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RESEARCH ARTICLE

Assessing the evolution of oases in arid regions by reconstructing their historic spatio-temporal distribution: a case study of the Heihe River Basin, China

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Abstract Oasis evolution, one of the most obvious surface processes in arid regions, affects various aspects of the regional environment, such as hydrological processes, ecological conditions, and microclimates. In this paper, the historical spatio-temporal evolution of the cultivated oases in the Heihe River Basin, the second largest inland watershed in the northwest of China, was assessed using multidisciplinary methods and data from multiple sources, including historical literature, ancient sites, maps and remotely sensed images. The findings show that cultivated oases were first developed on a large scale during the Han Dynasty (121 BC–220) and then gradually decreased in extent from the Six Dynasties period (220–581) to the Sui-Tang period (581–907), reaching a minimum in the Song-Yuan period (960–1368). An abrupt revival occurred during the Ming Dynasty (1368–1644) and continued through the Qing Dynasty (1644–1911), and during the period of the Republic of China (1912–1949), oasis development reached its greatest peak of the entire historical period. The oasis areas during seven major historical periods, i.e., Han, Six Dynasties, Sui-Tang, Song-Yuan, Ming, Qing, and Republic of China, are estimated to have been 1703 km^2, 1115 km^2, 629 km^2, 614 km^2, 964 km^2, 1205 km^2, and 1917 km^2, respectively. The spatial distribution generally exhibited a continuous sprawl process, with the center of the oases moving gradually from the downstream region to the middle and even upstream regions. The oases along the main river remained stable during most periods, whereas those close to the terminal reaches were subject to frequent variations and even abandonment. Socio-economic factors were the main forces driving the evolution of cultivated oases in the area; among them, political and societal stability, national defense, agricultural policy, population, and technological progress were the most important.

Keywords Heihe River Basin, cultivated oasis, spatio-temporal process, arid region, driving factors, landscape change

1 Introduction

Land use/cover change (LUCC) is an important driver of global environmental change (Turner et al., 2007). An understanding of LUCC throughout history forms the basis for the simulation of historical climate change and is an important parameter for diagnosing climate formation and for identifying the sensitivity of a climate system to natural and human disturbances (Li et al., 2006; Voldoire et al., 2007). In recent years, by virtue of improved methods of extracting data from an expanded variety of data sources, significant progress has been made in accurate long-term LUCC reconstruction (e.g., Ramankutty and Foley, 1999; Bender et al., 2005; Dahlström et al., 2006; McAllister, 2008; Schuppert and Dix, 2009; Xie et al., 2009).

The Heihe River Basin (HRB) is located between 98°–101°30′E and 38°–42°N and covers an area of approximately 1.429×10^5 km^2 (Fig. 1). Originating from the northern edge of the Qinghai-Tibet Plateau, the Heihe River, the second largest inland river in China, runs across Qilian Mountain, Hexi Corridor and Alxa Plateau and ends in the Ejina Basin. The HRB is one of the oldest areas of irrigation agriculture in Northwestern China and is also a region of severe ecological deterioration, which significant affects sustainable development (Cheng, 2009). At present,

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ecological problems such as a shortage of water resources, vegetation degradation and soil salinization have attracted considerable attention from researchers (e.g., Qi and Wang, 2003; Lan et al., 2004; Luo et al., 2005; Qi and Luo, 2005; Cheng, 2007).

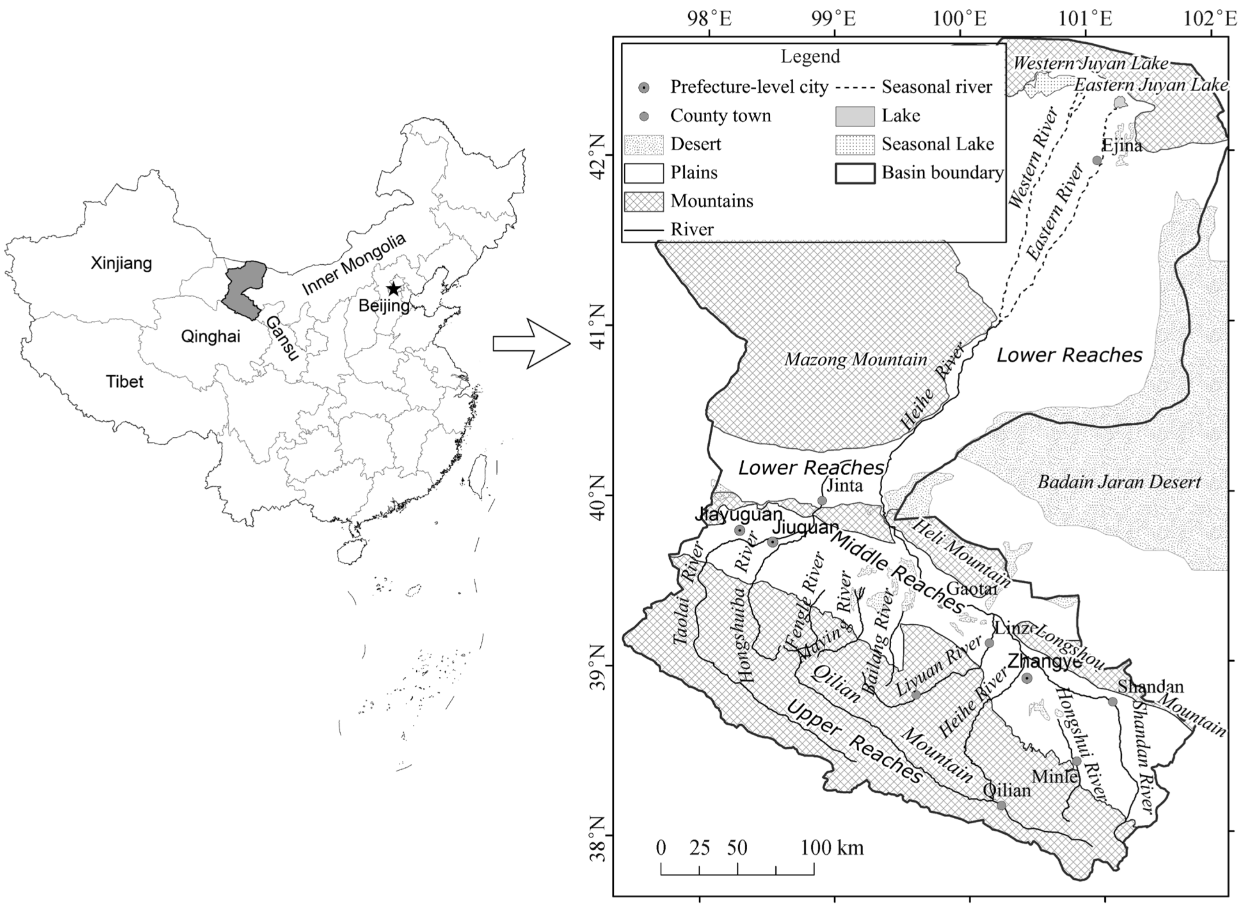
Several studies have been conducted on oasis agriculture in the HRB and its evolution, with focuses on agricultural development and livestock farming (e.g., Li, 1990a, b, 2001; Wu and Guo, 1996; Zhao, 1997; Wang et al., 2005; Chen, 2008; Xu, 2008; Gao, 2010), the historical process of water-land resource utilization (e.g., Xiao and Xiao, 2003; Xiao et al., 2004; Zhang, 2010; Xie and Wang, 2014), and oasis desertification (Chen, 1996; Liu et al., 2009; Wei et al., 2010). Furthermore, the impacts of oasis exploitation on climate change have also been discussed (Mitsuyuki et al., 2007; Masayoshi, 2011). Of these studies, some have addressed the spatio-temporal changes in the oasis distribution throughout different historical periods, but they have usually been concerned with only partial areas of the basin or only certain periods of the entire historical timeline, with very coarse spatio-temporal resolutions; therefore, the details of these changes, i.e., their locations and extent, have not been well revealed. This situation has hindered attempts to gain a deep and exact understanding of the interplay between human activities and nature in arid areas.

