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Relationships between climate change, agricultural development and social stability in the Hexi Corridor over the last 2000 years

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Abstract This case study of the Hexi Corridor, Northwestern China, utilizes statistical methods to estimate quantitatively the interaction at a regional level between climate change, ancient social developments, and political coping strategies over the past 2000 years. The data is sourced from high-resolution reconstructions of climate series (temperature and precipitation), and historical records of cultivated land, war, population, and changes in regional administrative systems. The results show that moisture conditions played a more significant role than temperature in driving land reclamation in the Hexi Corridor. Analysis also showed a negative correlation between war frequency and the area of cultivated land in the Corridor over 20-year time intervals. Population growth was found to have a significant positive correlation with the cultivated land area during the study period. The results indicate that a climate-induced decline in agricultural production and the subsequent fluctuations in population could act as a trigger for social unrest, which is especially true at the mutual decadal time-scales. However, the interaction with administrative reform also suggests that, in the face of social and economic turmoil, a reasonable administrative hierarchy could strengthen the social governance of regional government, and promote social stability and economic development at a regional level. The study substantiates this notion with empirical quantitative evidence.

Keywords Climate change, Agricultural development, Social stability, Regional administrative reform, Hexi Corridor

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1. Introduction

Recent intensive progress of global climate change, especially the significant improvements of high-resolution paleoclimatic reconstructions over past millennia (IPCC, 2013), make it possible to quantitatively study the long-term interaction between climate change and ancient society. Knowledge of the past impact of climate change on society and the economy, and of human responses, can provide historical references to better understand and manage human-climate-ecosystem interactions in the present and in the future (PAGES, 2009). During recent decades, an increasing number of studies have examined the impact of climate change on various aspects of human societies. Those aspects include agricultural production (Mall et al., 2007; Yin et al., 2015); population and migration (Fang et al., 2007; Lee et al., 2008; Lee and Zhang, 2010; Li Y P et al., 2017); epidemics (Pei et al., 2015b; Lee et al., 2017); economic fluctuations (Atwell, 2012; Zhao, 2012; Wei et al., 2014; Pei et al., 2015a); social unrest (Ge and Wang, 1995; Tol and Wagner, 2010; Lee et al., 2017); and the rise and fall of dynasties (Ge, 2011; Zheng et al., 2014; Li J Y et al., 2017). Based on various high-resolution paleoclimatic reconstructions and socio-economic series, this body of research has reached a general consensus that deteriorating climate (especially cold and dry weather) has triggered more fre-

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quent and more severe demographic, socio-economic and political crises from a macro-historical perspective.

However, the findings of the above studies are also subject to debate. The majority of these studies have taken the whole of China (or Europe) as the study area, assuming a vast territory to be uniform, which could weaken the impact of regional heterogeneity. The impact of climatic forces could be buffered by various agricultural, socio-economic and political institutions in some places (Fan, 2010). Also, a study of the engine of the Chinese economy suggests that the south of China may be better at coping with a spate of colder weather than the north (Zhang et al., 2006). As Catto and Catto (2004) mentioned, in some regions, climate change can act as a driving force and has played an important role; nevertheless, there are also regions where the effects of climate change are secondary, or merely serve as background noise.

Owing to the above concerns, scholars have attempted to focus on smaller geographic regions to examine the climate-society interaction in historical agrarian China. However, the studies are characterized by a strong regional bias. Northern China (Ye et al., 2012; Fang et al., 2013; Xiao et al., 2015) and Eastern China (Ren, 2004; Zhang et al., 2007; Bai and Kung, 2011) have been investigated repeatedly. Yet limited attention has been paid to climate-society interaction in Northwest China, which comprises approximately one-third of China's total land area. The present study seeks to fill this research gap. Based on high-resolution reconstructions of temperature and precipitation, cultivated land area, and other proxy series for social factors in Northwest China over the past 2000 years, covering Chinese dynasties from the Western Han dynasty to the Qing dynasty, this case study provides a quantitative analysis of the interactions between climate change, agricultural development and social stability in the Hexi Corridor.

