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ORIGINAL ARTICLE

Spatio-temporal process of oasification in the middle-Heihe River basin during 1368–1949 AD, China

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Abstract Understanding the oasis evolution process is one of the most important theses in arid regions, which could provide correlative theories for oasis exploitation. Currently, the researches implemented by a single method of document analysis with invisible results restricted the vision. By integrating and synthesizing records from historical documents, satellite images, local chronicles and maps, the spatial-temporal variability of oasification for nearly 600 years (1368–1949 AD) in the middle-Heihe River basin in western China was reconstructed. The conclusions are as follows: first, the oasis area in the five main periods, namely, the Early Ming, the Late Ming, the Early Qing, the Late Qing, and the Republic of China were 964, 840, 1205, 932 and 1917 km^2, respectively. Second, the oasis expanded during the Early Ming and Early Qing Dynasties as well as the Republic of China, whereas the intervenient periods namely, the Late Ming and Late Qing Dynasties shrunk. Third, the cultivated oasis sprawled out from the existing settlements established in the early Ming to surroundings, and the main sprawling period occurred in the early Qing in the downstream of the Taolai River, whereas the other oasis expansion appeared in the intermediate area of existing oases. It is indicated that the oasis distribution was restricted by the distribution of water resources and the oasification process is the result of climate change, political situation and policy as well as changes of population. The oasification process shows the active and adverse effects. The results describe a range of oasis conditions from 1368 to 1949 and provide a historical framework for measuring associated changes in ecosystems, which can be used to guide restoration where feasible and desirable.

Keywords Oasification · Spatio-temporal process · Historical reconstruction · The Heihe River basin · Historical period

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Introduction

Oasification and desertification processes in arid regions, which are important expressions of the land-use change, has become an active field in research concerning climate system, global change, land degradation, and regional sustainable development. Several studies indicate that land use/cover change (LUCC) has an important impact on climate and ecological environment changes in the regional and global scope (Ye et al. 2003; Foley et al. 2005). Reconstructing data on LUCC in historical periods provides reference information to explain the current status of land use and to predict the future land status (Andersen et al. 1996; Swetnam et al. 1999; Stäuble et al. 2008; Wulf et al. 2010). Moreover, the data have indicative significance for studying a long time series of regional environmental change (such as water cycle, carbon cycle, and climate change) (Petit and Lambin 2002; Lunt and Spooner 2005; Steyaert and Knox 2008; Ge et al. 2008; He et al. 2008; Yin et al. 2009; Miao et al. 2013).

Since the historical LUCC may change dramatically under strong disturbances, it is necessary to collect multi-source materials for spatial reconstruction. Due to the advancement of data extraction methods from the expanded data sources, multi-disciplinary approaches and a variety of data sources were applied. Most of the researches were concentrated in combination of historical documents,

ancient maps and survey data, which had been applied in different regions like the Massachusetts and the John Day and Deschutes river basins of eastern Oregon in the USA (Hall et al. 2002; McAllister 2008), Upper Franconia of Germany (Bender et al. 2005) and Sweden (Dahlström 2006). Recently, remote sensing, with the merit of large information capacity, huge observation scope, high accuracy and speed, has become one of the important means and data source for historical reconstruction (e.g. Hamandawana et al. 2005; Schuppert and Dix 2009; Xie et al. 2009; Liu and Tian 2010).

In China, arid land whose region encompasses most parts of northwest China accounts for nearly 25 % of the national total land area, with their cultivated oasis varying continuously on location and scope in the wake of long-term exploitation activities. As a typical and the second largest inland river basin in China, the Heihe River basin is a representative region on water and land resource utilization with the earliest irrigated agriculture, as well as a typical area in which rapid ecological deterioration significantly affects sustainable development (Cheng et al. 2009). Large-scale oasis exploitation in this region began in the Han Dynasty and changed subsequently with regime and social alternation in the past 2000 years. Since the Ming and Qing Dynasties, the development of the oasis reached a new climax due to the rapid growth in population and the expansion of cultivated land. However, after a long period of exploitation, serious ecological problems, such as surface water shortage, vegetation degeneration, land desertification, or salinization, began to emerge in some parts, which pose a threat to modern ecological security, sustainable development, and national defense building (Wang et al. 2003b; Pan et al. 2006; Yang et al. 2007). These issues, which are closely related to long-term human activities, particularly the oasification process since the Ming Dynasty, have attracted great attention from various social organizations and scholars (Qi and Wang 2003; Luo et al. 2005; Qi and Luo 2005; Wang et al. 2005).

Previous studies on oasis exploitation and agricultural development in this region since the Ming Dynasty were focused on the whole Hexi corridor or even a larger extent mainly by literature research, acquiring a large number of descriptive records. Currently, many researches have focused on agricultural production in historical prosperous periods, examining backgrounds, policies, and measures (e.g. Wu and Guo 1996; Zhang and Yang 2002; Zhao 1997, 2004; Yao 2004; Lv 2007; Chen YF 2008; Sang and Li 2011). Some other researches focus on water conservation projects, revealing many channels constructed in the Ming and Qing Dynasties (e.g. Wang 1996; Lv 1999; Pei and Guo 2008; Pan 2009).

However, most of these researches did not take the oasis evolution as the particular study subject. Due to the rough results without visual maps obtained through conventional methods, the details could not be disclosed. Therefore, it is necessary to have a more comprehensive research to reconstruct the spatio-temporal process of the cultivated oasis quantitatively in the Heihe River basin from the Ming Dynasty to the Republic of China (1368–1949 AD) through multi-disciplinary methods in large scale. The results are significant in understanding the environmental changes in arid regions under the impacts of human activities as well as the optimization of management models of oasis. Furthermore, it revealed the historical origins of ecological problems and provided references for drafting the policy for ecological environment recovery and protection.