In this study, we applied a multidisciplinary method in an attempt to reconstruct the spatial pattern of cultivated oases throughout the entire historical period, thus providing a useful context for analyzing the environmental changes induced by human activities. These results can be used in research on the relationship between humans and nature to identify the intensity of the impact of human activities. Additionally, understanding the historical changes in the oasis distribution can help to elucidate the origins of the ecological problems in the area, thereby providing a valuable reference for future oasis development.

2 Methodology and materials

2.1 Methodology

Reconstructing the distribution of cultivated oases throughout the historical period is a very complex task.



(a) (b)

Fig. 1 (a) The location of the HRB locates in northwest China and (b) the HRB origins from the Qilian Mountain, crossing the plains and falls into Juyan lakes in the north.

All of the factors associated with oasis cultivation should be comprehensively considered. In this study, multidisciplinary methods were applied in a synthetic manner, including historical literature analysis, archaeology, map analysis, visual interpretation of remote sensing (RS) images, and geographic information system (GIS)-based spatial analysis.

The historical literature is one of the most important sources of information. The sites of ancient cities, settlements, and irrigated channels and areas, which are direct evidence of oasis cultivation, are the main objects recorded in historical literature. Thus, historical literature analysis was adopted as one of the main approaches used to obtain information on oasis exploitation. Local chronicles compiled during the Ming and Qing Dynasties at the provincial, prefectural and county levels contain a large amount of diverse information on the population, production activities, and lifestyle in the region. Of these available data, the information about administrative systems, agricultural activities, populations, and settlements was particularly valuable for this study.

Archeological sites, i.e., ancient towns, tombs, the Great Wall beacon towers, and ancient sites of cultivated land and channels, serve as direct evidence of human activities. The spatial distributions of such sites are very valuable for reconstructing the distribution of cultivated oases. Fortunately, from 2007 to 2011, the Chinese government conducted the Third National Archaeological Survey of China (TNAS), in which all immobile relics throughout the entire country were surveyed in detail; thus, the quantity, distribution, characteristics, preservation status, and environmental situations of all immobile relics were investigated and recorded. The TNAS divided all immobile cultural relics into six types, among them, ancient town sites, ancient tombs (or tomb groups), ancient architecture, are most relevant to this study.

When using historic or modern maps to determine the locations of settlements and irrigated channels, it is necessary to perform map analysis. Based on the analysis of maps and literature and comparisons of the names of locations used in different historic periods and in modern times, the locations of settlements, channels and agricultural activities were determined.

Ancient cultivated oases, regardless of their age, can to some degree be identified by their white or off-white colors and disorganized textures in true-color-composite TM (Thematic Mapper) RS images. These areas exhibit characteristics distinct from those of their surroundings because of human disturbances and followed severe land salinization; by contrast, the primeval desert and Gobi Desert appear slate gray in color with uniform, smooth and homogeneous textures. Thus, visual interpretation of RS images was applied to observe the distribution boundaries of cultivated oases.

In order to acquire direct information about ancient relic sites and oases, establishing an interpretation index for RS images, a total of five rounds of fieldwork were conducted. The main tasks completed including determining the locations and sizes of ancient sites and observing their shapes, structures, and preservation statuses. Furthermore, the characteristics of the cultivated oases and their surrounding environments were also observed. A total of 44 existing ancient relic sites (e.g., ancient towns, tombs, and settlements) and 40 cultivated oasis sites (channels and cultivated land) were visited.

To effectively manage the spatial data to facilitate the integrated analysis, a GIS was used as the platform for data collection, storage, management, computing, analysis, display, and export.

2.2 Materials

Multisource materials were collected, including historical documents, information about archaeological sites, maps, and RS images (Table 1).

2.2.1 Historical documents

For the purposes of this study, chronicles are the most important source of information from historical literature. Among them, the provincial-level chronicles include the "*Gansu Chronicle*", the "*Gansu New Chronicle*," and the

Table 1 The Materials used in this study

Type	Era	Purpose
Official historical documents	Han to Republic of china	Extract administrative system, agricultural activities, population and settlements
Local chronicles	Ming, Qing, Republic of China	Extract the same to official historical documents in greater detail
Local archives	Republic of China	Obtain details of agricultural activities
Archaeological sites	Han to Yuan	Obtain positions of different types of ancient sites, like town and tombs
Historical maps	Ming, Qing, Republic of China	Extract distribution of settlements, channels
Modern Maps	Modern times	Basis of image geometric correction
Remote sensing images	Modern times	Visual interpretation of oasis and basis of reconstruction
Digital elevation model	Modern times	Digital terrain analysis
Records of field survey	Change with focus	Obtain the information of ancient sites, check the result

"*Gansu Chronicle Draft*"; the prefecture-level chronicles include the "*Suzhen Huayi Chronicle*", the "*Re-revised Ganzhen Chronicle*", the "*Suzhen Chronicle*", the "*Ganzhou Prefecture Chronicle*," and the "*New Re-revised Suzhou Chronicle*"; and the county-level chronicles cover almost every county in the study area.

In addition to the ancient chronicles, modern local chronicles for the prefectural and county levels were collected, including the chronicles of prefectural cities such as Jiuquan, Zhangye, and Jiayuguan and those for all counties, which also record a large amount of information on various historical periods in vernacular Chinese. Furthermore, the local archives from the Republic of China period, which provide considerable detailed information about the construction of irrigation areas and water conservancy projects, were also consulted.

2.2.2 Archaeological sites

The Gansu volume and the Inner Mongolia volume of *The Atlas of Historical Relics in China* (SACHC, 2003, 2011) record the administrative divisions, spatial locations, time periods, and sizes of the main cultural relics in the study area.

