989	Fang (1993)
3	Whole of China	Historical documents	Flood/drought ratio	AD 1–1996	20 yr for AD 1–999; 10 yr for AD 1000–1996	Zhang et al. (1997)
4	Haihe and Xi'an regions, northern China	Historical flood and drought records	Flood/drought ratio	50 BC–AD 1979	10 yr	Yan et al. (1993)
5	Guliya Ice Cap, Tibetan Plateau	Ice core accumulation	Annual precipitation	AD 300–1995	10 yr	Yao et al. (1996)
6	Qilian Mountains, Qinghai, China	Tree-ring	Annual precipitation	AD 904–1997	Annual	Kang et al. (2003)
7	Yangtze Delta, eastern China	Historical flood, drought and maritime event records for AD 1000–1950; instrumental observations after AD 1950	Flood/drought ratio	AD 1000–2002	10 yr	Jiang et al. (2005)

Table 3. Descriptions of various geographic regions in China

Geographic regions	Provinces included	Climate	General agricultural features
Northern China	Liaoning, Jilin, Heilongjiang, Hebei, Henan, Shandong, Shanxi, Sha'anxi, Beijing ^b , Tianjin ^b	Warm temperate humid to continental	Triple-cropping of winter wheat, corn, sorghum, millet and cotton in 2 yr
Central China	Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Shanghai ^b	Sub-tropical humid	Double-cropping of rice, winter wheat, corn and cotton in a year
Southern China	Fujian, Guangdong, Taiwan, Sichuan, Yunnan, Guizhou, Guangxi ^a	Tropical humid to sub-tropical humid	Double- or triple-cropping of rice, sweet potatoes and corn in a year
Marginal areas	Gansu, Qinghai, Inner Mongolia ^a , Ningxia ^a , Xinjiang ^a , Tibet ^a	Warm temperate desert to temperate desert	Animal husbandry

^aMunicipalities; ^bAutonomous regions

which should be removed prior to quantitative analysis (Galloway 1986, Chu & Lee 1994, Turchin 2003). In the present study the hyper-exponential function (Varfolomeyev & Gurevich 2001) was adopted to detrend the population data. The function can be expressed as:

$$\begin{aligned}\frac{dP_t}{dt} &= cJ_t P_t \\ \frac{dJ_t}{dt} &= kJ_t\end{aligned}\quad (1)$$

where P_t stands for population size at time step t , c represents the population growth rate constant, and k is the kinetic parameter for human ingenuity J_t (say pool of knowledge). Eq. (1) gives:

$$\hat{P}_t = P_0 \exp\left[\frac{k_a}{k} \exp(k \cdot t)\right] \quad (2)$$

where P_0 is population size at time step 0 and $\hat{P}_t$ denotes the estimated population size at time step t given by the hyper-exponential function. k_a is a complex parameter containing J_0 . Optimization of Eq. (2)

against the Chinese historical population record was accomplished using the Levenberg-Marquardt nonlinear least-squares method.

The fluctuation of Chinese population growth dynamics was identified by:

$$R_t = \frac{P_t - \hat{P}_t}{\hat{P}_t} \quad (3)$$

where R_t is the detrended population series. In this study, we hypothesized that R_t is significantly determined by climate change.

4.1.2. Applying the logistic model

Perceived wisdom indicates that climate affected human population in the past by altering agricultural productivity and, consequently, the population growth rate. The linkage between R_t and climate change is materialized via agricultural production. However, historical agricultural production data are sketchy and

confined to recent time spans. Consequently, the linkage of ‘climate → agriculture → land carrying capacity → population’ cannot be directly assessed. As a solution to the ‘patchy’ nature of agricultural production data, a logistic model has been applied. Demographers have long used the logistic model of population dynamics to understand the cause–effect relationship between land carrying capacity and population size (Hopfenberg 2003). The logistic model adopted here (Lotka 1925) takes the following form:

