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Social impacts of the climatic shift around the turn of the 19th century on the North China Plain

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Historical case studies of climate change impacts and the resulting social responses can provide analogies for better understanding the impacts of current and future climate changes. Around the turn of the 19th century, the climate of the North China Plain experienced a shift from a relatively warm stage in the 18th century to a colder stage in the 19th century, which was characterised by a much colder climate and more frequent and severe floods and droughts. Historical information about refugees, social disorder, grain transportation, and disaster relief on the North China Plain in 1780–1819 is collected from the *Veritable Records of the Qing Dynasty* (a collection of official records). The mechanism of climate change affecting the food security of the society, as indicated by the development of a refugee problem around the turn of the 19th century, is analyzed by examining the social vulnerability. There are four basic findings: (1) In the 40 years from 1780–1819, the society on the North China Plain was unstable and characterised by a significant deterioration of the refugee situation. The number of refugees increased markedly, and their behaviour became increasingly violent. In the 1780s, most of the disaster victims chose to stay at their residences waiting for relief. From 1790 to 1800, hundreds of thousands of refugees migrated to northeast China. In the 1810s, the frequency of farmer rebellions increased sharply. (2) The increase in instability corresponded to the climatic cooling over the same time period. The increased instability was a result of the negative impacts of climate change accumulating and transmitting to the social level. (3) For food security, a precondition for the negative impacts of climate change on human society was the vulnerability of the regional socioeconomic system, which had a high sensitivity and low capacity to respond. This vulnerability could be described by the following three observations: ① The regional balance of supply and demand for food was in a critical state, which led to a high sensitivity and dramatic reduction in yield that was caused by climate change; ② the capacity for disaster relief efforts by the government was too low to meet the needs of crisis management; ③ the capacity for refugees' resettlement in eastern Inner Mongolia and northeast China, which both border the North China Plain, was severely restricted by climatic conditions or the quarantine policy. (4) It is estimated that climate change caused the social vulnerability to reach a critical level approximately 20 years earlier on the North China Plain.

climate refugees, impact of climate change, Little Ice Age, North China Plain

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As one of the major forces affecting human decision-making and social development, environmental change functions as a base for the rise and fall of human civilisation [1]. Although it is unlikely for environmental changes today to produce the same impacts as those that happened in the past because of social development, past events can be used as analogies to provide an early warning scenario for the immediate future. The lessons learned from the past are also

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valuable for today's human beings who face the challenge of global change. One of the four themes of Past Global Changes (PAGES) is to improve our understanding of the impact of contemporary climate change and social adaptation by reconstructing past human-climate-ecosystem interactions at multiple spatiotemporal scales [2].

Many studies have found close and complicated correlations between climate change and historical social events, such as population variation and migration, economic fluctuation, social harmony and crisis, and even dynastic transition [3–8]. In Europe, wet and warm summers occurred during periods of Roman and medieval prosperity, while increased climate variability from approximately 250 to 600 AD coincided with the demise of the Western Roman Empire and the turmoil of the Migration Period [3]. China suffered from wars more often during cold phases; 70%–80% of wars, most of the dynastic transitions, and social unrest across the country occurred during cold periods. Climate change was one of the factors affecting the Chinese dynastic cycle and change from social harmony to crisis [7, 9]. In Africa, unlike in Europe and China, the risk of war increased during historical warming periods [10]. Conflicts were more frequent during colder periods over the last 1000 years in Europe, but this correlation weakened and destabilised during the industrialised era [4], indicating that the impacts of historical climate change varied with changing socioeconomic conditions. Studies [3] have shown that environmental changes affected the rise and fall of past civilisations, predominantly through water supply and agricultural productivity [11–15], human health [16], and civil conflicts [10]. The scientific understanding of the social impact of past climate changes and human adaptations remains uncertain due to the many factors that influence historical events, the complexity of the social response to climate change, and the uncertainty of the reconstructions of past climate change [6, 8, 10, 17–22].

Research on the social impacts of climate change should not only prove that past climate change impacted human society but also explain the process and mechanism of the impacts, including the positive or negative feedback of climate change on human society. Research should also separate the contributions of environmental and anthropogenic factors to the changes in past human civilisations. Most of the conclusions about the impacts of environmental changes on human history have been drawn from direct comparisons between the reconstructed time series of climatic elements (temperature or precipitation) and the social consequences of significant events in the corresponding time periods. Because past conclusions were limited by a lack of proxy data concerning the interactions between climate change and human response, they do not adequately describe this interaction.

In China, a country with a typical monsoon climate that is characterised by high annual variability and sensitivity to global climate changes, the socioeconomic system is strongly impacted by climate change. The impacts of climate change and its human responses have been well recorded in the abundant historical records dating back thousands of years. These unique historical records provide an opportunity to research the process and mechanism of the social impacts of past climate change and human adaptation, which has been proven by existing, historical case studies. The turn of the 19th century was a transition period in the Little Ice Age from the relatively warmer phase of the 18th century to the relatively colder phase of the 19th century. It was also a critical period during which the Qing Dynasty was declining. On the North China Plain (NCP), the political centre of the Qing Dynasty in China (the areas surrounding the capital), the climate change was characterised by much lower temperatures and more frequent severe floods and droughts [23–26]. At the same time, the phenomenon of social instability, including refugees, migration, and revolts, began to emerge [27]. In this paper, the relationship between the social impacts indicated by the development of the refugee problem and the climatic cooling around the turn of the 19th century are analysed in light of the food security. This analysis is based on social vulnerability and the impacts of climate change and social responses on the NCP that were collected from *The Veritable Records of the Qing Dynasty* [28] (a collection of official records), as well as the existing research about climate change, natural disasters, population, land use, and the evolution of administrative division. The goal of this study is to improve the understanding of climate change processes and mechanisms and the social responses to them by exploring the roles that natural, demographic, and social factors played in the transformation of the refugee problem in the context of climatic cooling.

This study also provides a typical case study for understanding the problem of climate refugees. Mass migration is one of the major negative impacts of global warming that concerns the current international community [29]. Extensive research has been conducted on the mechanisms of migration and social conflicts that are induced by climate change, based on case studies or combined cases with mechanistic models [30–33]. However, in the current resilient world, there is a lack of representative cases of mass migration or even conflicts induced by climate change, in addition to limited cases of inter-regional or international migrations and conflicts in developing countries located in environmentally sensitive areas [34–36].

1 Data and methods

1.1 Study area

This paper refers to the North China Plain (NCP) during the Qing Dynasty (1644–1911) as the 22 prefectures (Fu) and 198 counties (Xian) that include most of Zhili (south to the Great Wall), northeastern Henan, and northwestern Shandong provinces (according to the administrative divisions in 1820) [37, 38] (Figure 1). This area roughly covers modern Beijing and Tianjin, most of Hebei, and part of Henan and Shandong. The NCP is an alluvial floodplain of the Haihe and Yellow Rivers and is surrounded by the Yanshan Mountains to the north, the Taihang Mountains to the west, and the Shandong hills to the southeast. The flat and uniform terrain enabled people from different regions in the plain to migrate easily and develop similar social and economic structures.

