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The Demographic Changes and Their Driving Forces on the Loess Plateau since 4000 Years BP

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Abstract: The intensity of human activities on the Loess Plateau (LP) could affect the ecological health and socioeconomic development of the area and the lower reaches of the Yellow River (YR). Population size/density is used as an important indicator to evaluate the intensity of human activities, but there has been little research on its variation in history. Therefore, this study provided a comprehensive analysis of the change characteristics, drivers and development stages of the population on the LP over the past 4000 years. We found that: (1) The significant increase in population after the Warring States (475–221 BC) was due to increasing cropland area and grain yield as a result of the development of agricultural technology compared to that before the Warring States, but its exponential increasing trend depended on reductions in procreation cost due to tax policies, in particular the abolition of the poll tax. (2) Peasant revolts and wars for power in each dynasty, and military conflicts on the boundary between the farming and pasture areas during the dry and cold period, led to population mortality and migration, causing the population of the LP to show a cyclical pattern of decline with the change in dynasties. (3) The population change of the LP has passed through four major stages: the sparsely populated period of primitive agriculture (2000–476 BC), the population fluctuation period of traditional agriculture (475 BC–1530 AD), the population growth period of traditional agriculture (1531–1949 AD) and the rapid population growth period of modern agriculture (1950–2000 AD).

Keywords: population; cropland area; grain yield; taxation policy; war; climate

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1. Introduction

Human impacts on the global environment operate at unprecedented magnitudes, rates and spatial scales [1]. Land use/cover change (LUCC) is an important result of human activities affecting the terrestrial environment [2]. Since the birth of agriculture during the Holocene, the food needed to support population growth has been obtained mainly through the expansion of agricultural areas [3]. Bilsborrow and Geores studied the global man–land relationship and found that a country's population density was positively correlated with cropland area [4]. Looking back at world population history, the global population increased successively from 2.3×10^6 in 15,000 BP to 1.7×10^9 in 1900 and 7.3×10^9 in 2015 [5,6]. Accordingly, the global share of cultivated land area was less than 1% between the birth of agriculture and 1000 AD, increasing to 4.4% in 1850 and 12.2% in 2015 [7]. Population size/density is therefore a key indicator of the extent to which human activities affect the natural environment of a region [8].

The Loess Plateau (LP) (640,000 km^2) (Figure 1) is located in the middle reaches of the Yellow River (YR) and is characterized by fertile land and easy cultivation, which gave rise to the brilliant Chinese civilization [9]. However, environmental characteristics, such as droughts, low rainfall, concentrated rainstorms, sparse vegetation cover and a topography with millions of gullies, combined with increasingly intense human activities, have led

to soil erosion becoming the main environmental problem on the LP. By 1990, the area of soil erosion in the region was as high as 500,000 km^2, of which 145,000 km^2 was classified as erosion areas with an erosion modulus greater than 5000 t/km^2/a [10]. Severe soil erosion hindered the development of the local economy and environmental improvement, causing the political, economic and cultural center in China to move away from the LP after the Northern Song Dynasty (907–1127 AD). The sediment and flood entering the YR from the LP have led to the continuous siltation of the downstream riverbed and incessant flooding, seriously threatening the safety of people's lives and property and social stability on the North China Plain [11–13]. Studies have shown that vegetation was the most important factor preventing soil erosion on the LP [14–16]. Population growth necessitates the expansion of arable land and vegetation destruction. The rising population of the LP in historical times has become a consensus [14]. Accordingly, the arable land here was distributed only in the river valleys until the Spring and Autumn and Warring States period (770–221 BC), but as population increased, the agricultural area expanded into the loess hills and ravines, where soil erosion was most severe [17]. Vegetation cover was 53% during the Spring and Autumn and Warring States period, declining to 42%, 32% and 4% during the Qin–Han (221 BC–220 AD), Tang–Song (618–1279 AD) and Ming–Qing (1368–1911 AD) periods, respectively [18]. The amount of sediment imported into the YR increased from 5×10^7 tons/year from the Xia Dynasty (2070–1600 BC) to the Spring and Autumn Warring States to 1.6×10^9 tons/year during 1800–1970 AD [19]. The sedimentation rate in the lower YR increased from 0.3 cm/year between 300 BC and 550 AD to 8 cm/year between 1850 AD and 1980 AD [20], shaping the riverbed into a 'hung river' that led to frequent flooding events. The flooding frequency increased from once a year between the 10th and 17th centuries to as high as three times a year after the 17th century [9]. Therefore, exploring the demographic changes and their drivers on the LP during historical periods is crucial to better understand how human activities have impacted environmental evolution on the LP and in the lower reaches of the YR.