$$\frac{dN_t}{dt} = rN_t \left(1 - \frac{N_t}{K_t}\right) \quad (4)$$

where N_t is the number of individuals in the population, r is the Malthusian parameter representing the population growth rate (i.e. crude birth rate – crude death rate), and K_t is the varying upper limit of population size (i.e. land carrying capacity). The model suggests that when population size N_t increases, population growth rate slows down and eventually ceases, as the population approaches carrying capacity K_t (i.e. $K_t/N_t = 1$). This condition is known as negative density dependence, which guarantees the equilibrium to be locally stable. If N_t is perturbed below its equilibrium level, r increases and the population grows back to equilibrium. Conversely, if N_t is raised to some value above equilibrium, r becomes negative and the population shrinks back down again. This equation is widely used and has become the foundation of many human population growth models. The analytic solution to Eq. (4) (Hopfenberg 2003) takes the following form:

$$\widehat{N}_t = \frac{K_t}{1 + (K_t/N_t - 1)\exp(-r\Delta t)} \quad (5)$$

where $\widehat{N}_t$ denotes the estimated population size at time step t given by the logistic function.

Vasey (2001) and Haraldsson & Ólafsdóttir (2006) use temperature as a proxy for potential biological production available for livestock to estimate land carrying capacity. Inspired by their work, K_t was substituted with the various climate composites in Eq. (5) in a one-by-one manner. Since the values of K_t in the equation cannot be negative, the composites were converted into values between 0 and 1 by using the logarithmic sigmoid transfer function. The transformed series were adopted as K_t and then entered into Eq. (5) to simulate $\widehat{N}_t$. Subject to the logarithmic sigmoid transfer function, $\widehat{N}_t$ is in synthetic units that do not provide numerical values of population size, but which indicate the relative amplitude of population fluctuation. To generate a good fit with the actual population data, $\widehat{N}_t$ was correlated with R_t with the Malthusian parameter r being the optimizing parameter (see Table A1 in the Appendix for simulations according to Eq. 5). The optimization target was to maximize the correlation coefficient

between $\widehat{N}_t$ and R_t . In this research, we assess the relationship between climate change and the fluctuation of population size in historical China in terms of the match between $\widehat{N}_t$ and R_t .

4.2. Climate change and population distribution

In order to measure the shifting of population distribution in China over time, we applied spatial statistics to elicit the following population distribution parameters.

4.2.1. North:South population ratio

North:South population ratio (N:S ratio) is a rough measure of the northward and southward shift of population. It is calculated by the sum of population in the ‘north’ divided by the sum of population in the ‘south.’ The ‘north’ includes Gansu, Qinghai, Inner Mongolia, Ningxia, Xinjiang, Tibet, Liaoning, Jilin, Heilongjiang, Hebei, Henan, Shandong, Shanxi, Sha’anxi, Beijing, and Tianjin; the ‘south’ includes Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Shanghai, Fujian, Guangdong, Taiwan, Sichuan, Yunnan, Guizhou, and Guangxi.

4.2.2. Mean population center

Mean population center ($\bar{x}_{wmc}, \bar{y}_{wmc}$) gives the average location of a population (i.e. central tendency of a population distribution), which is operationally defined by a pair of coordinates (i.e. x_i, y_i). The mean population center was calculated by the following steps.

Step 1: determine the centroid (i.e. geographic center) of each province in China. The centroid can be determined by importing the digitized map of China at the provincial level into ArcView 3.5.2. The digitized map is created by the Center for International Earth Science Information Network (CIESIN) at Columbia University, and can be downloaded from <http://sedac.ciesin.columbia.edu/china/admin/bnd90/pbd90.html>. Once imported, the centroid of each province (x_i, y_i) can be retrieved via ArcView 3.5.2. It should be noted that the provincial centroids given by the above procedure are in map units.

