Climate change and migration across the Great Wall of China during the Little Ice Age

XIAORAN BU[1], YURAN SU[1], LINGYU FAN[1], QING PEI[1,2], PI-LING PAI[3], DONGMEI JIANG[4]

[1] The Hong Kong Polytechnic University, Department of Land Surveying and Geo-Informatics, Hong Kong SAR; e-mail: xiaoran.bu@polyu.edu.hk, yuran.su@connect.polyu.hk, lingyu.fan@connect.polyu.hk, qing.pei@polyu.edu.hk; peiqing618@gmail.com
[2] The Hong Kong Polytechnic University, Department of Chinese History and Culture, Hong Kong SAR; e-mail: qing.pei@polyu.edu.hk, peiqing618@gmail.com
[3] Academia Sinica, Research Center for Humanities and Social Sciences, Taipei, Taiwan; e-mail: lingpai@gate.sinica.edu.tw
[4] Zhengzhou University of Technology, Zhengzhou, China; e-mail: dongmei.jiang@zzut.edu.cn

Corresponding authors: Qing Pei (qing.pei@polyu.edu.hk, peiqing618@gmail.com), Dongmei Jiang (dongmei.jing@zzut.edu.cn)

ABSTRACT This study examines migration across the Great Wall of China in response to climate change in Chinese history during the Little Ice Age (1500–1850 ad) and assesses the effectiveness of the Great Wall as a barrier based on the push-pull theory. It empirically analyzes the spatiotemporal patterns of migration across the Great Wall based on datasets on precipitation, temperature, population size, and migration events. Here we show that more migration events occurred during the cooling climate period. Furthermore, more migrants came from farther north to cross the Great Wall during dry periods. These results imply the general ineffectiveness of the Great Wall in blocking migration. The findings serve as a reminder that if human survival is threatened (e.g., by climatic events), barriers may not successfully block migration. Thus, evaluating the effectiveness of barriers in accordance with the stressors of migration is important when applying the push-pull model.

KEY WORDS climate change – migration – barrier – push-pull theory – Great Wall of China

BU, X., SU, Y., FAN, L., PEI, Q., PAI, P.-L., JIANG, D. (2025): Climate change and migration across the Great Wall of China during the little ice age. Geografie, 130, 3, 299–320.
https://doi.org/10.37040/geografie.2025.009
Received March 2025, accepted July 2025.

1. Introduction

Recent studies have examined historical migration and relevant driving factors from multiple perspectives (Van Mol, De Valk 2016; Manning, Trimmer 2020). Apart from the discussions that focused on social (Carleton, Hsiang 2016), economic (Kwilinski et al. 2022), and political (Urbański 2022) factors, the role of climate change in interpreting historical migration has been emphasized more in recent years (Drake 2017; Damette, Goutte, Pei 2020). Although existing studies have explained past migration events from diverse viewpoints, push-pull theory has been largely considered a key theoretical framework for reviewing climate–migration relationship in global human history (Daoust, Selby 2024).

The core concept of the push-pull theory is that migration is determined by both push and pull factors, which could be economic, social, political or environmental (Kline 2003; Fouberg, Murphy, De Blij 2015; Jones 2016; Khalid, Urbański 2021). In the push-pull theory, migrant's decisions will consider the factors of origin, destination, intervening obstacles and personal preferences (Lee 1966; Bean, Brown 2014). More specifically, the push factor involves conditions that force people to leave their homes; and the pull factor attracts people to move to destinations (Zanabazar, Kho, Jigjiddorj 2021; Urbański 2022). Between the origin places and destinations, there stands intervening obstacles, which are the barriers that migrants have to overcome in their migration. The intervening obstacles may include geographical barriers, social barriers, political barrier, financial barrier and cultural barrier (Lisec et al. 2008; Myślicki 2016; Klaus, Pachocka 2019). Lee (1966) argues that migration occurs when the potential benefits of the destination outweigh the costs of crossing the barriers. Therefore, barrier is a factor that needs to be examined and evaluated in migration analysis, which influences migration decisions to a certain extent.

Although the push-pull theory has been widely used to explain historical migration, several aspects have not yet been sufficiently discussed. First, only a few studies have focused on the role of barriers in the framework of push-pull theory, even though barriers are considered critical intermediate elements to influence the migration process (Castelli 2018; Klaus, Pachocka 2019; Khalid, Urbański 2021). Second, quantitative attempts to uncover the role of barriers in blocking migration are limited. Although some studies have focused on the role of barriers, such as language (Davda, Gallagher, Radford 2018) and political (King 2018) barriers, they have only been conducted in a qualitative manner or on a case study basis. Third, research that has adopted a climate perspective to examine historical migration across barriers remains limited. The driving forces of climate change should be connected more with the role of barriers in the migration process to improve current knowledge in the framework of push-pull theory.

To advance critical evidence and findings from such case studies, recent research has investigated long historical time series to holistically reinterpret pre–1900 CE