The immobile relics suitable for use in reconstructing the distribution of cultivated oases were selected from the TNAS dataset for Gansu Province and the Inner Mongolia Autonomous Region (Table 2). A total of 1036 ancient sites from eras ranging from the Han to the Yuan Dynasty were used in this study. For periods since the Ming Dynasty, a large number of ancient sites have been recorded in detail in the local chronicles; thus, these records were used directly.

2.2.3 Maps

Historical and modern maps, which have different functions, were both collected in this study. The main historical maps were those included in the *Historical Atlas of China* (Tan, 1982) and the *Ancient Geography Evolution Map* by Ma Zhenglin (primarily for the Qing Dynasty). The historical illustrated maps included in the local chronicles directly describe the distributions of territory, major settlements, and channels of their corresponding times and thus were also very important for this study. The *River system map of the Heihe River in the Republic of China,* which was preserved in the archives (No. 38-1-8) of a local library, shows the detailed distribution of the river and channel systems in Zhangye and the southeast of Jiuquan. A similar map also exists for the Jiuquan and Jinta areas. Modern maps, including an administrative map, a topographical map, and a regional atlas, were used to precisely determine the locations of ancient features and to ensure that the field surveys proceeded smoothly.

2.2.4 Remote sensing images

A total of 7 Landsat TM image scenes recorded at a spatial resolution of 30 m$\times$30 m, which were acquired in the summer of 2010 and cover the entire basin, were downloaded from the USGS website. The necessary enhancement was first performed to improve the visualization of the features of interest. We also downloaded and collected high-resolution Google Earth images. In recent decades, the HRB has been strongly influenced by human activities, and the landscape has distinctly changed; therefore, Keyhole satellite images acquired in the 1960s at resolutions of 2.7–7.5 m were also collected.

2.2.5 Digital elevation model

The distribution of cultivated oases is strictly constrained by the local terrain. Areas of high altitudes and steep slopes cannot be developed into oases. Therefore, the ASTER GDEM produced by NASA, with a resolution of 1 arc-second (30 m), was used to determine the altitude and grade of a given location.

2.3 Reconstruction process

The overall technical flow of the reconstruction process, observing the principles of incremental refinement and using the multisource data described above, is illustrated in Fig. 2.

2.3.1 Data pre-processing

The reconstruction was performed digitally; therefore, it was necessary to convert all of the data into a digital format. The topographical maps were used as the

Table 2 The ancient sites of the HRB from the Han Dynasty to Yuan Dynasty

Era	Towns	Tombs	Settlements	Water conservancy projects	Military infrastructures	Kilns	Temples	Others	Total
Han	38	248	59	9	280	48	2	10	694
Jin	16	140	20	8	6	5	2	0	197
Tang	11	7	0	3	3	0	4	1	29
Yuan	10	4	56	4	6	3	27	1	111

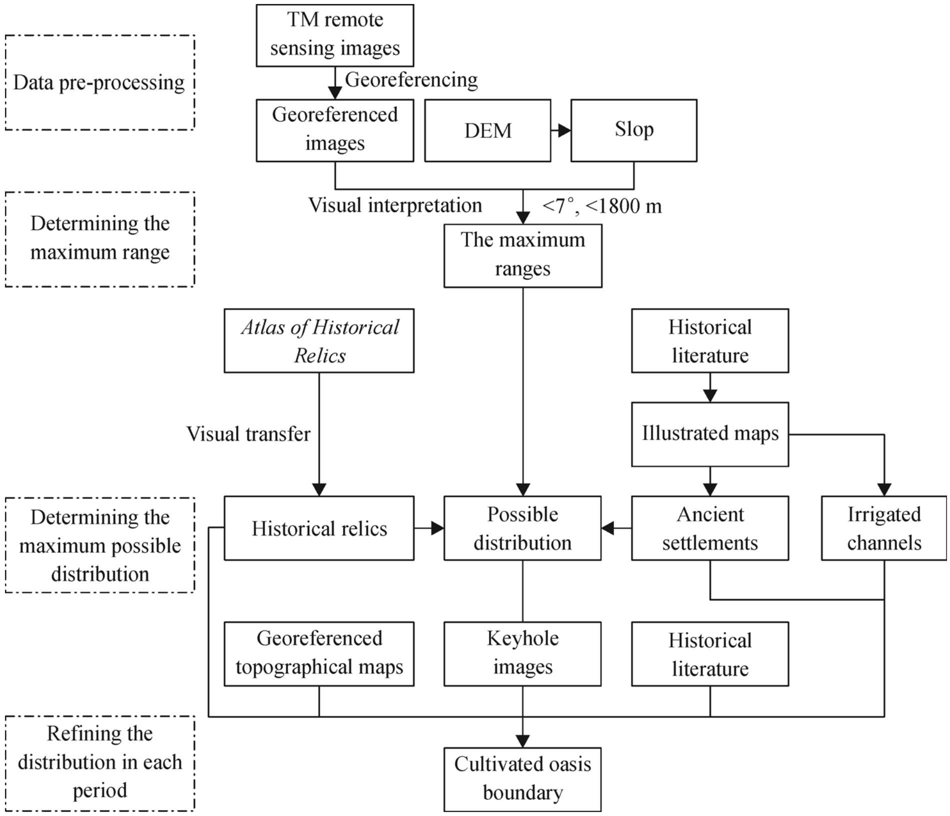


Fig. 2 Reconstructing flows includes data preprocessing, determining the maximum range by visual interpretation, redefining the maximum possible ranges and refining the distribution in each period.

positioning basis for the other data and were thus scanned and georeferenced first; then, the RS images and other data types were registered to these maps. Regarding the illustrated maps collected from the ancient literature, they are often simply sketches and may be inaccurate in scale and in the relative positioning of features; thus, visual transfer techniques were used to transfer all features of interest. To guarantee location accuracy, it was necessary to perform and verify this transfer operation very carefully, using the rivers, channels, and settlements that appear on both ancient and modern maps as references. After this pre-processing, all of the data could be simultaneously displayed on the computer screen using the GIS software.

2.3.2 Determining the possible maximum distribution area for all oases

In arid regions, because of the limitations imposed by terrain, water sources, and other conditions, the development of oases (whether natural or artificial, ancient or modern) is always restricted to low and flat areas; there is no possibility for oases to exist in regions of high mountains, primeval deserts, or the Gobi Desert. Moreover, areas with a slope of more than 7° are not suitable for cultivation (Lai, 2005). After overall observations of all sites throughout the entire basin, it was found that no oasis could exist under any conditions in areas above an altitude of 1800 m. Thus, by combining the results of visual interpretation of the RS images with the GDEM, the maximum area in which oases could possibly exist was determined (Fig. 3(a)).

2.3.3 Determining the possible distribution of cultivated oases

Cultivated oases form only part of the maximum possible distribution of all oases. Similarly, major human activities, i.e., production and habitation, are always distributed in relatively small regions. Thus, by overlaying all of the available information regarding ancient human activities on the possible maximum oasis range, the boundaries of cultivated oases, as a union set of all historical periods, could be roughly determined (Fig. 3(b)).