Step 2: weight the provincial centroids. This is done by multiplying the centroid of each province by its associated provincial population size as estimated by Zhao & Xie (1988). The mean of the weighted x coordinates and the mean of the weighted y coordinates define the position of the mean population center (Lee & Wong 2001). The equation for the mean population center is:

$$(\bar{x}_{wmc}, \bar{y}_{wmc}) = \left(\frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i}, \frac{\sum_{i=1}^n w_i y_i}{\sum_{i=1}^n w_i} \right) \quad (6)$$

where $\bar{x}_{wmc}$, $\bar{y}_{wmc}$ defines the weighted mean population center, x_i and y_i are the coordinates of the provincial centroid, and w_i is the weight of the centroid. In this study, the pair of coordinates of the mean population center will be decoupled into 2 population distribution parameters. Then, $\bar{x}_{wmc}$ will be treated as the indicator of eastward and westward population shifts and $\bar{y}_{wmc}$ will be treated as the measure of northward and southward population shifts.

4.2.3. Standard distance of population

Standard distance of population (SDist) indicates the degree of dispersal of a population. It tells how people in a distribution deviate from the mean population center. The more dispersed people are around the mean population center, the longer the SDist it will have (Lee & Wong 2001). SDist is the spatial analogy of standard deviation in classical statistics, which can be computed as:

$$SDist = \sqrt{\frac{\sum_{i=1}^n f_i(x_i - \bar{x}_{wmc})^2 + \sum_{i=1}^n f_i(y_i - \bar{y}_{wmc})^2}{\sum_{i=1}^n f_i}} \quad (7)$$

where $(\bar{x}_{wmc}, \bar{y}_{wmc})$ is the mean center of provincial centroids and f_i is the weight for a provincial centroid (x_i, y_i) .

In China, the western and northern parts are ecologically marginal. We hypothesized that in a favorable climate, the ecological condition in the west and north will be significantly improved, which will allow for more people. Therefore, the mean population center will be pulled westward and northward, and that population will be more dispersed or evenly distributed. Hence, N:S ratio increases, $\bar{x}_{wmc}$ decreases, $\bar{y}_{wmc}$ increases, and SDist increases. It should be noted that the meanings of $\bar{y}_{wmc}$ and the N:S ratio are basically the same.

There are 2 noteworthy points regarding the shifting of population in historical China. First, the change of various population distribution parameters can be caused by either population movement or regional population collapses. Although population movement plays a more important role in affecting population distribution in Chinese history (Zhao & Xie 1988, Shi 1991), regional population collapses can temporarily change the population distribution parameters, which may hamper the point-to-point scrutiny of the climate change and population distribution relationship.

The second point has to do with the inertia of the Chinese people to migrate. In historical Chinese societies, inter-regional migrations were largely voluntary decisions instead of driven by government enforcement (Ho 1959, Fang et al. 2007). Yet, subject to the influence of a small-scale peasant economy in which family is the basic unit of production, people were

emotionally attached to their homeland (*Antu Zhong-qian*). Only if their living condition became totally unbearable would they move to other places (where virgin land or wasteland were available to be opened up) to make their livings (Zhou 1997, Li 2000, Fang et al. 2007). Therefore, there may be a short delay between climate change and population shift.

Considering the above factors, it may be more appropriate to construe the relationship between climate change and population distribution in terms of their macro-cycles. To retrieve the macro-cycles, the time series of climate change and population distribution parameters were smoothed by the 100 yr Butterworth low pass filter (i.e. cycle = 10 data points, 1 point = 1 decade). Because the climate data are in normalized units but the population distribution parameters are in ratio or map units, to homogenize the unit of measurement of our data, all of the population distribution parameters were normalized prior to smoothing. In the present study, the relationship between climate change and the shifting of population distribution in China will be assessed in terms of the match between their macro-cycles.

5. RESULTS

Serial correlation of the climate and population time series prevents the application of standard tests for statistical significance. This is because the assumption that all data points are independent would produce unrealistically high significance levels. In the following statistical analyses, degrees of freedom of the correlated coefficients were corrected for autocorrelation of the time series by using the Cochrane-Orcutt estimation method. The minimum level of significance was chosen to be 0.05.