2. Data and methods

2.1 Study period and study area

The study period ranges from 210BC to AD1910, covering the Western Han Dynasty (202BC to AD8) to the Qing dynasty (AD1644 to 1911), a period commonly covered in our datasets. Regarding the study area, the Hexi Corridor is situated on the north slope of the middle Qilian Mountains in the northeastern part of the Tibetan Plateau, Gansu province, Northwest China. The study area includes the current city regions of Zhangye, Jiuquan, Wuwei, Jinchang and Jiayuguan (Figure 1). It is well known for its geographical importance as the most significant transportation hub of the Silk Road in historical and modern times, connecting North China to Xinjiang and Central Asia. The Hexi Corridor is the source of the Shiyang, Heihe and Shule rivers, and many oases are formed along these rivers, which gradually became areas for the concentration of human society and economic activity. The region is presently characterized by a continental arid climate. The mean annual precipitation ranges from 50 to 550 mm, decreasing from southeast to northwest (Meng et al., 2012). With scarce precipitation and high evaporation (it reaches 2000–3000 mm in most of the study area), the Hexi Corridor lacks water resources and is very sensitive to the effects of climate change.

2.2 Data sources

2.2.1 Temperature and precipitation

Temperature and precipitation are two crucial climatic elements for agrarian society throughout history. The spatial coverage, time span and temporal resolution of two recently published regional paleo-climate reconstructions met the entire needs of our study, and these reconstructed series have been verified by scholars. Therefore, we chose these series as the standard pole-climate series in the present study. The first series is the decadal averages of annual mean temperature fluctuations in the arid zones of Northwest China during the last two millennia, which is derived from variations of $\delta^{18}O$ in the Guliya ice core (Yang et al., 2004; Figure 2a). The second series is the variations in moisture conditions in the semi-arid regions of China over the last 2000 years, which is derived from more than 50000 reports of droughts and floods found in historical documents (Gong and Hameed, 1991; Figure 2b). These datasets were utilized to investigate the effects of temperature and precipitation fluctuations on agricultural development and social stability in the Hexi Corridor.

2.2.2 Cultivated land area

The cultivated land data utilized in the present study was reconstructed by Cheng (2007). The data spanned the years from AD2 to 2004 and its geographic coverage overlapped with our study area. Based on historical records of cultivated land, population size and grain production capability, Cheng (2007) estimates the coverage of cultivated land at irregular time intervals. To create an annual time series, we took the common logarithm of the data points, interpolated linearly and then anti-logged back (Figure 2c). This method helps to avoid distortions of raw data in interpolation, which has been confirmed by former studies (Lee, 2014; Lee et al., 2016).

2.2.3 Wars

As regards wars, our data was primarily derived from a multi-volume compendium *Tabulation of Wars in Ancient China*, which provides detailed records of wars that took place in China from 800BC to AD1911 (Editorial Committee of Chinese Military History, 2002). The records of wars include inception year, location, participants, proceedings and