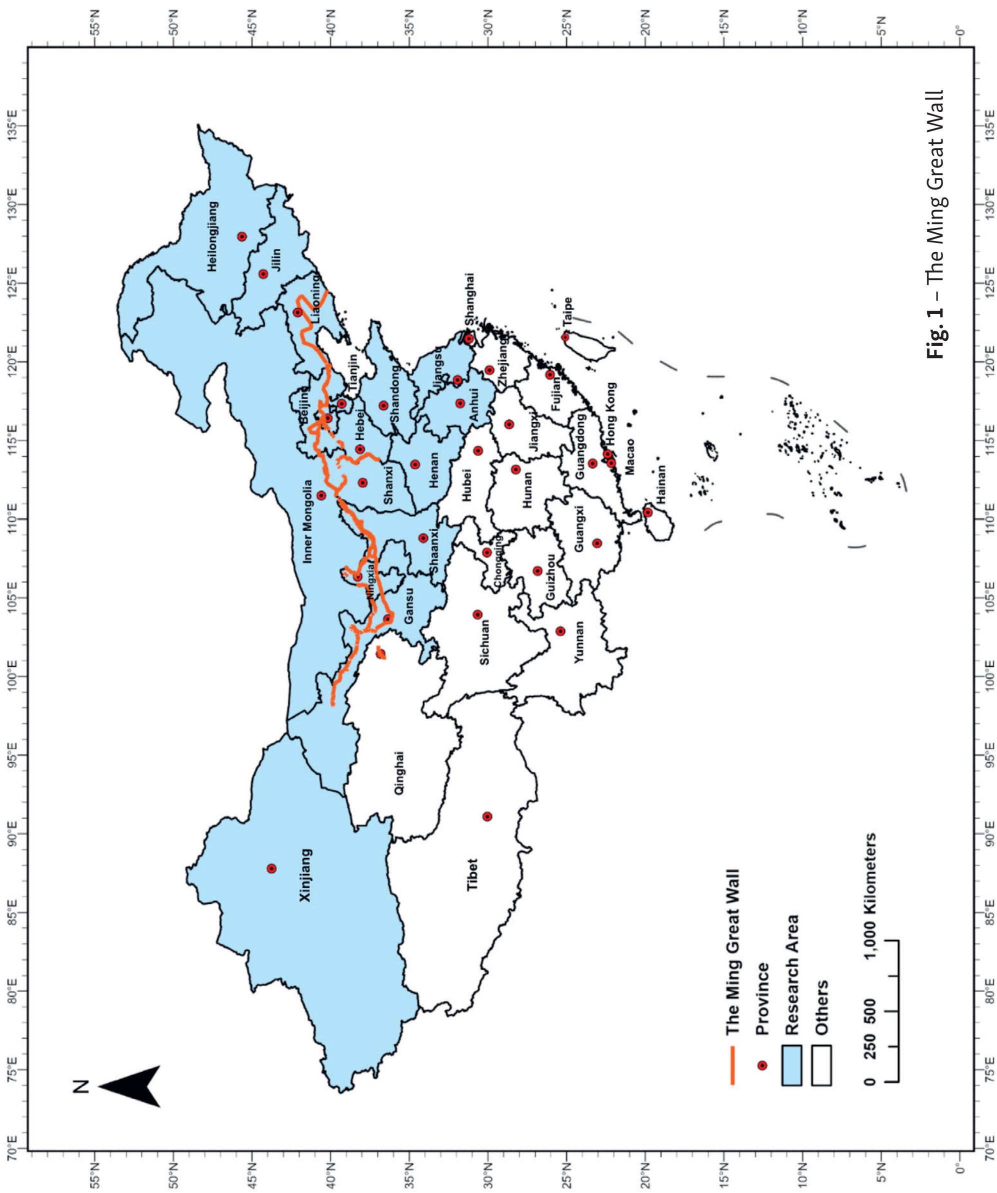

Fig. 1 – The Ming Great Wall

social dynamics under climate change (Hsiang, Burke, Miguel 2013). China has typically elicited considerable academic attention because of its rich records on past migration events. Furthermore, the Great Wall of China acted as a barrier to block agricultural and pastoral zones from 7th BC (Hang 2018). It was rebuilt as a military barrier roughly around the new boundaries in Ming Dynasty (Bai, Arabadzhyan, Li 2022) and inherited by the Qing Dynasty (Chen, Dong 2016). Therefore, the Great Wall is a perfect example for reinterpreting historical migration and the role of barriers in the framework of the push-pull theory (Fig. 1). In this frontier region of arid and semiarid land, ancient Chinese suffered from limited living resources because of climate change and sought survival through migration.

To address these existing gaps, the current study set the study period from 1500 CE to 1850 CE. The selected study period not only fits the background of the Great Wall but is also within the Little Ice Age to emphasize the influence of climate change in the past (Mann 2002; Chen et al. 2015). Moreover, this time span can be reasonably associated with the specific socioeconomic formation of imperial China before the widespread change brought about by the Opium War (Qiu et al. 2024). The Great Wall's adjacent regions, particularly Inner Mongolia and Manchuria, and Northern China set as the study area. The macroscale in the study will uncover temporal and spatial patterns of migration across the Great Wall under climate change in an empirical manner.

The current study is primarily based on empirical evidence from the quantitative analysis using paleoclimate data series and historical migration records across the Great Wall. Notably, this research is conducted on a macroscale, and the findings are concluded from a long time and a large spatial scale. Therefore, the findings may differ from the findings of existing studies conducted at a short term, a relatively small spatial scale or a case-based study. Our study does not reject and deny current knowledge or findings if a different scale in geography is being shared. This study only aims to supplement current knowledge on migration under climate change when facing the barrier of the Great Wall in historical China. Although limited in certain aspects, this broad-brush approach suits the study within the context of historical China to examine the effect of climate change on migration and evaluate the role of the Great Wall as a barrier in the framework of push-pull theory.

2. Data sources

2.1. Climate indicators: Precipitation and temperature

Precipitation and temperature are the two primary variables that determine climatic conditions (Gimmi et al. 2007). Therefore, the current study uses precipitation and temperature to reflect paleoclimatic conditions. In the present work, climate change largely refers to drought and cooling, which have been disastrous to human society in the past (Hsiang, Burke, Miguel 2013; Parker 2013; Degroot et al. 2021).

Precipitation in this study is indicated by the drought and flood indices (Fig. 2A) used by Yang (2024). Drought and flood indices by Yang (2024) from 57 monitoring stations were selected across North, Northwest, and Northeast China, which covered the regions of migration events that occurred during the study period. There are five levels to indicate the drought to flood: Level 1 is flood, Level 2 is relatively flood, Level 3 is normal, Level 4 is relatively drought, and Level 5 is drought. The determination of Level 1 requires clear records of flood disasters – large-scale or prolonged heavy precipitation leading to floods that cause significant socioeconomic losses and impacts. The determination of Level 5 is a long period without precipitation, and severe socioeconomic losses and impacts.

During the study period, the selected data by Yang (2024) is largely from the book *A Compendium of Chinese Meteorological Records of Past 3,000 Years* (Zhang 2013), which encompasses the weather and disaster data in the official histories and local gazetteers. It is currently the most comprehensive and available collection of climate data in China (Xia 2015; Yang 2024). Yang (2024) applied the 5-level classification to assess drought and flood conditions based on historical records in China. The method of Yang (2024) was commonly accepted and firstly applied in the *Atlas of Drought and Flood Distribution in China Over the Past Five Hundred Years* (Chinese Academy of Meteorological Sciences 1981) and has been proven to be feasible and scientifically robust (Shen et al. 2007; Yi et al. 2012).

The book *A Compendium of Chinese Meteorological Records of Past 3,000 Years* edited by Zhang (2013) is widely recognized as an important resource for paleoclimate reconstruction (Yin, Su, Fang 2016). At present, many studies have conducted precipitation reconstruction based on the work by Zhang (2013), such as reconstruction of May – September precipitation field in China (Shi et al. 2017) and reconstruction of grid precipitation anomaly field from 1501 to 1900 CE (Zhang, Wang, Sun 2003). This study thus followed the current practice to use drought and flood indices by Yang (2024) to represent the precipitation anomaly. Any missing value will be assigned as Level 3 in accordance with the current common practice (He et al. 2016). Then, the drought and flood indices will be reversed by multiplying −1 before conducting statistical analysis. Finally, the five-level drought and flood indices from the 57 stations will be annually summed and averaged to produce the regional series for this study.

Temperature in this study (Fig. 2B) is adopted from the reconstruction by Ge et al. (2013), which was based on multiple proxies, including sediments, stalagmites, historical documents, tree rings, and ice cores. Furthermore, this temperature reconstruction is regarded as one of representative climatic reconstructions in China (Mauelshagen 2014).

Notably, paleoclimate reconstructions only reflect precipitation and temperature anomalies, but not actual instrumental records. Researchers have reconstructed paleoclimate conditions based on different proxies, including documents, tree rings, lake sediments, and ice cores (Mann et al. 2008, 2009). These climate reconstructions only capture and reflect the climatic fluctuations but not absolute temperature or precipitation values in the past climate conditions (Ljungqvist et al. 2012, 2016). Although there are regional differences in climate conditions, the fluctuation patterns follow similar trends across the regions with a large-scale reconstruction (Ge et al. 2013). Therefore, reconstructed climate anomalies are scientific indicators of paleoclimatic conditions, which can be adopted to explore the relationship between climate change and migration when facing the barrier.

2.2. Population size

Population has increased rapidly since the 17th century (Ho 1959), resulting in tension between access and use of resources (Lee, Campbell 1997). Therefore, population pressure must be included to understand the phenomena of past migration patterns across the Great Wall. Considering both the trajectory of the Great Wall and the regions from which the drought and flood indices were derived, the study uses population data from Northwest, North, and Northeast China to enable a more regionally accurate analysis. Data on population (Fig. 2C) are retrieved from *The History of Chinese Population* by Zhao and Xie (1988) to estimate the size of historical Chinese population. The population data of Zhao and Xie (1988) have been recognized as the most reliable population data series at present (Turchin 2005).

However, many data are missing in the population records. To interpolate missing data, the common logarithm of data points is obtained, linearly interpolated, and anti-logged to create an annual time series. This method prevents any distortions in the population growth rate that originate from the linear data interpolation process because population growth follows exponential changes. The log transformation stabilizes the variances of these variables (Durbin et al. 2002). Such a practice follows the traditional interpolation method on missing population data (Galloway 1986; Zhang et al. 2011).