Study area and periods divisions

The Heihe River originates from the middle Qilian Mountains in the northwest of China, and the range of this river basin covers 11 counties/districts in three provinces, with a total area of 1.429×10^5 km^2. Before the Ming and Qing Dynasties, the cultivation activities occurred in the midstream that covers Zhangye and Jiuquan, and downstream that covers Ejina County. However, Ejina was abandoned as the "land outside the boundary" in the Ming Dynasty, and consequently, became a region of the wild and no cultivation activities occurred from the Ming Dynasty to the Republic of China. Therefore, the reconstruction is only focused on the regions in Gansu (Fig. 1).

As the historical records often focus on the most prosperous times only instead of covering all the years in each dynasty, the time point with abundant historical records in each period is selected to represent the oasis exploitation. Based on the existing historical records and according to the social development, the Ming and the Qing Dynasties are divided into two stages, respectively. The Republic of China was marked as one period since it was too short. These periods are the Early Ming which is from the beginning of Ming Dynasty to the Zhengde Period (1368–1521 AD), the Late Ming which is from Jiajing Period to the end of Ming Dynasty (1522–1644 AD), the Early Qing Dynasty, which is from the beginning to the Opium War of 1840 (1644–1840 AD), the Late Qing which is from the Opium War to the end of Qing Dynasty (1841–1912 AD), and the Republic of China (1912–1949 AD).

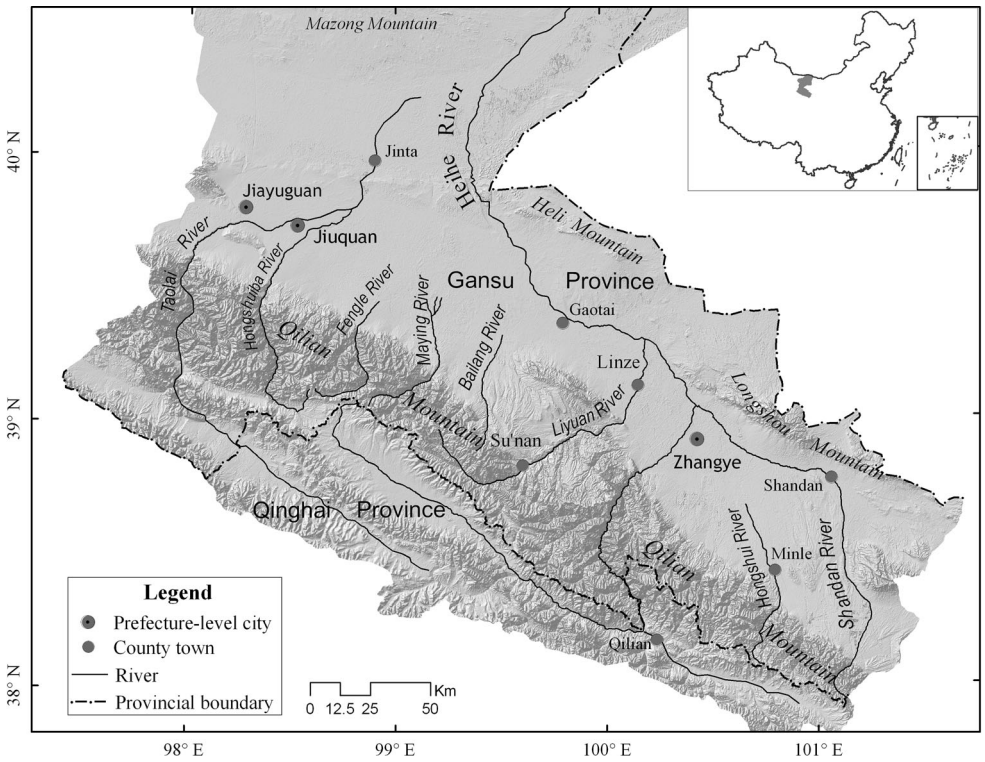

Fig. 1 General situation of middle reaches in Heihe River basin

Materials and methods

Materials

Historical chronicles

Local chronicles during the Ming Dynasty include the *Ganzhen Chronicle* (rehabilitated in the Qing Dynasty), which recorded the agricultural production of the five guardians of Ganzhou (Ganzhou District, Minle County, and Linze County in Zhangye City today) from Early Ming Dynasty to 1608 AD, and the *Suzhen Hua Yi Chronicle*, which recorded the details from 1372 AD to the Late Wanli Period (1573–1620 AD).

Not until the Qianlong Period (1736–1796 AD) in the Qing Dynasty were the new chronicles in compilation. On the one hand, the details of geography, administrative system, customs, and products of Suzhou and Gaotai were recorded in *New Rehabilitation Suzhou Chronicle*. On the other hand, details of the cultivation in Ganzhou, Shandan, and Fuyi (Linze today) were recorded in the *Ganzhou Prefecture Chronicle*. By the end of the Qing Dynasty, only a few chronicles were compiled. However, several of them, such as *Dongle County Chronicle* and *New Gaotai County Chronicle* compiled during the early period of the Republic of China, mostly recorded information from the Late Qing Dynasty and could be used as main materials of the Late Qing Dynasty. In the period of the Republic of China, most of the county chronicles that recorded the agricultural developments were completed, such as *New Zhangye County Chronicle*, *Linze County Chronicle*, and so forth. In addition, archives, questionnaires, and some statistical materials also have great reference values for obtaining the agricultural development in the Republic of China.

