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Spatial-Temporal Patterns and Influencing Factors of Epidemics in Gansu Province During the Qing Dynasty (1644–1911)

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ABSTRACT

Understanding the historical dynamics of epidemics is crucial for addressing contemporary global health threats under climate change and globalization. However, most existing studies on historical epidemics in China have focused on eastern coastal regions, while northwestern areas like Gansu-a critical ecological transition zone-remain understudied. Furthermore, comprehensive analyses integrating both natural and social environmental drivers are lacking. To address this research gap, this study investigates the spatial-temporal distribution patterns and influencing factors of plague epidemics in Gansu Province during the Qing Dynasty (1644–1911) using historical records, spatial autocorrelation analysis, and geographic detectors. Results reveal that plague frequency peaked during the Tongzhi era (1863–1874), with epidemic coverage and affected counties reaching maxima in 1724 and 1769, respectively, predominantly occurring in summer and autumn. Spatially, plague spread evolved from fragmented distributions in the early period to increasingly clustered and contiguous patterns in central and eastern Gansu. The epidemics were driven by the interplay of natural and social factors, with the interaction between transportation route length and elevation exhibiting the strongest synergistic effect. These findings provide historical insights for understanding regional epidemic dynamics and inform contemporary public health strategies in ecologically vulnerable regions.

KEYWORDS

Epidemics; Spatio-temporal Patterns; Influencing Factors; Gansu; Qing Dynasty.

1. INTRODUCTION

Epidemics have consistently threatened the survival and development of human societies, with major types including bubonic plague, smallpox, cholera, typhoid fever, and malaria [1]. These typically require three conditions: an infectious source, transmission routes, and susceptible populations [2]. In fact, plague transcend mere medical concerns, profoundly shaping human history and societal progress. Snowden asserts that infectious diseases constitute "a major force driving the course of human history" [3]. The 14th-century Black Death decimated approximately one-third of Europe's population [4], triggering severe social and economic upheaval; similarly, 19th-century cholera and 20th-century AIDS inflicted global devastation [5]. Entering the 21st century, SARS and the COVID-19 pandemic have once again revealed the cross-border nature and systemic risks of plagues in the era of globalization [6]. In China, epidemics have similarly reshaped social and regional landscapes multiple times throughout history. Since ancient times, the distribution of epidemics across China has exhibited significant temporal and spatial variations. Climate fluctuations, population movements, and transportation patterns during different periods profoundly influenced the characteristics of epidemic transmission. Particularly during the Qing Dynasty, rapid socioeconomic development, population growth, and the refinement of regional transportation systems made plague spread more frequent and regionally concentrated. The northwest region, particularly Gansu Province, situated at the crossroads of the agro-pastoral transition zone and the Silk Road, became a critical corridor and high-risk zone for epidemic transmission due to its unique geography, climate, and transportation networks. Therefore, systematically examining the spatio-temporal patterns and influencing factors of epidemics in Qing Dynasty Gansu deepens our understanding of historical human-land interactions and environmental changes, while offering historical insights for contemporary public health risk prevention and control. The current "Healthy China 2030" strategy and national public health security system construction emphasize preventing regional major infectious disease risks. Analyzing the spatiotemporal evolution and environmental drivers of plagues in Gansu from a historical perspective can provide scientific support for enhancing public health governance capabilities and optimizing health spatial patterns in western China.

The historical and societal impacts of epidemics have long been central themes in their study. Extensive literature reviews have examined the profound impacts of major plagues like the Black Death and the Spanish Flu on population size, labor force structure, political systems, and cultural concepts, revealing the significant role of plagues in shaping the course of human civilization [7]. Regarding pathogenesis and transmission mechanisms, scholars have employed the "pathogen-host-environment" triadic model to elucidate the complex relationships among infectious sources, transmission routes, and susceptible populations [8]. Modern research indicates that emerging infectious diseases often originate from zoonotic spillover events, closely linked to human activities, land use, and frequent contact with wildlife [9]. Epidemiological modeling and data analysis methods, such as SEIR models and scenario simulations, are widely employed to deduce epidemic transmission trajectories and evaluate containment effectiveness [10]. Concurrently, the adaptability of public health systems and social governance has become a research priority, with national prevention strategies, healthcare resource allocation, and societal resilience significantly influencing pandemic response outcomes [11] . Against the backdrop of globalization and climate change, the interplay between plagues and environmental shifts, transnational mobility, and economic globalization has garnered increasing attention [12]. Particularly following the COVID-19 pandemic, academic discourse has intensified its focus on the long-term impacts on the global economy, education, and social stability [13].

Epidemics-related research exhibits distinct interdisciplinary characteristics in methodology. Historical studies primarily rely on historical texts, inscriptions, archives, church records, archaeological materials, and other sources to reconstruct the transmission pathways and societal impacts of plagues across different periods [14] . Modern research extensively employs mathematical modeling, such as SIR and SEIR models, to estimate the basic reproduction number (R_0), incubation periods, and the effectiveness of intervention measures [15]. With technological advancements, methods like GIS spatial analysis, social network analysis, and big data mining are now widely employed to study the spatiotemporal patterns of epidemic spread and population contact dynamics [16]. Concurrently, public health and economics research integrates econometric models to assess the impacts of plagues on social governance, international trade, and the global economy.

The research perspective on plagues has continually expanded, evolving from an early focus on medicine and pathology to a comprehensive, interdisciplinary approach. From a biomedical perspective, research emphasizes pathogen characteristics, transmission mechanisms, and vaccine development. Historically, plagues are viewed as pivotal forces driving demographic shifts, institutional transformations, and civilizational progress. From the perspective of social sciences and global governance, they are recognized as critical components of public risk and global security [17]. Recent research emphasizes the amplifying effects of globalization, climate change, and social inequality on plagues risks, advocating for understanding plagues within frameworks of global governance and sustainable development [18]. Consequently, plagues research has evolved from single-discipline approaches toward comprehensive, multidimensional, and systematic inquiry.

Research on plagues has yielded rich findings across medicine, history, and the social sciences. Existing studies have revealed the profound impact of plagues on human and societal development, developed diverse research methodologies, and fostered multidimensional perspectives. However, several shortcomings remain: First, research perspectives lack sufficient integration and interdisciplinarity. Most studies remain confined to medical history or social history, lacking a comprehensive framework that integrates historical geography, environmental change, and human-land system interactions to explore the patterns of plague occurrence. Second, regional studies exhibit unevenness. Existing studies have mostly focused on the densely populated areas in eastern China and the coastal trade regions, while relatively little attention has been given to Northwest China—especially Gansu Province, which lies at the junction of the arid and semi-arid regions, the eastern monsoon region, and the alpine region of the Qinghai-Tibet Plateau. This area exhibits diverse natural and human geographical characteristics, functioning both as a climate-sensitive zone and an ecologically fragile area. Its unique geographical environment and human-land relationship patterns may profoundly influence the spatiotemporal distribution and transmission pathways of plagues. Third, Qing dynasty epidemic studies often emphasize social and political history perspectives, paying insufficient attention to environmental factors and regional variations. Although existing literature has examined the frequency and historical impact of plagues during the Qing Dynasty, comprehensive studies integrating natural and human factors such as climate, topography, water systems, and transportation remain scarce. Therefore, investigating the spatio-temporal characteristics and influencing factors of plagues in Gansu province during the Qing Dynasty holds significant scientific and practical value. On the one hand, it helps to reveal the environmental sensitivity and regional variations in epidemic transmission within the arid-monsoon-alpine transition zone, deepening our understanding of regional epidemic patterns. On the other hand, it provides historical insights and spatial references for identifying public health risks and establishing regional epidemic prevention systems in contemporary ecologically fragile areas.