2.3. Migration

Migration events (Fig. 2D) are collected from the latest chronology *The History of Chinese Migration* (Ge 2022), which provides migration events for the entirety of China from 2100 BC to 2000 CE based on the works of ancient Chinese royal historians and scientists. Migration is broadly defined and includes most human

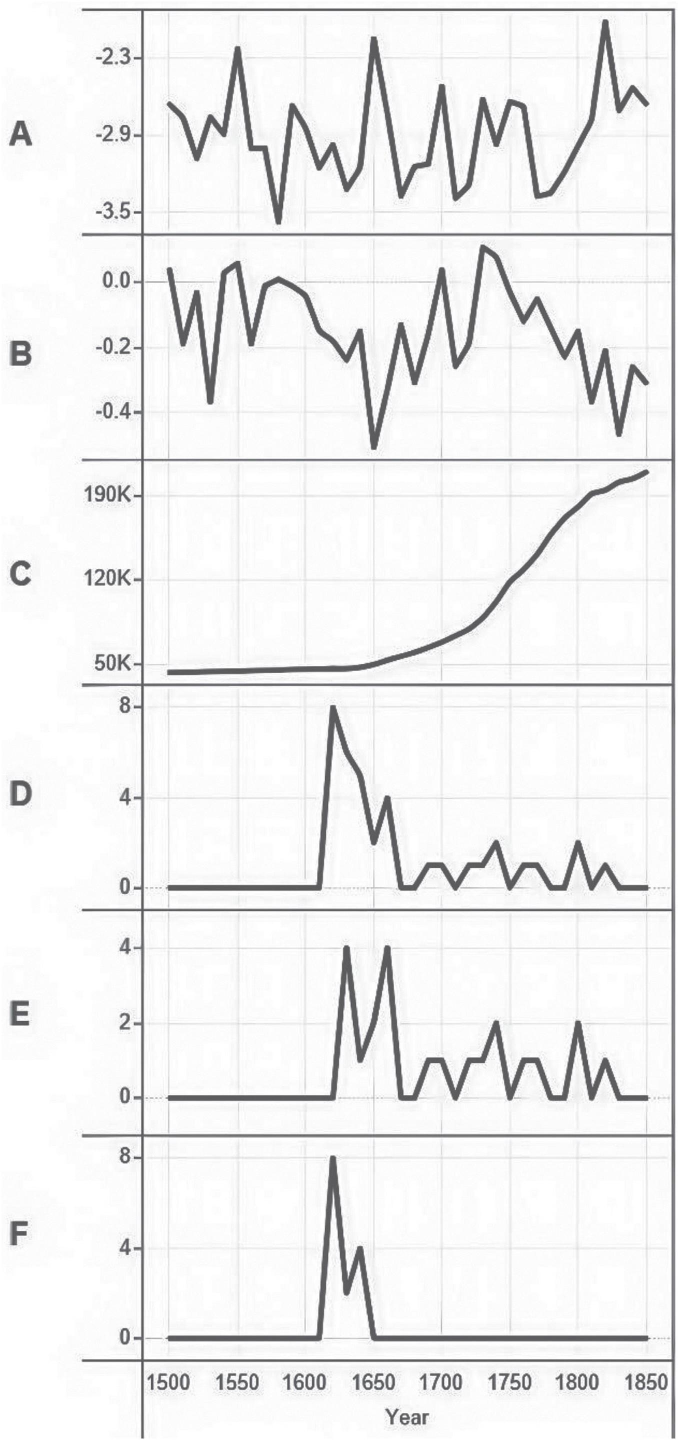

Fig. 2
A – Drought and flood indices (Yang 2024).
B – Temperature anomaly (°C; Ge et al. 2013).
C – Population size (Zhao, Xie 1988).
D – All migration events across the Great Wall (number of events; Ge 2022).
E – Northward migration events across the Great Wall (number of events; Ge 2022).
F – Southward migration events across the Great Wall (number of events; Ge 2022).

movement in historical China, including information on departure, destination, or migrant identity (Ge, Wu, Cao 1997). This latest chronology also has updated a previous version on Chinese migration in history by Ge, Wu, Cao (1997), which has been extensively used in studies on Chinese migration (Campbell, Lee, Elliott 2002; Pei et al. 2019), because these historical records on migration across the Great Wall have been collected from sources based on official histories.

Chinese records provide detailed information on locations of departure and arrival, and thus, the direction of migration is regarded as northward migration across the Great Wall (Fig. 2E) and southward migration across the Great Wall (Fig. 2F). The two directions have been identified as the major spatial preference in migration studies of China's history (Bai, Kung 2011; Pei, Zhang, Lee 2016). Moreover, the latitude of departure, longitude of departure, latitude of arrival, and longitude of arrival are determined in accordance with information on departure and destination locations in migration events.

3. Methodology

The current study will conduct statistical analyses on the temporal and spatial scales by Poisson regression and one-way analysis of variance (ANOVA). For temporal patterns, data on migration from historical documents are recorded in the format of count data. Poisson regression is thus used in this study because it is the most appropriate method for processing and validating count data (Cameron, Trivedi 2013), which is designed use the logarithm model format (Brouhns, Denuit, Vermunt 2002). Moreover, Poisson regression in this study is designed as a non-linear multivariate model (Pei, Lee, Zhang 2018) with climate variables, population, and migration counts. The dependent variable is the number of migration events that crossed the Great Wall, while the independent variables include decadal anomalies of temperature, drought and flood indices, and population size. These variables were selected to capture the core climatic and demographic factors that may influence large-scale migration dynamics. The statistical significance criterion is set as 0.05 (95%) in the current study.

Notably, the temporal analysis is conducted at the decadal scale to maintain consistency with the temporal resolution of previous studies (Fang, Liu 1992; Pei et al. 2024). The decade-scale research is a good balanced temporal scale to review past social dynamics, because the historical miseries and collapse of past dynasties typically represent multi-annual to multi-decadal temporal shifts of environmental or demographic state (Fan 2015). In addition to theoretical considerations, the decadal scale also avoids the problem of numerous zeros in Poisson regression at the technical level (Hall 2000). In sum, such temporal resolution of decadal scale to quantitatively analyze climate–society relationship in historical China has been widely applied (Feng et al. 2019). Therefore, we make the data series of drought and flood indices, temperature, population, and migration into 10-year intervals in the current study. All datasets have been standardized for statistical analysis.

For spatial patterns, this study employed the one-way analysis of variance (ANOVA) to statistically assess potential differences of migration origins and destinations across distinct climatic conditions. This method is appropriate because ANOVA tests for statistically significant differences in the means of variables (departure/arrival latitude and longitude) between defined categorized climatic groups (wet/dry, and mild/cold; Zhang et al. 2020). Notably, we use "mild" instead of "warm" in below categorization of climatic phase, because the Little Ice Age is generally a cold period, and we hope to establish a name that is different from the current "warming" trend of climate change. Therefore, using the "mild" to indicate a climatic condition above the average temperature during the study period is better.

Moreover, the study uses provinces as the basic unit because historical records are typically compiled based on current provinces, and thus, the provincial scale can achieve a good balance between spatial resolution and accuracy (Ge, Wu, Cao 1997). Therefore, the latitude and longitude of departure and arrival are calculated in accordance with each provincial centroid to examine the spatial patterns of migration in the current study.