Maps

Maps used in the research include historical maps and modern ones. Illustrative maps in local chronicles are important references in reconstructing after the spatial correction. The *The Historical Atlas of China* which was edited by Tan Qixiang, is helpful to understand the administration system for each period although its scale is small. Moreover, *The water system map of Jiuquan and Jinta* found in the Gansu Province library and *The water system map of Heihe* preserved in the Gansu archives are important references in reconstructing the irrigation canals. The old and large-scale topographic maps of Linze and Gaotai produced in the 24th year in the Republic of China (1935 AD) have great reference values. Topographic maps which cover the whole area of the Heihe River basin in different periods were collected. Among them, those published in 1959 or 1960 AD are the most important resources because of the well-preserved geographical characteristics of the Republic of China. Finally, the

modern administrative maps of each county and atlas of Zhangye and Jiuquan, which were edited by the Gansu Bureau of Surveying and Mapping, mark the current geographical conditions in detail, which ensures the implementation of fieldworks.

Remote sensing images

The distributed area of the cultivated oasis in historical periods could be obtained partly by interpreting the remote sensing images. The raw desert regions in which the oasis had no possible existence can be excluded directly according to the image characteristics. Five scenes of the TM images (with 30 m spatial resolution) acquired from June to September 2009 were used to identify the historical cultivated oasis. Meanwhile, Google Earth images with high spatial resolution (with 0.61 to 2.44 m resolution) were downloaded to serve as reference. To make the research results close to the original appearance in the historical periods, the Keyhole satellite images (with 2.7 to 7.5 m resolution) acquired in the 1960s in which preserved features in the historical period maximally were also put into use.

Methods

The main purpose of the reconstruction is to restore the distributed area of cultivation activities to the greatest extent, and the focus is to determine the location and changes of the cultivated oasis boundaries. Therefore, the properties of spatial distribution, which includes the distribution area and boundary, should be found. Its era property, which is the era for oasis development, utilization and abandonment, should also be identified.

Owing to limited materials directly reflecting the oasification process, multi-disciplinary approaches which include historical geography and geographical information science are applied. First, as the science of studying geographical environment changes in history (Li 2000), the principles and methods of historical geography play an important role in reconstruction. Historical geography methods commonly used include literature research, field study, archeology method, and ancient map analysis. Second, surface landscape changes dramatically because large-scale cultivation altered the surface forms, and ancient sites can often be identified through remote sensing images. GPS navigation and positioning, topographic maps, and remote sensing images are vital in fieldworks to determine the deficiency of distinctive features in desert regions. Meanwhile, the GPS records the locations of ancient cities, channels, and farmlands along the field of study, which could provide important references for image interpretation. Finally, various complicated data could be converted into data layers with a unified spatial framework in a geographic information system (GIS) platform, which provides an integrated environment for analyzing a variety of spatial information comprehensively. Therefore, the 3S technology, which includes RS, GIS and GPS, is significant in this research.

Before the reconstruction, the range of raw deserts was excluded through image interpretation. Then the cultivated oasis could be determined by four kinds of proofs. Based on these proofs, the workflow was designed and it was shown in Fig. 2.

The first is the distribution of ancient settlements, which can be regarded as cornerstones. The central cities distribution could be confirmed according to historical documents and combined with the information obtained from *The Historical Atlas of China*. Other common settlements could be identified through early topographic maps and historical records in local chronicles as well as field investigation. When the settlements become intensive, they can reflect the oasis range to some extent.

The second is the distribution of irrigated channels. Irrigation is a prerequisite to ensure the existence of cultivated oasis in the arid regions, which is a strong evidence to determine the location and scope of the oasis. Their position and direction can be reconstructed by using early topographic maps and the illustrative maps in local chronicles and old maps in the Republic of China.

The third is the record of the population, irrigated areas of channels and farmland area in historical documents. Population is the basis for agricultural development in the historical period and a parameter to indicate the level of agricultural development, by which the cultivated oasis scale can be roughly estimated. The cultivated land is not just the main land type, but is the most important characteristic that distinguishes cultivated and natural oases. Historical literature contains the records on population and irrigated areas of channels, and can be obtained after unit conversion. The total area of cultivated land for each administrative cell could be extracted and used as reference data for the oasis reconstruction.

After obtaining the distribution of settlements and irrigated channels, they were overlaid together in a GIS. Then the buffer analysis was used to create the buffer of each channel with 1 km width. The result could be regarded as the preliminary results of the reconstruction. Next, the TM and Keyhole satellite images were overlaid on the layers of preliminary results and the raw deserted regions were excluded by image interpretation. Then the slope layer which is obtained by creating the DEM with 5 m resolution after the digitization of the topographic maps was overlaid. As the land with the slope is larger than 7° is not suitable for cultivation due to the difficulties of irrigation (Lai 2005), therefore the areas with micro topographic

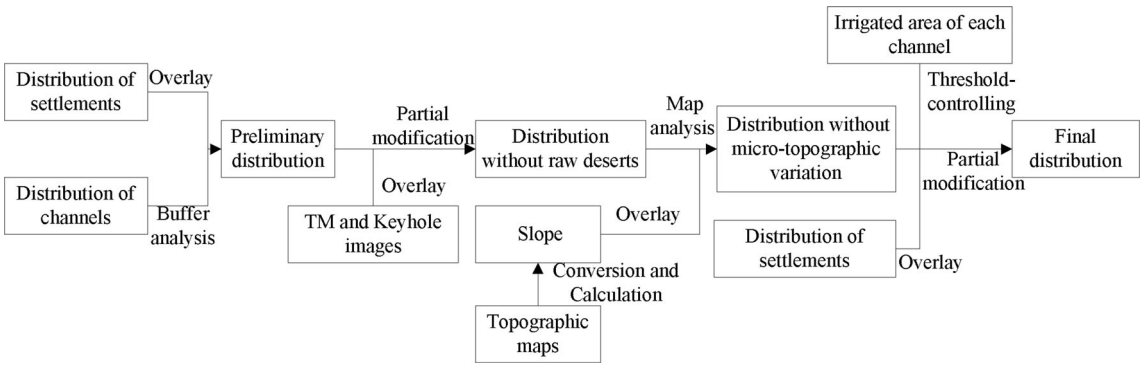

Fig. 2 The flowchart of the reconstruction

variations greater than 7° were excluded. Finally, taking the irrigated area of each channel as threshold, then the settlements were overlaid and the results were modified together. Checking against the size of irrigated area of each channel in historical records, some regions that covered the rivers, lakes and wetlands were excluded so that the oasis area of each channel would be consistent with that of the historical records.