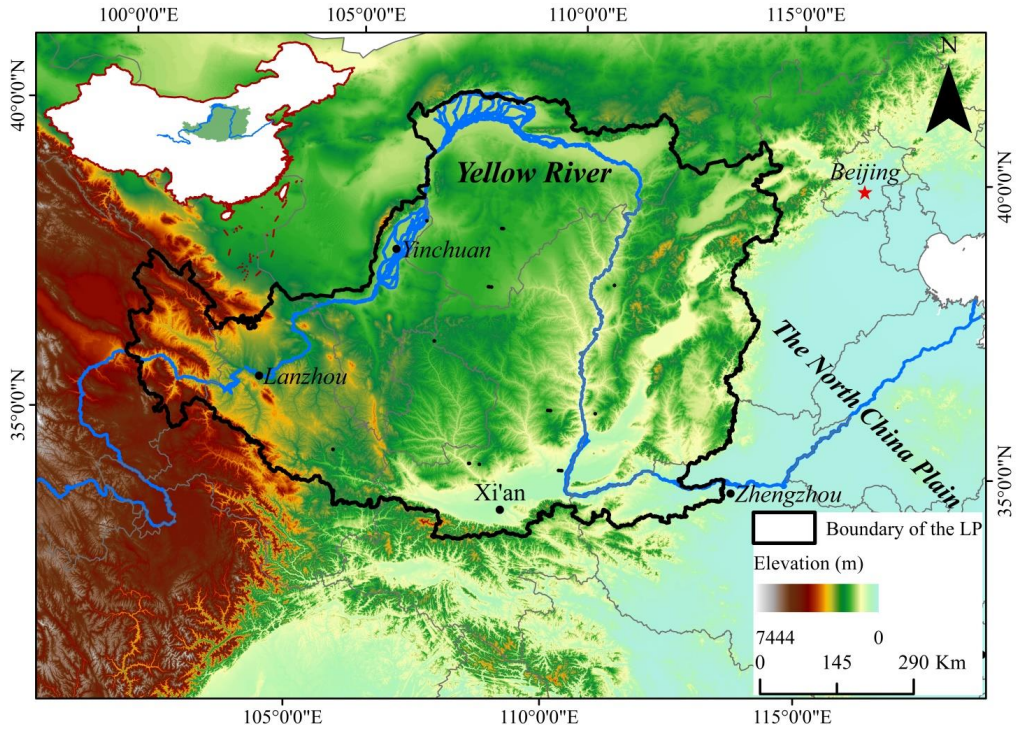


Figure 1. Location of the Loess Plateau (LP).

Current studies have focused only on population size/density [10], the spatial distribution of the population [17,21], population load [22] and patterns of local population evolution [23] on the LP in certain years. However, it is unclear what the long-term patterns

of demographic change are on the Loess Plateau, what the main influencing factors are and how these factors operate during different historical periods. Thus, this study used population size as the research object and linked data on proxy indicators that characterized natural and social factors to analyze the influence of each factor on population size to reveal the patterns of population change and their driving mechanisms on the LP over the past 4000 years and provide insights for the formulation of policies to cope with ecological and environmental changes.

2. Data and Methods

The information relating to the population of the LP and its associated indicators of natural and social factors is summarized in Table 1. Temperature, rainfall, frequency of droughts and gales, tax (expressed in grain weight) and grain yield per unit area (kg/km^2) (during the peacetime of dynasties) were obtained from published monographs/papers [24–28].

The war frequency was obtained statistically at a 20-year temporal resolution based on the book *Chronology of China's Wars Through the Ages* [29]. Types of warfare have included peasant revolts, battles for power and military conflicts on the boundary between the farming and pasture areas.

Migration frequency was obtained statistically with a temporal resolution of 20 years based on the first volume of *The History of Chinese Migration* [30]. Here, migration refers to the forced movement of the population off the LP as a result of war, disasters and policies.

There were three ways of acquiring population data for this paper: (1) Direct acquisition (years included are 2000–771 BC, 2 AD, 140 AD, 280 AD, 609 AD, 742 AD, 1291 AD, 1820 AD, 1840 AD, 1873 AD, 1911 AD, 1928 AD, 1949 AD and 2000 AD) [10,17,31]. (2) Adding up the population of counties in Ningxia, Shanxi, Shaanxi, Gansu and the Inner Mongolian Provinces on the LP in published monographs (years included are 340 BC, 202 BC, 639 AD, 983 AD, 1102 AD, 1207 AD, 1330 AD, 1381 AD, 1578 AD and 1661 AD) [32]. (3) Considering that the LP basically covers the middle reaches of the YR, the population ratio in two adjacent periods of these two areas could be assumed to be equal. Therefore, the population of the LP in 25 AD, 105 AD, 581 AD and 934 AD was obtained by multiplying the ratio of the population in each of these four periods to that of the previous period in the middle reaches of the YR by the population of the LP in the previous period. The population in the middle reaches of the YR was taken from the book *An Anthology of Research on the Environmental Evolution and Water–Sand Operation Patterns of the Yellow River Basin* [8].