5.1. Climate change and population size

5.1.1. Temperature and population growth

For China as a whole, as shown in Fig. 3a, positioning of the complete temperature composite as the sole variable in the logistic model that accounts for land-carrying capacity yields the relative amplitude of population fluctuation ($\hat{N}_t$) that closely approximates the actual historical one (R_t) ($r = 0.346$, $p < 0.001$, $n = 98$) (Table 4). $\hat{N}_t$ shows an oscillating trend, with 5 sine waves (ups) and 4 cosine waves (downs). The approach adopted in the present study effectively predicts the historical chaos observed in Chinese history. The 'downs' are associated with population collapses that occurred at the end of Northern Song, Yuan, and Ming dynasties and also after

the Taiping Rebellion. Only the population collapse that occurred at the end of the Southern Song dynasty was not captured by $\widehat{N}_t$. At the regional level, the impacts of temperature change varied in the 4 major geographical regions of China. The correlation between $\widehat{N}_t$ and R_t was only significant for central China ($r = 0.458$, $p < 0.001$, $n = 98$) and marginal areas ($r = 0.243$, $p < 0.05$, $n = 98$), while the correlation results for northern China and southern China were not satisfactory (i.e. not statistically significant) (Fig. 3b–e, Table 4).

Regarding the influence of long-term and short-term temperature change on population growth, for the whole of China, population growth dynamics were only correlated with the long-term temperature change ($r = 0.389$, $p < 0.001$, $n = 98$) (Fig. 3f, Table 4). At the regional level, the population size of central China was shown to be re-

sponsive to both the long-term trend ($r = 0.366$, $p < 0.001$, $n = 98$) and the short-term variability of temperature change ($r = 0.306$, $p < 0.01$, $n = 98$), while in marginal areas population growth was only sensitive to the short-term temperature fluctuation ($r = 0.267$, $p < 0.01$, $n = 98$). On the other hand, northern China and southern China were rather insensitive to both long-term and short-term temperature changes (Fig. 3g to j, Table 4).

5.1.2. Aridity threshold and population growth

The complete aridity threshold composite was substituted into Eq. (5) to generate $\widehat{N}_t$ and then it was compared with R_t . For China as a whole, using the complete aridity threshold composite as the sole vari-

Fig. 3. Comparisons of R_t (the detrended population series generated by Eq. (3), in ratio units) and its fitted value $\widehat{N}_t$ (the estimated population size given by Eq. (5) with the temperature as data input, in synthetic units) for various geographic regions in China. In all panels, solid lines represent R_t . In Panels (a) to (e) 'circle' lines represent $\widehat{N}_t$ with the complete temperature composite as data input. In (f) to (j) 'bar' and 'star' lines represent $\widehat{N}_t$ with long-term trend and with short-term fluctuation (respectively) of temperature composite as data input

Table 4. Correlation coefficients between R_t and its fitted value $\hat{N}_t$ (with the temperature and aridity threshold composites as data input, respectively) for various geographic regions of China, $N = 98$. Degrees of freedom of the correlation coefficients were corrected for autocorrelation of the time series by using the Cochrane-Orcutt estimation method. Significance (2-tailed): * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

	Temperature			Aridity threshold		
	Complete composite	Long-term trend	Short-term variation	Complete composite	Long-term trend	Short-term variation
Whole of China	0.346***	0.389***	0.108	0.169	0.252*	0.200
Northern China	-0.012	0.039	0.010	-0.143	-0.257*	-0.119
Central China	0.458***	0.366***	0.306**	0.117	0.103	0.143
Southern China	0.097	0.116	-0.060	-0.040	-0.226*	-0.012
Marginal areas	0.243*	0.030	0.267**	-0.010	-0.163	0.019

able in the logistic model that yields the relative amplitude of population fluctuation ($\hat{N}_t$) did not approximate well to the actual historical one (R_t) ($r = 0.169$, $p > 0.05$, $n = 98$) (Fig. 4a, Table 4). At the regional level, the results were also disappointing, as none of the correlations between $\hat{N}_t$ and R_t were statistically significant for all of the regions (Fig. 4b to e, Table 4).