This study aims to explore the spatiotemporal evolution of epidemic outbreaks in Gansu Province and their environmental influencing factors from the historical medical geography perspective. By systematically compiling and spatially representing historical records, local gazetteers, and archival documents from the Qing Dynasty, it uses spatial analysis methods to address the following scientific questions: (1) What patterns emerge in the temporal evolution and spatial distribution of plagues in Gansu during the Qing Dynasty? (2) How do environmental factors such as climate change, natural disasters, and transportation patterns affect the spread and clustering of plagues? The findings will provide scientific insights for understanding eco-social vulnerability in geographically convergent zones, enhance disaster prevention and public health governance capabilities in Gansu and similar regions, and offer new perspectives on human-environment system response mechanisms under historical environmental change.

2. METHODOLOGY

2.1. Study Area

In this study, "Gansu region" refers to the jurisdiction of the Qing Dynasty's Gansu Province, encompassing parts of present-day Gansu, Qinghai, and Ningxia provinces, with a total land area of 488,300 km^2. During the Ming Dynasty, Gansu belonged to the Shaanxi Provincial Administration, with its northwestern territories divided into various military districts under the jurisdiction of the Shaanxi Provincial Commandery. The Qing Dynasty established Gansu Province west of Shaanxi, breaking the Ming administrative framework and marking Gansu's independent establishment. The administrative center was relocated from Gongchang (present-day Longxi Xian) to Lanzhou. By 1911, Gansu Province administered 67 county-level administrative units (Fig. 1), with each prefecture overseeing its subordinate counties as detailed in Table 1. Situated in China's northwestern hinterland along the upper reaches of the Yellow River basin, the region lies at the junction of three major natural regions-the arid and semi-arid region of Northwest China, the eastern monsoon region, and the alpine region of the Qinghai-Tibet Plateau. Its terrain is elongated and narrow, with higher elevations in the west and lower in the east. The climate exhibits significant diversity, encompassing subtropical, warm temperate, temperate, humid, semi-humid, semi-arid, and arid zones. Except for the shaded, humid high-mountain areas, most of the province experiences a dry climate characterized by large annual and daily temperature variations, pronounced continentality, abundant sunshine, and a rainy season coinciding with the warm season. Water and heat resources decrease progressively from southeast to northwest, resulting in considerable regional variation.

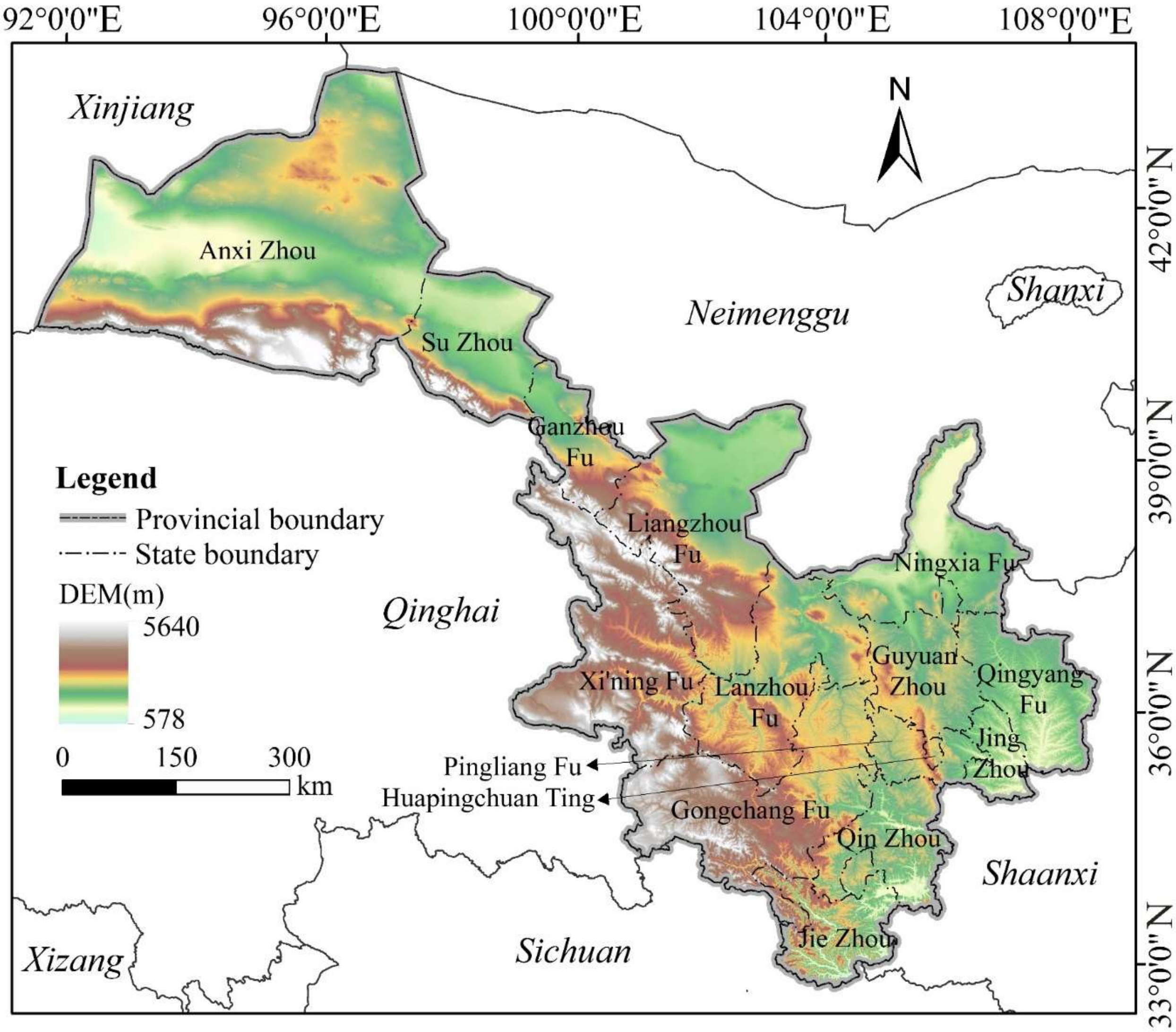

Fig. 1 Administrative map of Gansu Province, 1911 (Source: Administrative district data for 1911 from the China Historical Geographic Information System)

Table 1. Names of prefectures and 67 county-level divisions in Gansu Province during the Qing Dynasty

State/Province under jurisdiction	County-level name
Lanzhou Fu	He Zhou, Jingyuan Xian, Jin Xian, Didao Zhou, Weiyuan Xian, Gaolan Xian,
Ningxia Fu	Zhongwei Xian, Ningling Ting, Ningshuo Xian, Pingluo Xian, Ningxia Xian, Ling Zhou
Pingliang Fu	Pingliang Xian, Huating Xian, Longde Xian, Jingning Xian
Gongchang Fu	Huining Xian, Taozhou Ting, Anding Xian, Longxi Xian, Tongwei Xian, Ningyuan Xian, Fuqiang Xian, Xihe Xian, Min Zhou
Qingyang Fu	Huan Xian, Heshui Xian, Ning Zhou, Zhengning Xian, Anhua Xian
Xi'ning Fu	Datong Xian, Xi'ning Xian, Dan'gaer Ting, Bayanrongge Ting, Nianbo Xian, Guide Ting, Xunhua Ting
Liangzhou Fu	Yongchang Xian, Zhenfan Xian, Wuwei Xian, Gulang Xian, Pingfan Xian
Ganzhou Fu	Fuyi Ting, Zhangye Xian, Shandan Xian
Qin Zhou	Qin'an Xian, Li Xian, Liangdang Xian, Hui Xian, Qin Zhou, Qingshui Xian
Jie Zhou	Cheng Xian, Jie Zhou, Wen Xian
Guyuan Zhou	Pingyuan Xian, Haicheng Xian, Guyuan Zhou
Jing Zhou	Zhenyuan Xian, Jing Zhou, Lingtai Xian, Chongxin Xian
Su Zhou	Su Zhou, Gaotai Xian
Anxi Zhou	Dunhuang Xian, Yumen Xian, Anxi Zhou
Huapingchuan Ting	Huapingchuan Ting

2.2. Methods

This study adopts an integrated "time-space-mechanism" analytical framework, employing a combination of mathematical statistics, spatial analysis, and geophysical detection methods. It systematically reveals the spatio-temporal evolution patterns of plague outbreaks in Qing Dynasty Gansu and their environmental determinants, progressing from macro to micro levels and from description to explanation. Through multidimensional quantitative analysis and model validation, this study not only seeks to reconstruct the spatial patterns and evolutionary characteristics of plague during the historical period but also aims to explore the logic of disaster formation under the interaction of natural and human factors.