The cropland area (km^2) on the LP was obtained by interpreting raster data on land use from the Historical Database of the Global Environment (HYDE) reconstructed by the Netherlands Environmental Assessment Agency (NEAA) [7,33–35] and correcting it with the national cropland area reconstructed by Chinese scholars based on historical records (population, tax, field acres, maps and descriptive information on land development and agricultural activities) and archaeological data. Although Chinese scholars have reconstructed the total cropland area of the country for different dynasties over 2500 years, only nearly 300 years of reconstructed data are available for the arable land area of the LP [3,36]. In contrast, the global historical environmental dataset, while extending over a large time span (10,000 BP), has a low spatial resolution (5′ × 5′). However, we recognized a strong correlation between the total national cropland area interpreted from HYDE and that reconstructed by Chinese scholars ($r = 0.91$, $n = 15$, $p < 0.01$). Therefore, a highly accurate cropland area for the LP over the past 4000 years was obtained by bringing the arable area of the LP from HYDE into the national arable area regression equation ($y = 0.4947x$, $n = 15$, $R^2 = 0.63$, $p < 0.01$) for both datasets.

The grain yield per capita (kg) was obtained from the following equation:

$$\text{Grain yield per capita} = \text{Grain yield per unit area} \times \text{Cropland area}/\text{Population}$$

The main data analysis method of this study is to use relevant geoscience theories to compare population change curves and fluctuation lines of proxy indicators for influencing factors to analyze the population response processes to various environmental factors. In

addition, we conducted a fitting analysis of the population change trend over time after the Warring States period using an exponential function and calculated the population growth rate in different historical periods using a univariate linear regression equation.

Table 1. Information about the historical datasets.

Order	Dataset	Type	Time Span	Temporal Resolution	Spatial Range	Original Material	Data Source
1	Population	Historical records	2000 BC–2000 AD	—	LP	Household registra-tioninformation	[10,17,31,32]
2	Cropland area	Reconstructed	2000 BC–2000 AD	1000 and 100 years before and after 0 AD, respectively	LP	Datasets reconstructed based on population and land use	[7,33–35] http://themasites.pbl.nl/en/themasites/hyde/download/index.html (accessed on 20 June 2020)
3	Grain yield per unit area	Inferred	475 BC–1911 AD	—	All China (covering the LP)	Estimated based on system of weights and measures, population, cropland area and grain ration	[28]
4	Tax in China	Inferred	206 BC–1911 AD	—	All China (covering the LP)	Chinese historical documents	[27]
5	Precipitation	Reconstructed	2000 BC–2000 AD	—	YR Basin (covering the LP)	—	[25]
6	Temperature	Reconstructed	2000 BC–2000 AD	—	All China (covering the LP)	Estimated based on phenological and meteorological information in historical documents	[24]
7	Drought and gale events	Historical records	2000 BC–2000 AD	100 years	North China (covering the LP)	Annual drought/gales derived from the historical archives	[26]
8	War frequency	Historical records	2000 BC–1911 AD	20 years	LP	A compendium that records information on the wars in China	[29]
9	Immigration frequency	Historical records	2000 BC–1949 AD	20 years	From the LP	Immigration chronology	[30]

3. Results and Discussions

3.1. Climate, Agricultural Technique, Grain Yield per Unit Area and Cropland Area

In the agricultural history of the LP, the development of agricultural technology has been a key factor in both offsetting the grain yield-reducing effects of climate deterioration to promote an increase in grain yield per unit area and increasing cropland area. Grain yield per unit area, which is the main indicator assessing the level of agricultural productivity in a region, forms the material basis for a given number of people together with the area of cultivated land [28]. Key factors constraining grain yield per unit area on the LP are climate and agricultural technology. On the one hand, the LP, with its typical semi-humid and semi-arid monsoon climate, is the most sensitive region in China to climate change [31,37]; hence, climate deterioration is likely to cause crop failure [38]. Studies have shown that a 1 °C/100 mm drop in temperature/rainfall on the LP was associated with a 10% reduction in grain production [39]. On the other hand, sloping land, which accounts for more than 60% of the total cultivated area, requires a high input of agricultural power [40]. Therefore, it seems that the development of drought-resistant and agricultural power technology has become a necessary condition to increase grain yield. However, the change in climate from warm and wet to cold and dry since the Warring States (475–221 BC) did not stop the trend of increased grain yield per unit area (Figure 2a,b). Both the temperature anomaly and the rainfall showed a significant downwards trend, being above 0 °C and 500 mm before 1000 AD and below 0 °C and 500 mm after 1000 AD (Figure 2a). In contrast, grain yield per unit area increased from 1.62 t/ha in the Warring States to 4.58 t/ha in 1982 AD (Figure 2b). Thus, it can be argued that the development of agricultural technology has maintained the sustained increase in grain yield on the LP. The invention of the iron plough and the