Field investigation can also be implemented to verify the results. A total of three field trips over a distance of 10,000 km were conducted. For the first trip, most parts of the oasis regions were examined and substantial information about the historical economic and social condition was obtained. For the second and the third trips, a total of 44 and 40 existing ancient sites (channels, settlements or cities) were investigated, respectively, as references to determine the boundary of cultivated oases ancient sites. The geographic coordinates were measured with GPS as well as the shape features with tape measures. The surroundings, structural characteristics, etc., were also investigated. It was found that some of them are located in the modern oasis and some of them are situated in the deserted regions. In general, large areas of cultivated land surround some of the ancient sites. In some regions, wind erosion marks on surface are clear and farmlands are interbedded with nebkhas, which resulted from the blowing around some ancient sites. In addition, substantial amounts of clear channel banks with dry paleochannels intersect the lands, and ancient pottery shards, bricks, and other remains of human activity are found around these farmlands.

Results

The oasis exploitation of the Ming Dynasty was based on the previous dynasty, Yuan. During the Yuan Dynasty, the Gansu Province was established in the 18th year of the Zhiyuan Period (1281 AD), and its administrative center was located in Ganzhou (Ganzhou District in Zhangye City today). A movement of immigration and cultivation had taken place along the mainstream of Heihe and Taolai River, and Ejina in the downstream (Li 1990). But to the end of the Yuan Dynasty, social unrest and sharp decline in the population resulted in extensive abandonment of the oasis except for a few regions around main administrative centers.

The Ming Dynasty (1368–1644 AD)

The Early Ming Dynasty (1368–1521 AD)

The Ming government ruled Heihe River basin from 1372 AD, but the actual territory was limited to the east of Jiayuguan pass and south of the Great Wall. The Mongolian Tartars controlled the northern region, which posed a serious military threaten. Therefore, the regime combined administration with military and the Guardian-Bureau administrative system was implemented. Seven guardians and two bureaus, included the Shandan Guardian, five Guardians in Ganzhou, Suzhou Guardian, Gaotai Thousand Household, and Zhenyi Thousand Household Bureau (Fig. 3), governed by the Shanxi Provisional Government in Xi'an were established in the midstream. In the 26th year of the Hongwu Period (1393 AD), the Shanxi Provisional Government was moved to Ganzhou.

To supply food to the garrison, the government implemented the policy of "Agriculture Combined with Defense" to encourage people to migrate and to cultivate farmland. According to the *History of the Ming Dynasty*, about 5,600 soldiers per Guardian were in each guardian and 1,120 in each bureau. According to the *New Rehabilitation Suzhou Chronicle* and *New Rehabilitation Ganzhen Chronicle*, the troops comprised 26,662 households with 57,178 populations. Some civilian population also lived among the guardians and bureaus, and was estimated to be within 20 to 30 % of the military population (Cao 2000). The number of the civilian population could reach 14,295 if estimated by 25 %. Thus, the total number of population in this period is 71,473.

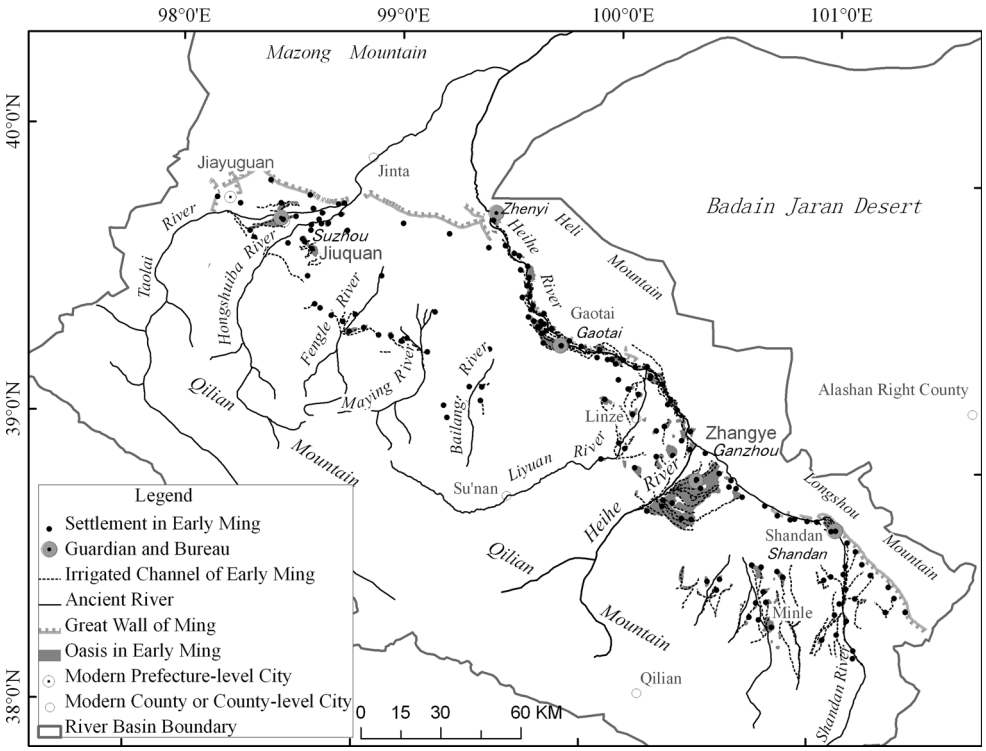

Fig. 3 Spatial distribution of administrative system, settlements, irrigated channels and cultivated oasis in the Early Ming Dynasty

The farmland areas reached approximately 933 km^2 in the third year of the Zhengtong Period (1438 AD) with more than 160 settlements according to the Ganzhen Chronicle. According to the early topographic map, the distribution of the major settlements can be determined (see Fig. 3). Most settlements were distributed along the river. Some settlement vestiges such as Xiaheqing Fort (Zijin Fort) and Hongsi Fort in Jiuquan were seen in field study. Moreover, some modern countries and villages still keep using the name of ancient settlements, such as Da Huajian Fort and Xidianzi Fort.