The composites of the long-term trend and short-term variation of the aridity threshold changes were also substituted individually into Eq. (5) to generate the $\hat{N}_t$ of the various macro-regions in China. For the whole of China, population growth was positively correlated with the long-term aridity threshold change ($r = 0.252$, $p < 0.05$, $n = 98$) (Table 4). Although this correlation supports our hypothesis, it is problematic in nature, as shown in Fig. 4f. At the regional level, none of the correlation coefficients between $\hat{N}_t$ and R_t was statistically significant, except some 'strange' associations. The population growth was shown to be weakly negative to the long-term aridity threshold change in both northern China ($r = -0.257$, $p < 0.05$, $n = 98$) and southern China ($r = -0.226$, $p < 0.05$, $n = 98$) (Fig. 4g to j, Table 4).

5.2. Climate change and population distribution

5.2.1. Temperature

Fig. 5 and Table 5 reveal that in a warm period, population distribution shifted to the north; in a cold period, the mean population center moved to the south. This is indicated by the positive correlations between the various temperature composites and $\bar{y}_{wmc}$ (for the complete temperature composite and $\bar{y}_{wmc}$: $r = 0.411$, $p < 0.001$, $n = 98$; for the long-term temperature trend and $\bar{y}_{wmc}$: $r = 0.267$, $p < 0.001$, $n = 98$; for the short-term temperature variation and $\bar{y}_{wmc}$: $r = 0.273$, $p < 0.001$, $n = 98$). Such a consistent relationship was also

echoed by the positive correlation between the complete temperature composite and N:S ratio ($r = 0.248$, $p < 0.05$, $n = 98$). For the relationship between temperature change and $\bar{x}_{wmc}$ that represents the eastward and westward shift of population, the results themselves were somehow contradictory. The long-term cooling trend was associated with the eastward population shift ($r = -0.221$, $p < 0.05$, $n = 98$); this agrees with our hypothesis. However, short-term cooling was associated with a westward population shift ($r = 0.344$, $p < 0.001$, $n = 98$). On the whole, population was more evenly distributed and widely dispersed in a warm climate, as reflected by the strong positive correlation between the long-term temperature trend and SDist ($r = 0.571$, $p < 0.001$, $n = 98$).

5.2.2. Aridity threshold

Regarding the relationship between the aridity threshold and population distribution, all of the statistical results were contradictory to our hypothesis (Fig. 6, Table 5). For instance, in a wet period, more people were clustered in the south as shown by the negative correlations between the aridity threshold composites and $\bar{y}_{wmc}$ (for the complete aridity threshold composite and $\bar{y}_{wmc}$: $r = -0.354$, $p < 0.001$, $n = 98$; for the long-term aridity threshold trend and $\bar{y}_{wmc}$: $r = -0.338$, $p < 0.001$, $n = 98$) and also between the aridity threshold composites and N:S ratio (for the complete aridity threshold composite and N:S ratio: $r = -0.276$, $p < 0.01$, $n = 98$; for the long-term aridity threshold trend and N:S ratio: $r = -0.211$, $p < 0.05$, $n = 98$). In addition, population shifted to the east (for the complete aridity threshold composite and $\bar{x}_{wmc}$: $r = 0.332$, $p < 0.001$, $n = 98$; for the short-term aridity threshold variation and $\bar{x}_{wmc}$: $r = 0.280$, $p < 0.01$, $n = 98$). Strangely, population was less dispersed in a wet period, as indicated by the negative correlation between the long-term aridity threshold variation and SDist ($r = -0.206$, $p < 0.05$, $n = 98$).

Fig. 4. Comparisons of R_t (the detrended population series generated by Eq. (3), in ratio units) and its fitted value $\hat{N}_t$ (the estimated population size given by Eq. (5) with the aridity threshold as data input, in synthetic units) for various geographic regions in China. In all panels, solid lines represent R_t . In Panels (a) to (e) 'circle' lines represent $\hat{N}_t$ with the complete aridity threshold composite as data input. In (f) to (j) 'bar' and 'star' lines represent $\hat{N}_t$ with long-term trend and with short-term fluctuation (respectively) of aridity threshold composite as data input

6. DISCUSSION

Our research findings can be recapitulated as follows:

(1) Long-term temperature change significantly determined the fluctuation of population size in agrarian China. However, spatial variation existed: whilst population growth in central China was shown to be responsive to both long- and short-term temperature changes, in marginal areas population growth was only sensitive to short-term temperature fluctuations.