ANOVA tests were conducted for each of the four primary geographic coordinates: departure latitude, departure longitude, arrival latitude, and arrival longitude. The independent variables were defined as classified climatic conditions. The first classification is dry and wet periods, determined by comparing drought and flood indices against the average value across the research period (periods above average termed as "Wet", and below as "Dry"). The second classification is mild and cold periods, which also use reconstructed temperature values compared to the average value to determine (periods above average termed as "Mild", and below as "Cold"). Consequently, each geographic coordinate was independently tested for significant differences between wet and dry period, and separately between mild and cold period, resulting in totally eight ANOVA analyses as shown in Tables 2 and 3.

4. Results

4.1. Temporal patterns of migration across the Great Wall under climate change

The statistical results provided in Table 1 show that all migration events across the Great Wall exhibit a significantly negative relationship with temperature rather than with precipitation. When temperature was lower, more migration events

Table 1 – Poisson regression results of climate change and migration

	All migration events across the Great Wall	Northward migration events across the Great Wall	Southward migration events across the Great Wall
Constant	−0.150	−0.537*	−6.635*
Precipitation	−0.155	0.050	−0.880*
Temperature	−0.363*	−0.281	−0.797*
Population	−0.510*	−0.187	−7.921*

* Significant at 0.05 level.

occurred during the study period. When considering the direction of migration, southward migration across the Great Wall exhibits a significantly negative relationship with precipitation and temperature. That is, less precipitation or lower temperature drives more southward migration across the Great Wall. Meanwhile, northward migration across the Great Wall exhibits no direct linkage with climate change, as indicated by the insignificant results in Table 1.

In accordance with the results, migration across the Great Wall, particularly southward migration, is significantly related to climate change. The migrants who crossed the Great Wall in a southward direction were definitely from the north of China, where the local ecosystem was more vulnerable to climate change (Soussana et al. 2013). Reduced rainfall and decreased temperature can lead to land degradation and even desertification (Zhang et al. 2007). Therefore, southward migration from the north across the Great Wall is more sensitive to climate change. Generally speaking, temperature is more important to affect migration across the Great Wall according to our results because temperature is significant to both all migration events and southward migration events. The cooling climate during the Little Ice Age made social communities along the Great Wall particularly vulnerable to temperature decrease, which was also the case worldwide during the same climatic epoch (Atwell 2002; Fan 2015).

However, northward migration across the Great Wall presented a different image. In Chinese history, northward migration across the Great Wall was more affected by many political and social factors (Reardon-Anderson 2000; Ye, Fang, Aftab U Khan 2012; Xiao, Fang, Ye 2013). During the Qing Dynasty, some farmers were even driven by the Qing government to move northward across the Great Wall (Fang, Yin 2007; Jia, Li, Fang 2018). Therefore, the results do not completely refute the importance of climate change in northward migration across the Great Wall, but it only exerted a limited driving effect compared with other socioeconomic factors to northward migration.

4.2. Spatial patterns of migration across the Great Wall under climate change

As mentioned earlier, ANOVA is employed to check whether a significant difference exists in the spatial patterns of migration during the wet–dry and mild–cold periods. The statistical results presented in Tables 2 and 3 indicate that departure and arrival information in space are checked in accordance with the wet or dry and mild or cold periods. When comparing the latitude of departure, longitude of departure, latitude of arrival, and longitude of arrival during the wet and dry periods, the latitude of departure, latitude of arrival, and longitude of arrival are significant via the ANOVA test. Therefore, the ANOVA results indicate that precipitation exhibits a closer association with the spatial patterns of migration.

In particular, the latitude of departure during the dry period is significantly higher than that during the wet period because more migrants in the north suffer from drought. Therefore, drought will cause more migrants to travel from even farther north to cross the Great Wall. The latitude of arrival during the dry period is significantly lower than that during the wet period, while the longitude of arrival during the dry period is significantly higher than that during the wet period. Drought will cause migrants to travel to more southern regions where they may eventually have sufficient heat and water. Many migrants originate from Northeast China, and thus, they will move westward if they come to Central China, where climate is warmer and wetter.

From the analysis of the temporal and spatial patterns of migration across the Great Wall, temperature and precipitation have demonstrated significant effects

Table 2 – ANOVA results on departure and arrival locations between wet and dry periods

	Wet	Dry	Comparison	F-test	P-value
Latitude Departure	38.149	40.237	Wet < Dry	5.944	0.027*
Longitude Departure	115.330	119.584	—	3.471	0.081
Latitude Arrival	45.017	40.012	Wet > Dry	6.235	0.024*
Longitude Arrival	110.579	117.866	Wet < Dry	5.335	0.035*

* Significant at 0.05 level.

Table 3 – ANOVA results on departure and arrival locations between mild and cold periods

	Mild	Cold	Comparison	F-test	P-value
Latitude Departure	39.053	40.308	—	2.969	0.104
Longitude Departure	117.176	119.725	—	1.826	0.195
Latitude Arrival	43.172	39.683	—	4.462	0.051
Longitude Arrival	117.859	115.883	—	0.391	0.541

* Significant at 0.05 level.

on migration. Temperature is more related to temporal patterns, while precipitation is more associated with spatial patterns. From a climatic perspective, the push factors are social and economic crisis derived by climate change (Pei, Lee, Zhang 2018). The pull factors are the mild and wet climatic conditions, such as rice region and wheat region in the south of pastoral region (Pei, Zhang, Lee 2016).

5. Discussion

5.1. Migration across the Great Wall as an adaptive choice to climate change

Temperature and precipitation are important for understanding migration across the Great Wall. Although the study period is set during the Little Ice Age, any further decrease in temperature will cause historical Chinese people to suffer more from climatic stressors in accordance with Table 1. However, the Little Ice Age lasted for hundreds of years. Despite the ability of humans to adapt to climatic effects, institutional and social buffering mechanisms will be ultimately exhausted by recurrent subsistence crises caused by long-term climate change (Orlove 2005).

In accordance with our results, migration to a mild or wet region will be preferred as an adopted adaptation under climatic stress, despite the barrier posed by the Great Wall. Although social institutions and technology can improve resilient capacity to climate change, cultural adaptation is a difficult and time-consuming process for any society, and it takes several decades to thousands of years to accomplish (Burton, Kates, White 1993). By contrast, migration is an instantaneous way of adapting to climate-generated ecological stress. However, drought plus coldness will cause migrants to travel longer distances, as indicated in Tables 2 and 3. That is, the regions in the south of the Great Wall may not be suitable under unfavorable climate. Migrants have to face more uncertainties to cross the Great Wall and look for suitable destinations in the farther south as shown in Tables 2 and 3. Therefore, migration is still not a pleasant adaptive choice during climate change, and it may even lead to other form of social chaos through a domino effect (Feng et al. 2019).

5.2. Revisiting the role of the Great Wall from a climate perspective

The Great Wall was built in the 7th BC to protect against invaders as a military barrier (Di Cosmo 1993). The history of the Great Wall involves the relationship between the so-called civilized agricultural China and the barbarians from Central Asia, Mongolia, and Manchuria, i.e., the group of nomads mentioned in the beginning of this paper. During the Ming Dynasty, the Great Wall was rebuilt to make a complete defense system made up of passes, forts, watchtowers and beacon towers (Tackett 2008, Zhang 2015). Moreover, the Great Wall has very long walls built along mountain ridges on steep slopes and surrounded by forests and other unvisited places (Bai, Arabadzhyan, Li 2022).

However, the Great Wall has been proven as a failure in achieving this goal as indicated by our results in Tables 1–3. Migration across the Great Wall is significantly associated with changing climate. As shown in Figure 2, climate has always been changing over decades and centuries (Huggett 1991; Pei at al. 2017). Within these time scales, macroscale climatic changes have markedly affected human society during prehistoric and historic periods (Bell, Walker 2014). In reality, the Great Wall never succeeded in blocking interactions among different regions (Jing 2015). Therefore, the Great Wall could be interpreted more from the perspective of cultural symbol (Di Cosmo 1993) or a farming divide (Liu, Gao, Yang 2003). As a military defense against the invasion of people from the north (Gao et al. 2023), the Great Wall did not successfully prevent their southward migration, as further supported by our results.