The government of the Ming Dynasty attached importance to water conservancy construction from the early period. According to the *New Rehabilitation Suzhou Chronicle* and the *New Rehabilitation Ganzhen Chronicle*, about 125 channels were found, and the data were recorded in historical maps, namely "*Water System Map of Jiuquan and Jinta*" and *Water System Map of Heihe*. Based on the historical names, the distribution of channels can be approximately reconstructed. For instance, the "Huangcao Dam started from Taolai River in southwest of Suzhou and ended at Shuimo Channel in the northeast of Suzhou, with 10 ft width and 3 ft 5 inches depth, extending to more than 60 yards with 13 grooves named Grape Groove, Up-Laijia Groove, Sanbaihu Groove…" According to the two maps, the intakes of Huangcao Dam are located in the southwest of Suzhou near the South Dragon King Temple and extended to northeast until Suzhou City. After acquiring the general direction and approximate length, the spatial distribution and scale of this channel could be reconstructed on the basis of place names and topographical features found on topographic maps published in 1959 or 1960 AD (see Fig. 3).

According to the areas of irrigated farmlands, taking settlements and channels in the topographic maps as reference, the boundaries of oasis can be recovered along the irrigation canals on the basis of remote sensing images (see Fig. 3). The oases are mainly scattered and distributed along Rivers in large scale in the northwest of Shandan, southwest of Minle, south of Gaotai, and locations around Zhangye and Jiuquan. Among them, the area around Zhangye is the largest. Most cultivated oases sprawled out from villages and forts, and the distribution was very dispersed because of water resource, terrain, and so forth (Wu and Guo 1996). The total area of cultivated oasis was 963 km^2 during this period.

The Late Ming Dynasty (1522–1644 AD)

It was unstable until an amiable companionship was established between the Ming Government and the Mongolian to enter a peaceful trade from the 5th year of the Longqing Period (1571 AD) (Compiling group of "History of Mongol" 1985). However, early in the Zhentong Period (1436–1449 AD), the cultivation policy slackened, resulting in abandonment of farmlands. "Local officials and despotic force not only encroached on military cultivated lands to gain rich profits, but also occupied water

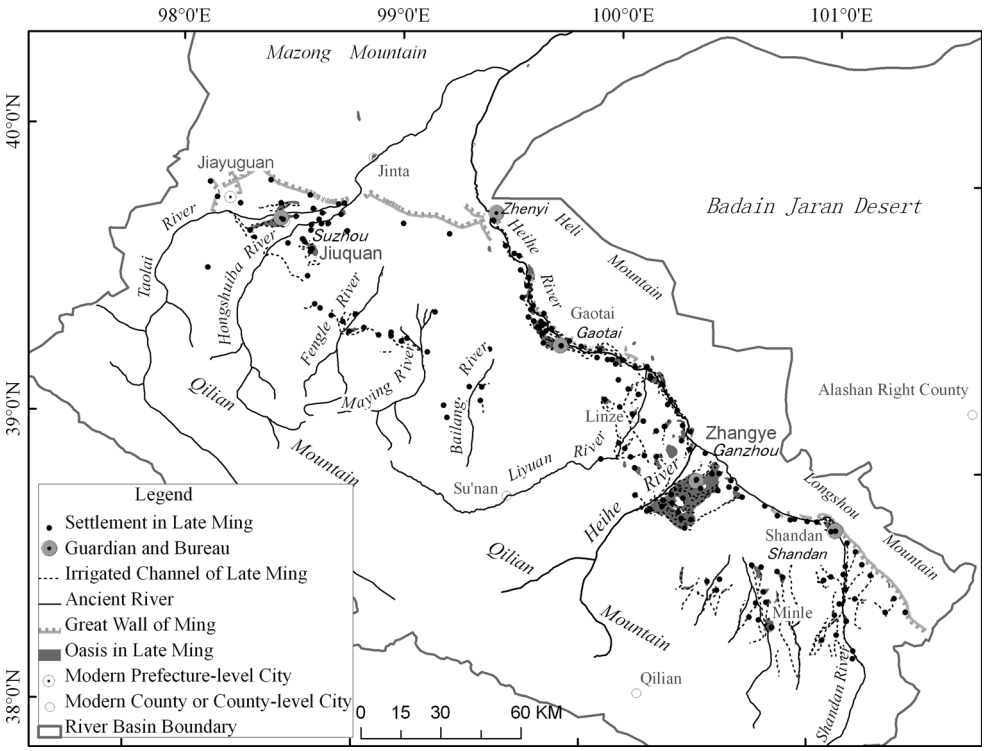

Fig. 4 Spatial distribution of administrative system, settlements, irrigated channels and cultivated oasis in the Late Ming Dynasty

conservancy, so that many military people could only get a little food and escaped" (*Annals of the period of Wuzong in Ming*). Therefore, "it was difficult for cultivation without defense and life was hard" (*Practical Articles of Ming*). Under the circumstances, government appealed to more people "do one's utmost to cultivate mountainous areas without tax" (*Ming Hui Dian*). Thus, the population increased and agricultural system was gradually restored. According to the records in *Jing-shi Wen-bian of Ming*, "It was considered that five guardians in Ganzhou were shorthanded since they had been established for long. But why the number of people increased?" It reflected population growth during the Guardian of Ganzhou. The population during the Jiajing Period (1522–1566 AD) was recorded in the Gansu Chronicle at 92,030. According to the *New Rehabilitation Ganzhen Chronicle* and *Suzhen Hua Yi Chronicle*, the settlement number increased slightly to 176, and the distribution of newly founded ones can be determined based on early topographic maps (Fig. 4).