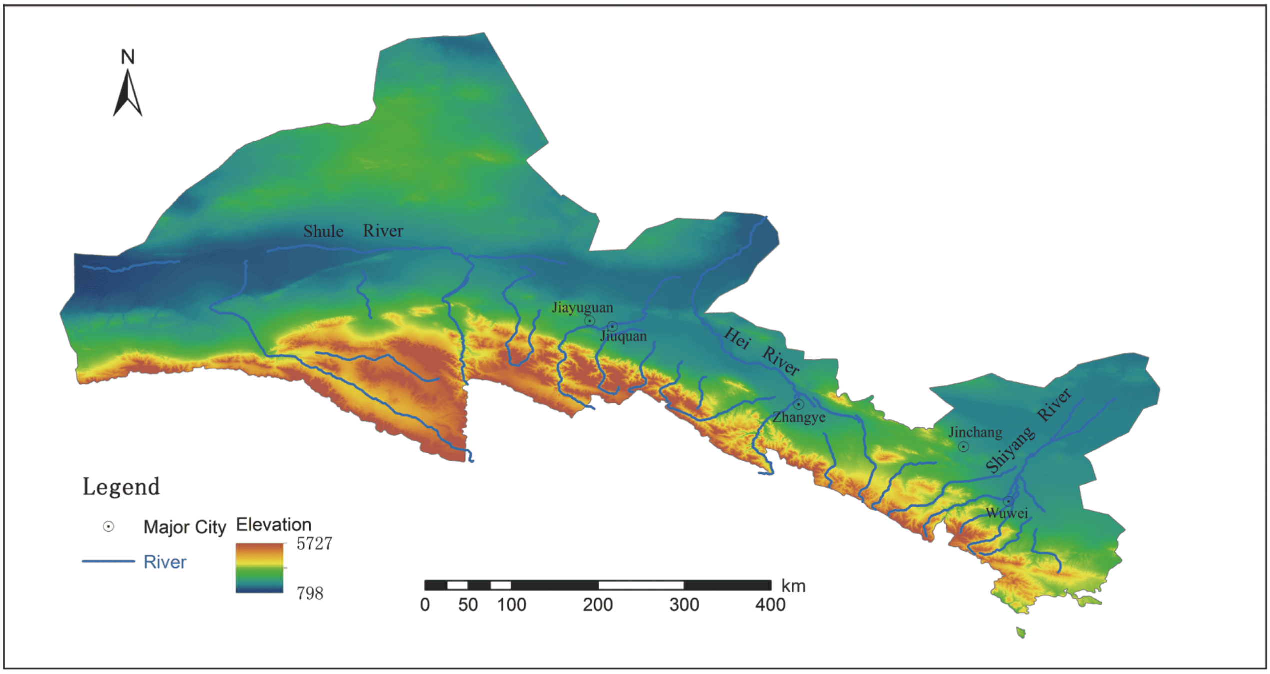

Figure 1 Map showing the Hexi Corridor and the dry/wet zones of China.

results. Based on geographical occurrence, year of inception and participants, the frequency of the wars that took place in the Hexi Corridor can be calculated with reference to a time series (Figure 2d).

2.2.4 *Population*

We retrieved historical data on population size in the Hexi Corridor from Cheng (2007). Based on abundant historical documents about population, and verification using various methods, Cheng provided relatively high reliability for population data of the study area. As Cheng provided estimates of the Hexi Corridor population size at irregular time intervals, we took the common logarithm of the data points, interpolated linearly, and then anti-logged back to create an annual time series (Figure 2e). This method helps to avoid distortions in the population growth rate in data interpolation. The population growth rate was calculated by the following formulae:

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

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

where P is the population size, t is the time interval (in years) and A is the land area (km^2). The land area includes the areas of the Shule river basin, Heihe river basin and Shiyang river basin.

2.2.5 *Regional administration data*

The records of regional administration were derived from *The History of Chinese Administrative Divisions* and some studies of the Hexi Corridor administrative systems (Cheng, 2007; Zhou et al., 2013). It was during the reign of Emperor Han Wudi that the central government established a system of regional administration in the Hexi Corridor. Since then, the administrative system of the Hexi Corridor has experienced several changes including the shift from a two-level to a three-level hierarchy (Figure 2f).

2.3 Methods

The nexus between climate and human society, covering a wide range of elements, is highly complex. Climate change affects human societies through diverse pathways. The interaction between climate and socio-economic factors in arid areas during agricultural periods can be summarized as follows: deteriorating climate causes a decrease in land reclamation and agricultural production, followed by population fluctuations and strained relationships between herders and farmers, and eventually wars and social instability. Social governance by regional government, based on a reasonable administrative hierarchy, can be the solution to restoring social stability. Pearson's correlation coefficient (PCC) is widely used to measure correlation between variables. In this study, we employ PCC and a theoretical framework (Figure 3) to evaluate whether there is sufficient statistical evidence for a relationship between variables, and to verify the impact and response pathways of the climate and human society nexus.