The NCP during the Qing Dynasty (1644–1911) is a representative case for studying the social impacts of climate change. First, it is located in the warm, temperate monsoon climate zone, with high annual and inter-annual variation in temperature and precipitation. The NCP was historically densely populated and agricultural. The society in the NCP was moderately sensitive to the impacts of climate change; it was more sensitive to climate change than areas to the south (e.g. the Yangtze River Delta) but less sensitive and more responsive than the agro-pastoral transitional zone to the north. The impacts of climate change can be observed at several different levels, ranging from agricultural production to the economy and politics. Second, as the seat of the political centre in the Qing Dynasty, social order and stability in the NCP was a priority for the government. During natural disasters, the disaster relief activities in the NCP were often supervised directly by the emperor, and relief supplies were also directly distributed from the national reserve. Multi-level social responses to the impacts of climate change occurred in the area, from individuals, local government, and the central government. Third, the balance of supply and demand for food in the NCP relied on the importation of grain from southern China [39–41] and the population migration to eastern Inner Mongolia and north-

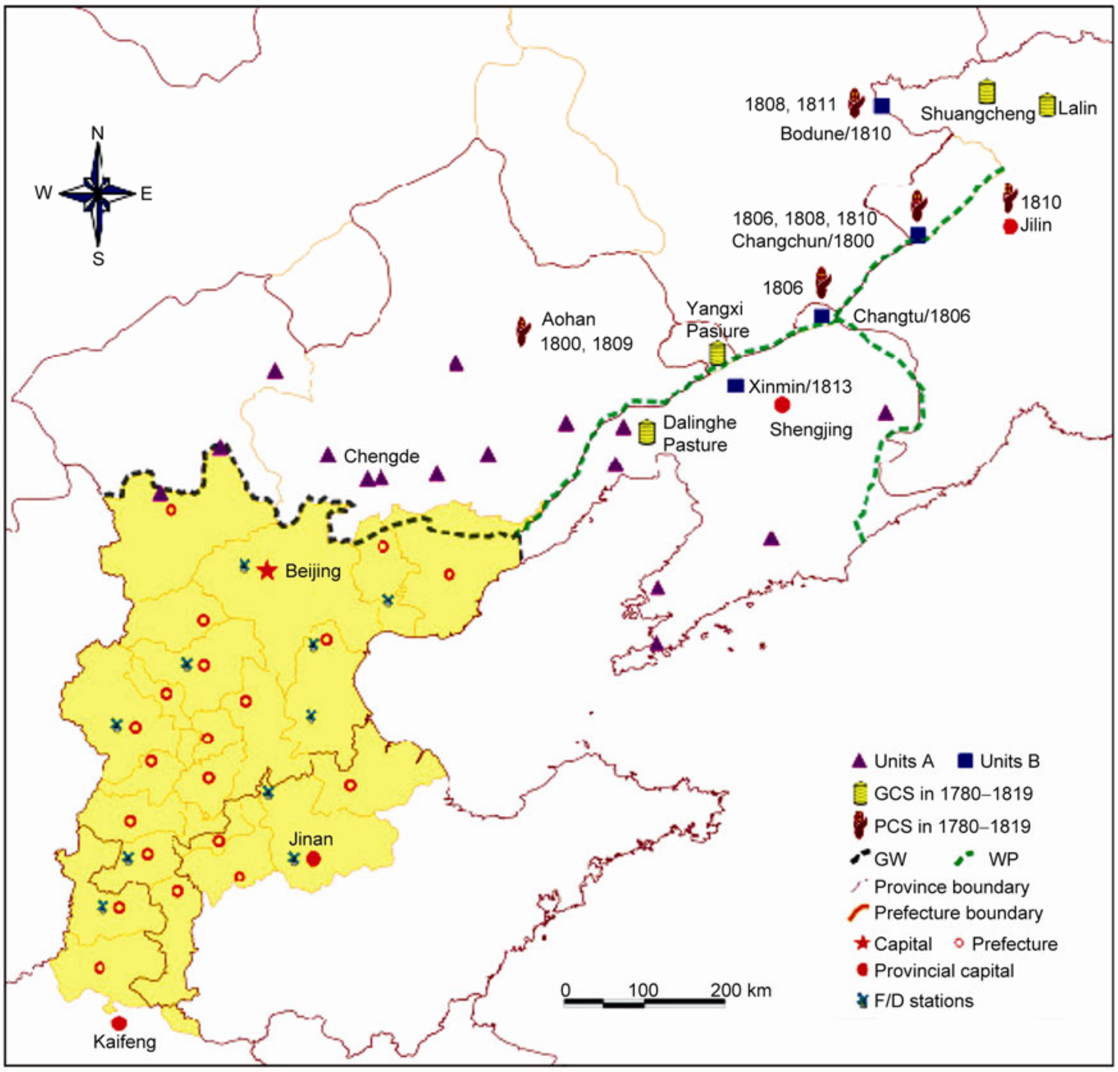

Figure 1 Map of the study area (North China Plain) and changes of administrative divisions in eastern Inner Mongolia and Northeast China in 1720–1819. Based on the administrative divisions in 1820 from Yugong Site (http://yugong.fudan.edu.cn/default.asp); Units A: administrative units set up in 1720–1779; Units B: administrative units set up in 1780–1819; GCS: governmental cultivation-settlements; PCS: private cultivation-settlements; GW: the Great Wall; WP: the Willow Palisade; F/D: flood/drought.

east China to the north. The social impacts of climate change that occurred in the NCP could diffuse to these surrounding areas through food transportation and mass migration [42–45] instead of being limited to the NCP. The historical case study of the NCP contributes to a more comprehensive understanding of the interactive mechanism between the impacts of climate change on society and human responses.

1.2 Selection of proxy indicators

The impacts of historical climate change and social adaptation can be attributed to the issue of risk or security that is induced by global change. The social impact of climate change is a result of the interaction between climate change as an external perturbation and the vulnerable exposure of the social system. Vulnerability is defined as the sensitivity to climate change and the capacity of the social system to respond [29, 46]. Thus, the extent of the social impact of climate change is determined not only by the climate change intensity but also by the state of the society and human responses (Figure 2).

Climate change could impact many aspects of the social system. All of the impacts to different social dimensions could eventually be reflected in the social stability or the level of risk. The existence of a large number of refugees is an important factor in the threat to social stability. In the history of China, refugee behaviours can be divided into three groups corresponding to the level of social instability, including refugees waiting for relief in their homeland, displaced refugees, and revolts caused by refugees. Displaced refugees are those refugees who left their homelands temporarily or permanently without a means of survival. In the context of the traditional Chinese culture of unwillingness to migrate, a sharp increase in displaced refugees was a sign of a survival crisis for the refugees because their food security was not guaranteed in their homeland. Revolts caused by refugees reflected the behaviours of the refugees or displaced refugees and tended to be more violent. The outbreak of revolt marked the passage of the society into instability (or high risk). The difference in the dominant type of revolts and the frequency of occurrence for each type further reflects the level of social instability or security risks.

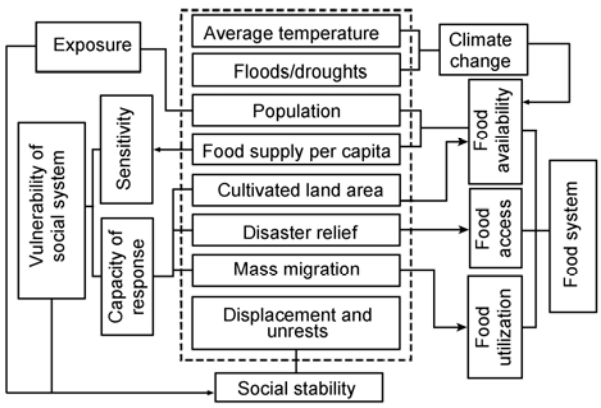

Figure 2 Food-security-based framework of the impacts of historical climate change and social responses in China. Proxy indicators are shown in the dashed box.