After the reorganization and repairing of a large number of abandoned channels, villages, and forts, the cultivated oasis recovered and developed during the Jiajing and Longqing periods (1522–1572 AD) (see Fig. 4). The proportion of civil farmlands increased rapidly due to the enlistment of more peasants to cultivate. According to the *New Rehabilitation Ganzhen Chronicle* and *New Rehabilitation Suzhou Chronicle*, the area of cultivated land in the 29th year of the Jiajing Period (1550 AD) was 835 km^2. According to the distribution of settlements, channels, and combined with irrigated area, the oasis distribution was reconstructed (see Fig. 4). The results calculated by GIS show that the area was about 840 km^2 in this period.

At the end of the Ming Dynasty, the cultivated oases were partly abandoned because of the damage in the cultivation to guard system and the frequent peasant uprising caused by political corruption.

The Qing Dynasty (1644–1912 AD)

The Early Qing Dynasty (1644–1840 AD)

At the beginning of the Qing Dynasty, the society and economy were seriously damaged with barren land and sparse population after successive years of wars and natural disasters. The situation gradually stabilized after the control by the Qing government, and the Guardian-Bureau administrative system of the Ming Dynasty was again followed. After the pacification of the Galdan's rebellion in Xinjiang, the Heihe River basin entered a stable period. From 1725 AD, the prefecture-county administrative system began to take effect, and the entire administrative system with the Ganzhou Prefecture and Suzhou as center was formed. The system included Zhangye, Shandan, Gaotai, Fuyiting (Linze today), Dongle (Minle today), Wang Zizhuang (Jinta today), and the sub-county of Gaotai (Dingxin Town today) as counties by 1750 AD (Fig. 5). Meanwhile, the stable situation and the implementation of the policy, called "Assessment According to Farmland,"

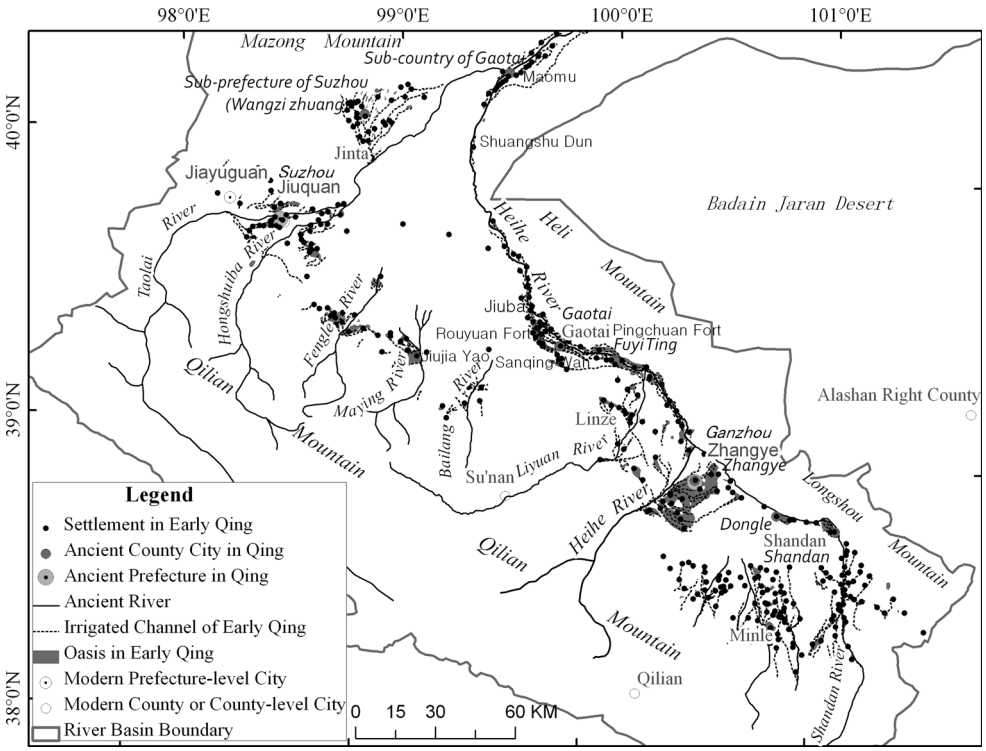

Fig. 5 Spatial distribution of administrative system, settlements, irrigated channels and cultivated oasis in the Early Qing Dynasty

led to the growth of population. According to the *Ganzhou Prefecture Chronicle* and *New Rehabilitation Suzhou Chronicle*, the population in Ganzhou up to 810,000, the number in Suzhou was 405,000, and the total amount reached 1,215,000 in 1820 AD. Although the data may be exaggerated since the *History of the Qing Dynasty* recorded that Zheng Huizu reported that live births statics were the same in different years and it seemed to copy the data, it is sure that the population was large in this period.

During this period, the government implemented measures to develop agriculture, such as forbidding land occupation by Manchu nobility, commanding sergeant demobilizing and participating in agricultural production, water conservancy construction, and so forth (Wu and Guo 1996). Aside from restoring the channels of the Ming Dynasty, new areas were reclaimed, including "Jiujia Yao, Sanqing Wan, Rouyuan Fort, Shuangshu Dun, Maomu, and Jiuba in Suzhou as well as Pingchuan Fort in Ganzhou" (*New Rehabilitation Suzhou Chronicle*) (see Fig. 5). Thus, the cultivation area expanded to the north of Gaotai. Meanwhile, Jinta, located in downstream of Taolai River was exploited again after being abandoned for 1,000 years since the Wei and Jin Dynasties. Oasis exploitation was in full swing during the reign of Emperor Qianlong (1736–1795 AD) with the boom of the agricultural economy.