ridge cultivation technique and the introduction of drought-tolerant plants were landmark events in the history of Chinese agricultural technology. To improve agricultural power, the straight shaft plough, curved shaft plough and mechanized farming tools were invented in the Warring States in the Tang Dynasty (618–907 AD) and after the founding of the People's Republic of China (PRC) in 1949 [3,9,41]. The ridge cultivation technique is an important drought-resistant technology that began in Western Zhou (1046–771 BC), was developed in the Warring States and matured in the Ming and Qing Dynasties (1368–1911 AD) [42]. In addition, the introduction of drought-tolerant maize and potato plants during the Ming and Qing Dynasties also contributed significantly to increased grain yield [43,44]. There is less information on agricultural activities before the Warring States, but it is not difficult to infer that grain yield per unit area was much lower in this period than that after the Warring States. In terms of agricultural technology, the period was characterized by a backwardness in all agricultural techniques and had a small probability of providing sufficient agricultural power and withstanding a dry climate. From a climate perspective, there were two climatic phases, hot dry and cold dry, before the Warring States (Figure 2a), both of which were unfavorable for crop growth. While the cropland area is largely determined by population size [45], the condition of agricultural power is another important limiting factor. Before the Warring States, cultivated land was located only in flat valleys due to the predominance of stone tools and then expanded from plains to mountains with the invention and spread of iron tools and the cattle plough [9]. Thus, the innovation of agricultural technology was an important non-demographic factor in the explosion in cropland after the Warring States (Figure 2b).

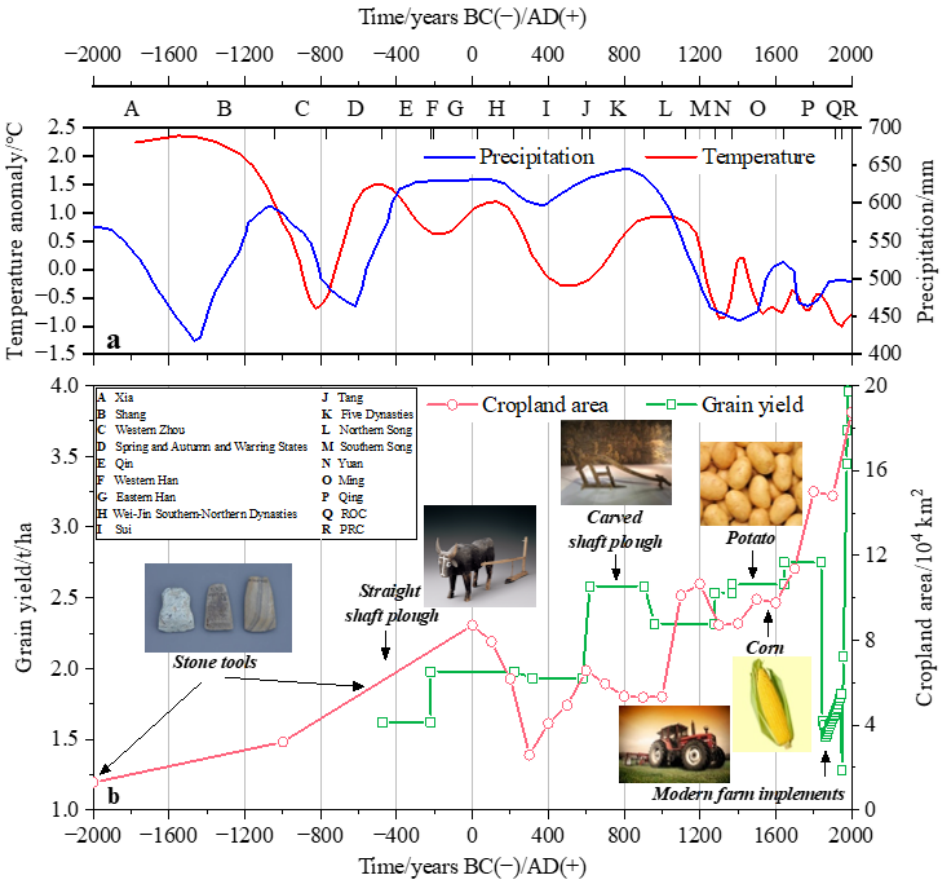


Figure 2. (**a**) Temperature anomalies in China and precipitation in the YR basin; (**b**) grain yield in China and cropland area on the LP.