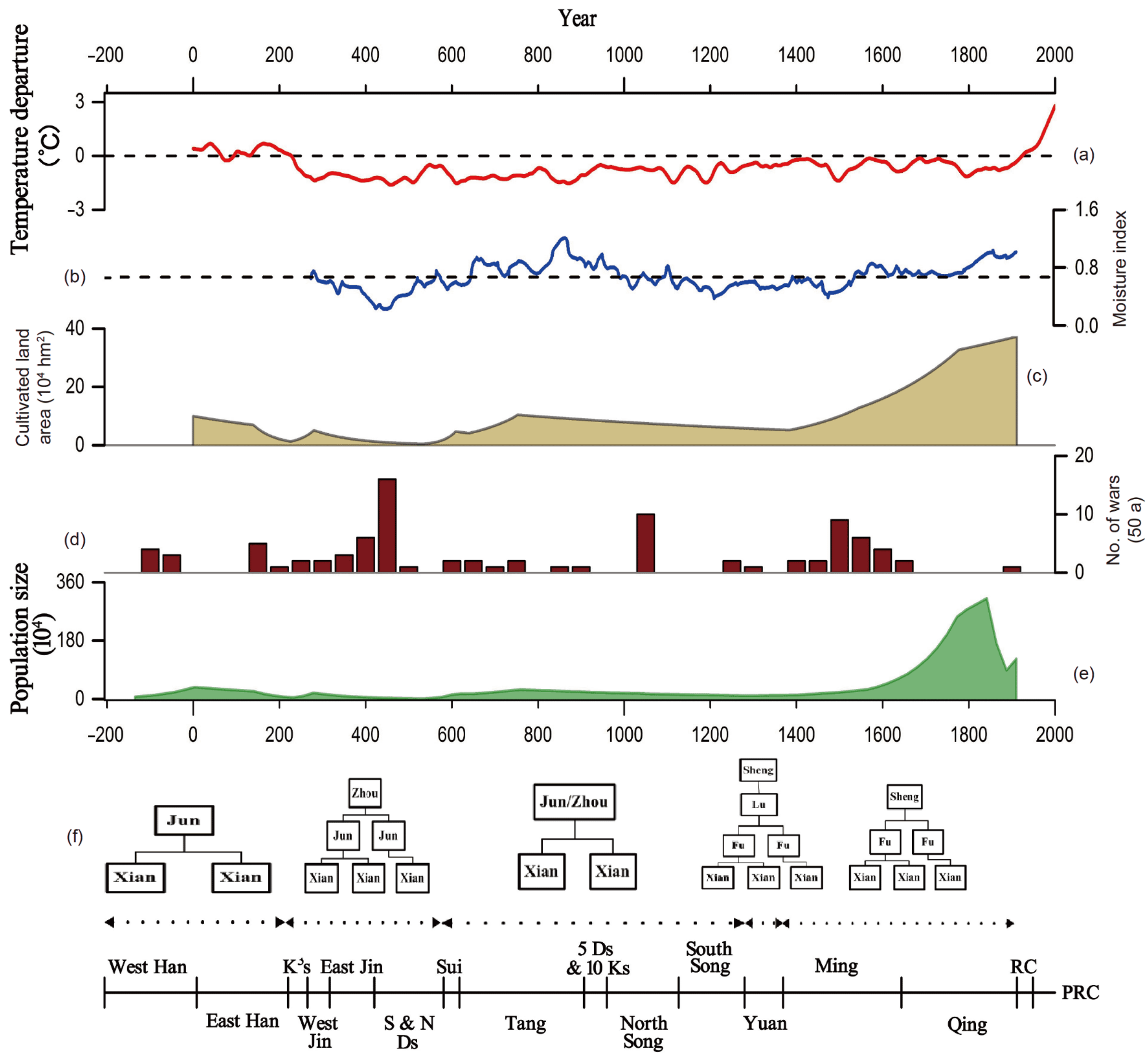

Figure 2 Climate change, agricultural production and social stability in the Hexi Corridor over the last 2000 years. (a) Temperature departures relative to the mean value (horizontal dotted line) of the 1900–1990 period in Northwest China (Yang et al., 2004); (b) variations in the moisture indices for semi-arid areas of China (Gong and Hameed, 1991); (c) cultivated land area of the Hexi Corridor (Cheng, 2007); (d) frequency of wars in the Hexi Corridor (Editorial Committee of Chinese Military History, 2002); (e) population growth dynamics in the Hexi Corridor (Cheng, 2007); (f) administrative division reform in the Hexi Corridor over the last 2000 years (Zhou et al., 2013; Cheng, 2007).