Regardless of their eras, the locations of ancient cultivated oases can be categorized into two types: those located in regions that are currently desert areas and those located in regions that are currently oasis areas. Each of them has different characteristics: desert-located ancient oases can be easily differentiated using RS images combined with the distribution of human relic sites, whereas oasis-located ancient oases can only be estimated from the historical literature and relic sites.

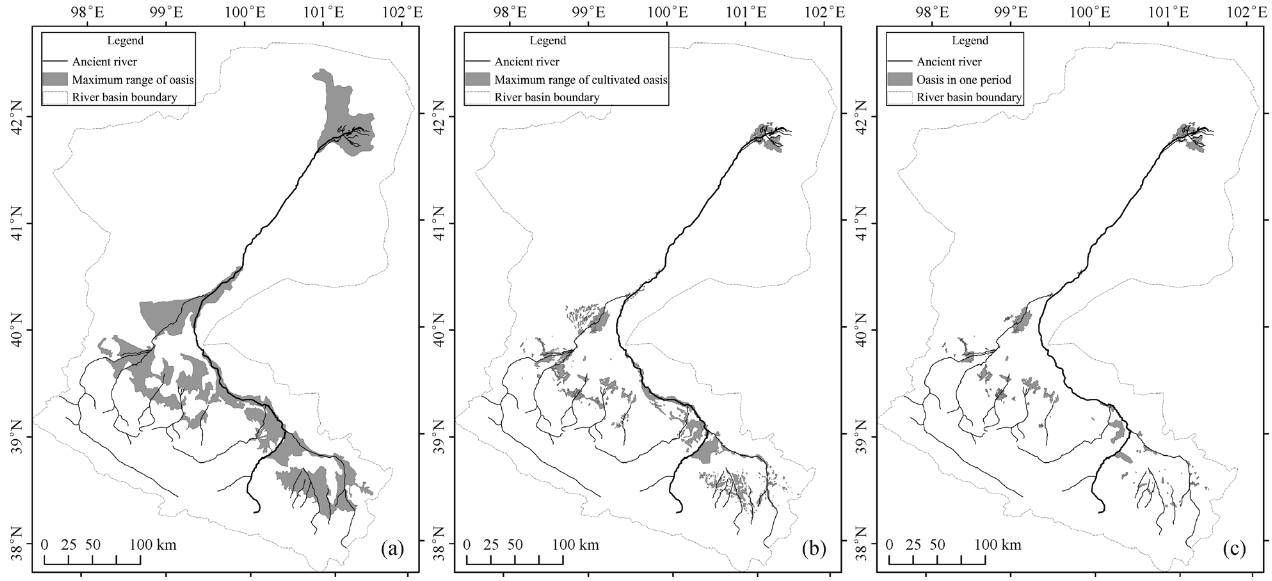


Fig. 3 The main process of determining the cultivated oasis boundaries, including the maximum range (a), the maximum possible range (b) and the oasis in one period (c).

In subsequent field studies, we intentionally focused on areas that had been identified as ancient cultivated oases, and we found that most such areas could be confirmed as ancient cultivated oases by the presence of historical relics, such as fragments of bricks, pottery, ditches, or farmland. These findings show that the reconstructed results are reliable.

2.3.4 Refining the distribution of cultivated oases in each period

The task in this step was to separate the identified cultivated oases into the different dynasties to which they belonged (Fig. 3(c)). This was the most important and also the most difficult step of the entire process, because the materials that are available to serve as the basis for such discrimination are generally scarce.

Based on the different materials available, the task was completed in different ways for periods prior to the Ming Dynasty (121 BC–1368) and following the Ming Dynasty (1368–1949).

Prior to the Ming Dynasty (121 BC–1368):

For periods prior to the Ming Dynasty, ancient relic sites are the main evidence available; thus, their locations were used as the primary basis for determining the boundaries of cultivated oases. The accurate locations of these ancient sites were obtained from the TNAS or via field surveys. The corresponding information about agricultural cultivation, including the official policies, population size, official executive institutions (counties and prefectures) and locations of agricultural activities, provided the most important references. Based on the historical records and topographical maps, the spatial distribution of these official executive institutions could be reconstructed.

Using the distribution of the ancient sites and the corresponding population and area data as references, all areas with a high density of ancient sites and the areas surrounding isolated ancient sites were identified as oasis areas. The cities with official executive headquarters were generally the major agricultural centers. With the RS images and topographical maps as the background, the boundaries of cultivated oases were manually drawn.

Example:

Here, the analysis for the Han Dynasty (121 BC–220 AD) is presented as an example to illustrate how the reconstruction was performed (for the other dynasties before the Ming Dynasty, please refer to Xie and Wang (2014).

According to the historical records, the Han Dynasty is the historical period during which the large-scale development of cultivated oases began. With the victory of the Han Dynasty against the Huns, the HRB became a part of Han territory in 121 BC. To guarantee the normal operation of the Silk Road, guard the border frontier, and develop the economy, the Han government took a series of measures that included establishing prefectures and counties, relocating residents of the Central Plains to the border, constructing water conservancy facilities and cultivating land, thereby initiating an unprecedented development of cultivated oases (Wu and Guo, 1996; Gao, 2010). Approximately 180 thousand military personnel were sent to Juyan (in the lower reaches of the HRB) and Xiutu (in the north of Wuwei) for protection and cultivation. The HRB was mainly governed by Zhangye Prefecture (which comprised a total of 10 counties), with 7 counties and 88,731 inhabitants in the HRB, and Jiuquan Prefecture (which comprised a total of 9 counties), with 5 counties and 76,726 inhabitants in the HRB. Approximately 110 thousand people lived in the HRB, and according to Wang et al. (2013), nearly 100 thousand military personnel were deployed to cultivate the land. Large-scale reclamation occurred in the regions around Lude (a northern town of Heishui), Jiuquan, and Juyan (Ejina), among which that near Juyan was the largest (Wu and Guo, 1996; Zhao, 1997).

A total of 699 ancient sites from the Han Dynasty were distributed throughout the entire basin, according to the results of the TNAS (Table 2). They were generally distributed in the terminal fan of the mainstream (Juyan) and along the Taolai River (Huishui), the Fengle River (Leguan) and the Maying and Bailang Rivers (near Biaoshi), as well as in the midstream region of the mainstream (Lude) and along the Taolai River (Jiuquan). A great deal of pottery and brick debris as well as evidence of ancient farmland and channels can be observed in various locations.

Based on the information presented above, we developed the boundaries of the oases that existed during the Han Dynasty in the GIS, finding them to cover a total area of approximately 1701 km^2 (see Fig. 4(a)).

Following the Ming Dynasty (1368–1949):

From the Ming Dynasty on, with the consolidation of territory and the stabilization of society, the historical records become unprecedentedly rich and detailed; thus, these documents were used as one of the primary source of information. The main task in this stage was to associate the historical records with spatial positions.