The current study uses climate change as an essential factor to explain migration across the Great Wall. In this regard, our study claims that the Great Wall should be interpreted more as an ecological divide as already emphasized in academia (Su et al. 2016). The Great Wall roughly coincides with the 400 mm precipitation line in China (Zhu, Chen, Guo 2018; Wang et al. 2022), signifying that the regions along the Great Wall overlap with the agricultural and pastoral transitional zone in Northern China (Wang et al. 2024). Therefore, when the climate becomes cold and dry, this transitional zone shifts southward, reaching areas with relatively sufficient water and heat, and accompanying the migration of residents. Furthermore, the differences between the two ecological environments have led people to make different cultural choices to adapt to their survival needs, resulting in the divergence between nomadic and agrarian cultures (Pei, Lee, Zhang 2018).

5.3. Reviewing the barrier of the push-pull theory from the lessons of China's past

The significant association between climate change and migration across the Great Wall indicates that barriers cannot effectively block migrants if they are under survival pressure. Climate change directly and strongly affects human lives and living quality (Edwards, Kerber, Wirsching 2013). This phenomenon was even true in past societies with high vulnerabilities. Studies on climate change may be generalized to other types of fatal natural stressors, such as sea floods and heat waves, which cause people to migrate. These migrants who are facing "live or dead" situations are usually forced to cross all barriers for survival.

However, the findings from China's past do not refute the role and importance of barriers in the framework of pull–push theory. Existing research considers that barriers can block migration mostly from the cultural and linguistic aspects (Klugman 2009; Wang, De Graaff, Nijkamp 2018). Moreover, economic barriers are also among the crucial barriers in the migration process (Li et al. 2016). In addition, migration has legal, physical, and other barriers (Choudhury, Khanna 2012; Wang, Benjamin 2019). However, these aforementioned barriers, which can successfully block most migration events, are not accompanied by survival pressure.

In summary, the study on China's past has provided a reminder for scholars when using the push-pull theory for migration studies in the future. If push or pull factors are related to survival, then the barrier may be unable to block migrants. When analyzing migration in the future, assessing first whether the pressure of push and pull factors is related to basic survival needs is necessary. If a push or pull factor is linked to survival, then barriers will not be effective in blocking migration. However, many factors in the past, present, and even future may affect human survival and drive mass migration. Among these factors, climate change is one of the fundamental driving forces.

6. Conclusion

The current study identifies the effect of climate change on migration across the Great Wall during the Little Ice Age from 1500 CE to 1850 CE. More migration events occurred during the unfavorable climate period, particularly southward migration across the Great Wall. Furthermore, more migrants came from even farther north to cross the Great Wall and reach farther south during the dry periods. These results suggest that the Great Wall did not effectively block migration as a political, physical, or military barrier, indicating that barriers can be overcome when people are forced by driving factors from survival pressure. The Great Wall should be regarded more as an ecological divide from a climate perspective as claimed in this study, which supplements the current views on the Great Wall. In this regard, this study suggests that the application of push-pull theory should first assess whether pressure from push and pull factors is related to basic survival needs.

As claimed, the present study is different from existing ones in terms of spatiotemporal scale and adopted methods. It does not claim that climate change is the only or most important trigger behind migration events that occur across the Great Wall. This study adopts a macro view and recognizes the importance of other factors to understand the history of climate and society (White et al. 2023). The findings will add an environmental value to advance current knowledge from a climatic perspective.

At present, we are facing ambiguous changes in climatic conditions. Certain countries and regions may still share a development level similar to that in historical China during our study period. The findings of this study can serve as a historical reference, offering insights into contemporary climate migration. Moreover, more migration events will possibly occur in the future due to climate change, and the phenomenon of "environmental migration" will worsen in the coming years (Warner et al. 2008; Kartiki 2011). For example, people from Kiribati and Tuvalu are migrating across the ocean barrier to New Zealand in search of refuge from the existential threat posed by rising sea levels due to global warming (Yates et al. 2023). However, given the complex immigration system, many migrants are currently living in invisible space as illegal immigrants, trapped in a state of "deportability" purgatory (Menjívar, Abrego 2012). In recent years, the construction of the U.S. border wall has been shown to increase cross-border migration flows (Schon, Leblang 2021). These contemporary migration phenomena demonstrate that natural, physical, political, and economic barriers are ineffective in consequence under the current climate change and other survival crises. In addressing contemporary climate migration, survival pressure should be closely monitored. Once survival pressure exceeds a critical threshold, potential arrival locations for climate migrants should focus on their proper resettlement rather than on constructing barriers to block them. The latter will be ineffective and can even provoke conflicts and unrest in accordance with our historical reference.

References

ATWELL, W.S. (2002): Time, Money, and the Weather: Ming China and the "Great Depression" of the Mid-fifteenth Century. The Journal of Asian Studies, 61, 1, 83–113. https://doi.org/10.2307/2700190

BAI, Y., KUNG, J.K.S. (2011): Climate Shocks and Sino-Nomadic Conflict. The Review of Economics and Statistics, 93, 3, 970–981. https://doi.org/10.1162/REST_a_00106

BAI, Y., ARABADZHYAN, A., LI, Y. (2022): The Legacy of the Great Wall. Journal of Economic Behavior & Organization, 196, 120–147. https://doi.org/10.1016/j.jebo.2022.01.010

BEAN, F., BROWN, S. (2014): Demographic analyses of immigration. Migration theory: talking across discipline. Routledge, New York.

BELL, M., WALKER, M.J. (2014): Late Quaternary Environmental Change: Physical and Human Perspectives. Routledge. https://doi.org/10.4324/9781315847740

BROUHNS, N., DENUIT, M., VERMUNT, J.K. (2002): A Poisson Log-bilinear Regression Approach to the Construction of Projected Lifetables. Insurance: Mathematics and Economics, 31, 3, 373–393. https://doi.org/10.1016/S0167-6687(02)00185-3

BURTON, I., KATES, R.W., WHITE, G.F. (1993): The Environment as Hazard. New York, Guilford Press.

CAMERON, A.C., TRIVEDI, P.K. (2013): Regression Analysis of Count Data. Cambridge University Press. https://doi.org/10.1017/CBO9781139013567

CAMPBELL, C., LEE, J.Z., ELLIOTT, M. (2002): Identity Construction and Reconstruction: Naming and Manchu Ethnicity in Northeast China, 1749–1909. Historical Methods: A Journal of Quantitative and Interdisciplinary History, 35, 3, 101–115. https://doi.org/10.1080/01615440209601201

CARLETON, T. A., HSIANG, S.M. (2016): Social and Economic Impacts of Climate. Science, 353, 6304, aad9837. https://doi.org/10.1126/science.aad9837

CASTELLI, F. (2018): Drivers of Migration: Why do People Move? Journal of Travel Medicine, 25, 1, tay040. https://doi.org/10.1093/jtm/tay040

CHEN, H., DONG, Y. (2016): Chronicles of the Great Wall of China. Nanjing, Jiangsu.

CHEN, J., CHEN, F., FENG, S., HUANG, W., LIU, J., ZHOU, A. (2015): Hydroclimatic Changes in China and Surroundings during the Medieval Climate Anomaly and Little Ice Age: Spatial Patterns and Possible Mechanisms. Quaternary Science Reviews, 107, 98–111. https://doi.org/10.1016/j.quascirev.2014.10.012

CHINESE ACADEMY OF METEOROLOGICAL SCIENCES (1981): Atlas of the distribution of droughts and floods in China over the past five hundred years. Ditu Press, Beijing.