3. Results

3.1 Correlation between climate change and agricultural development

Analysis revealed a positive correlation between a temperature departure series for Northwest China and the cultivated land area of the Hexi Corridor over the last 2000 years (Table 1). According to a 2000-year temperature reconstruction from the Guliya ice core and other evidence, the highest temperatures of the past 2000 years in Northwest China occurred during AD30–270. After AD270, temperature dropped drastically, but the rainfall remained high until the beginning of the fourth century. This favorable period of environmental conditions was found to have a high correspondence with the first period of rapid agricultural development in the Hexi Corridor; i.e., from the reign of Emperor Han Wudi to the West Jin dynasty (Figure 2a and 2c).

Analysis also revealed a significant positive correlation between the semi-arid area moisture index and the cultivated land area in the Hexi Corridor (Table 1), which suggests that moisture conditions played a greater role than temperature in driving land reclamation in the Hexi Corridor during our study period. As shown in Figure 2b, the moisture index is characterized by two waves. The minimum and maximum of the first wave occurred around AD400 and AD850, respectively. Simultaneously, the Hexi Corridor ushered in large areas of land abandonment around AD500, and a rapid expansion of land reclamation around AD750 (Figure 2c). The trough of the second wave is marked by two minima, around AD1200 and AD1450, while the peak occurred in the nine-

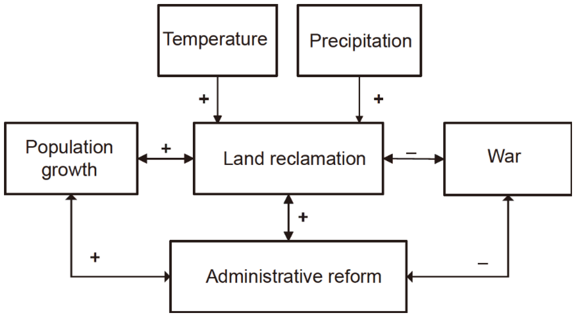

Figure 3 Simplified pathways for interactions between climate change, agricultural production, regional administrative reform and social stability.

teenth century. In terms of land reclamation, the cultivated land area went into a gradual decline from AD800, and the minimum occurred around AD1380. Following that minimum, the Hexi Corridor ushered in another boom in land reclamation, with the peak value occurring around AD1900.

3.2 Correlation between the cultivated land area and war frequency

Pearson's coefficients for the correlation between war frequency and the cultivated land area have been computed at two different time-scales: 20-year and 50-year time intervals. The results show a negative correlation between war frequency and cultivated land area in the Hexi Corridor at the 20-year time lag (Table 1), which means frequent wars would be adverse to land reclamation. Comparing Figure 2c with Figure 3d, we found that land reclamation in the Hexi Corridor has experienced three periods of rapid development: 60BC to AD200, AD620 to 750 and AD1400 to 1900, which basically corresponds to periods of peace. In addition, large areas of land desolation occurred in a period of frequent wars (AD200–600). This analysis provides a quantitative expression of the relationship between land reclamation and war. It is not surprising that frequent wars could trigger large areas of land abandonment. This is due to the fact that frequent wars in the Hexi Corridor caused a large number of local residents to become destitute and homeless, and gradually exhausted the supply of agricultural labor.

Indeed, the relationship between herders and farmers in the Hexi Corridor, which is located in an agricultural-pastoral zone, has been shaped by both cooperation and conflict over land. During the AD200–600 period, prolonged periods of drought and low temperatures resulted in a certain degree of environmental degradation. To maintain their means of survival, both herders and farmers could move to more fertile areas. Herders would be more likely to use this option as they have a higher level of mobility, and this kind of migration for access to the means of production could easily lead to conflict.

3.3 Correlation between the cultivated land area and population growth

Population growth was found to have a significant positive correlation with the cultivated land area of the Hexi Corridor during the study period (Table 1), which is consistent with previous findings that population growth in historical agrarian society was primarily determined by agricultural production (Lee, 2014). Figure 2c shows that land cultivation can be divided into two periods. First, before AD1600, land cultivation had generally remained at a low level. Second, after AD1600, the Hexi Corridor ushered in a period of rapid development in land reclamation. Meanwhile, the population is characterized by similar growth dynamics in the two periods.