2.2.1. Conceptual Definitions

Based on historical records of plague disasters, a chronological framework of epidemic outbreaks was established. Drawing on previous studies, this research employs indicators such as the number of affected counties, affected area, frequency, widespread, thickness, trend, cycle, and seasonal incidence rate to analyze the overall characteristics, interannual variations, and seasonal patterns of plague epidemics. Epidemic frequency refers to the proportion of years with recorded outbreaks relative to the total observation period. Epidemic extent denotes the number of affected counties or the area impacted, which can also be expressed as the percentage of affected counties within the total number of counties in the region. Epidemic intensity represents the ratio of the cumulative affected area over multiple years to the total land area of the region. Seasonal incidence rate refers to the percentage of plague occurrences in a particular season relative to the total number of seasonal plague events during the study period.

2.2.2. Spatial Autocorrelation Analysis

To reveal the spatial distribution characteristics and spatial dependency of plagues in Qing Dynasty Gansu, spatial autocorrelation analysis was employed to investigate the spatial clustering patterns of plagues. Through global spatial autocorrelation analysis, we can assess whether the spatial distribution of plagues within the study area exhibits significant clustering or dispersion phenomena. This helps us understand the spatial distribution patterns and overall correlations of plagues in Qing Dynasty Gansu at the regional scale, providing a basis for subsequent local spatial analysis. The calculation formula is as follows [19]:

$$I = \frac{\mathrm{n}\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{1}$$

where I represents the global Moran's I index, which measures whether spatial clustering or anomalous distribution occurs. x_i denotes the observed variable value at spatial location i, n is the total number of samples, and W_{ij} represents the spatial weight matrix. The value of I ranges between [-1, 1]. A value less than 0 indicates negative correlation, greater than 0 indicates positive correlation, and equals 0 indicates random distribution. The closer I is to 1, the more pronounced the spatial clustering effect; conversely, the closer it is to -1, the more evident the spatial dispersion.

To further reveal the spatial clustering and variation patterns of plagues within local spatial scales, local spatial autocorrelation analysis was employed to examine detailed spatial distribution characteristics. Local spatial correlation indices effectively reveal spatial relationships between study units and their neighboring units, quantifying the degree of local spatial clustering for each unit [20]. Employing the local Moran's Index I_i as an analytical tool enables the identification of high-value and low-value spatial clusters of plagues, thereby revealing the spatial clustering characteristics of plagues at the county level and their interactions with surrounding regions. Its calculation formula is:

$$I_i = \frac{\mathrm{n}(x_i - \overline{x})\sum_{j=1}^{n} W_{ij}(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{2}$$

2.2.3. Spearman Correlation Analysis

To identify significant factors influencing plague plagues, this study employs Spearman correlation analysis. This nonparametric statistical test does not require variables to follow a normal distribution and effectively reflects monotonic relationships between variables. It is particularly suitable for analyzing historical statistical data with small sample sizes or outliers. Spearman correlation analysis reveals the direction and strength of associations between environmental factors and epidemic frequency, providing a basis for variable selection in subsequent geodetector analysis. Its calculation formula is:

$$\rho = 1 - \frac{6\sum d_{i^2}}{n(n^2 - 1)} \tag{3}$$

where ρ denotes the Spearman rank correlation coefficient, with values ranging from -1 to 1. di represents the difference in rank values between the i-th data pair, and n denotes the total sample size. Table 2 presents the selection criteria and definitions of the influencing factors in this paper:

Table 2. Explanation of plague impact factor indicators

Basic Data	Indicators	Unit	Indicator Definitions
Climate Factors	Annual precipitation	mm	Average precipitation variation
	Average annual temperature	°C	Average temperature variation
Topography Factors	Elevation	m	Elevation differences
Water Source Factors	Distance from county center to nearest watercourse	km	River influence variations
Drought Factors	Number of drought years	Year	Impact of drought years
Population Factors	Population density	Per 10,000 km²	Population density variations
Transportation Factors	Length of transportation routes	km	Transportation conditions influence
	Distance from county center to major transportation routes	km	

2.2.4. Geodetector Analysis

Geodetectors constitute a set of statistical methods for detecting spatial differentiation and revealing its underlying drivers [21]. This study employs geographic detectors to investigate the driving forces of various factors influencing epidemic outbreaks. Interaction detectors are applied to examine the interactions between natural environmental factors (climate, topography, water sources, drought, etc.) and human environmental factors (population, transportation, warfare, etc.) affecting epidemic spread. This enables the assessment of how different factors collectively impact plagues. The formula is as follows:

$$q = 1 - \frac{1}{N_{\sigma^2}} \sum_{h=1}^{L} N_{h\sigma h^2} \quad (4)$$

where h represents the stratification of attribute Y or factor X. $N_h$and N denote the number of units in stratum h and the entire area, respectively. σh^2 and σ^2 are the variances of h and Y, respectively. The value of q ranges from [0, 1], with a larger q indicating stronger explanatory power of independent variable X for attribute Y. The Geographic Detector first employs the Factor Detector to investigate the extent to which a factor X explains the spatial variation of attribute Y. The Interaction Detector further assesses whether the interaction between any two influencing factors enhances, weakens, or is independent of the spatial variation of geographic phenomena. The Interaction Detector results primarily encompass five types: nonlinear weakening, single-factor nonlinear weakening, dual-factor enhancement, independence, and nonlinear enhancement.

2.3. Data Sources

Based on the *Compilation of Historical Materials on Plagues in China over Three Millennia* (Qing Dynasty Volume) [22], historical records of plagues in Gansu Province during the Qing Dynasty were systematically compiled and statistically analyzed at the county level. A total of 179 historical records documenting plagues in Gansu during the Qing Dynasty were identified, with 4 additional records supplemented from Volume 126 of the *Draft General Gazetteer of Gansu* [23] and Volume 14 of the *Revised Gazetteer of Gaolan County from the Guangxu Reign* (Part II) [24]. Based on information from the historical records regarding the time, location, severity, and outcomes of plagues, a chronological sequence of plague disasters in Qing Dynasty Gansu was reconstructed. This sequence spans from the first year of the Shunzhi reign (1644) to the third year of the Xuantong reign (1911), with a temporal resolution of one year. It covers all 67 counties under the jurisdiction of Qing Dynasty Gansu Province, with a spatial resolution at the county level. Using ArcGIS 10.8, we analyzed the spatial distribution of plague disasters within the study area. Maps in the spatial data were created based on the 1911 administrative district data from the China Historical Geographic Information System (https://chgis.fas.harvard.edu/data/chgis/v6/). Among the influencing factor data, meteorological data originated from the National Meteorological Center. Elevation and river channel data were extracted from Digital Elevation Model (DEM) data of Gansu, Qinghai, and Ningxia Hui Autonomous Region, along with national five-tier river channel data. Drought data were sourced from the *Compendium of Meteorological Disasters in China* (Gansu Volume) [25]. Population data were sourced from the *Draft General Gazetteer of Gansu* and Volume V of the *History of the Chinese Population* [26], while war-related information was drawn from the *Chronology of Chinese wars* [27].