The great majority of the historical revolts were triggered by a survival crisis for refugees who were suffering from a shortage of food. This condition implies that, if the revolts could be proven to be correlated with climate change, the occurrence of these revolts would signify that the accumulated negative effects of climate change had reached such an extent that the response and adaptation of society to climate change was in serious disorder or even full collapse [47]. However, the difficulty remains that compared with the many social factors that directly affected the occurrence and development of revolts, climate change only affected revolts directly or indirectly through several key links, many of which were not even recorded. Considering the difficulties in directly demonstrating that climate change, indeed, caused these impacts, we conduct an in-depth analysis and careful verification of the key links and related conditions under which climate change might play an important role governing social vulnerability, and we exclude the probability that these links were decided by non-climatic factors.

As a country founded on agriculture, food security was the foundation for maintaining the economic and social stability in ancient China. The vast majority of revolts originated from people's inability to make ends meet. Therefore, the degree of food security can be used to measure the vulnerability of the social system. By definition [48], food security can be measured with three variables: food availability, food access and food utilisation. At a regional scale in ancient China, food availability depended predominantly on the agricultural production within the region. Food access incorporates the capability of the society to supplement and distribute food, which first relied on the social distribution system and then was subject to the ability of the community to regulate food distribution. Food utilisation represented the real, usable amount of food per capita. Among these three variables, food production (food availability) was the most important. The impact of climate change on the society was fundamentally a direct impact on food production. A community could essentially regulate their level of food security through the processes of food access and utilisation. When the regional food production failed to meet the need for food security, it was conventional to increase the local supply by shipping grain from outside regions or to decrease the requirement for food by migrating outward.

The sensitivity of social systems can be measured by differences in the regional output of grain per capita relative to the critical share of food security. The grain output per capita was determined by both the crop yield per unit area, which was directly affected by climate change, and the cropland per capita, which may also have been affected by climate change in some regions. The regional grain output per capita represented the maximal share of food that could be obtained within the region. If the grain output per capita was greater than the critical share, the social system would not be sensitive to external forces (including climate change) because survival would not be a problem. In contrast, the sensitivity of a social system would increase when the regional grain output per capita was close to or below the critical share.

The capacity of the social response is indicated by the degree to which the society adjusts its capacity to provide access to food. There were two basic ways to regulate food access in the NCP during the Qing Dynasty. One was to increase the food supply or food purchasing power with governmental or civil relief; the other was to increase food availability per capita by spontaneous or organised population migrations.

In summary, food security was considered to be a fundamental variable for analysing the mechanism of the social impacts of climatic cooling around the turn of the 19th century in the NCP, taking into account the availability of related information from historical documents and previous studies. The grain output per capita, the capacity for disaster relief, and the capacity for refugees' resettlement at a new destination were selected as proxy indicators of the vulnerability of the social system, and revolts were selected to indicate the stability of the social system (Figure 2).

1.3 Data sources and methods

The main source of historical information used in this paper was *The Veritable Records of the Qing Dynasty* [28], which is a collection of official records (4433 volumes edited on a daily basis) and the most important original document for studying the Qing Dynasty, including the archives from the Cabinet and bureaucratic ministries, the literature from the Research Institute of the Qing Dynasty History, and the imperial instructions and anthology, etc.

The historical information about the shipping of grain, disaster relief, migration and social disorder in the NCP from 1780–1819 was collected from the *Veritable Records of the Qing Dynasty* to reconstruct a historical proxy series of climate change impacts. In addition to referencing previous studies, we attempted to make a quantitative analysis of the behaviours of refugees and their social consequences due to the impacts of climate change during this period.

1.3.1 Historical climate change in the NCP

A series of temperature data at an annual or decadal resolution is collected from previous studies [23, 49–51]. The magnitude of temperature changes during the study period is estimated based on the average annual temperature anomaly series in North China since 1380 [23] (Figure 3(a)) and the winter half-year temperature anomaly series over the past 2000 years in eastern China [50] (Figure 3(b)).

Changes in floods and droughts in the NCP from 1644–1911 are calculated using the dryness/wetness grade data from 10 stations (Beijing, Tianjin, Tangshan, Baoding, Cangzhou, Shijiazhuang, Handan, Anyang, Dezhou, and Jinan (Figure 1)) on the NCP, described in the *Yearly Charts of Dryness/Wetness in China for the Last 500-Year Period* (classified into 5 grades: 1, very wet; 2, wet; 3, normal; 4, dry; 5, very dry) [52]. The annual drought index, Zd (Figure 3(c)), and flood index, Zf (Figure 3(d)), in the NCP are defined in eq. (1):

$$Z=M_1\times W_1+M_2\times W_2, \tag{1}$$

where M_1 is the number of severely affected stations, specifically, those whose dryness/wetness grade is 1 or 5; M_2 is the number of minimally affected stations, with corresponding grades of 2 or 4; W_1 and W_2 are the weights, which are assigned as 0.8 and 0.2, respectively.

1.3.2 Changes in population, cropland, and grain output per capita

Changes in the population and cropland in the Zhili Province during the Qing Dynasty, which are representative of the NCP, are collected for calculating cropland area per capita (Figure 3(f)). Cropland data in Zhili were recorded in the *"Statistics of Population, Land and Tax in Chinese History"* [54]. Demographic changes in Zhili, collected from the *"Chinese Population History"* [55], are used to estimate the population size during the years corresponding with the cropland area data, based on the population growth rate. An estimate of the unit crop yield in the NCP during the Qing Dynasty is in the range of 1–2 Dan per Mu (Dan is an ancient Chinese unit of capacity, and in the Qing Dynasty, 1 Dan of grain was equivalent to approximately 70 kg; Mu is a traditional Chinese unit of area, and 1 Mu $\approx$ 0.067 hm^2) [56–59]. In this paper, a relatively conservative estimate of 93 kg/Mu has been used [59]. Based on these data, the cropland and the grain output per capita in Zhili at each of the time nodes from 1780–1819 are calculated. Referenced to the modern subsistence level of 300 kg per capita, where a critical share of food security is guaranteed [60], the deviation in the grain output per capita and the critical share during different periods are calculated to assess the regional social sensitivity to climate change (eq. (2)).

$$S=\frac{Fp-F_0}{F_0}=\frac{Yp\times Ap-F_0}{F_0}, \tag{2}$$

where S is the sensitivity of the social system (a positive S indicates that sensitivity is low and a negative S indicates that sensitivity is high); Fp is the grain output per capita; F_0 represents the critical share of food security (300 kg per capita); Yp is the yield per unit area, which is directly affected by climate change; and Ap stands for the cropland area per capita.