3.2. Grain Yield, Cropland Area, Policy Initiatives and Population Growth

The sudden increase in population after the Warring States was due to increases in cropland area and grain yield per unit area compared to the period before the Warring States, but its exponential increase depended on tax policies, especially the reduction and abolition of the poll tax, which reduced the procreation cost. In terms of procreation decisions, people's behaviors, both individual and collective, are choices made within the constraints of resources and policies [27]. Resources and policies should therefore rightly be important variables in examining population change. Considering that grain is the most important material for living and production in traditional agricultural societies, resource conditions can be represented by cropland area and grain yield per unit area. Policy conditions are expressed in terms of tax and marriageable age. The correspondence between the indicators and population can reflect the role of resources and policies in regulating the population. In contrast to the period before the Warring States (475–221 BC), reforms in agricultural techniques after the Warring States led to a steady increase in cropland area and grain yield per unit area, with a corresponding increase in population from less than 4×10^5 to over 5×10^6 (Figure 3a,b). However, the increase in cropland area and grain yield per unit area was not sufficient to explain the increasing population trend after the Warring States, as grain-holding per capita had a declining trend. The population grew exponentially during this period ($y = 2.9719e^{0.0014x}$, $n = 52$, $R^2 = 0.7864$, $p < 0.01$; x and y refer to years and population, respectively), with significant fluctuations (average of 5×10^6) between the Warring States and Ming Dynasty (475 BC–1644 AD), growing rapidly after the end of the Ming Dynasty and reaching 1×10^8 in 2000 AD (Figure 3c). The cropland area, which was below 4×10^4 km^2 before the Warring States, increased to an average of 6.9×10^4 km^2 between the Warring States and Yuan Dynasty (475 BC–1368 AD) and reached 18.7×10^4 km^2 in 2000 AD (Figure 3a). The grain yield per unit area increased linearly from 1.62 t/ha in the Warring States to 2.75 t/ha in 1840 AD and reached an all-time high (4.58 t/ha) in 2000 AD (Figure 3a). In contrast, there was a declining trend in grain-holding per capita (Figure 3b). In terms of policies, almost every dynasty, such as Western Zhou (1046–771 BC), Spring and Autumn (770–476 BC), Western Han (206 BC–25 AD), Southern-North Dynasty (420–581 AD), Tang Dynasty (618–907 AD), Song Dynasty (907–1279 AD) and Qing Dynasty (1644–1911 AD), tried to lower the marriageable age to stimulate population growth, with the marriageable age for women being 20, 17, 15, 15, 13 and 14 years, respectively [46,47]. However, the marriageable age remained largely unchanged at 15 years old, which is also insufficient in explaining the increasing population trend.

Continuing with the above chain of logic, reducing the tax may have been key to stimulating population growth, as the average tax was reduced from 119 kg in the Western Han (206 BC–25 AD) to 6 kg in the Ming Dynasty (1368–1644 AD), lowering the procreation cost (Figure 3b). In particular, the abolition of the poll tax after the Qing Dynasty (1644–1911 AD) provided an unprecedented stimulus to procreative autonomy. In the history of Chinese taxation, poll tax has long dominated various taxes before the enactment of the "Single Whip Law" by Zhang Juzheng in the Ming Dynasty, "no increase in taxes for additional population" by Emperor Kangxi in the Qing Dynasty and "Tan Ding Ru Mu" by Emperor Yongzheng in the Qing Dynasty [48]. The Single Whip Law, introduced in 1530 and implemented in 1581, provided for combining agricultural tax, servitude and other taxes into one single tax levied on a per-acre basis, which to some extent reduced the tax on groups of commoners with large populations and small land holdings [49]. The policy "no increase in tax for new population" ensured that the total poll tax in 1711 was treated as a fixed poll tax thereafter, regardless of the increase in population size [50]. In 1723, the policy of "Tan Ding Ru Mu" further merged the fixed poll tax into an agricultural tax, following the principle that those who had more land paid more, thus ending the poll tax that had lasted for thousands of years [50]. Of course, the modernization of agriculture, industrialization and marketization since the founding of the People's Republic of China in 1949 further stimulated population growth.