3. RESULTS

3.1. Temporal Distribution Characteristics of Epidemic Outbreaks in Gansu Province

3.1.1. Changes in Plague Incidence by Imperial Era

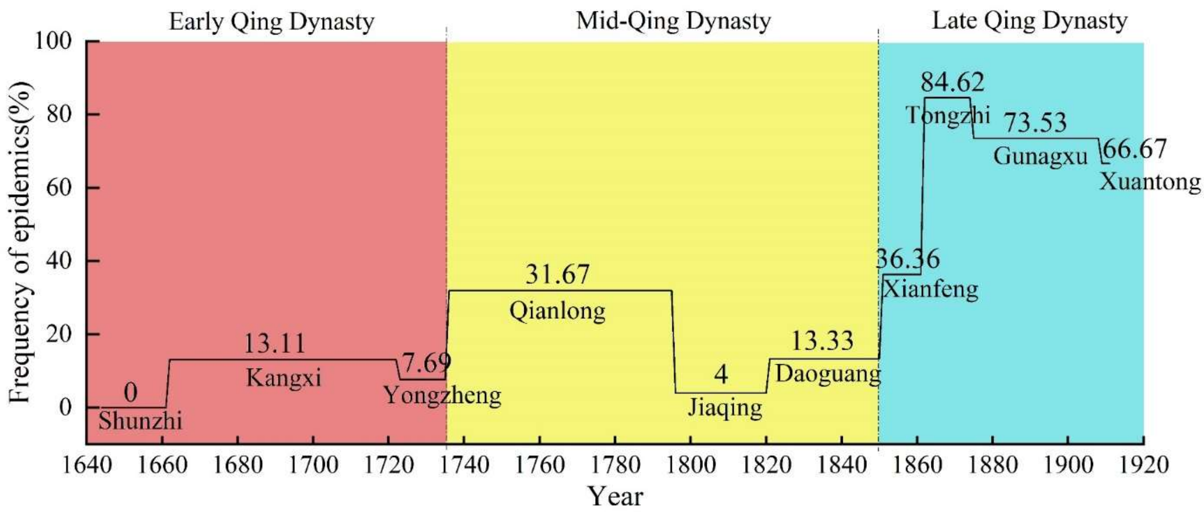

Fig. 2 Epidemic frequency changes across Qing Dynasty reigns

The frequency of epidemics during the Qing Dynasty showed significant variations across different periods (Fig. 2). Prior to the Xianfeng reign, plague incidence in Gansu was generally low, but it rose sharply thereafter. The early Qing period saw relatively low plague frequency, which increased during the mid-Qing Dynasty, culminating in an extreme peak during the Tongzhi period. Early Qing Dynasty (plagues occurred in only 9 of 92 years): Average occurrence every 10.22 years, epidemic frequency 9.78%. The Kangxi reign had the highest frequency, while the Shunzhi reign saw no plagues. During the mid-Qing Dynasty (24 plague outbreaks in 115 years), plagues occurred on average every 4.79 years, with a frequency of 20.87%. The Qianlong reign recorded the highest plague frequency. During the late Qing Dynasty (42 plague outbreaks in 60 years), the average interval between outbreaks was 1.43 years, with a plague frequency reaching 70%-the highest in the Qing Dynasty. The Tongzhi reign (1863–1874) recorded a plague frequency of 80%.

3.1.2. Interannual Variation in Plague Outbreaks

Analysis of interannual trends in various epidemic disasters across Gansu Province during the Qing Dynasty reveals that plague's interannual variation aligns with that of all epidemic types (including plague, diphtheria, and measles) (Fig. 3). The overall widespread of plague outbreaks shows a pronounced upward trend, with a linear trendline slope of 0.3819. However, pronounced fluctuations were evident. Overall, plague plagues in Qing-era Gansu can be divided into four phases: Phase I (1644–1719): Plague occurred infrequently, affecting a very small area-maximum 51,300 km², average 6,000 km². The number of affected counties was also low-maximum 5, average 1. The second phase, spanning 1720–1774, coincided with the early to mid-period of the Prosperous Era of Kangxi and Qianlong. Population growth and increased mobility led to a marked rise in both epidemic coverage and affected counties compared to the first phase. Epidemic coverage peaked at 206,400 km² in 1724 before declining. After 1750, it fluctuated upward again, with the number of affected counties peaking at 25 in 1769. The third phase, from 1775 to 1850, resembled the first phase, characterized by relatively small epidemic areas and affected counties, both exhibiting fluctuating trends. The fourth phase spanned 1851–1911, featuring relatively widespread plagues. A secondary peak in epidemic coverage and affected counties occurred in 1864, potentially linked to the Hui Muslim uprising in the fourth year of the Tongzhi reign and subsequent years of famine following the conflict. In terms of epidemic cycles, plague outbreaks occurred approximately every 10 to 20 years, persisting for extended periods. Three distinct peaks emerged: 1724, 1769, and 1864. These align with all major epidemic peaks, further underscoring plague's significance in Gansu's epidemic history.

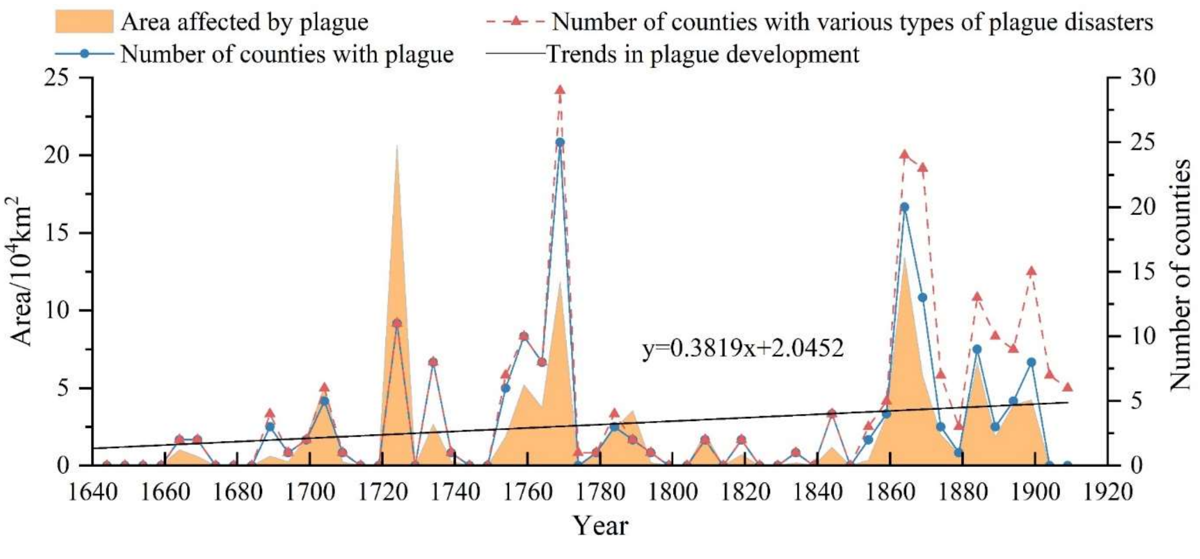

Fig. 3 Trends in all types of epidemic disasters and plagues during the Qing Dynasty

3.1.3. Seasonal Variations in Plague Outbreaks

Based on historical records with clearly documented seasons, over 179 plague outbreaks of varying severity occurred during the study period. There were 37 years with explicitly recorded epidemic seasons, involving a total of 59 seasonal outbreaks. These included 9 outbreaks in spring (15.25%), 23 in summer (38.98%), 17 in autumn (28.81%), and 10 in winter (16.95%). Plagues peaked in summer and autumn, accounting for 67.79% of all outbreaks. Regarding seasonal variations in plague occurrence (Fig. 4), plagues in the early and mid-Qing Dynasty occurred and spread in only one or two seasons. However, by the late Qing Dynasty-particularly after 1860-years with plague occurring in three to four seasons increased significantly. This indicates plagues occurring or spreading across multiple seasons, or even throughout all four seasons in a single year. When considering the geographical scope of plague outbreaks, a cumulative total of 61 counties in Gansu Province during the Qing Dynasty had recorded seasonal plague occurrences. Among these, 8 counties (13.11%) experienced plague outbreaks in spring; 25 counties (40.98%) experienced outbreaks in summer; 20 counties recorded plague outbreaks in autumn, accounting for 32.79%; and 8 counties recorded outbreaks in winter, accounting for 13.11%.