Settlements of all kinds, such as cities, towns, and villages, are the most important indicators of the existence of cultivated oases. The locations of cities could be easily confirmed based on the TNAS, "*The Historical Atlas of China*", and other historical documents. The locations of towns and villages, in most cases, could be identified by tracing the changes in the names used to refer to geographic regions and features. The extents of the settlements themselves reflect the approximate scope of the cultivated oases.

Another important type of evidence is the presence of irrigated channels, which could be reconstructed based on illustrated historical maps. Sketches of the channels in certain areas have been well preserved since the Ming Dynasty. Some of the names of these irrigated channels are used even today, resulting in little difficulty in reconstructing their locations.

By combining the available information on settlements and irrigated channels and considering the corresponding records related to oasis development, the scope of the cultivated oases that existed during these periods could be inferred.

Example:

Here, the analysis for the Qing Dynasty (1644–1911 AD) is presented as an example to illustrate how the reconstruction was performed (for the other dynasties since the Ming Dynasty, please refer to Xie et al. (2015).

During the Qing Dynasty, the study area entered a much more stable state because of improved relations with the surrounding powers. The military Wei-Suo administrative system was replaced with the prefecture-county system, and the Ganzhou and Suzhou prefectures, comprising 8 counties, were established (Fig. 4(f)). The military-oriented agricultural system gradually shifted to civil agriculture. It was estimated that there were approximately 400,000 and 600,000 people living in the region in the 43rd year of the Qianlong Period (1778 AD) and the 25th year of the Jiaqing Period (1820 AD), respectively, and approximately 442,000 in 1908 AD, according to the local chronicle.

The number, density, and range of settlements increased, reaching 355 distinct settlements and expanding to the terminal area of the Taolai River and its juncture with the mainstream (Wangzizhuang and the sub-county of Gaotai) (Fig. 4(f)).

The Qing Government placed great importance on repairing the original irrigated channels from the Ming Dynasty and constructing new irrigated channels, a total of 207 channels were in use, causing the oasis to expand significantly (Fig. 4(f)). The most significant changes occurred at the juncture of the Taolai River and the Heihe River, with the construction of 18 channels near the river. Moreover, seven new small cultivated regions were established, six named Jiuba, Maomu, Jiujiayao, Sanqingwan, Rouyuanbu, and Shuangshudun in Suzhou and one named Pingchuanbu in Ganzhou, according to the cultivation records in the *New Revised Suzhou Chronicle*.

By outlining the distribution of settlements and channels, we estimated the total cultivated oasis area to be 1205 km^2 (Fig. 4(f)).

3 Spatio-temporal evolution of cultivated oases

Using the methods and workflow described above, the cultivated oasis distributions in all dynasties were obtained, and the results are illustrated in Fig. 4. From the figure, we can observe the spatio-temporal changes in the oasis distribution throughout the historical period.

The figure shows that since the beginning of the investigated historical period, the oases exhibited different spatial distributions during different periods, with a trend of moving from the lower reaches to the middle and even upper reaches and expanding from the center outward. It is estimated that before the Han Dynasty, there were fewer than 100 thousand minority inhabitants living in the Hexi Corridor, following a nomadic lifestyle (Zhao, 1986), and very little cultivated oasis area should have existed at that time. With the Han Dynasty, a large cultivated oasis area was simultaneously reclaimed in the middle and lower reaches. During the Six Dynasties period, the extent of cultivation was dramatically reduced, especially in the

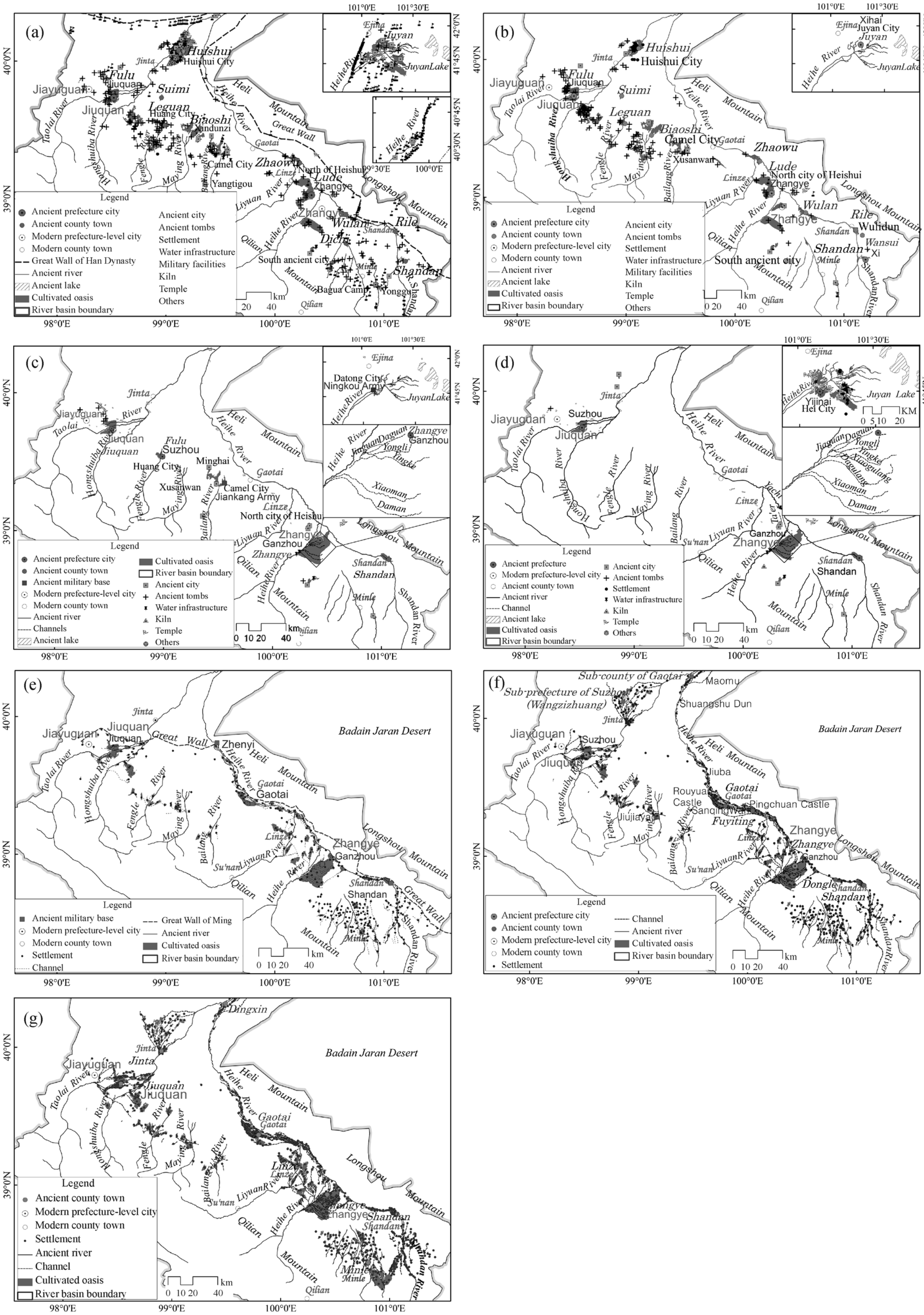


Fig. 4 (a) to (g) show the administrative systems, ancient sites, settlements, irrigated channels and cultivated oases ranges in the HRB in the Han to the Republic of China, experiences a process that enlarged at first and then shrank.