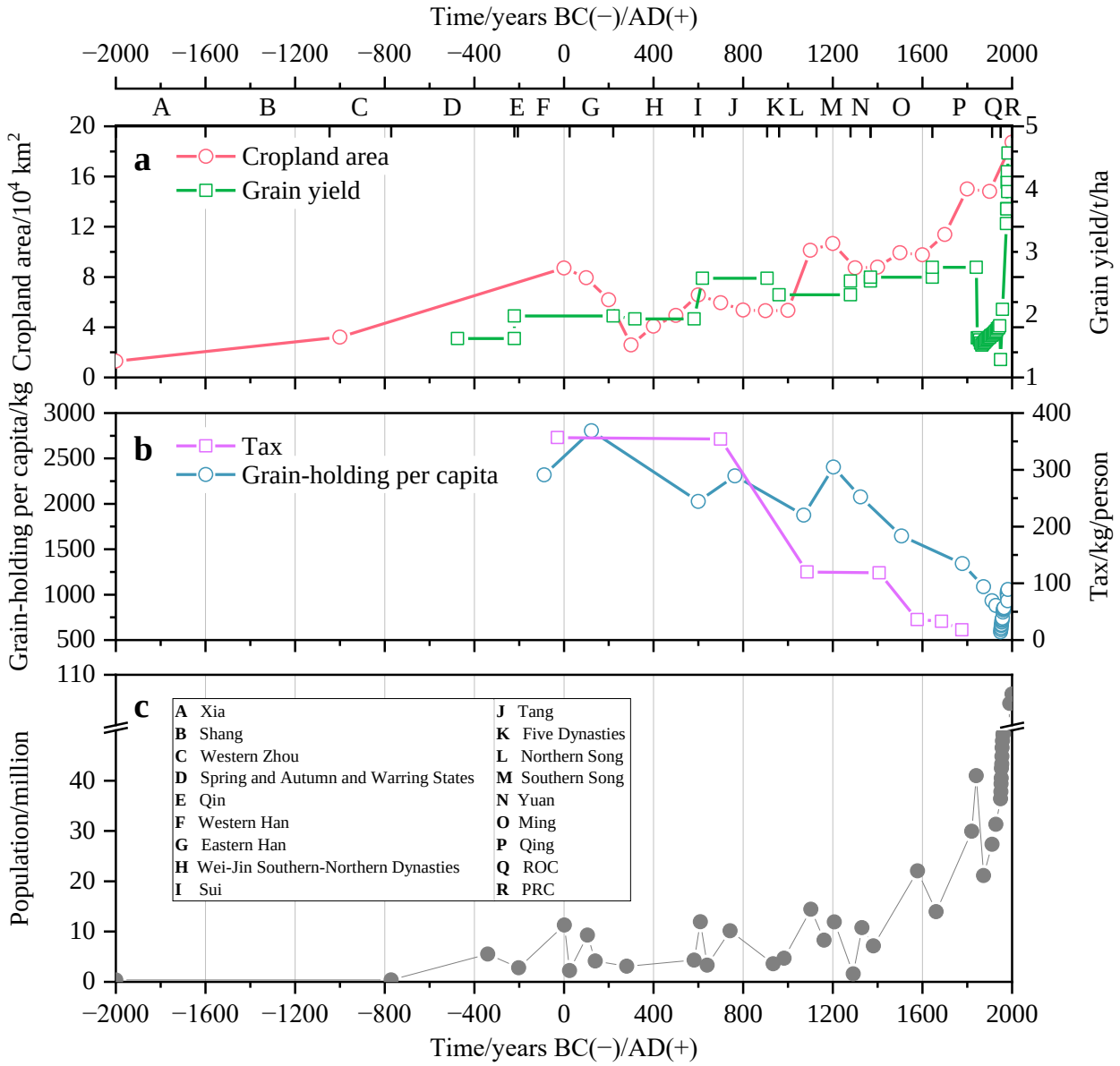


Figure 3. (**a**) Cropland area on the LP and grain yield in China; (**b**) grain-holding per capita on the LP and tax in China; (**c**) Population on the LP.

3.3. Climate, Wars and Depopulation

Peasant revolts and wars for power in each dynasty and military conflicts on the boundary between the farming and pasture areas during the dry and cold period led to population mortality and migration, causing the population of the LP to show a cyclical pattern of decline with the change in dynasties. There were 17 major dynasties/historical periods in Chinese history, and the population in almost every late dynasty declined in response to increased warfare (Figure 4b,c). The wars included, on the one hand, peasant revolts provoked by class conflicts and wars for power. On the other hand, the LP, which is suitable for both agriculture and pastoralism, saw frequent clashes over land resources between farming tribes in the south and nomadic tribes in the north, with the agricultural-pastoral divide thus losing its natural properties and being forced to move south or north as the military forces of both sides waxed and waned [51,52]. The Xia-Shang period (2070–1046 BC), Western Zhou (1046–771 BC), Han Dynasty (221 BC–220 AD), Tang Dynasty (618–907 AD), Northern Song (907–1127 AD), Southern Song (1127–1279 AD) and Ming Dynasty (1368–1644 AD) were dominated by the military power of the southern

farming tribes, with the corresponding northern nomadic tribes being the Guifang, the Rongdi, the Huns, the Turks, the Jurchen, the Mongolian and the Jurchen. The Yuan Dynasty and Qing Dynasty were established by nomadic tribes, namely the Mongols and the Jurchen, and the agro-pastoral boundary was therefore a natural dividing line on which there was little military conflict. Military conflicts on the agro-pastoral divide are closely linked to climate. During the warm and wet period, there was less conflict along the agro-pastoral divide and the dynasties were ended by peasant revolts or wars for power (Figure 4a−c). In contrast, during the dry and cold period the change in dynasties was mostly associated with the southward migration of nomadic tribes. For pastoralists living on the arid northern LP, climate deterioration means water scarcity, land degradation and a reduction in population-carrying capacity, which can force nomadic tribes to choose to move south to expand their pastures [53]. During the Wei-Jin Northern-Southern Dynasty and Northern Song, the Republic of China was dominated by a cold and dry climate, a period of frequent drought and gale events and endless conflicts between farming and herding tribes (Figure 4a,b). In the five dynasties after the Northern Song, Nomadic tribes put an end to the Northern Song, Southern Song as well as the Ming Dynasty, establishing the Yuan (1279–1368 AD) and Qing (1644–1911 AD) Dynasties. The ways in which war leads to population decline include death and population migration. In history, 118 migrations out of the LP have taken place (Figure 4c), of which 85 were caused by wars, 24 by policies (18 in the Ming Dynasty) and 9 by famine.