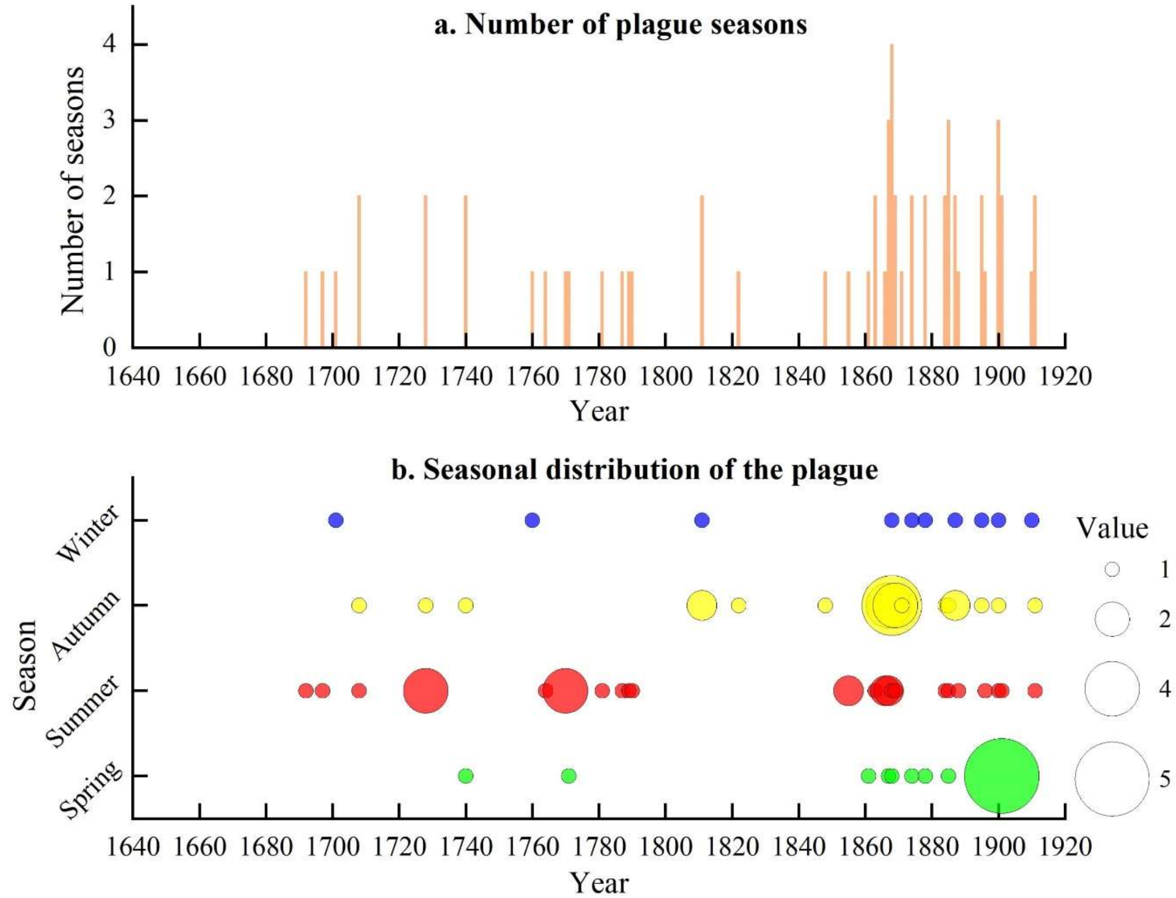

Fig. 4 Seasonal variation of plagues in Qing Dynasty

3.2. Spatial Distribution Patterns of Plague Outbreaks in Gansu Province

3.2.1. Phases of Spatial Distribution Characteristics

Overall, during the early, middle, and late Qing Dynasty periods, Gansu Province recorded cumulative plague years of 9, 24, and 42 respectively, with cumulative plague-affected counties totaling 62, 87, and 119. The number of plague-affected years indicates a continuous increase in epidemic frequency, with high-frequency plague zones expanding in scope. The number of affected counties reveals an overall trend of expanding epidemic coverage across Gansu during the Qing Dynasty. Throughout the entire Qing Dynasty, Lanzhou Fu, Pingliang Fu, Qin Zhou, Gongchang Fu, and Liangzhou Fu were regions with high plague incidence.

Early Qing Dynasty (1644–1735). Epidemic zones were relatively dispersed, exhibiting discontinuous patchy distribution (Fig. 5a). During this period, the number of epidemic years remained low across the entire region, but the spread of plagues was extensive, affecting 46 counties. The epidemic coverage reached 68.66%, with counties under Gongchang Fu, Liangzhou Fu, and Qingyang Fu being relatively frequent epidemic areas.

Mid-Qing Dynasty (1736–1850). Epidemic areas decreased significantly compared to the previous period. In southeastern Gansu, an epidemic cluster centered on Qin Zhou, Pingliang Fu, Jin Xian and Jingyuan Xian under Lanzhou Fu, with Gongchang Fu and Jing Zhou flanking it, encompassed 30 counties (Fig. 5b). A distinct high-frequency epidemic zone emerged in Qingshui Xian, where plague outbreaks occurred for seven consecutive years.

Late Qing Dynasty (1851–1911). Both the frequency and scope of plague plagues reached unprecedented levels (Fig. 5c). In the Hexi region, Gaotai Xian and Zhenfan Xian became the areas with the highest plague incidence frequency. In the central and eastern Gansu regions, Gaolan Xian, He Zhou, and Jingyuan Xian under the jurisdiction of Lanzhou Fu formed the core, with the plague-affected areas spreading once again to Guyuan Zhou, Qingyang Fu, and Ningxia Fu, creating a high-frequency plague zone.