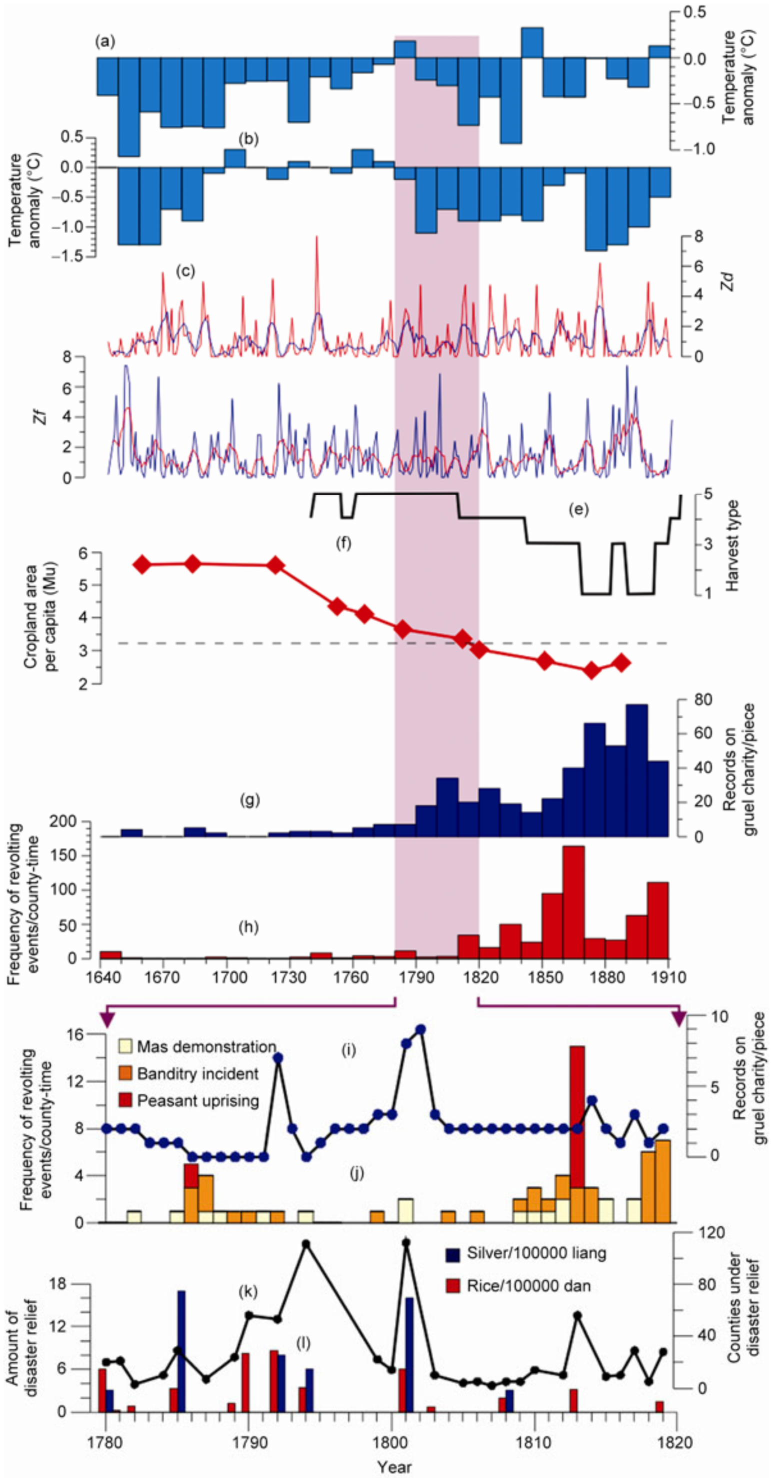

Figure 3 Climatic cooling and social responses around the turn of the 19th century on the North China Plain. (a)–(h) stand for the changes in proxies from the 1640s–1900s to 1644–1911: (a) 10-year average anomaly in annual temperature in North China [23]; (b) the winter half-year temperature anomaly in eastern China [50]; (c) the yearly drought index and its 5-year running mean; (d) the yearly flood index and its 5-year running mean; (e) 5-year running autumn harvest types [53][1)]; (f) cropland per capita in the Zhili Province [54, 55]; the horizontal dashed line corresponds to the cropland area with a grain output per capita of 300 kg; (g) frequency of records of gruel charity in Beijing; (h) frequency of revolting events in the NCP; (i)–(l) the annual change in proxies from 1780–1819: (i) the frequency of records on gruel charity in Beijing; (j) the frequency of revolts in the NCP; (k) the number of counties under disaster relief in the NCP; (l) the amount of disaster relief in the NCP.

1) According to the fuzzy clustering analysis of the agricultural harvest sequence, the harvest types can be divided into five categories: 5/1 indicates that the harvest/failure years account for a vast majority of the year plus 2 years before and after (5 years totally); 4/2 indicates that the harvest/failure years are relatively more frequent; and 3 indicates that the harvest/failure years are the same (according to ref. [53]).

1.3.3 Change in disaster relief for victims on the NCP

Relief supplies awarded by the Qing government for victims in the NCP are divided into two types: silver (one of the main currencies in the Qing Dynasty) and grain. The quantity of relief supplies can be used to quantify the governmental efforts to provide disaster relief. Based on the records in *The Veritable Records of the Qing Dynasty* [28], the number of counties that received governmental relief (Figure 3(k)) and the amount of relief supplied to each county are recorded from 1780 to 1819 (Figure 3(l)). The relief density (Q) was calculated after converting the amount of silver to grain (eq. (3)).

$$Q = \frac{F_1 / 1.5 + F_2}{C}, \tag{3}$$

where F_1 is the amount of silver, F_2 is the amount of grain, and F_1 can be converted to F_2 roughly by the equation 1.5 liang (liang is a Chinese traditional unit of weight, and in the Qing Dynasty 1 liang was equivalent to about 37.3 grams) of silver = 1 Dan of grain, according to the major food prices cited in ref. [61]; C is the number of counties receiving disaster relief.

1.3.4 Changes in the number of refugees and their destinations

The sparsely populated eastern Inner Mongolia (currently the northern Hebei province and eastern Inner Mongolia) and northeast China, to the north of the Great Wall, were the major destinations for the outward migration of refugees induced by climate change and natural disasters in the NCP during the Qing Dynasty. Settlement and cultivation in the two regions were very important factors in regulating the social responses to climate change in the NCP, which could be considered to be an off-site response to climate change and natural disasters in the NCP, to a certain extent [42–44]. Based on the historical records of migration and cultivation and the establishment of administrative divisions in *The Veritable Records of the Qing Dynasty* [28] and other historical literature, the time and location of private cultivation-settle- ments, governmental cultivation-settlements, and the new administrative units in eastern Inner Mongolia and northeast China were identified and marked on the map to reflect the spatiotemporal pattern of settlement and the reclamation of refugees from the NCP from 1780 to 1819 (Figure 1).

1.3.5 Proxy series of social stability as indicated by displaced refugees and revolts in the NCP

The changes in the social stability on the NCP can be described by the different refugee behaviours, from refugees waiting for relief in their homelands to displaced refugees (leaving their homelands temporarily or permanently without a means of survival) and revolts caused by refugees (violent refugees). Large numbers of displaced refugees indicated a survival crisis for the refugees suffering from food insecurity in their homeland. The outbreak of revolts indicated social instability (or high risk). The difference in the dominant type of revolt and the frequency of occurrence for each type could further reflect the level of social instability or security risks.