CHOUDHURY, P., KHANNA, T. (2012): Physical, Social, and Informational Barriers to Domestic Migration in India. Institutions and Comparative Economic Development, Springer, 173–183. https://doi.org/10.1057/9781137034014_10

DAMETTE, O., GOUTTE, S. PEI, Q. (2020): Climate and Nomadic Migration in a Nonlinear World: Evidence of the Historical China. Climatic Change, 163, 4, 2055–2071. https://doi.org/10.1007/s10584-020-02901-4

DAOUST, G., SELBY, J. (2024): Climate Change and Migration: A Review and New Framework for Analysis. Wiley Interdisciplinary Reviews: Climate Change, 15, 4, e886. https://doi.org/10.1002/wcc.886

DAVDA, L.S., GALLAGHER, J.E., RADFORD, D.R. (2018): Migration Motives and Integration of International Human Resources of Health in the United Kingdom: Systematic Review and Meta-synthesis of Qualitative Studies Using Framework Analysis. Human Resources for Health, 16, 1–13. https://doi.org/10.1186/s12960-018-0293-9

DEGROOT, D., ANCHUKAITIS, K., BAUCH, M., BURNHAM, J., CARNEGY, F., CUI, J., LUNA, K., GUZOWSKI, P., HAMBRECHT, G., HUHTAMAA, H., IZDEBSKI, A., KLEEMANN, K., MOESSWILDE, E., NEUPANE, N., NEWFIELD, T., PEI, Q., XOPLAKI, E., ZAPPIA, N. (2021): Towards a Rigorous Understanding of Societal Responses to Climate Change. Nature, 591, 539–550. https://doi.org/10.1038/s41586-021-03190-2

DI COSMO, N. (1993): The Origins of the Great Wall. History, 129.

DRAKE, B.L. (2017): Changes in North Atlantic Oscillation Drove Population Migrations and the Collapse of the Western Roman Empire. Scientific Reports, 7, 1, 1–7. https://doi.org/10.1038/s41598-017-01289-z

DURBIN, B.P., HARDIN, J.S., HAWKINS, D.M., ROCKE, D.M. (2002): A Variance-stabilizing Transformation for Gene-expression Microarray Data. Bioinformatics, 18, suppl 1, S105–S110. https://doi.org/10.1093/bioinformatics/18.suppl_1.S105

EDWARDS, J., KERBER, G., WIRSCHING, S. (2013): Climate Change-Induced Displacement: What is at Stake? A Climate Justice Perspective. Climate Refugees People Displaced by Climate Change and the Role of the Churches, 23–53.

FAN, K.W. (2015): Climate Change and Chinese History: A Review of Trends, Topics, and Methods. Wiley Interdisciplinary Reviews, Climate Change, 6, 2, 225–238. https://doi.org/10.1002/wcc.331

FANG, J., LIU, G. (1992): Relationship between Climatic Change and the Nomadic Southward Migrations in Eastern Asia during Historical Times. Climatic Change, 22, 2, 151–168. https://doi.org/10.1007/BF00142964

FANG, X., YIN, P. (2007): Review on the Three Key Concepts of Resilience, Vulnerability and Adaptation in the Research of Global Environmental Change. Progress in Geography, 26, 5, 11–22.

FENG, Q., YANG, L., DEO, R.C., AGHAKOUCHAK, A., ADAMOWSKI, J.F., STONE, R., YIN, Z., LIU, W., SI, J., WEN, X. (2019): Domino Effect of Climate Change over Two Millennia in Ancient China's Hexi Corridor. Nature Sustainability, 2, 957–961. https://doi.org/10.1038/s41893-019-0397-9

FOUBERG, E.H., MURPHY, A.B., DE BLIJ H.J. (2015): Human geography: people, place, and culture. John Wiley & Sons, New Jersey.

GALLOWAY, P.R. (1986): Long-term Fluctuations in Climate and Population in the Preindustrial Era. Population and Development Review, 12, 1, 1–24. https://doi.org/10.2307/1973349

GAO, M., GU, Q., HE, S., KONG, D. (2023): The Long-run Effects of the Imperial Bureaucracy: Two Tales along the Great Wall of Ming China. Asia-Pacific Economic History Review, 63, 2, 249–293. https://doi.org/10.1111/aehr.12267

GE, J. (2022): Zhong Guo Yi Min Shi (Chinese Migration History). Fudan University Press.

GE, J., WU, S., CAO, S. (1997): Zhong Guo Yi Min Shi (Chinese Migration History). Fujian People's Publishing House, Fu Jian.

GE, Q., HAO, Z., ZHENG, J., SHAO, X. (2013): Temperature Changes over the Past 2000 yr in China and Comparison with the Northern Hemisphere. Climate of the Past, 9, 3, 1153–1160. https://doi.org/10.5194/cp-9-1153-2013

GIMMI, U., LUTERBACHER, J., PFISTER, C., WANNER, H. (2007): A Method to Reconstruct Long Precipitation Series Using Systematic Descriptive Observations in Weather Diaries: the Example of the Precipitation Series for Bern, Switzerland (1760–2003). Theoretical and Applied Climatology, 87, 1–4, 185–199. https://doi.org/10.1007/s00704-005-0193-5

HALL, D.B. (2000): Zero-Inflated Poisson and Binomial Regression with Random Effects: A Case Study. Biometrics, 56, 4, 1030–1039. https://doi.org/10.1111/j.0006-341X.2000.01030.x

HANG, J. (2018): Comparison of Zhongnan Culture and Nomadic Culture. 2nd International Conference on Culture, Education and Economic Development of Modern Society (ICCESE 2018), Atlantis Press. https://doi.org/10.2991/iccese-18.2018.121

HE, W., ZHAO, S., LIU, Q., JIANG, Y., DENG, B. (2016): Long-range Correlation in the Drought and Flood Index from 1470 to 2000 in Eastern China. International Journal of Climatology, 36, 4. https://doi.org/10.1002/joc.4450

HO, P.T. (1959): Studies on the Population of China, 1368–1953. Harvard University Press. https://doi.org/10.4159/harvard.9780674184510

HSIANG, S.M., BURKE, M., MIGUEL, E. (2013): Quantifying the Influence of Climate on Human Conflict. Science, 341, 1235367. https://doi.org/10.1126/science.1235367

HUGGETT, R.J. (1991): Climate, Earth Processes, and Earth History. Berlin, Springer-Verlag. https://doi.org/10.1007/978-3-642-76268-0

JIA, D., LI, Y., FANG, X. (2018): Complexity of Factors Influencing the Spatiotemporal Distribution of Archaeological Settlements in Northeast China over the Past Millennium. Quaternary Research, 89, 2, 413–424. https://doi.org/10.1017/qua.2017.112

JING, A. (2015): A History of the Great Wall of China. World Scientific. https://doi.org/10.1142/z006

JONES, R.C. (2016): Harbingers of Migration Regression: Global Trends and a Mexican Case Study. Social Science Quarterly, 97, 2, 293–310. https://doi.org/10.1111/ssqu.12172

KARTIKI, K. (2011): Climate Change and Migration: a Case Study from Rural Bangladesh. Gender & Development, 19, 1, 23–38. https://doi.org/10.1080/13552074.2011.554017

KHALID, B., URBAŃSKI, M. (2021): Approaches to Understanding Migration: a Mult-country Analysis of the Push and Pull Migration Trend. Economics & Sociology, 14, 4, 242–267. https://doi.org/10.14254/2071-789X.2021/14-4/14

KING, R. (2018): Context-based Qualitative Research and Multi-sited Migration Studies in Europe. Qualitative Research in European Migration Studies, 35–56. https://doi.org/10.1007/978-3-319-76861-8_3

KLAUS, W., PACHOCKA, M. (2019): Examining the Global North Migration Policies: A "Push out–Push back" Approach to Forced Migration. International Migration, 57, 5, 280–293. https://doi.org/10.1111/imig.12575

KLINE, D.S. (2003): Push and Pull Factors in International Nurse Migration. Journal of Nursing Scholarship, 35, 2, 107–111. https://doi.org/10.1111/j.1547-5069.2003.00107.x

KLUGMAN, J. (2009): Human Development Report 2009. Overcoming Barriers: Human Mobility and Development. UNDP-HDRO Human Development Reports.