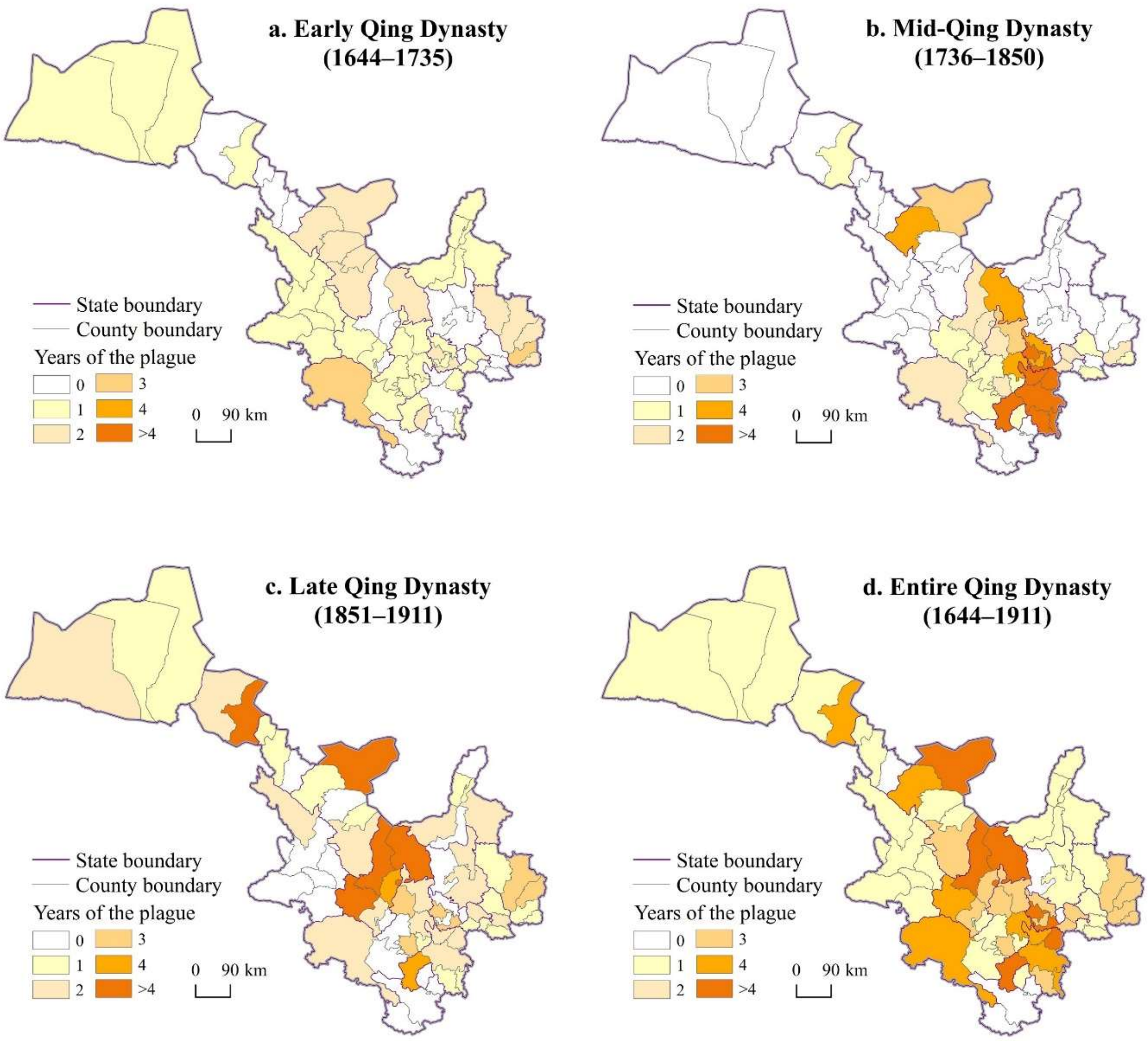

Fig. 5 Spatial Variations of Plague during the Qing Dynasty

3.2.2. Spatial Aggregation of Plague Outbreaks

During the Qing Dynasty, plague outbreaks occurred across the vast majority of Gansu Province (Fig. 6a). Among the province's 67 counties, only Shandan Xian, Jie Zhou, Cheng Xian, Wen Xian, Haicheng Xian, and Huapingchuan Ting remained unaffected. Overall, the spatial distribution of plagues exhibited significant unevenness, with the central Gansu region showing the highest concentration, followed by eastern and western Gansu, while the Hexi Corridor and southern Gansu mountainous areas experienced relatively lower incidence. At the prefectural level, counties within Lanzhou Fu, Pingliang Fu, and Qin Zhou constituted the primary high-incidence zones, whereas Jie Zhou demonstrated markedly low incidence.

Spatial autocorrelation analysis revealed a Moran's I value of 0.26 (z=3.20, p=0.001), indicating pronounced geographical clustering of plague outbreaks in Gansu during the Qing Dynasty. Further local spatial autocorrelation analysis (Fig. 6b) revealed that high-value clusters were primarily distributed in the central Gansu region, including Jin Xian under Lanzhou Fu, Anding Xian and Huining Xian under Gongchang Fu, and Qinan Xian under Qin Zhou. Low-value clusters were concentrated in Xining Fu, parts of Qingyang Fu in eastern Gansu, and Ningxia Fu.

From the perspective of geographical environment and human settlement patterns, the central Gansu region features relatively flat terrain, a temperate climate, relatively developed agriculture, and high population density. Historically, it served as a crucial node along the Silk Road and the Longhai Corridor, facilitating frequent human movement and providing favorable social and transportation conditions for epidemic transmission. In contrast, areas like Xining, Longnan, and the Hexi region were predominantly plateau and mountainous terrain with cold, dry climates, relatively isolated transportation networks, and sparse populations. These conditions were unfavorable for pathogen diffusion and sustained transmission, resulting in lower epidemic prevalence.

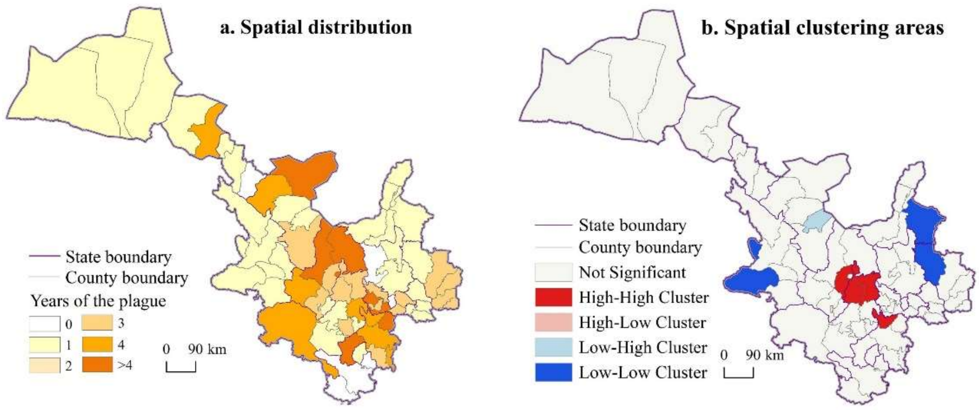

Fig. 6 Spatial distribution and aggregation areas of Plague during the Qing Dynasty

3.3. Factors Influencing Epidemic Outbreaks in Gansu Province During the Qing Dynasty

3.3.1. Natural Factors

On the whole, the natural environment exerted a fundamental influence on the spatio-temporal patterns of plague outbreaks in Gansu Province during the Qing Dynasty. Situated in the northwestern geographical transition zone, Gansu's complex and diverse climate types, pronounced topographical variations, and hydrological conditions collectively influenced pathogen habitats, population density, and transportation networks, resulting in marked spatial disparities in epidemic prevalence. Overall, epidemics were more frequent in areas characterized by warm, humid climates, abundant water sources, lower elevations, developed agriculture, and concentrated populations, while they were relatively rare in regions with harsh natural conditions such as aridity, cold temperatures, and high altitudes. Specifically, in terms of climate, annual precipitation showed a significant positive correlation with the number of plague outbreaks ($r = 0.281$, $p < 0.05$). Outbreaks were concentrated in southeastern Gansu, where the annual temperature ranged from 7–15°C and annual precipitation from 700–1300 mm, with a peak incidence during summer and autumn (Fig. 7a). This indicates that humid and warm climates may promote epidemics. Regarding topography, elevation showed a negative correlation with the number of plague-affected years ($r = -0.279$, $p < 0.05$). Plains served as the primary epidemic zones, while high-altitude mountainous areas experienced milder outbreaks (Fig. 7b). In terms of water sources, the minimum distance between counties and rivers also exhibited a negative correlation with plague incidence ($r = -0.248$, $p < 0.05$), indicating higher epidemic risks in areas closer to rivers. Analysis of 3 km and 10 km buffer zones around rivers of grade IV and above revealed that 40% of counties experiencing epidemics for nine or more years were within the 3 km buffer zone, while 48.6% of all epidemic-affected counties were within the 10 km radius (Fig. 7b). This indicates that regions with extensive water systems are more susceptible to epidemic transmission. Furthermore, drought disasters showed a highly significant positive correlation with plague epidemics ($r = 0.466$, $p < 0.01$). Overlaying the plague prevalence years with the drought frequency density map (Fig. 7c) reveals that the southeastern Gansu region experiences frequent droughts. The primary plague-affected areas in Qing Dynasty Gansu also predominantly lie within zones characterized by higher drought frequency.