We then sought explanations for this wave of land reclamation since the 1600s and the population explosion in the Hexi Corridor. From historical records, we found that the boom in land cultivation coincides with the active implementation by the Qing government of a land reclamation policy in Northwest China during that period. The population of China was less than 150 million in the early years of the Qing dynasty, but increased rapidly subsequently, reaching 311 million by AD1776 (Ge, 2001). In order to cater for the subsistence needs of the extra numbers, the Qing government adopted a land reclamation policy to promote a garrison system and to encourage migration to Northwest China to relieve pressure on the population (Zhao, 2006). The government provided various incentives to peasants and soldiers, including farming and tillage implements, cattle, seeds, silver (as currency), and levies or tax exemptions, which

Table 1 Pearson's correlation coefficients for interactions between annual temperature departure, moisture index, war frequency, population growth rate and cultivated land records for the Hexi Corridor[a)]

Variable		Correlation coefficient	*P* value
Temperature departure (°C)		0.125	<0.01
Moisture index		0.527	<0.01
War frequency	20-year time interval	−0.207	<0.01
	50-year time interval	−0.243	>0.05
Population growth rate		0.877	<0.01

a) ** Correlation is significant at the 0.01 level (2-tailed). The time series of population growth rate is in decadal units.

greatly facilitated the reclamation of previously uncultivated land. In the meantime, foreign food crops such as maize and sweet potatoes were also introduced to Northwest China during the Qing dynasty. Those crops could be planted in poor soils or hilly regions, which enhanced the agricultural capacity of Northwest China and its potential to support a growing population in the future. Hence social factors and government policy played a large part in the boom in land cultivation and population growth during the Qing dynasty.

4. Discussion

4.1 Interactions between climate change, agricultural development and social stability

Population growth is constrained by food subsistence. In the agrarian age, because of the low level of technology, agricultural production was largely dependent on climatic conditions (Ge et al., 2014). Such climate dependence is particularly significant in semi-arid areas, and precipitation availability has been shown to be the most critical variable in determining agricultural production, which might further affect human settlement intensity (Li H M et al., 2017). Even with improved farming technology in recent decades, the yields of the main crops in the Hexi Corridor are affected by climate to a large extent. In concrete terms, Pearson's coefficient for the correlation between the yields of the main crops (wheat and maize) and air temperature is 0.68 and 0.75, respectively; the correlation between those yields and precipitation is 0.64 and 0.79, respectively (Zhang et al., 2016). Therefore, a decline in agricultural production induced by climate change, and the subsequent fluctuations in population, could trigger social unrest, which is especially true at the mutual decadal time-scales reported above.

In the face of social and economic turmoil, governance appears as a crucial regulatory factor in maintaining social stability both at a regional and a national level (Li Y P et al., 2017; Ge, 2011). In this study, we found that a reasonable administrative hierarchy could strengthen the social governance of regional government, and promote social stability and economic development. On the other hand, when the cultivated land area was declining and the population density was low, the overabundance of administrative classes would reduce the efficiency of administrative management, which probably exacerbated the social instability.