KWILINSKI, A., LYULYOV, O., PIMONENKO, T., DZWIGOL, H., ABAZOV, R., PUDRYK, D. (2022): International Migration Drivers: Economic, Environmental, Social, and Political Effects. Sustainability, 14, 11, 6413. https://doi.org/10.3390/su14116413

LEE, E.S. (1966): A Theory of Migration. Demography, 3, 47–57. https://doi.org/10.2307/2060063

LEE, J.Z., CAMPBELL, C.D. (1997): Fate and Fortune in Rural China: Social Organization and Population Behavior in Liaoning. Cambridge, UK, 1774–1873. https://doi.org/10.1017/CBO9780511563058

LI, X., XU, H., CHEN, J., CHEN, Q., ZHANG, J., DI, Z. (2016): Characterizing the International Migration Barriers with a Probabilistic Multilateral Migration Model. Scientific Reports, 6, 1, 32522. https://doi.org/10.1038/srep32522

LISEC, A., FERLAN, M., LOBNIK, F., ŠUMRADA, R. (2008): Modelling the Rural Land Transaction Procedure. Land Use Policy, 25, 2, 286–297. https://doi.org/10.1016/j.landusepol.2007.08.003

LJUNGQVIST, F.C., KRUSIC, P.J., BRATTSTRÖM, G., SUNDQVIST, H.S. (2012): Northern Hemisphere Temperature Patterns in the Last 12 Centuries. Climate of the Past, 8, 1, 227–249. https://doi.org/10.5194/cp-8-227-2012

LJUNGQVIST, F.C., KRUSIC, P.J., SUNDQVIST, H.S., ZORITA, E., BRATTSTRÖM, G., FRANK, D. (2016): Northern Hemisphere Hydroclimate Variability over the Past Twelve Centuries. Nature, 532, 7597, 94–98. https://doi.org/10.1038/nature17418

LIU, Y., GAO, J., YANG, Y. (2003): A Holistic Approach towards Assessment of Severity of Land Degradation along the Great Wall in Northern Shaanxi Province, China. Environmental Monitoring and Assessment, 82, 187–202. https://doi.org/10.1023/A:1021882015299

MANN, M.E. (2002): Little Ice Age. Encyclopedia of Global Environmental Change, 1, 504–509.

MANN, M.E., ZHANG, Z., HUGHES, M.K., BRADLEY, R.S., MILLER, S.K., RUTHERFORD, S., NI, F. (2008): Proxy-based Reconstructions of Hemispheric and Global Surface Temperature Variations over the Past Two Millennia. Proceedings of the National Academy of Sciences, 105, 36, 13252–13257. https://doi.org/10.1073/pnas.0805721105

MANN, M.E., ZHANG, Z., RUTHERFORD, S., BRADLEY, R.S., HUGHES, M.K., SHINDELL, D., AMMANN, C., FALUVEGI, G., NI, F. (2009): Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly. Science, 326, 27, 1256–1260. https://doi.org/10.1126/science.1177303

MANNING, P., TRIMMER, T. (2020): Migration in World History. Routledge. https://doi.org/10.4324/9781351256681

MAUELSHAGEN, F. (2014): Redefining Historical Climatology in the Anthropocene. The Anthropocene Review, 1, 2, 171–204. https://doi.org/10.1177/2053019614536145

MENJÍVAR, C., ABREGO, L. (2012): Legal violence: Immigration Law and the Lives of Central American Immigrants. American Journal of Sociology, 117, 5,1380–1421. https://doi.org/10.1086/663575

MYŚLICKI, A. (2016): Ukrainians' Crisis Immigration to Poland–a Chance for Polish Demography? European Journal of Geopolitics, 4, 68–94.

ORLOVE, B. (2005): Human Adaptation to Climate Change: A Review of Three Historical Cases and Some General Perspectives. Environmental Science & Policy, 8, 6, 589–600. https://doi.org/10.1016/j.envsci.2005.06.009

PARKER, G. (2013): Global Crisis: War, Climate Change and Catastrophe in the Seventeenth Century. New Haven, Yale University Press. https://doi.org/10.2307/j.ctt32bksk

PEI, Q., LEE, H.F., ZHANG, D.D. (2018): Long-term Association between Climate Change and Agriculturalists' Migration in Historical China. The Holocene, 28, 2, 208–216. https://doi.org/10.1177/0959683617721325

PEI, Q., NOWAK, Z., LI, G., XU, C., CHAN, W.K. (2019): The Strange Flight of the Peacock: Farmers' atypical northwesterly migration from central China, 200BC–1400AD. Annals of the Association of American Geographers, 109, 5, 1583–1596. https://doi.org/10.1080/24694452.2019.1570837

PEI, Q., ZHANG, D.D., LI, J., LEE, H.F. (2017): Proxy-based Northern Hemisphere temperature reconstruction for the mid-to-late Holocene. Theoretical and Applied Climatology, 130, 3, 1043–1053. https://doi.org/10.1007/s00704-016-1932-5

PEI, Q., QIU, M., LI, G., WU, K.M., MORDECHAI, L., LIU, W., ZHANG, H. (2024): Cost of Resilience to Climate Change: Migration, Conflicts, and Epidemics in Imperial China. Environmental Research Letters, 19, 11, 114025. https://doi.org/10.1088/1748-9326/ad7a8e

PEI, Q., ZHANG, D.D., LEE, H.F. (2016): Contextualizing Human Migration in Different Agro-ecological Zones in Ancient China. Quaternary International, 426, 65–74. https://doi.org/10.1016/j.quaint.2015.12.007

QIU, M., PEI, Q., LO, A., FEI, J. (2024): Lost in Luxury: Climate Change and Silk Consumption in Mid-Qing China (1735–1840 CE). The Professional Geographer, 76, 5, 543–556. https://doi.org/10.1080/00330124.2024.2345883

REARDON-ANDERSON, J. (2000): Land Use and Society in Manchuria and Inner Mongolia during the Qing Dynasty. Environmental History, 5, 4, 503–530. https://doi.org/10.2307/3985584

SCHON, J., LEBLANG, D. (2021): Why Physical Barriers Backfire: How Immigration Enforcement Deters Return and Increases Asylum Applications. Comparative Political Studies, 54, 14, 2611–2652. https://doi.org/10.1177/00104140211024282

SHEN, C., WANG, W.-C., HAO, Z., GONG, W. (2007): Exceptional Drought Events over Eastern China during the Last Five Centuries. Climatic Change, 85, 3, 453–471. https://doi.org/10.1007/s10584-007-9283-y

SHI, F., ZHAO, S., GUO, Z., GOOSSE, H., YIN, Q. (2017): Multi-proxy Reconstructions of May–September Precipitation Field in China over the Past 500 Years. Climate of the Past, 13, 12, 1919–1938. https://doi.org/10.5194/cp-13-1919-2017

SOUSSANA, J.-F., BARIONI, L.G., ARI, T.B., CONANT, R., GERBER, P., HAVLIK, P., ICKOWICZ, A., HOWDEN, M. (2013): Managing Grassland Systems in a Changing Climate: the Search for Practical Solutions.