As a means of relief, gruel charity in the capital (Beijing) was directly related to the displaced refugees. Therefore, the frequency of the records of gruel charity could reflect the severity of the displaced refugees' problem. As a regulation, charitable institutions in the capital set up by the Qing government would offer gruel to displaced refugees every winter. In case of an emergency, such as a large number of refugees arriving in Beijing during a severe natural disaster, the government would break the rule by prolonging the duration of relief or supplying more food and funds to mitigate the increasing pressure. With the decline of regular measures of disaster relief after the late 18th century, gruel charity, which had been a supplementary measure, became increasingly important in governmental disaster relief. The increase in the gruel charity records reflects the escalation of the refugee problem. Gruel charity-related records were available in *The Veritable Records of the Qing Dynasty* [28] as frequency statistics at annual and decadal resolutions (Figure 3(g), (i)).

Revolt-related records in the *Veritable Records of the Qing Dynasty* [28] can be divided into three categories according to the severity of the action against the government: (1) mass demonstrations: various types of mass incidents at the edge of the legal framework, such as collective resistance to taxes and rents, secret associations and religions, gambling, and blackmail; (2) banditry incidents: vicious incidents at a small scale, including robbery, murder, prison breaks, etc., involved with gangs of thieves, bandits, traveling bandits, etc., who were simply destroyers of the social order; and (3) peasant uprisings: usually a more closely knit organisation with distinctive political aspirations, affecting one or several counties at the small scale or the entire NCP at the larger scale. The scale of revolts, from mass demonstration and banditry incidents to peasant uprisings, reflected the increase in the degree of social instability. The frequency of the three types of revolts from 1780 to 1819 is reported in the units of "county-time" (1 county-time signifies that one county was affected by a revolt in one year) (Figure 3(j)). The county-time of total revolts is summed for the entire Qing Dynasty (Figure 3(h)). Because the records during the Boxer Movement were far from complete in *The Veritable Records of the Qing Dynasty* [28] , the frequency of revolts from 1899–1901, during the Boxer Movement, is also calculated using the records from *Brief Records on Boxer Movement* [62].

2 Results and analysis

2.1 Climate changes

The climate in the 18th century was relatively warm compared to other periods during the Little Ice Age. The climate shifted into the last cold period of the Little Ice Age from the end of the 18th century to the early 19th century. As a regional response to climatic variation in the Little Ice Age, this cooling could be identified in the NCP, in other regions of China, and even throughout the Northern Hemisphere. According to the 10-year average annual temperature anomaly series from North China, the temperature dropped by approximately 1°C in the 1790s–1810s, when the more rapid cooling occurred. The average temperature in the 1780s–1810s was lower than that of the 1740s–1770s by 0.8°C [23] (Figure 3(a)). According to the winter half-year temperature anomaly series in eastern China, the winter half-year temperature decreased by 1.4°C during the 1770s–1790s. The temperature began to decrease in the 1770s and fell below the average of 1951–1980 in the 1780s. In the 1790s, it dropped sharply by 0.9°C [50] (Figure 3(b)). A similar cooling period lasting for approximately 40 years (1780s–1820s) was found in the series of average July temperatures from Beijing in 1724–1982 [51]. In other reconstructed historical cold/warm series, such as the one for Shandong, the sharp cooling approximately 1800 was also identified [49], similar to other regions of China [63–65].

Precipitation during this period increased, but with higher interannual variability [66, 67]. Consequently, significantly more frequent and severe floods and droughts occurred. The standard deviation in annual precipitation averaged from the four stations of Shijiazhuang, Hejian, Jinan, and Anyang increased from 91.89 mm in 1740–1779 to 112.3 mm in 1780–1819 [67]. The average drought index, calculated from the dryness/wetness grade series from 10 stations in the NCP increased from 0.94 in 1740–1779 to 1.08 in 1780–1819, whereas the flood index increased from 1.00 to 1.16. An increase in extreme droughts and floods can be inferred from the fact that the numbers of stations with both grade 1 (extreme flood) and grade 5 (extreme drought) on the dryness/wetness grades significantly increased in 1780–1819 (32 and 33, respectively) compared to the numbers in 1740–1779 (29 and 26, respectively) [52]. The extreme droughts in 1785 [68-69] and 1813 and the extreme flood in 1801 [25] were all rare cases of the most severe natural disasters in the last several centuries (Figure 3(c), (d)).

2.2 Social vulnerability to the impacts of climate change

2.2.1 Continued population growth increased the food security risk to a high level

Rapid population growth occurred from 1644–1911 in the NCP. In Zhili (now the Hebei Province); the population increased from approximately 8 million in the early Qing Dynasty to more than 37 million at the end of the Qing Dynasty [55]. The man-land contradiction gradually intensified as the population increased. Food security was in a critical state approximately 1800 and became an important turning point in the man-land relationship on the NCP during the Qing Dynasty.

From the beginning of the Qing Dynasty to approximately the 1720s, the pressure of population growth was largely offset by expanding cropland in Zhili. The cropland area per capita was maintained above 5.6 Mu. Based on the unit yield of 93 kg/Mu [59], the grain output per capita could be more than 500 kg, which was much more than the critical food security share of 300 kg per capita. After the 1730s, the cropland in Zhili was nearly stagnant. Meanwhile, the continued growth of the population gradually decreased the cropland per capita in Zhili to 3.71 Mu by 1781. Consequently, the grain output per capita was 345 kg, barely above the critical share. By 1820, the cropland per capita was further reduced to 3.03 Mu, and the grain output per capita dropped to 281 kg, already below the critical share (Figure 3(f)).

By the early 19th century, population growth alone had led to a breaking point for the critical share of food security in the NCP, even if the inequity in food distribution is ignored across different social classes for landlords and official exploitation. Food insecurity contributed to a sharp rise in the social sensitivity to external perturbation, such as climate change and extreme floods or droughts. When a natural disaster or climate change occurred, famine or even bankruptcy would be inevitable for most of the peasants who already had no surplus grain.

2.2.2 Climatic cooling exacerbated the food crisis

The temperature change directly affected crop yields. The autumn harvest in North China began to deteriorate from the 1810s, when the number of years of poor harvest increased markedly. Until the late 19th century, during the colder phase of the Little Ice Age, poor harvests occurred nearly annually (Figure 3(e)). The crop yield per unit area in the 19th century was significantly lower than that in the 18th century [53]. According to the modern (1950s–1980s) relationship between temperature change and crop yield in China, temperature increases of 1°C could result in a potential increase of yield by 10%. Even higher growth yields could be achieved if fewer damaging cold days in a warmer climate are considered. The reverse is also true [70]. The average temperature in the 40 years between the 1780s and the 1810s was lower by approximately 0.8°C than that of the 1740s–1770s [23], which could lead to at least an 8% decrease in crop yields.

In addition to the impacts caused by more frequent extreme floods and droughts that were induced by the higher variability of precipitation, the reduction in crop yields caused by climate change would be even greater. For example, the harvest in Zhili decreased during the flood of 1801 to only 25% of normal years [25], the lowest yield in the past 300 years. This extreme flood disaster alone could reduce the average crop yield in 1780–1819 by 1.88%. There were five years of extreme floods or droughts with the flood/drought index ⩾ 4 in 1780–1819 (floods in 1790, 1794 and 1801; and droughts in 1792 and 1813), which was 3 more years than in 1740–1779 (drought in 1743, flood in 1761). According to the modern agricultural disaster statistics, a decline of 30% of the normal harvest is defined as a disaster year [71]. Postulating that there was a decline of 50% in the above-mentioned 5 disaster years (currently equivalent to a moderate disaster), the three extra disaster years of extreme floods and droughts alone would reduce the average crop yield in 1780–1819 by another 3.75%, in addition to the reduction caused by the climatic cooling.