4.2 Interactions between population growth and administrative division reform in the Hexi Corridor

Population has always been an important basis for administrative divisions. An appropriate population density and a reasonable administrative hierarchy can strengthen the social governance of regional government. During the reign of Emperor Han Wudi, the central government took control of the Hexi Corridor and established a regional administration system (Li, 2017). Subsequently, reforms of the regional administration division in the Hexi Corridor over the past 2000 years can be divided roughly into four phases (Figure 2f). First, during the Western Han and Eastern Han dynasties (121BC to AD220), the central government established a two-level administrative system (Jun-Xian) in the Hexi Corridor. In this phase, the population density was 0.3–1.5 people per square kilometer, and the regional social governance had achieved remarkable success, as reflected by the low war frequency and an increase in the cultivated land area. Second, during the AD220–581 period (the Three Kingdoms, Western and Eastern Jin, Southern and Northern Dynasties), the administrative system changed from two-level to three-level (Zhou-Jun-Xian), while the population density in that period was lower than 0.9 people per square kilometer. However, the social governance had little success, as reflected in frequent wars and the abandonment of large areas of cultivated land. Third, during the AD581–1279 period (Sui, Tang, Five Dynasties and Ten Kingdoms period, North and South Song Dynasties), the regional administrative system had once again become two-level (Zhou/Jun-Xian), while the population density in the Hexi Corridor was 0.3–1.4 people per square kilometer. In this phase, the regional social governance had worked pretty well, as reflected by a reduction in war frequency and the reclamation of large areas of land. Fourth, the Yuan government (AD1271–1368) established a four-level provincial administration system (Province-Lu-Fu-Xian) in most parts of China. Subsequently, based on the administration system of the Yuan dynasty, the Ming and Qing government (AD1368–1911) built a three-level provincial administration system (Province-Fu-Xian) across the country. In this fourth period, the population density of the Hexi Corridor had increased from 0.5 to 14 people per square kilometer and the population had increased almost 28 times, with the main explosion of growth occurring in the Qing dynasty (AD1644–1911). With regard to war, high war frequencies occurred mainly during the Ming dynasty (AD1368–1644); subsequently, there was almost no war in the Hexi Corridor. During the Qing dynasty, the regional social governance achieved remarkable success, as reflected by the explosive growth in population, a significant increase in the cultivated land area, and the very low war frequency.

Generally, the evolution of the administrative system in the Hexi Corridor has experienced two significant conversion processes over the past 2000 years, both from a two-level to a three-level hierarchy. In the first process, with the increase in administrative levels, the Hexi Corridor was in a state of severe social unrest for a long period. This confirms the phenomenon suggested above; i.e., when regional socio-economic factors, such as land reclamation and population growth, were not achieving significant levels of development, then administrative reforms could weaken the social governance of regional government in historical agrarian China. In the second process, as the administrative level increased, the Hexi Corridor ushered in relative stability and periods of development. Based on the development of regional socio-economic factors, a reasonable administrative hierarchy reform could strengthen the social governance of regional government and play a positive role in the socio-economic development of agrarian China.

5. Conclusions

Based on historical records of climate change (temperature and precipitation), cultivated land area, war frequency, population growth and administrative division reform in the Hexi Corridor over the past 2000 years, this paper presented a quantitative case study that investigated the interaction between climate change, agricultural development, population growth, social unrest, and administrative reform strategies. Hence this study provides a better understanding of the impact-response chains among climate change and these socio-economic factors, and also suggests that a reasonable administrative hierarchy could strengthen the social governance of regional government, and promote social stability and economic development. The main conclusions are as follows.

(1) Analysis found a positive correlation between a temperature departure series for Northwest China and the cultivated land area in the Hexi Corridor over the last 2000 years. The correlation between the moisture index in semi-arid areas and the cultivated land area in the Hexi Corridor was also significantly positive. In particular, the periods of moisture index maxima and minima showed a significant correspondence with the periods of large areas of land reclamation and abandonment, respectively, which suggests that moisture conditions played a greater role than temperature in driving land reclamation in the Hexi Corridor during our study period.

(2) Correlation analysis also revealed a negative correlation between war frequency and cultivated land area in the Hexi Corridor over 20-year time intervals, which means frequent wars would be adverse to land reclamation.

(3) Population growth was found to have a significant positive correlation with the cultivated land area in the Hexi Corridor during the study period. As for the boom in land cultivation and population in the Hexi Corridor during the Qing dynasty, social factors (i.e., the pressure on population in Central China) and policy (i.e., the active implementation of land reclamation and migration incentives) played a large part in these developments.

(4) Climate change, especially precipitation, was confirmed to be the most critical external variable in determining agricultural production in the Hexi Corridor. A climate-induced decline in agricultural production, and the subsequent fluctuations in population, were found to be potential triggers of social unrest, which is especially true at mutual decadal time-scales. In the face of social and economic turmoil, a reasonable administrative hierarchy could strengthen the social governance of regional government, and promote social stability and economic development.

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