The number of settlements and irrigated channels increased massively during this period. Based on the records in the *Ganzhou Prefecture Chronicle*, *New Rehabilitation Suzhou Chronicle*, and the early topographic maps, the spatial distribution of 354 settlements was determined and the results are shown in Fig. 5. The settlements in Shandan and Minle increased significantly, whereas a large number of settlements appeared in Jinta. More channels were constructed to enlarge the irrigated areas. "Yang Yingju who was the governor of Shanxi asked people to cultivate the wilderness in Suzhou with whole energies and to construct channels for irrigation in 25th year in Qianlong Period (1760 AD)" (*Gansu Chronicle*). According to the *Ganzhou Prefecture Chronicle* and *New Rehabilitation Suzhou Chronicle*, the irrigated channels during this period numbered more than 190, and their distribution is shown in Fig. 5. Thus the channel density increased further, and the Jinta irrigation district began to form.

The *Ganzhou Prefecture Chronicle* and *New Rehabilitation Suzhou Chronicle* indicate that cultivated land areas with bountiful crops reached 1119 km^2 in the 1770s. The distribution of settlements, channels, and their irrigated areas were included in the oasis distribution reconstruction (see Fig. 5). The reconstruction shows that the oasis area was approximately 1205 km^2 in this period.

The Late Qing Dynasty (1841–1912 AD)

After the outbreak of the Opium War in 1840 AD, the situation worsened as more unrest happened in other

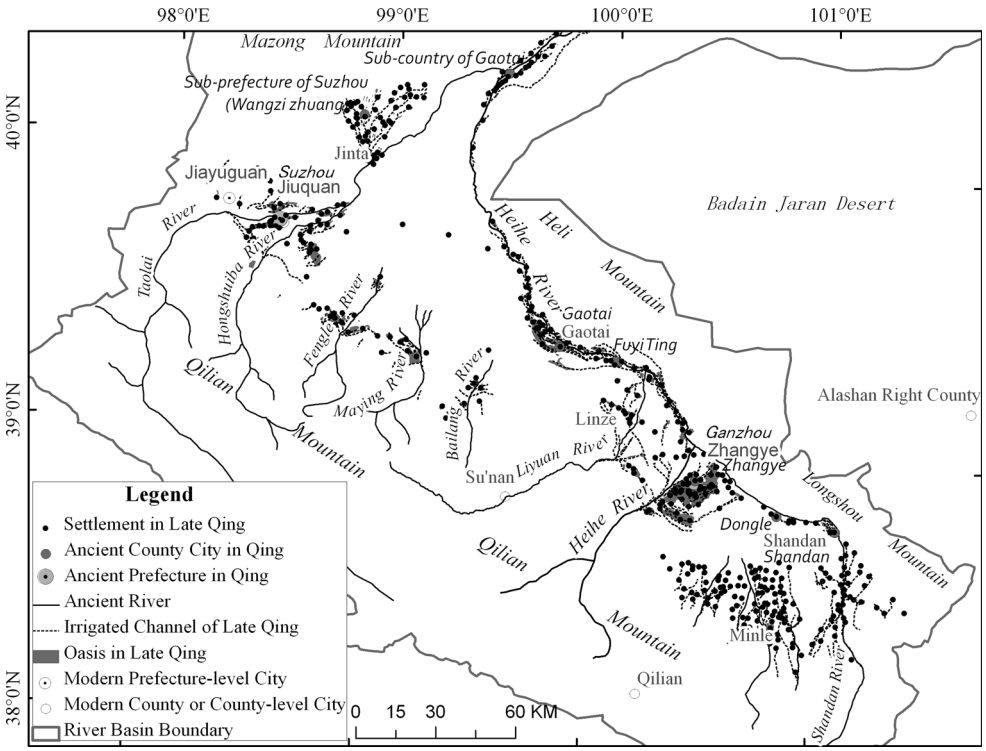

Fig. 6 Spatial distribution of administrative system, settlements, irrigated channels and cultivated oasis in the Late Qing Dynasty

parts of China. From 1862 to 1873 AD, the long-term Hui uprising in the northwest led to population decline, which caused severe damage to agricultural production. In 1867, Zuo Zongtang implemented measures to restore production in different regions and agricultural production soon began to recover (Peng 2001; Yan and Ma 2002).

The settlements in this period were recorded in the *Dongle County Chronicle*, *New Gaotai County Chronicle*, and other county chronicles compiled in the Republic of China. According to these records, the number of settlements increased to 429 in this period. Meanwhile, no marked changes in the irrigated channels and other water conservancy facilities were observed (Fig. 6).

The cultivated land in Zhangye, Fuyiting, Shandan and Gaotai covered an area of 722 km^2 according to the records in *New Chronicle of Gansu*. After restoring the distributions of settlements and irrigated channels, the cultivated oasis was reconstructed with the support of GIS (see Fig. 6). The area of the oasis was about 932 km^2 in this period.

At the end of the Qing Dynasty, agricultural production declined rapidly due to wars and military conflicts. According to the study, the population was about 475,000 in 1910 AD (Cao 2001). A large number of settlements that were relatively small or located in the traffic arteries were destroyed by the war, and resulted in the reduction in the oasis areas.

The Republic of China (1912–1949 AD)

From 1912 to 1937 AD, the Heihe River basin was entirely in a state of political unrest. Successive years of tangled warfare among warlords and severe natural disasters caused the huge loss of population. From the end of Qing Dynasty, a great deal of channels and farmlands were abandoned and people decreased gradually indicated by *Statistical Yearbook of Gansu Province, 1948*. Thus the agriculture stagnated and the oasis areas diminished during this phase.