The combination of the negative impacts of lower temperatures with the more frequent extreme floods and droughts caused by the higher variability in precipitation would reduce the average crop yield in 1780–1819 decrease by at least 11.75% compared with normal years. This decrease would exacerbate the food insecurity problem and, subsequently, pose a more serious threat to social adaptability and stability in the NCP.

2.2.3 A significant decrease in the governmental capacity for disaster relief

In ancient China, the governmental capacity to respond to climate change, particularly extreme floods and droughts, was very important for reducing the vulnerability of the social system because individual households of peasants usually had very limited abilities to resist natural disasters. In the flourishing periods of the Qing Dynasty, especially the mid-18th century, the Qing government played a very active role in disaster relief in the NCP. The government effectively ameliorated the negative impacts of floods and droughts with a timely allocation and distribution of large amounts of relief materials and funds in addition to the conventional means, such as tax cuts [45, 61, 72].

The turn of the 19th century coincided with the end of the golden periods of the Qing Dynasty (the so-called “Kong and Qian Eras”). After the “Kong and Qian Eras”, both the central and local governments suffered severely from financial and grain-storage deficits. To put down the White Lotus uprising, which lasted for nine years (1796–1804), the government incurred military expenditures of more than 100 million liang silver and provided a large amount of military grain by water transport. These actions caused deficits in the state treasury and grain stocks in the capital and, consequently, caused a sharp drop in the amount of relief supplies held by the government at the beginning of the 19th century. The governmental capacity for disaster relief in the NCP had been in decline, despite more frequent and severe floods and droughts, since the late 18th century. The governmental disaster relief, which was sharply lower after the flood of 1801, caused an inability to mitigate the severe food insecurity and social crisis in the NCP (Figure 3(k), (l)).

Among the 10 dryness/wetness grade stations of the NCP, the total number of stations affected by flood/drought (grades of 1 and 2 for flood, and grades of 4 and 5 for drought) in 1780–1819 was 252 station-times, with 65 station-times severely affected (grades of 1 and 5). In 1780–1801, 138 station-times were affected, with 41 station-times severely affected, accounting for 54.8% and 63.1% of the total, respectively. The total number of counties that received governmental relief was 674 county-times, 482 of which were in 1780–1801. These county-times accounted for 71.5% of the total, which was higher than the proportion of the affected (as well as severely affected) station-times. In contrast, the proportion of county-times that received governmental relief versus the total number was lower than that of the affected (and severely affected) station-times in 1802–1819, indicating that many affected counties failed to receive relief in the later 18 years. Even for the relieved counties, the relief efforts were significantly lower compared to those of earlier times. The Qing government allocated nearly 5×10^6 liang silver and 3.8×10^6 Dan of rice for disaster relief in the NCP in 1780–1801, but only 0.3×10^6 liang silver and 0.73×10^6 Dan of rice in 1802–1819. The relief density (Q) was 1.47×10^4 Dan/county in 1780–1801, three times more than the 0.48×10^4 Dan/county in 1802–1819.

2.2.4 Migration outside the NCP was severely restricted by the capacity-saturated eastern Inner Mongolia and the quarantine policy in northeast China

In ancient China, spontaneous or organised migration was also an effective method to alleviate the pressure of food supply and increasing population and to reduce social vulnerability. Eastern Inner Mongolia and northeast China north of the Great Wall were the major destinations for migration and reclamation of the refugees from the NCP during the Qing Dynasty. Since the beginning of the Qing Dynasty, a flexible quarantine policy had been implemented by the authorities for the migrants from the NCP to eastern Inner Mongolia or northeast China, which could be described as rigorously prohibiting migration in normal years and relaxing in disaster or famine years. Compared with the rigorously prohibited northeast China, the quarantine policy in eastern Inner Mongolia north of the Great Wall was not very strict. Therefore, eastern Inner Mongolia was the major destination for migration of the bankrupt refugees from the NCP during the early Qing Dynasty [42–44].

After the implementation of the quarantine policy in northeast China in the 1680s, most of the migrants from the NCP were resettled in eastern Inner Mongolia, particularly in the regions surrounding Chengde. In the early and mid-18th century, when the climate was relatively warm, agriculture in eastern Inner Mongolia developed rapidly with the labour of numerous migrants from the NCP. Communications, in terms of the exchange of population and grain between the NCP and eastern Inner Mongolia, were active. From 1720 to 1779, due to the growth of cultivation-settlements, 10 out of 16 newly established counties (excluding the ones that were repealed shortly after they were established) outside the Great Wall were within eastern Inner Mongolia, especially in Chengde (7 new counties) (Figure 1), which formed the first centre of the administrative establishment and reformation of the region in the Qing dynasty. Almost all of the bumper harvest years (14 out of 15 years) in eastern Inner Mongolia that were recorded in *The Veritable Records of the Qing Dynasty* [28] occurred in the 18th century. Agricultural prosperity allowed eastern Inner Mongolia to not only achieve food self-sufficiency but also to supply surplus grain to the NCP for disaster relief. All of the seven records regarding grain transportation from eastern Inner Mongolia to the NCP in *The Veritable Records of the Qing Dynasty* [28] occurred in the 50 years between the 1720s and the 1760s [44].

However, after the Chengde administration adjusted the administrative division into one prefecture and six counties in 1778 [73], no more new administrative units were set up for nearly a hundred years (until 1876, when Weichang Ting was set up) in eastern Inner Mongolia, indicating that the development of the region had slowed. In 1782–1820, the population in the Chengde prefecture increased from 557, 222 to 783, 897 at an average annual growth rate of 9‰, already nearing the natural growth rate of the population at that time. This growth rate indicated that the region was no longer the major destination for the migrants from the NCP [74]. The decline of agricultural development near Chengde coincided with many factors, including the implementation of the quarantine policy and the saturation of the agricultural population [75] as well as climate change. Climate change played a very important role in limiting the development of agriculture in eastern Inner Mongolia to a certain extent [44, 76]. The cooling period after the end of the 18th century was one of the most important factors resulting in a southward shift of the agro-pastoral transitional zone in northern China.

As the capacity of Chengde to receive migrants from the NCP decreased, the number of refugees moving toward northeast China began to increase gradually. Following the severe drought of 1792 in the NCP, to release the pressure of numerous displaced refugees, the Qing government relaxed the rigorous quarantine policy in northeast China publicly for the first time since the 1680s and allowed, or even encouraged, the famine refugees to make a living in eastern Inner Mongolia and northeast China outside the Great Wall and the Willow Palisade[2)]. This measure immediately led to an unprecedented scale of refugee migration and a significant shift in their destination. "Since late September, the people with their families who went through the northwestern cols (such as Zhangjiakou and Gubeikou along the Great Wall where the routes to eastern Inner Mongolia were located) continuously decreased. But people who went through Shanhaiguan (the route to northeast China) were still an endless stream"[3)]. Northeast China, especially areas along the Willow Palisade, received a large number of migrants after this time.