lower reaches. During the Sui and Tang Dynasties, the cultivated oases shrank further almost everywhere, until the extent of cultivation reached its minimum in the Song and Yuan Dynasties. Oases in the terminal regions of branch rivers such as the Taolai, Maying, Bailang, and Fengle Rivers were gradually abandoned from the Tang to the Yuan Dynasty. After the Ming Dynasty, the cultivated oases in the downstream region were completely abandoned. Meanwhile, oases along both the mainstream and various branches began to be recovered, shifting in the upstream direction compared with those of the Tang Dynasty. During the Qing Dynasty, oases expanded into the surrounding area, and more oases were developed in the upstream direction. Most strikingly, oases began to be developed in the Jinta area of the Taolai River. During the Republic of China period, the oases expanded farther into the surrounding areas and became more disperse in their distribution.

All of the oasis areas in each period are shown in Fig. 5 and it is seen that the changes in the oasis areas formed a "U" shape. It is evident that the oasis areas during the Han, Six Dynasties, Sui-Tang, Song-Yuan, Ming, Qing, and Republic of China periods were 1703 km^2, 1115 km^2, 629 km^2, 614 km^2, 964 km^2, 1205 km^2 and 1917 km^2, respectively. The extent of cultivation reached a peak during the Han Dynasty, declined beginning in the Six Dynasties period to reach its minimum during the Yuan Dynasty, and then gradually increased beginning with the Ming Dynasty and reached its overall maximum in the Republic of China period.

Furthermore, the oases along river banks remained stable, whereas those in terminal regions were subject to dramatic changes. Oases along river banks with stable water supplies, which had existed since the Han Dynasty, rapidly expanded after the Ming Dynasty, whereas oases in terminal regions, where the water supply was affected by changes in the upstream direction, were readily abandoned.

It is also interesting to note that the cultivated areas tended to be larger when the area was governed by powerful central governments, such as the Han, Ming, and Qing Dynasties and the Republic of China. By contrast, the areas occupied by cultured oases were smaller during other historical periods, which were characterized by societal instability and a preference for grazing activities.

4 Discussion

4.1 Possible factors driving oasis evolution

Because oases are complex and integrated systems composed of economic, social, and ecological subsystems, changes in their spatio-temporal patterns are related to both natural and human factors. The natural factors affecting oases include climate and water resources, whereas the human factors include the political situation, policies, population and technological progress.

4.1.1 Natural factors

A. Climate changes

Agriculture is very sensitive to changes in climate. These changes can affect the volume and distribution of water resources, ultimately resulting in changes to the oasis distribution. The climate in the HRB has been characterized in terms of temperature anomalies (Yang et al., 2002) and annual precipitation (Zhang et al., 2003) through reconstruction based on tree rings on the Northwest Qinghai-Tibet Plateau (Fig. 6).

It can be observed that the climate has experienced several obvious changes, with temperature anomalies ranging from –1.8 °C to 0.7 °C and annual precipitation ranging from 213 mm to 650 mm during the period of 1–1949 AD. During most of this time, the temperature was lower than that in modern times, whereas the annual precipitation tended to remain at approximately 300 mm, with three peaks during periods at around 400 AD, 850 AD, and 970 AD. In terms of dynasties, the climate was warm-wet during the Han Dynasty, cold-dry during the Six Dynasties period, warm-dry to warm-wet during the Sui-

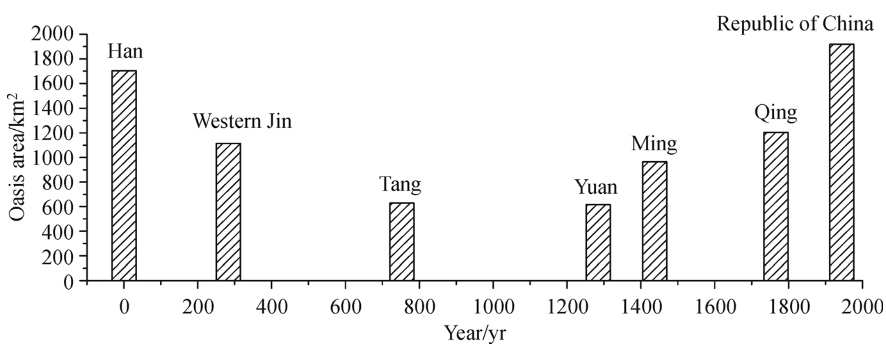


Fig. 5 Change of oasis area in HRB from the Han to the Republic of China shows the oasis area firstly decreased and then increased in the past 2000 years.

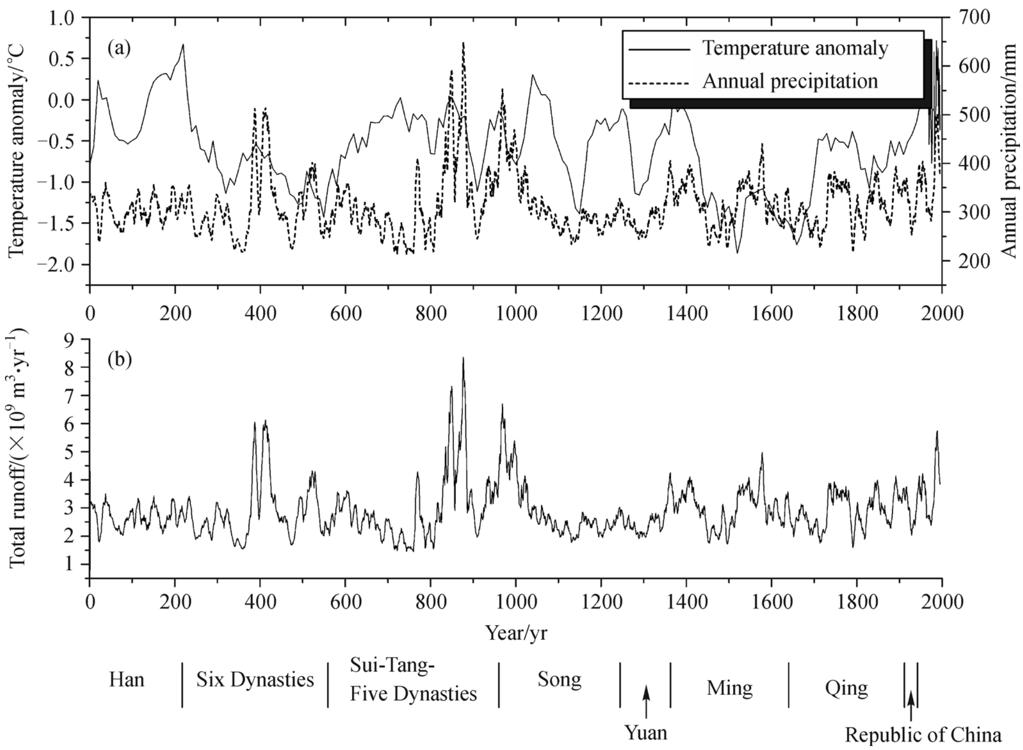


Fig. 6 Annual mean temperature anomaly (from Yang et al., 2002), annual precipitation (from Zhang et al., 2003), calculated from the index of tree-ring width and the total annual catchment runoff (from Sakai et al., 2012) in the HRB using the annual precipitation at Dulan, China.