(2) Temperature change significantly determined the shifting of population distribution in agrarian China, especially regarding northward and southward population shifts.

(3) Aridity threshold change could not satisfactorily explain the fluctuation of population size and shifting of population distribution.

In short, a climate–population relationship was evident in agrarian China, in which temperature was more influential than the aridity threshold in explaining the fluctuation of population size and shifting of population distribution. Having observed the strikingly strong coincidence between climatic, dynastic, and population cycles in Chinese history, some authors also emphasize the role of climate change in structuring the pathway of population growth in China (Li 1999, Tang & Tang 2002, Lan & Jiang 2005). Our results basically agree with their viewpoint. However, we have taken a step towards establishing a climate–population relationship

Fig. 5. Comparisons of the temperature and population distribution parameters. In all panels, solid lines represent the various population distribution parameters. In Panels a to d 'circle' lines represent the complete temperature composite. In Panels (e) to (h) 'bar' and 'star' lines represent the long-term trend and short-term fluctuation (respectively) of temperature composite. All data are in normalized units and smoothed by the 100 yr Butterworth low-pass filter (cycle = 10 data points, 1 point = 1 decade)

Table 5. Correlation coefficients between the climate composites (temperature and aridity threshold) and population distribution parameters, $N = 98$. Degrees of freedom of the correlation coefficients were corrected for autocorrelation of the time series by using the Cochrane-Orcutt estimation method. Significance (2-tailed): * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

	Temperature			Aridity threshold		
	Complete composite	Long-term trend	Short-term variation	Complete composite	Long-term trend	Short-term variation
N:S ratio	0.248*	0.166	0.162	-0.276**	-0.211*	-0.097
$\bar{X}_{wmc}$	0.190	-0.221*	0.344***	0.332***	0.043	0.280**
$\bar{Y}_{wmc}$	0.411***	0.267***	0.273***	-0.354***	-0.338***	-0.086
SDist	0.178	0.571***	-0.121	-0.012	-0.206*	0.119

via quantitative means. Temperature is probably the most important climatic variable influencing human societies (National Research Council 1998). We also find that temperature was more influential than the aridity threshold in determining the relationship. Regarding our research findings, there are 3 noteworthy issues that will be discussed in the following subsections.

6.1. Temperature change and regional fluctuation of population size

Throughout China's long history, the important roles of agro-climate and land condition have been recognized. China's economy, social activities, and even peasants' subsistence were heavily dependent on agri-

Fig. 6. Comparisons of the aridity threshold and population distribution parameters. In all panels, solid lines represent the various population distribution parameters. In (a) to (d) 'circle' lines represent the complete aridity threshold composite. In Panels (e) to (h) 'bar' and 'star' lines represent long-term trend and the short-term fluctuation (respectively) of the aridity threshold composite. All data are in normalized units and smoothed by the 100 yr Butterworth low-pass filter (cycle = 10 data points, 1 point = 1 decade)

cultural production. Dependence on agriculture meant that temperature change could have serious economic and social consequences, resulting in the fluctuation of population size. Supposedly, the higher a region's latitude, the stronger will be the impact of temperature fluctuations on human society. However, we find that central China, rather than northern China and marginal areas, was more vulnerable to temperature change. This does not concur with the above supposition, which brings to light the factors associated with regional variation, such as socio-political context and population density, which were explained in detail in our previous study (Lee et al. 2008).

6.2. Temperature change and population shifts

Temperature change significantly determined the northward and southward shifts of population, but not the eastward and westward ones. One possible expla-

nation is that within the geographic context of China, westward migration is obstructed by the Qinghai-Tibetan Plateau. This physical barrier may dampen the relationship between temperature change and eastward and westward population shifts. Furthermore, the variations of temperature and the associated ecological conditions are much more pronounced across latitudes than altitudes. Temperature change (say a 1°C drop in temperature) exerts a stronger ecological impact in the north than in the west. Therefore, the correlation results between the temperature composites and northward and southward population shifts were more significant. Scholars have shown that in historical China, mass migrations in a cold climate were primarily characterized by southward movement, while the ones in a warm climate were characterized by northward movement (Chang 1946, Fang & Liu 1992). For instance, the latitudinal variations of the southern boundaries of political power for nomadic tribes correspond to temperature change in the past 4000 yr. In a warm pe-