3.4. Historical Stages of Demographic Changes and Their Driving Factors

Based on population size and key drivers and with reference to the way in which China's agricultural history is divided into development stages [3], the 4000-year population history of the LP can be divided into four stages (Figure 5). (1) The sparsely populated period of primitive agriculture (2000–476 BC): the limited area of arable land and grain yield per unit area in this period were due to the predominance of stone-made agricultural implements and the start-up phase of ridge cultivation techniques, combined with little warfare, and left the population at fewer than one million. (2) The population fluctuation period of traditional agriculture (475 BC–1530 AD): with the invention and development of agricultural techniques such as the straight shaft plough, curved shaft plough and ridge cultivation techniques, the history of Chinese agriculture entered a period of traditional agriculture during which an increase in cropland area and grain yield greatly stimulated the incentive to have a baby, but the population always fluctuated approximately 6.8×10^6 due to frequent wars and the expensive poll tax. (3) The population growth period of traditional agriculture (1531–1949 AD): this phase saw the development of traditional agriculture reach its peak. The increases in cropland area and grain yield did not contribute to an increase in the amount of grain-holding per capita, but the abolition of the poll tax, which had been in place for thousands of years, and the reduction in warfare during this period led to an increase in the population, reaching 4×10^7 in 1840 AD (4.43×10^6/year growth rate). (4) The rapid population growth period of modern agriculture (1950–2000 AD): with the development of modern agriculture since the founding of the People's Republic of China in 1949 and the economic stimulation of the reform and opening-up policy in 1978, the population increased from 3.6×10^7 in 1949 to 1×10^8 in 2000 in less than 50 years (1.36 million/year growth rate).

3.5. Limitations of the Study

The data used in this study have certain limitations, which may lead to insufficient justification of the research results. These limitations are mainly reflected in two aspects. Firstly, the proxy indicators of environmental factors are reconstructed or calculated based on historical data unique to China, which has important significance for the analysis of environmental evolution in China. However, it poses a challenge to verify these results by collecting similar data in other countries. Secondly, these data have low temporal and spatial resolutions, such as the spatial resolution of arable land area ($5' \times 5'$) and the

temporal resolution of grain yield, which may also lead to insufficient justification of the results. In the future, it is necessary to further explore historical data to obtain higher resolution data or obtain more universal proxy indicators to verify our viewpoints.