Tang period, warm-wet to cold-dry during the Song Dynasty, cold-dry during the Yuan Dynasty, warm-wet to cold-dry during the Ming Dynasty, and warm-wet during the Qing Dynasty and the Republic of China period. The prosperous periods for oases generally coincided with a warm-wet climate during the Han, Qing, and Republic of China periods, whereas the periods of decline coincided with cold-dry and warm-dry climates in the Six Dynasty, Sui-Tang and Yuan periods.

B. Water resources

The variations in water resources may drive changes in cultivated oases. The total runoff of the entire river basin has been reconstructed based on tree rings (Sakai et al., 2012; see Fig. 6). The average total runoff is approximately 3×10^9 m^3, with three peaks in 377–535 AD, 800–900 AD and 926–1038 AD, which are uncorrelated with the periods of oasis prosperity. Additionally, four small peaks were observed in 1271–1430 AD, 1521–1585 AD, 1731–1785 AD and 1940–1949 AD, the latter three roughly coinciding with the prosperity of oases during the Ming, Qing, and Republic of China periods. However, the runoff was normal or lower during the Han Dynasty, the first period to see the establishment of large areas of cultivated oases. Thus, the oasis evolution does not appear to have been closely correlated with the runoff, probably because the water supply was always sufficient for oasis development regardless of the variations in water resources.

4.1.2 Human factors

A. Political stability and the needs of national defense

A study of the development of cultivated oases should not neglect the socio-economic context of the day, especially the stability of the political situation. Generally speaking, two types of production modes have been prevalent in the northwest of China: agricultural and nomadic. Between the peoples practicing these two modes, many wars broke out. To supply the military forces, oasis-based agriculture was developed. However, extensive oasis development requires peaceful and friendly surroundings.

Throughout the various historical periods, the Hans and the nomadic tribes, i.e., the Huns during the Han Dynasty, the Xianbei and the Huns during the Six Dynasties period, the Turkic peoples and the Tubo during the Sui-Tang period, the Mongols and the Tanguts during the Song-Yuan period, the Tartars during the Ming Dynasty, and the Junggar tribe during the Qing Dynasty, co-existed or clashed for nearly two millennia in the study area. To cope with the military threats from these nomadic nations, the central governments pursued agricultural development for military supplies. China was united and strong during the Han, Sui-Tang, Qing, and Republic of China periods, which laid the groundwork for massive oasis development. However, when the national power was weak and the inhabitants of the region were unable to live peacefully, during the Six Dynasties, Song, and Ming periods, the extent of cultivated oases inevitably decreased.

B. Agricultural policy

Agricultural and livestock policies, which are commonly established in accordance with the political situation, the needs of national defense and the customs of the local culture, have both direct and indirect effects on oasis development. China has a centuries-old tradition of developing and protecting its border regions by stationing troops to cultivate and guard the frontier areas, among which the HRB is included. The records consulted to determine the policies or strategies enacted during the main periods of interest are listed in Table 3.

It can be seen from Table 3 that most of the governments in the different periods treated agriculture as a serious priority, thereby promoting oasis exploitation. However, the weakness of the national government and the unstable political situation restricted the development of oases during the Six Dynasties period and the Ming Dynasty.

C. Population

Population is one of the important factors affecting oasis development in a region because it affects the availability of labor for agricultural activities. The percent of the population engaged in agricultural activities in the HRB can be found in various historical documents (Fig. 7). The population experienced trends of decrease and increase over the past two millennia that roughly coincided with the trends of the changes in oasis area. Therefore, it can be concluded that there was a positive correlation between the population size and the extent of oasis exploitation.

Moreover, the differences in customs among inhabitants of different nationalities also impacted economic policy, thereby affecting the oasis evolution. From the beginning of the considered historical period, the minority nationalities exhibited the typical characteristics of nomadic cultures (Table 4). Of course, these nomads occasionally engaged with agriculture to strengthen their reign, but they were not able to overtake the Han nation.

Following the Han Dynasty, the Huns, Uighur, and Tubo established regional regimes during the Six Dynasties period (after the Western Jin Dynasty), the Tang Dynasty and the Five Dynasties period. During the Song and Yuan Dynasties, the entire basin was under the rule of the Tanguts and the Mongols, respectively; livestock was prosperous, and the cultivated oases were small. When the HRB was governed by the Han nation under united and powerful regimes such as the Han Dynasty, the Qing Dynasty and the Republic of China, vast areas of cultivated oases were established.

D. Technological progress

Technological progress, as embodied in the prevalent mode of production and improvements to infrastructure,

Table 3 Agricultural policy in each period in the HRB

Dynasty			Policy	Source
Han			Migrating people to strengthen to the border area;	*History of Han the Dynasty (Han Shu)*
			Setting the agricultural prime minister to govern the cultivation	*History in the Later Han Dynasty (Houhan Shu)*
Six Dynasties	Three Kingdoms (Wei)		Developing paddy fields and recruiting people to supervise	*Annals of the Three Kingdoms (Sanguo Zhi)*
			Assigning militaries to cultivate lands	*History of the Jin Dynasty (Jin Shu)*
	Western Jin		Cutting militaries to to cultivate lands	*History of the Jin Dynasty (Jin Shu)*
	Eastern Jin	Former Liang	Engaged in agriculture and sericulture	*History Supplements of the Sixteen Kingdoms*
		After the Former Liang	Without clear policies	—
Sui			Constructing the castles and cultivating lands to cope with border conflicts	*History of the Sui Dynasty (Sui Shu)*
Tang			Promoting agriculture with light taxes	*New Book of the Tang Dynasty (Xin Tang Shu)*
Song (Western Xia) and Yuan			Livestock-based	—
Ming			Setting the Wei with troops and cultivating lands to feed them; Troops used three points for defending cities and seven points for cultivation in the border area	*History of the Ming Dynasty (The Ming History)*
Qing		Former period	Stationing troops to cultivate and guard the frontier areas and build self-sufficiency	*Hui 2003; Yao, 2004; Ma 2012*
		Late period	Promoting agriculture after military actions	*A Little knowledge of Xinjiang*
Republic of China			Paid attention to the development	—