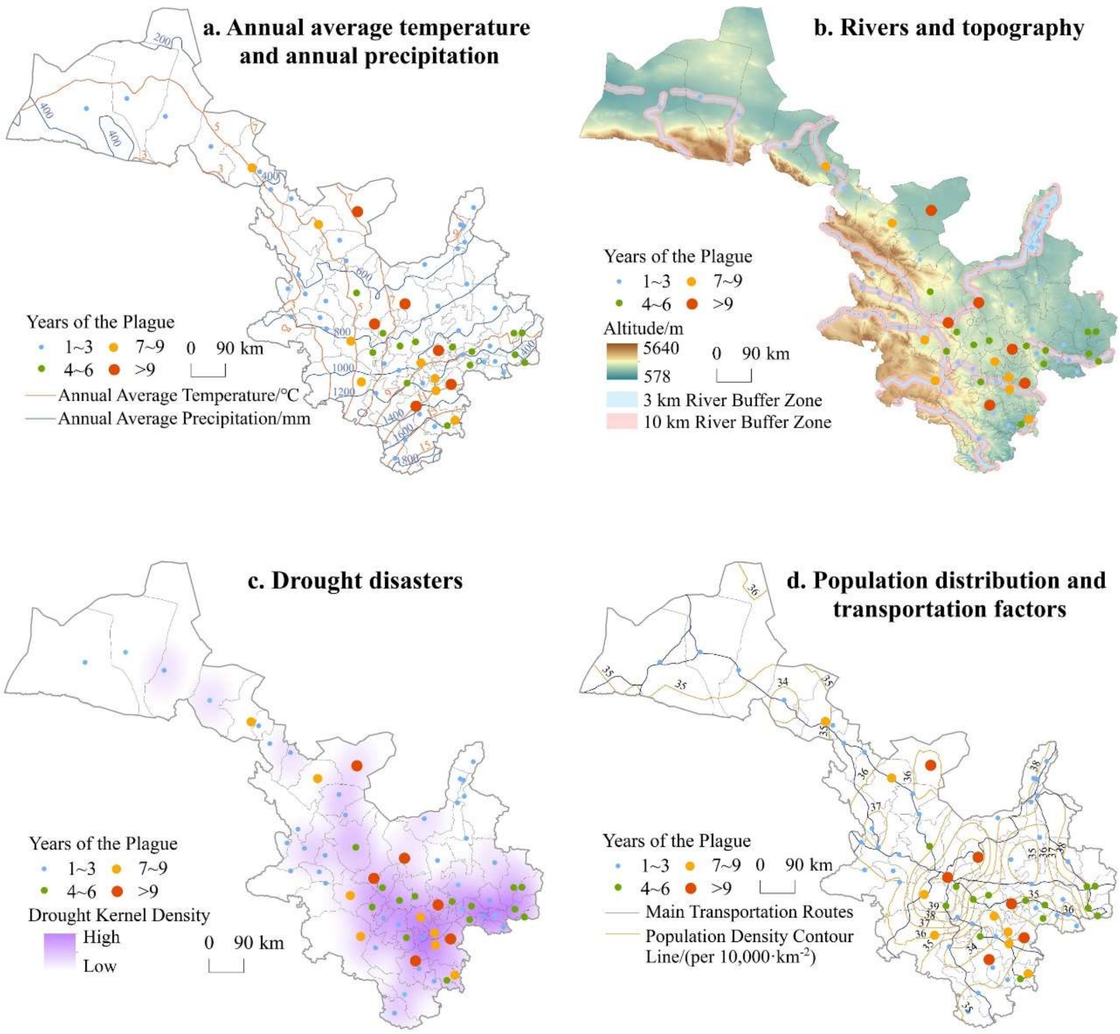

Fig. 7 The coupling of plague and geographical factors in the Qing Dynasty

3.3.2. Social Factors

Social and human factors played a decisive role in the occurrence and spread of plagues in Qing-era Gansu Province. While climate and environmental changes significantly influenced epidemic frequency, the dominant influence stemmed from human activities. During the Qing Dynasty, Gansu underwent a critical phase of socioeconomic transformation and demographic restructuring. Population concentration, transportation accessibility, war-induced instability, and disparities in governance capacity directly influenced disease transmission pathways and spread velocity. In general, regions characterized by high population density, extensive transportation networks, and frequent warfare experienced higher epidemic incidence rates and longer disease durations.

Population density showed a positive correlation with the number of plague years ($r=0.246$, $p<0.05$). Overlaying population density contour lines with plague years reveals that regions with more severe plagues generally corresponded to areas of relatively higher population density (Fig. 7d). Similarly, transportation conditions exerted a substantial influence on plague transmission. Total transportation route mileage and the distance between county centers and major transportation routes showed significant positive ($r=0.310$, $p<0.01$) and negative ($r=-0.242$, $p<0.05$) correlations, respectively, with the number of plague years. That is, higher transportation accessibility and closer proximity of county centers to major routes correlated with increased plague incidence. Considering the distribution of transportation routes (Fig. 7d), regions along major transportation lines with higher accessibility experienced relatively more severe plagues. Furthermore, warfare significantly exacerbated epidemic risks. Historical records (Table 3) indicate that many plagues originated in military camps before spreading to surrounding civilian areas. War frequently triggered famines and social unrest, creating ideal conditions for epidemic transmission. The peak epidemic period from 1863 to 1868 may correlate with contemporary military unrest. For instance, in 1867, "bandits plundered grain, plunging the populace into famine. Corpses littered the fields as the law of the jungle prevailed. Plague spread, infecting nearly every village and town"[22]. The military unrest primarily occurred in counties such as He Zhou, Tongwei Xian, and Heshui Xian, which were also areas where plague disasters were relatively prevalent.

Table 3. Historical records of military turmoil and plagues in Gansu Province during the Qing Dynasty

Epidemic Era	Epidemic Zone	Epidemic Situation	Epidemic Outcomes
1781	He Zhou	Su Sishisan raised an army but was killed, and the people of Su were struck by an epidemic.	The bandit's lair has no leader, A rabble of a thousand men remains, Long plagued by disease.
1863	Heshui Xian	The plague raged, compounded by war.	Numerous citizens died or fled, reducing the county's population from over 60,000 to just 7,000.
1866	Zhongwei Xian	Following the war, consecutive years of famine led to the outbreak of a plague epidemic.	Death lay in heaps
1867	Chongxin Xian	Bandits plundered grain, leaving the people starving. Plague spread, infecting nearly every village and town.	Bodies littered the ground
1867	Heshui Xian	War ravaged the land, plunderers looted everything in sight, people resorted to cannibalism, and plague ran rampant.	Two out of ten people died.
1868	Tongwei Xian	Spring drought, war, and plague	Cannibalism has occurred in many places.