riod, the nomadic tribes dwelled north of the Great Wall. In a cold period, the nomads moved southward due to the substantial shrinkage of pastoral resources in the north. As the cooling periods grew longer and more severe in the past 2 millennia, the extent of nomadic southward migration grew larger, as well (Wang 1996). In addition, 2 waves of large-scale southward migration over the past millennium have been recorded in both historical documents and in recent studies, the first from 1000 to 1300 and the second from 1630 to 1900 (Fang & Liu 1992). In fact, these 2 migrations overlap with the 3 long cold phases (1194 to 1302, 1583 to 1717, and 1806 to 1911). In the early 1900s, as the NH became warmer again, people from Shandong and Henan, which were by then over-populated, flooded into north-eastern China (Zhang et al. 2007b).

6.3. Influence of aridity threshold change on population growth dynamics

In the present study, we have shown that temperature was more pertinent than the aridity threshold in determining population growth dynamics in historical China. Nonetheless, several studies emphasize that the aridity threshold is also a vital control over agricultural production (e.g. Utterström 1955, Hsu 1998). For early societies, the aridity threshold was critical in determining the development of civilizations, cultural shifts, and evolution (Lamb 1995, Polyak & Asmerom 2001, Acuna-Soto et al. 2005), as well as in determining dwelling abandonment and population redistribution (Fang & Liu 1992, Núñez et al. 2002, Huang et al. 2004). All of these concur with our hypothesis. In fact, the apparently weak effect of the aridity threshold change on the population growth dynamics may be owing to the considerable regional variation of the aridity threshold across China.

The regional aridity threshold difference in China is primarily taken to be a north to south disparity, especially in the past millennium. Such a regional variation pattern also changes with different climatic phases

(Zheng et al. 2001, Dong et al. 2002, Wang et al. 2006). In eastern China, when the climate is cold, summer rainfall over northern China is greater than normal and drought occurs along the lower-middle Yangtze River valley. When the climate is warm, drought is found over northern China and flooding appears along lower-middle Yangtze River valley (Dong et al. 2002). Also, the regional variation of precipitation becomes stronger in some periods. Opposite trends were found between the Jiang-Nan and Jiang-Huai areas in the 11th to 13th centuries, and between the North China Plain and Jiang-Nan area since the 16th century (Zheng et al. 2006).

The regional variability of the chosen aridity threshold proxies can be divulged by their cross correlation coefficients. From the correlation matrix of the chosen aridity threshold reconstructions, only 3 out of the 21 correlations were positively significant (Table 6). This means that considerable discrepancies exist among the chosen aridity threshold proxies. In comparison, although there have been significant temperature differences between northern and eastern China in the past millennium, the direction of the temperature changes has been the same, except in the 1400s to 1550s (Wang et al. 2001). Hence, the correlation matrix of the chosen temperature proxies was fairly consistent, as 17 out of the 21 correlations were positively significant. Most of the proxies showed good agreement (Table 7).

With regard to our method for obtaining the aridity threshold composite by arithmetically averaging all of the chosen aridity threshold reconstructions, this procedure may 'cancel out' any signal of the regional aridity threshold variation; for example, the wet signal in one region is offset by the drought signal in another region. This 'cancel out' effect also explains why the amplitude of fluctuation for the aridity threshold composite is relatively small ($\pm 1\delta$) when compared with the one for the temperature composite ($\pm 2\delta$) on a country-wide level (Fig. 2a,b). The associated aridity threshold composite cannot portray an accurate aridity threshold condition at either the country-wide or regional level.