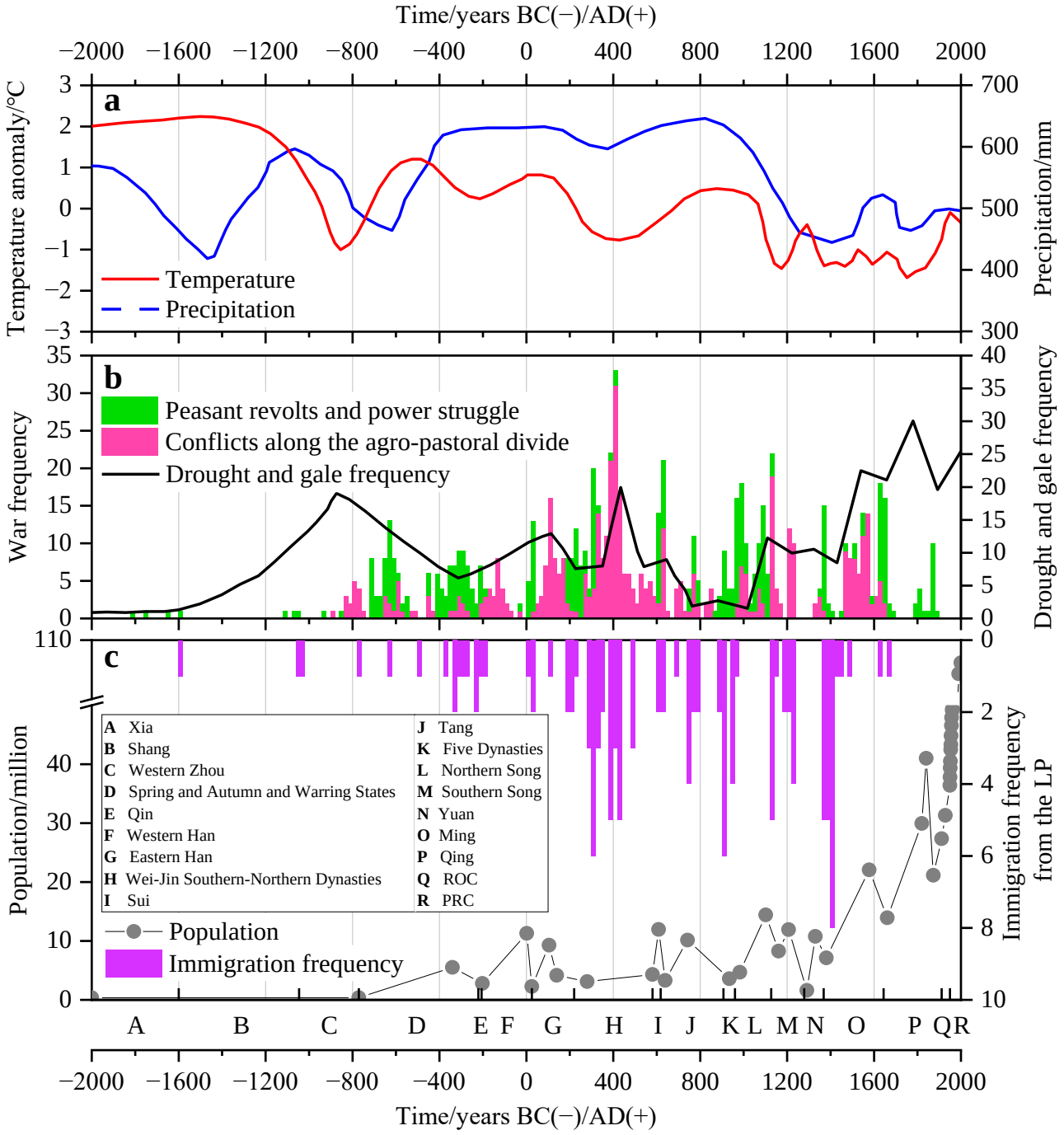


Figure 4. (**a**) Temperature anomalies in China and precipitation in the YR basin; (**b**) war frequency on the LP and drought and gale frequency in North China; (**c**) population and immigration frequency on the LP.

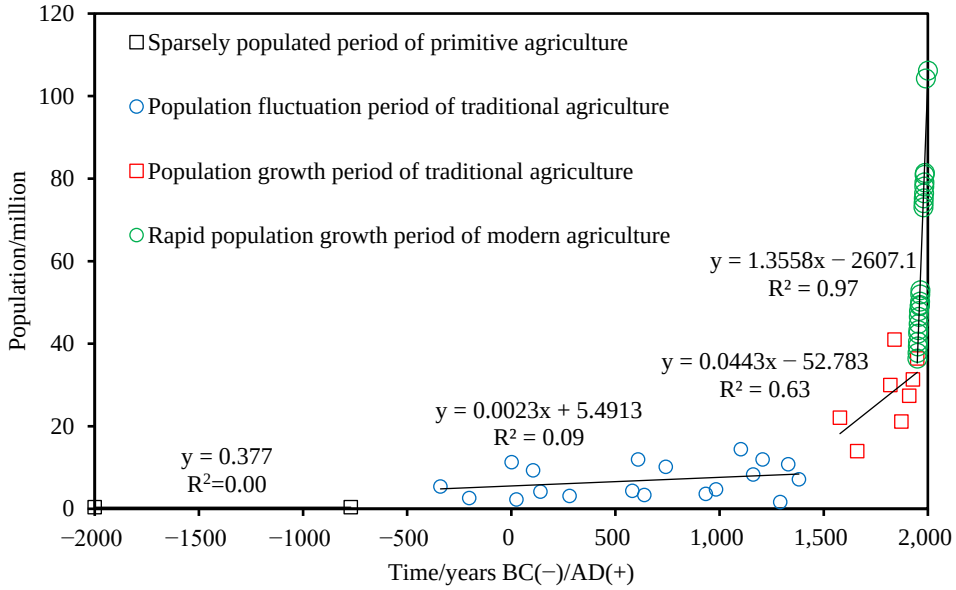


Figure 5. Historical stages of demographic change in the LP.

4. Conclusions

By correlating the population and indicators of the natural and social factors directly or indirectly linked to it over the past 4000 years, this study used traceability analysis to explore the characteristics, drivers and stages of population development on the LP over the past 4000 years, with the following conclusions:

(1) Although the climate has changed from warm and wet to cold and dry over the past 4000 years, the invention and development of agricultural techniques such as the iron plough and ridge cultivation techniques and the introduction of drought-resistant crops have ensured continued increases in cropland area and grain yield per unit area on the LP.

(2) The sudden increase in population after the Warring States (475–221 BC) was due to increases in cropland area and grain yield per unit area compared to the period before the Warring States, but its exponential increasing trend depended on tax policies, especially the abolition of the poll tax, which reduced the procreation cost.

(3) Peasant revolts and wars for power in each dynasty and military conflicts on the boundary between the farming and pasture areas during the dry and cold period led to population mortality and migration, causing the population of the LP to show a cyclical pattern of decline with the change in dynasties.

(4) The history of population development on the LP included four stages: the "sparsely populated period of primitive agriculture" with poor agricultural technology and low agricultural productivity; the "population fluctuation period of traditional agriculture" with an increase in cropland area and grain yield but limited by tax and warfare; the "population growth period of traditional agriculture" with the abolition of poll tax and reduced frequency of warfare; and the "rapid population growth period of modern agriculture" with no war, industrialization and a market-oriented economy.

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