After the drought of 1792, the government estimated that the "victims leaving for Shengjing (Liaoning Province), Jilin, and Mongolia to seek living were no less than hundreds of thousands" [4)]. This figure might be slightly exaggerated and contained temporary migrants but it reflected an unprecedented scale. The registered victims who settled in the Jilin province alone amounted to more than 15000[5)], not counting the greater number of those who were unregistered or near Shengjing and Mongolia, etc. Over the next 10 years after the drought of 1792, the Qing government established four administrative units (Changchun, Changtu, Bodune, and Xinmin) along the Willow Palisade in northeast China to manage the migrants. In this vicinity, there were governmental cultivation-settlements, such as the Dalinghe pasture, the Yangxi pasture, Lalin, and Shuangcheng (Figure 1). The population of northeast China increased remarkably from 0.95 million in 1780 to 2.47 million in 1820 [77], 1.6 times more than that in 1780. The average annual growth rate reached 24.2‰, the majority of which was contributed by migrants (approximately 1 million, and Jilin Province received 0.3 million migrants alone) [74]. For example, the increasing trend of migration was extremely remarkable in Changchun and its surrounding districts, which received more than 7000 migrants (kou)[6)] in six years after its establishment in 1800; in the subsequent two years, another 3010 households (hu)[7)] came; and, in the next two years, 6953 households (hu)[8)] immigrated.

2) *The Veritable Records of the Qing Dynasty*, 1792-08-21.

3) *The Veritable Records of the Qing Dynasty*, 1792-12-31.

4) *The Veritable Records of the Qing Dynasty*, 1794-09-04.

5) *The Veritable Records of the Qing Dynasty*, 1793-12-03.

6) Changchun Ting was established to manage migrants who had cultivated in Guo'erluosi. According to the originally proposed constitution, no more cultivation and settlement were allowed from then on. However, in the last few years, displaced persons continued to reclaim there, increasing by more than 7000 kou. *The Veritable Records of the Qing Dynasty*, 1806-09-02.

7) In Changchun Ting, another 3010 hu of migrants have been searched out. If all of them were deported, they might become homeless. In this case, they could be registered as local residents, but form now on, no more cultivation and settlement would be allowed. Punishment for private migration should be more severe in the future. *The Veritable Records of the Qing Dynasty*, 1808-07-10.

8) Another 6, 953 hu of migrants have been searched out in Changchun Ting. At the request of local officials, they have been registered as residents. From now on, local officials should implement quarantine policy more strictly and put an end to private migration. The officials of cols along the route to Changchun would be punished for releasing migrants. The Court of Colonial Dependencies (Lifanyuan) should instruct the Mongol lords in Guo'rluosi to check out accurate quantity of cultivated land area and Han residents, and ensure that no more cultivation and settlement would occur. If they privately tout Hans to cultivate land, they would also be punished. *The Veritable Records of the Qing Dynasty*, 1810-11-27.

However, relaxing the quarantine policy for northeast China in 1792 was no more than an emergency measure. Under the pressure of the migrants' surge, the Qing government reaffirmed the quarantine policy in 1803, and thoroughly investigated the private cultivation-settlements outside the Great Wall and the Willow Palisade. Records about the private cultivation-settlements in the *Veritable Records of the Qing Dynasty* were concentrated in the 10 years or more around the 1800s. After 1811, there were few records about the private cultivation-settlements in *The Veritable Records of the Qing Dynasty*. The rapid growth of the population in the northeast between 1781 and 1820 slowed significantly after 1820. In 1850, the population in northeast China was approximately 3.4 million, with an average annual growth rate falling to 10.7‰ [77]. The establishment of administrative units in northeast China was also at a standstill, and no new counties were set up in the 50 years between the establishment of Xinmin Ting in 1813 and Hulan Ting in 1862.

2.2.5 The high social vulnerability set the stage for the impacts of climate change on the social stability of the NCP

It could be concluded from the above analysis that the human society in the NCP around the turn of the 19th century was very vulnerable to external pressure, which provided a precondition for climatic cooling to impact the social stability. The vulnerability was characterised by a high sensitivity and low capacity for response, which can be explained with the following three observations: (1) Regional food security was in a critical state. The decrease in cropland area per capita from 3.71 to 3.03 Mu in 1781–1820 alone was enough to cut the annual grain output per capita from 345 to 281 kg. It broke through the critical share of food security and might have caused the social system to be highly sensitivity to crop failure due to climate change and extreme disasters. (2) The governmental capacity for disaster relief was too weak to meet the need for crisis management, which declined annually, especially after 1801. (3) The role of eastern Inner Mongolia as a destination for migrants from the NCP was reduced. The agricultural decline was related to climatic cooling, and the reaffirmation of the quarantine policy in northeast China after 1803 sharply reduced the migration. Both factors accelerated the intensification of the refugee problem in the NCP.

2.3 Social stability under climate change in the NCP tended to decrease

Against the background of climatic cooling around the turn of the 19th century, a series of significant changes occurred within the society in the NCP. One of the changes was the refugee problem, which ultimately increased to an uncontrollable level. The society in the NCP became unstable after 1803, when the quarantine policy was reaffirmed. The social instability in the NCP was indicated by the sharp increase in displaced refugees and the significant rise in the frequency and severity of revolts. Following the changes in the governmental disaster relief and quarantine policies, the behaviours of the bankrupt refugees in the NCP could be divided into three stages: waiting for relief in their homeland (1780s), leaving their homeland temporarily or permanently ("displaced refugees") (1790s–1800s), and, finally, participating in rebellions ("violent refugees") (1810s).

During the drought of 1785, most of the disaster victims chose to wait for relief in their homeland. However, the refugee problem had already emerged by the 1780s, indicated by the increase in the gruel charity in Beijing, which meant that displaced refugees increasingly flocked to the capital. During the drought of 1792 and the flood of 1801, large numbers of displaced refugees were forced to leave their homeland temporarily (to the capital) or permanently (outside of the NCP). A large number of displaced refugees (up to tens of thousands[9)]) that were temporarily sheltered in the capital created a serious threat to social order. In response, the Qing government repeatedly expanded the gruel institutions and extended the duration of the gruel charity. Conversely, during the decline of agricultural development in eastern Inner Mongolia and the relaxed quarantine policy in northeast China, many of the refugees migrated and settled along the Willow Palisade.

The violent trend of refugees' behaviour had already appeared by the 1780s, proven by the rise in the frequency of revolts in and after the drought of 1785. After a relatively peaceful period in the 1790s–1800s, violent behaviour of refugees became a serious threat to society in the NCP again. Incidents of banditry related to armed groups of displaced refugees increased by up to 24 county-times in the 1810s, accounting for 64.9% (Figure 3(j)) of the total number from 1780–1819 (37 county-times), and the affected areas spread throughout the NCP. The Tian-li Religion uprising during the drought of 1813 was the first large-scale peasant uprising, affecting 12 counties and involving a multitude of disaster victims in the NCP during the Qing Dynasty.

3 Discussion

3.1 Contribution of climatic cooling to social instability in the NCP

The high sensitivity of the regional society after it fell below the critical share of food security (300 kg per capita), in

9) For example, "unexpectedly, more than 20 thousand displaced people have gathered in gruel institutions of the capital (*The Veritable Records of the Qing Dynasty*, 1792-08-17)", "in recent days, hungry refugees for relief around the capital have increased up to 25–26 thousand (*The Veritable Records of the Qing Dynasty*, 1802-03-27)".

addition to the low capacity for social response during the corresponding period, made it possible for a crisis chain, from regional agricultural production to society, to be triggered by climate change and extreme floods and droughts. The negative impacts of climate change and extreme floods and droughts were summarised and assessed using the variables of food availability, food access and food utilisation. These factors led to large-scale famine, mass migration of refugees, and, finally, revolts.