Table 6. Correlation matrix of the chosen aridity threshold reconstructions, N = 98. Significance (2-tailed): *p < 0.05, **p < 0.01, ***p < 0.001

	Fang (1993)	Zhang et al. (1997)	Yan et al. (1993)	Yao et al. (1996)	Kang et al. (2003)	Jiang et al. (2005)
GKJW (1990)	0.147	0.120	0.097	0.082	−0.057	0.336***
Fang (1993)		0.334***	0.067	0.058	−0.307**	0.034
Zhang et al. (1997)			0.227*	−0.001	0.235*	−0.050
Yan et al. (1993)				0.037	−0.045	0.109
Yao et al. (1996)					−0.501***	0.164
Kang et al. (2003)						−0.124

Table 7. Correlation matrix of the chosen temperature reconstructions, N = 98. Significance (2-tailed): *p < 0.05, **p < 0.01, ***p < 0.001

	Yang et al. (2002)	Tan et al. (2003)	Ge et al. (2003)	D'Arrigo et al. (2001)	Mann & Jones (2003)	Moberg et al. (2005)
Wang et al. (2001)	0.601***	0.400***	0.427***	0.366***	0.644***	0.523***
Yang et al. (2002)		0.607***	0.377***	0.149	0.729***	0.601***
Tan et al. (2003)			−0.048	0.071	0.591***	0.599***
Ge et al. (2003)				0.204*	0.344***	0.239*
D'Arrigo et al. (2001)					0.354***	0.129
Mann & Jones (2003)						0.779***

Therefore, it cannot satisfactorily explain historical population growth dynamics. Nevertheless, a recent study shows that summer monsoon (the blend of temperature and the aridity threshold) was imperative in affecting historical Chinese societies (Zhang et al. 2008). The issue of how to combine the 2 climatic variables in explaining population growth dynamics should not be overlooked.

7. CONCLUSIONS

The present study quantitatively explores the climate–population relationship in agrarian China. Although human societies have become more complex and the role of agricultural production in the world economy has been gradually replaced by secondary and tertiary production since the Industrial Revolution, most of the world's population continued to rely on small-scale agriculture. The biological needs of human beings for food have never changed over time. Food availability is still an important factor in determining human population growth, and human beings continue to increase their numbers until presently approaching the limit of food availability. This has been repeatedly evidenced by empirical data (Harris & Kennedy 1999, Hopfenberg 2003). Therefore, any reduction of agricultural production will cause considerable subsistence shortage for a significant portion of the world's population.

The present study covers the period from 1000 to 1979. While special attention should be paid to the regional variability of the aridity threshold, our statistical results show that temperature change significantly influenced population growth dynamics. Since the 1980s, global warming has attracted much attention. The recent warmth is anomalous and has been unprecedented in the past 2 millennia. Global temperature is continuing to rise at an accelerated rate (Mann & Jones 2003, Moberg et al. 2005). Although higher temperatures will increase total bio-productivity according to biological principles, when the temperature

is already very high, any further temperature rises can also bring adverse impacts on agriculture.

Recent research also confirms that the detrimental impact of increasing warmth on agricultural production appears to be overriding its beneficial effect (Brown 2004, Lobell & Field 2007). In fact, the greatest threat from global warming comes from the uncertainty of ecosystem change; perhaps we are reaching the point at which it might break the balance of agroecosystems that have been long established at a lower temperature. In addition, many secondary and tertiary effects of global warming cannot be predicted based on current knowledge (Zhang et al. 2007a). How big the associated demographic impact will be is largely contingent upon the effectiveness of existing social buffering mechanisms, including social institutions at both international and national levels and social and technological developments. This topic deserves our further investigation.

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Appendix.

Table A1. Values of Malthusian parameter r in each simulation via Eq. (5)

	Temperature			Aridity threshold		
	Complete composite	Long-term trend	Short-term variation	Complete composite	Long-term trend	Short-term variation
Whole of China	0.0078	0.0058	0.0300	0.0400	0.0001	0.0400
Northern China	0.0078	0.0058	0.0400	0.0001	0.0001	0.0001
Central China	0.0133	0.0075	0.0191	0.0400	0.0001	0.0400
Southern China	0.0095	0.0103	0.0307	0.0400	0.0001	0.0400
Marginal areas	0.0367	0.0065	0.0228	0.0001	0.0024	0.0001