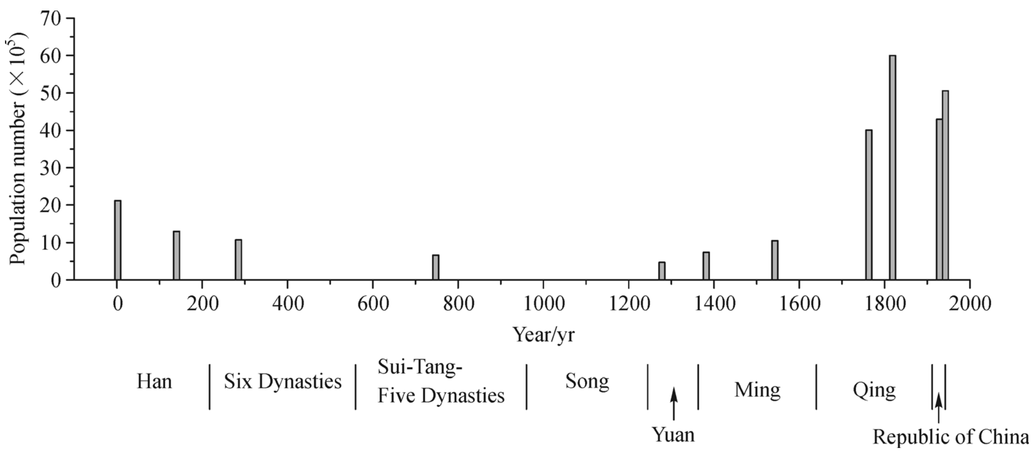


Fig. 7 Population changes in the HRB in the past 2000 years obtained from the historic documents, generally firstly decreased and then increased.

Table 4 The customs of different nationalities in the HRB

Nationality	Contents	Source
Han	Planting in spring, weeding in summer, harvesting in autumn, storing in winter, cutting wood, following local authorities, implementing corvee tax	*History of the Han Dynasty (Hanshu)*, volume 24
The Huns	Migrating with the grasslands without cities and long term agricultural cultivation	*Historical Records*, volume 110
Yuezhi	Migrating khanates, migrating with the livestock, having the same custom as the Huns	*Historical Records*, volume 123
Tubo	Engaging in livestock, moving constantly with the grasslands and without fixed settlements	*New Book of the Tang Dynasty* (*New Tangshu*), volume 216
Uighur	Moving constantly with the grasslands	*Old Book of the Tang Dynasty* (*Old Tangshu*), volume 195
Tangut	Never knew the agricultural planting and harvesting, without any corns	*Old Book of the Tang Dynasty* (*Old Tangshu*), volume 198
	Dressing the furs, raising the livestock, caused by its custom	A continuation of Zizhi Tongjian, volume 111
Mongol	From summer to winter, moving with the grasslands in any places	*History of the Yuan Dynasty*, volume 100

especially irrigation infrastructure, can promote the development of cultivated oases.

As early as the Han Dynasty, the advanced agricultural technology of the Central Plains was introduced into the study area. With the spread of cow-drawn ploughs and iron farm implements into Northwestern China, the productive forces in the society of the area achieved great progress (Liang, 1989). The method of dividing a field into many ditches and ridges, planting crops in the ditches in the current year and alternating in subsequent years, was taught to the inhabitants, who could then achieve "less input for greater output", as recorded in *The History of the Han Dynasty* (*Hanshu*). In the Six Dynasties period, "moving the stones out and carrying earth into the field to cultivate" made it possible to exploit the edges of the oases *(History of the Wei Dynasty)*. These measures alleviated the tension between the available land and the population it was obliged to support.

Progress was also achieved in irrigation technology, especially during the Qing Dynasty and the Republic of China period. Various advanced methods such as "cutting holes in the mountains to divert water", "setting up overhead channels", "diverting water from very difficult locations", and "lining channels" (*New Revised Suzhou Chronicle*) made it possible for oases to expand to higher-altitude terrain even during the Qing Dynasty. This may be one of the reasons for the expansion of oases near mountains.

4.2 Implications of oasis evolution

Several implications can be identified based on this study of oasis exploitation and evolution. The first is that maintaining peaceful international relations and a stable domestic environment is a prerequisite for oasis reclamation. The evolution of cultivated oases is a manifestation of the health of the agricultural economy, which is closely related to societal conditions. The obvious contrast between the prosperity of oases during stable and powerful dynasties and their decline and even desertification during times of turmoil proves that oases can enjoy continuous development and progress only under conditions of stability. Therefore, enhancing the unity of nations is crucial for oasis development in any era.

Water plays a key role in the sustainable development of oasis agriculture (Wang and Cheng, 1999). However, agricultural water consumption is high even with the advanced technology of modern times, still accounting for 78% of the available fresh water in the HRB (Chen et al., 2005). Because of the limited water resources in arid regions, it is unreasonable only to develop the agricultural economy; it should also be ensured that sufficient water resources are available to satisfy ecological needs. Historical records show that conflict arose between the water demand and the water supply in the HRB during the Qing Dynasty (Li, 2002; Wang, 2004). Thus, ecological effects must be considered when pursuing oasis exploitation. Readjusting the industrial structure and determining the appropriate size of the oasis based on the carrying capacity are essential for this purpose. It is also very important to balance the water supply between the midstream and downstream regions of the basin.

5 Conclusions

Using a multidisciplinary approach based on multisource data, we reconstructed the spatio-temporal pattern of cultivated oases in the HRB throughout seven historical dynasties over the past two millennia. The main findings are as follows:

First, the extent of cultivated oases has alternated between periods of prosperity and decline, with the largest cultivated areas arising during the Han, Qing, and Republic of China periods. By contrast, the shrinkage of the areas of cultivated oases during other periods can most likely be attributed to the cold and unpleasant climate, unstable political regimes, and a decreased population in the study area.

Second, the spatial pattern of cultivated oases has changed dramatically, remaining stable along the rivers but fluctuating in the terminal regions. The center of the oasis distribution has gradually moved from the terminal regions to the middle reaches of the basin.

Third, the cultivated oasis evolution in the HRB has been driven by both natural and socio-economic factors. The oases were prosperous during warm periods, although their prosperity was not directly correlated with the availability of water resources. The oasis evolution was also consistent with conditions of political stability and national defense, closely linked with the customs of the inhabitants of different nationalities and the state of technological progress. Under consolidated rule, the oasis area was enlarged, whereas it declined during turbulent times and under frequent regime changes.

Finally, the integrated multidisciplinary approach used in this study, combining methods such as literature-based research, archaeological investigation, the interpretation of RS images and map analysis, to reconstruct the historical trajectory of geographic phenomena is very effective and shows promise for application in the analysis of similar arid zones.

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