The year 1820, following the end of the study period, could be considered the starting point of the unstable society. Grain output per capita in Zhili in 1820 could be estimated at approximately 281 kg, based on the cropland per capita without the impacts of climate change. When a decrease of 11.75% caused by cooling and more frequent floods and droughts was considered, the grain output per capita would be approximately 249 kg in 1820. This value (approximately 250 kg per capita) could be regarded as the threshold for social instability under the capacity of social response at that time. The critical year when the grain output per capita reached the value of 250 kg in Zhili was estimated, assuming no climatic cooling, no change in the unit grain yield, and the natural rate of population growth. The population in Zhili was 17.799 million in 1776. Under the assumptions that the population grew at the growth rate of 5.92‰, based on the population in 1776 and 1820, and the cropland area was kept stable at 1820 levels (69, 860, 981 Mu), the year when the grain output per capita reached the critical value of 250 kg was calculated to be 1841. In other words, the reduction of the crop yield due to climate change was about half of that due to population increase. Climate change accelerated the intensification of the food insecurity in the NCP by approximately 20 years (Figure 4).

Furthermore, the climatic cooling event happened across the nation, and the impacts of climate change in adjacent areas would most likely affect the NCP indirectly. For example, the southward shift of the agro-pastoral transitional zone in eastern Inner Mongolia would reduce the carrying capacity for migrants from the NCP, and the colder climate and more frequent disasters in southern China would influence the amount of grain it transported to the NCP. The degree to which the capacity of the social response in the NCP would be affected remains to be studied.

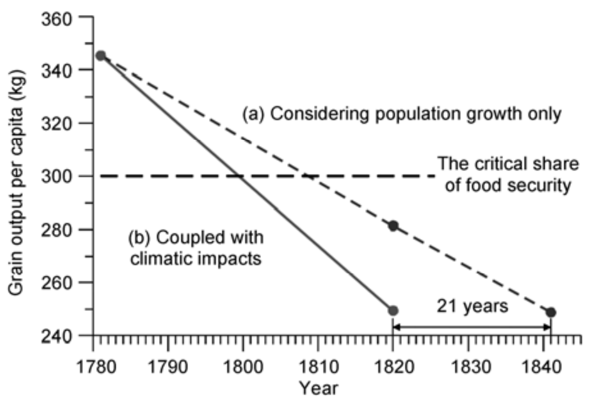

Figure 4 Changes of grain output per capita in Zhili in two scenarios. (a) Considering population growth only; (b) coupled with impacts of climate change.

3.2 The role of government in social response to climate change

The government played an important role in the interaction between climatic cooling and social responses in the NCP around the turn of the 19th century. This role was highlighted in two aspects of disaster relief, based on the scheduling of funds and materials and the quarantine policy for migrants (Figure 3). The behavioural strategies of bankrupted refugees in the NCP, especially those created by the extreme floods and droughts, varied following the changes in governmental countermeasures and response policies. Marked by the year 1792, when quarantine policy in northeast China was relaxed, and the year 1803, when the policy was reaffirmed, the countermeasures of response to climate change could be divided into three stages (Figure 3).

The period between 1780 and 1791 was dominated by disaster relief. In this stage, the governmental disaster relief could be characterised by a high intensity and efficiency in scheduling and distribution. The relief density (Q) was approximately 19500 Dan/county. Governmental disaster relief played a positive role in maintaining social stability post-disaster. However, the occurrence of sporadic revolts indicated that it was difficult to resolve the refugee problem with disaster relief alone.

The period between 1792 and 1803 included the responses of both disaster relief and the opening of northeast China. In this stage, relief efforts began to decline (Q = 12000 Dan/county, approximately two thirds of that in 1780–1791). Forced by an increasingly severe refugee problem, the Qing government relaxed the quarantine policy that had been strictly implemented for more than 100 years in northeast China, which effectively eased the pressure on society in the NCP. The decline in the frequency of revolts in the 20 years from 1790–1809 could partly indicate the effectiveness of the relaxed quarantine policy.

The period between 1804 and 1819 was dominated by the reaffirmation of the quarantine policy. In this stage, the disaster relief capacity of the government declined sharply (Q=4700 Dan/county, about a quarter of that in 1780–1791). To protect Manchu's homeland, the Qing government wrongly decided to reaffirm the quarantine policy and forbade further migration and reclamation to northeast China. Consequently, it exacerbated the social situation in the NCP. After the 1810s, as the quarantine policy came into effect and the development of private cultivation-settlements slowed, the refugee problem in the NCP gradually became uncontrollable and the refugees' behaviour became increasingly violent. Against this background in the NCP, banditry incidents occurred more frequently and the first large-scale peasant uprising during the Qing Dynasty broke out during the drought of 1813.

4 Conclusions

In the clue of food security, this case study analysed the roles that natural, demographic, and social factors played in the transformation of the refugee problem during the climatic cooling around the turn of the 19th century in the North China Plain, which would improve the understanding of the process and mechanism of the social impacts of climate change in relation to social vulnerability.

The refugee problem in the NCP significantly intensified between 1780 and 1819, with a transition of refugee behaviours from victims to displaced refugees and, finally, to violent refugees. In the beginning of the research period, most of the bankrupted refugees in the NCP, especially those created by extreme floods and droughts, chose to stay in their homeland waiting for relief (for example, in the drought of 1785). Subsequently, large numbers of victims became displaced refugees with the decrease of governmental disaster relief. They were forced to flow into the capital or migrate outside of the NCP (for example, in the drought of 1792 and the flood of 1801). Many of the migrants settled along the Willow Palisade as a result of the decline of agricultural development in eastern Inner Mongolia and the relaxation of the quarantine policy in northeast China. However, after 1803, when the Qing government reaffirmed the quarantine policy, the refugees who could not secure enough relief or migrate to other places to make a living had to risk revolt. Consequently, during the drought of 1813, a multitude of victims joined the Tian-li Religion uprising.

The cooling of climate during the decades around 1800 was an important background for the above evolution of the refugee problem in the NCP. The transition from the relatively warm stage in the 18th century to the last cold stage of the Little Ice Age was expressed by a colder climate and more frequent and severe floods and droughts. The negative impacts of climate change were an important factor in the increasing social instability of the NCP. The most direct impact of climate change on human society was crop failure, which was caused by lower temperatures and frequent natural disasters. It was estimated that the reduction in crop yield due to climate change was approximately half of that due to population increase, which accelerated the intensification of the food insecurity in the NCP by approximately 20 years, according to the proportion of yield reduced by climate change.

The vulnerability of the regional socioeconomic system in the NCP, with a high sensitivity and low capacity for response, was a precondition that enabled the crisis of agricultural production, which was caused by climate change around the turn of the 19th century, to be quickly transformed into economic and political dimensions and cause severe social consequences. The vulnerability of the regional socioeconomic system could be summarised by the following three factors: (1) The decrease in cropland per capita for an increasing population placed the balance of the regional food supply and demand in a critical state, which led to a high sensitivity to the grain yield reduction caused by climate change; (2) the governmental capacity for disaster relief had been too weakened to meet the needs of crisis management; and (3) the capacity for refugees' resettlement in eastern Inner Mongolia and northeast China, which border the NCP, was severely restricted by climatic conditions and the quarantine policy.

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