Note: Source: Compiled by Gong Shengsheng, Compilation of Historical Materials on Plagues in China Over Three Millennia (Qing Dynasty Volume), Qilu Press, 2019, pp. 657, 836, 853, 858, 862.

3.3.3. Interaction of Influencing Factors

Under single-factor analysis, the strength of influencing factors ranked from largest to smallest as follows: length of transportation routes > number of drought years > elevation > distance between county center and major transportation routes > distance between county center and nearest river > annual precipitation > population density. Among these, the social environmental factor and natural environmental factor contributing most significantly to epidemic outbreaks are transportation infrastructure and drought disasters, respectively. This further validates that plagues often spread along transportation routes, while frequent droughts typically lead to widespread famine and subsequent major epidemic outbreaks. Topography also significantly influenced epidemic spread. Compared to plateaus and mountainous regions, plagues spread more rapidly and frequently across flat plains and lowlands.

Fig. 8 presents the results of geodetector calculations for each influencing factor. X1-annual precipitation, X2-elevation, X3-the distance from the county center to the nearest river, X4-number of drought years, X5-population density, X6-transportation line length, X7-the distance from the county center to the nearest major transportation routes. The analysis reveals that interactions between any two influencing factors exhibit either nonlinear enhancement or dual-factor enhancement. The synergistic enhancement between natural and human environmental factors was particularly pronounced, most notably in the interaction between elevation and transportation network length. The q-value for this interaction rose to 0.6045, compared to 0.1345 and 0.3702 for their individual effects. Flat terrain typically facilitates more accessible transportation, higher population density, and greater human mobility. Transportation networks lay the groundwork for the spread and transmission of plague disasters. Under the combined influence of multiple environmental factors, these areas are more prone to becoming frequent plague hotspots. High-incidence plague zones in Qing Dynasty such as He Zhou, Qin Zhou, Gaolan Xian, and Jingyuan Xian all exhibited these characteristics. Geodetector results further indicate that the interaction between natural and social environments exerts a powerful driving force on plagues.

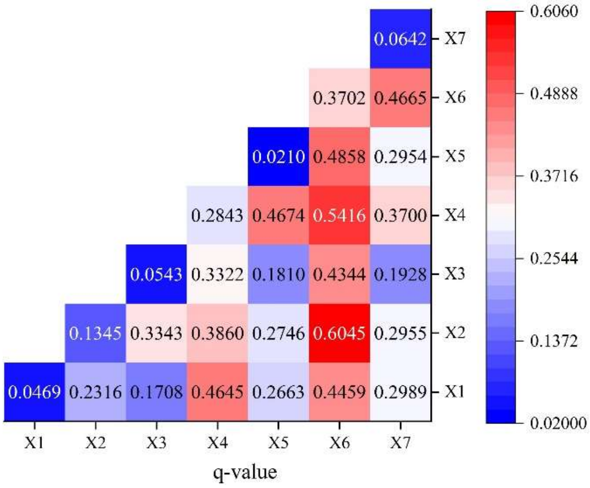

Fig. 8 Geodetector computation results

4. DISCUSSION

Plague in Gansu during the Qing Dynasty showed significant temporal phases and was spatially concentrated in regions such as central Gansu and southeastern Gansu. This pattern emerged due to the region's unique natural geography and social environment. Situated at a geographical crossroads, Gansu features complex natural conditions, severe climate fluctuations, and fragile ecosystems. Abrupt climatic shifts frequently triggered cascading effects such as droughts and famines, creating conducive conditions for the emergence and spread of plagues. Droughts led to water contamination and food shortages, while famine and population displacement further heightened disease transmission risks, forming a classic "disaster-famine-epidemic" chain. Additionally, social unrest, frequent warfare, and inadequate medical infrastructure in Gansu during the mid-to-late Qing Dynasty provided a critical social backdrop for epidemic outbreaks. The expansion of Silk Road transportation routes and modern railway networks significantly increased the flow of people, goods, and information within the region, facilitating cross-regional disease transmission. Transportation hubs like Lanzhou Fu, Pingliang Fu, and Qin Zhou, characterized by dense populations and high mobility, became focal points for epidemic outbreaks. Thus, natural factors provided the "context for emergence", while socioeconomic factors served as the "driving force for transmission".

Existing research indicates that plague outbreaks occurred with higher frequency and concentration in the eastern Gansu region, while the Hexi Corridor experienced fewer plagues. This aligns with the findings of this paper, which identifies central and eastern Gansu as the primary areas affected by plague plagues, with the Hexi Corridor, Xining, and Ningxia regions experiencing relatively fewer plague incursions. Compared to previous studies focusing on plague outbreaks in eastern coastal or North China regions, this paper reveals the distinct characteristics of plague disasters in the arid northwest. Existing research generally attributes plagues in southeastern coastal areas to high temperatures, humidity, dense populations, and port trade (e.g., Jiangnan, Fujian, Guangdong), with plague primarily spreading along waterways or seaports. This study, however, finds that in the arid and ecologically fragile Gansu region, plague outbreaks were more frequently linked to climate anomalies, recurrent droughts, and war-induced migrations. Its transmission pathways relied more heavily on land-based transportation routes (such as postal roads, river valleys, and Silk Road corridors). This study partially fills a regional gap in research on epidemic disasters in Northwest China and reveals the multifaceted driving mechanisms of plague epidemics from a natural-societal composite perspective.

Although this paper has achieved certain results in revealing the spatio-temporal patterns and influencing factors of plague outbreaks in Qing-era Gansu, several limitations remain. First, the completeness and consistency of historical records are limited, with missing or ambiguous plague data for certain regions or years potentially affecting the precision of statistical analysis. Second, this study primarily relies on historical records and local gazetteers, without fully utilizing modern climate reconstruction data, archaeological environmental information, or population migration records. This limits the quantitative characterization of the interaction between natural and human factors. Future research could be enhanced in the following areas: First, integrating multi-source data—combining historical archives, climate reconstructions, and GIS spatial data—to improve spatio-temporal resolution. Second, deepening comparative studies by systematically contrasting Gansu with other regions (e.g., the southeastern coastal areas, the North China Plain, and the Qinghai-Tibet Plateau) to reveal distinct mechanisms of plague transmission across different ecosystems. Third, this study has not yet thoroughly examined the specific operations and effectiveness of relevant treatment systems and prevention mechanisms. Subsequent research could systematically analyze the division of roles among different levels of power in disaster management, the effectiveness of policy implementation, and the operational logic of social mutual aid networks, providing more targeted historical insights for contemporary infectious disease prevention and control.

5. CONCLUSION

Based on spatiotemporal analysis and geodetector methods, this study systematically reveals the evolutionary characteristics and driving mechanisms of plague epidemics in Gansu during the Qing Dynasty. The findings demonstrate a clear temporal periodicity, characterized by "low incidence in the early period, rising incidence in the middle period, and peak incidence in the late period," with three major outbreak peaks occurring in 1724, 1769, and 1864, following an approximate 10–20 year cyclical pattern. Spatially, the epidemics exhibited a distinct southeast-northwest differentiation, evolving from fragmented distributions to concentrated clusters, particularly in central and eastern Gansu. Spatial autocorrelation analysis confirmed significant geographical aggregation, with high-risk areas centered around Lanzhou Fu, Pingliang Fu, Qin Zhou, and Gongchang Fu. The interaction between natural and social factors played a decisive role in this process, with the synergistic effect of elevation and transportation route length being the most prominent, indicating that flat terrain and developed transportation networks jointly shaped high-risk zones for disease transmission. These findings not only deepen the understanding of the dynamic mechanisms of historical epidemics in Northwest China from a human-environment system perspective but also provide a historical basis for regional public health risk assessment and the optimization of epidemic prevention strategies.

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