SU, Y., LIU, L., FANG, X., MA, Y. (2016): The Relationship between Climate Change and Wars Waged between Nomadic and Farming Groups from the Western Han Dynasty to the Tang Dynasty Period. Climate of the Past, 12, 1, 137–150. https://doi.org/10.5194/cp-12-137-2016

TACKETT, N. (2008): The Great Wall and Conceptualizations of the Border under the Northern Song. Journal of Song-Yuan Studies, 3, 1, 99–138.

TURCHIN, P. (2005): War and Peace and War: The Life Cycles of Imperial Nations. New York.

URBAŃSKI, M. (2022): Comparing Push and Pull Factors Affecting Migration. Economies, 10, 1, 21. https://doi.org/10.3390/economies10010021

VAN MOL, C., DE VALK, H. (2016): Migration and Immigrants in Europe: A Historical and Demographic Perspective. Integration Processes and Policies in Europe: Contexts, Levels and Actors, 31–55. https://doi.org/10.1007/978-3-319-21674-4_3

WANG, K., ZHAO, X., ZHENG, H., ZHENG, B., XU, Y., ZHANG, F., DUAN, Z. (2024): The Agro-Pastoral Transitional Zone in Northern China: Continuously Intensifying Land Use Competition Leading to Imbalanced Spatial Matching of Ecological Elements. Land, 13, 5, 654. https://doi.org/10.3390/land13050654

WANG, S.X., BENJAMIN, F.Y. (2019): Labor Mobility Barriers and Rural-urban Migration in Transitional China. China Economic Review, 53, 211–224. https://doi.org/10.1016/j.chieco.2018.09.006

WANG, X., ZHANG, B., GUO, Q., PEI, Q. (2022): Discussion on the Environmental Adaptability of Weather-resistant Measures for Earthen Sites in China. Built Heritage, 6, 1, 19. https://doi.org/10.1186/s43238-022-00065-x

WANG, Z., DE GRAAFF, T., NIJKAMP, P. (2018): Barriers of Culture, Networks, and Language in International Migration: A Review. Region, 5, 1, 73–89. https://doi.org/10.18335/region.v5i1.203

WARNER, K., AFIFI, T., DUN, O., STAL, M., SCHMIDL, S., BOGARDI, J. (2008): Human Security, Climate Change, and Environmentally Induced Migration. Climate Change: Addressing the Impact on Human Security, 46–67.

WHITE, S., PEI, Q., KLEEMANN, K., DOLÁK, L., HUHTAMAA, H., CAMENISCH, C. (2023): New Perspectives on Historical Climatology. Wiley Interdisciplinary Reviews Climate Change, 14, 1, e808. https://doi.org/10.1002/wcc.808

XIA, M. (2015): Big Data and Ecological History: Sorting and Database Construction of Disaster Historical Materials in China. Research on Qing History, 2, 67–82.

XIAO, L.B., FANG, X.Q., YE, Y. (2013): Reclamation and Revolt: Social Responses in Eastern Inner Mongolia to Flood/drought-induced Refugees from the North China Plain 1644–1911. Journal of Arid Environments, 88, 9–16. https://doi.org/10.1016/j.jaridenv.2012.07.022

YANG, Y. (2024): Atlas of Extreme Droughts and Floods in China during the Past Millennium. China Cartographic Press.

YATES, O.E., GROOT, S., MANUELA, S., NEEF, A. (2023): "There's so much more to that sinking island!" – Restorying Migration from Kiribati and Tuvalu to Aotearoa New Zealand. Journal of Community Psychology, 51, 3, 924–944. https://doi.org/10.1002/jcop.22928

YE, Y., FANG, X., AFTAB U KHAN, M. (2012): Migration and Reclamation in Northeast China in Response to Climatic Disasters in North China over the past 300 years. Regional Environmental Change, 12, 193–206. https://doi.org/10.1007/s10113-011-0245-6

YI, L., YU, H., GE, J., LAI, Z., XU, X., QIN, L., PENG, S. (2012): Reconstructions of Annual Summer Precipitation and Temperature in North-central China since 1470 AD based on Drought/flood Index and Tree-ring Records. Climatic Change, 110, 469–498. https://doi.org/10.1007/s10584-011-0052-6

YIN, J., SU, Y., FANG, X. (2016): Climate Change and Social Vicissitudes in China over the Past Two Millennia. Quaternary Research, 86, 2, 133–143. https://doi.org/10.1016/j.yqres.2016.07.003

ZANABAZAR, A., KHO, N.S., JIGJIDDORJ, S. (2021): The Push and Pull Factors Affecting the Migration of Mongolians to the Republic of South Korea. SHS Web of Conferences, EDP Sciences, 01023. https://doi.org/10.1051/shsconf/20219001023

ZHANG, D. (2013): A Compendium of Chinese Meteorological Records of Past 3,000 Years. Jiangsu Education Press, Nanjing. 2nd Edition.

ZHANG, D.D., LEE, H.F., WANG, C., LI, B., PEI, Q., ZHANG, J., AN, Y. (2011): The Causality Analysis of Climate Change and Large-scale Human Crisis. Proceedings of the National Academy of Sciences, 108, 42, 17296–17301. https://doi.org/10.1073/pnas.1104268108

ZHANG, D.D., ZHANG, J., LEE, H.F., HE, Y.Q. (2007): Climate Change and War Frequency in Eastern China over the last millennium. Human Ecology 35: 403–414. https://doi.org/10.1007/s10745-007-9115-8

ZHANG, D.D., PEI, Q., LEE, H.F., JIM, C.Y., LI, G., ZHANG, M., LI, J., WU, Z., WANG, L., YUE, R.P., ZHANG, S. (2020): Climate Change Fostered Cultural Dynamics of Human Resilience in Europe in the Past 2500 Years. Science of the Total Environment, 744, 140842. https://doi.org/10.1016/j.scitotenv.2020.140842

ZHANG, D., WANG, L., SUN, X. (2003): Inversion of Annual Grid Point Precipitation Anomaly Fields Based on Historical Literature Records: A New Discussion on Objective Quantitative Research of Climate Historical Materials. Quaternary Research, 23, 2, 177–184.

ZHANG, Q. (2015): An Introduction to Chinese History and Culture. Springer, New York.

ZHAO, W., XIE, S.Z. (1988): History of Chinese Population. People's Publishing Press, Beijing.

ZHU, X., CHEN, F., GUO, H. (2018): A Spatial Pattern Analysis of Frontier Passes in China's Northern Silk Road Region Using a Scale Optimization BLR Archaeological Predictive Model. Heritage, 1, 1, 15–32. https://doi.org/10.3390/heritage1010002

ACKNOWLEDGEMENT

The research has been generously supported by the Research Grants Council of Hong Kong SAR under Humanities and Social Sciences Prestigious Fellowship Scheme [Ref. No. 38000322]; "Climate Reconstruction and Impacts from the Archives of Societies", a working group of the Past Global Changes (PAGES) project; Cooperative Research Plan for Overseas Experts in Zhengzhou City, Henan Province; the Hong Kong Polytechnic University Strategic Hiring Scheme [Ref. No. P0048587] and the Hong Kong Polytechnic University Internal Research Fund [Ref. No. P0051110].

ORCID

XIAORAN BU
https://orcid.org/0009-0001-2455-1603

YURAN SU
https://orcid.org/0009-0000-1001-3508

LINGYU FAN
https://orcid.org/0009-0003-5961-7144

QING PEI
https://orcid.org/0000-0002-9699-2950

PI-LING PAI
https://orcid.org/0000-0002-8236-1912

DONGMEI JIANG
https://orcid.org/0009-0000-9477-4362