Not until 1937 AD did the situation become stable after the breakout of the War of Resistance against Japan. There were no marked changes in the administrative system, with eight counties in this region (Fig. 7). Under this circumstance, the total population in each year from 1937 to 1948 AD was about 500,000 as indicated in the archives of the Republic of China. Meanwhile, great importance was attached to the exploitation of northwest China, and several measures were taken, such as adding water conservancy section to government in 1940 AD, building the Forestry and Livestock Company of Gansu, and constructing Yuanyang Lake Reservoir in Jinta, to facilitate the recovery of agriculture.

According to the local chronicles in each county of this period, the settlements increased to 685 with much higher density along the river (see Fig. 7). However, since agricultural activities were mainly limited to dredging and

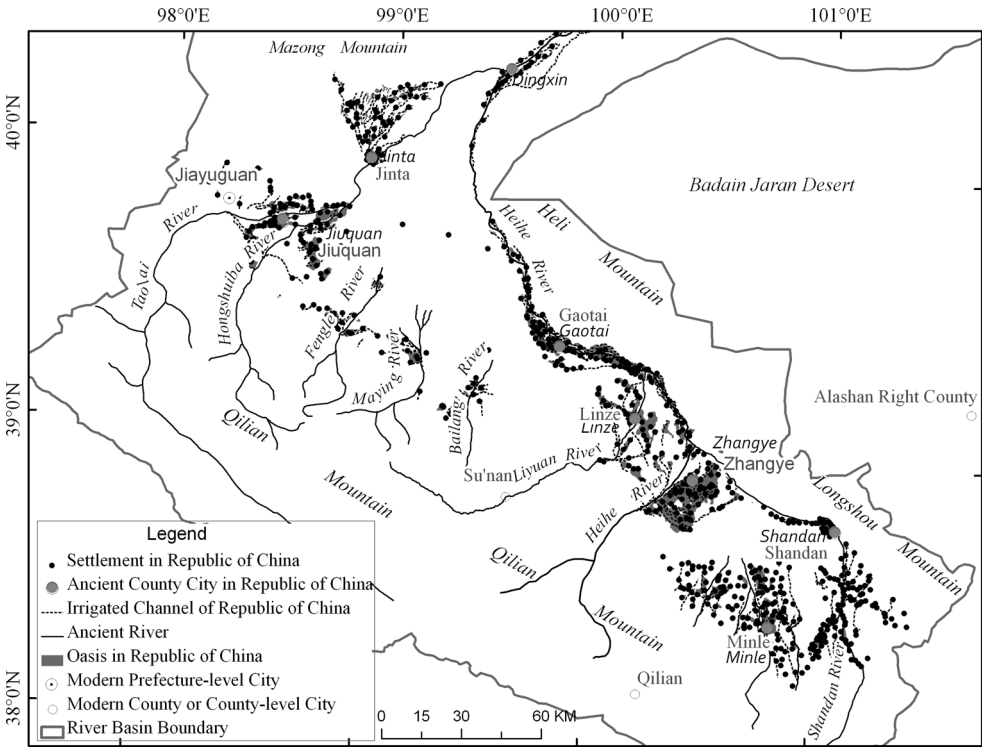

Fig. 7 Spatial distribution of administrative system, settlements, irrigated channels and cultivated oasis in the Republic of China

repairing of the original channels of the Qing Dynasty, the newly development oasis was restricted in edges of existing regions, especially the east part of Jiuquan. But technical progress promoted the agricultural development, such as spreading the improved seeds, pests and diseases control, utilization of fertilizer, as well as improvement of farm tools and methods (Zhang and Yang 2002). According to the statistics recorded in the archives of the Republic of China and the local history of each county, the cultivated land area was 1873 km^2 after the 1940s.

Drawing near the modern period, the spatial distribution of oasis can be explored from the topographic maps of the 1950s and remote sensing images of the 1960s. To interpret the image, the distribution of settlements and channels were first recovered using a combination of archives and topographic maps. Then, Keyhole images of 1963 AD were overlaid using the data above. Finally, the distribution of the cultivated oasis can be obtained with visual interpretation (Fig. 7). By measurement and calculation, the area of the cultivated oasis during this period was 1917 km^2.

Analysis of change process

From the Ming Dynasty to the Republic of China, oasis area had changed evidently (Fig. 8a. Overall, the cultivated oasis increased with the fluctuation during nearly 600 years.

At the beginning of the Ming Dynasty, the agricultural production was damaged greatly by the wars, so the cultivated oasis was quite small (without exact number due to rare materials). After 100 years of exploitation, the oasis area increased unprecedentedly during the Early Ming Dynasty, with an area of 964 km^2. However, although rectification followed, the oasis decreased owing to the abandonment of the military cultivation policy in the late period. The covered area was down to 840 km^2. During the period between the Late Ming and Early Qing periods, the cultivated oasis substantially reduced because of social unrest (without exact number due to rare materials). The oasis area expanded rapidly during the Early Qing period. The area reached 1205 km^2 with the continuing economic and social development, but the oasis area shrank with the increasing social unrest during the Late Qing Dynasty. After entering the Republic of China, the oasis area increased unprecedentedly and reached 1917 km^2, which is the largest one in the whole historical periods because of the population growth and scientific-technological progress. Overall, the cultivated oasis gradually increased, with the largest number found during the Republic of China and the smallest number in the Late Ming era. This finding indicates that the oasification process gradually strengthened with the enhancement of the human ability of transforming nature.

On the spatial distribution pattern, most of the cultivated oases were distributed along the sides of mainstream and branches, showing the zonal or scattered shape of the distribution. During nearly 600 years from the Ming Dynasty to the Republic of China, the oasis distribution pattern in

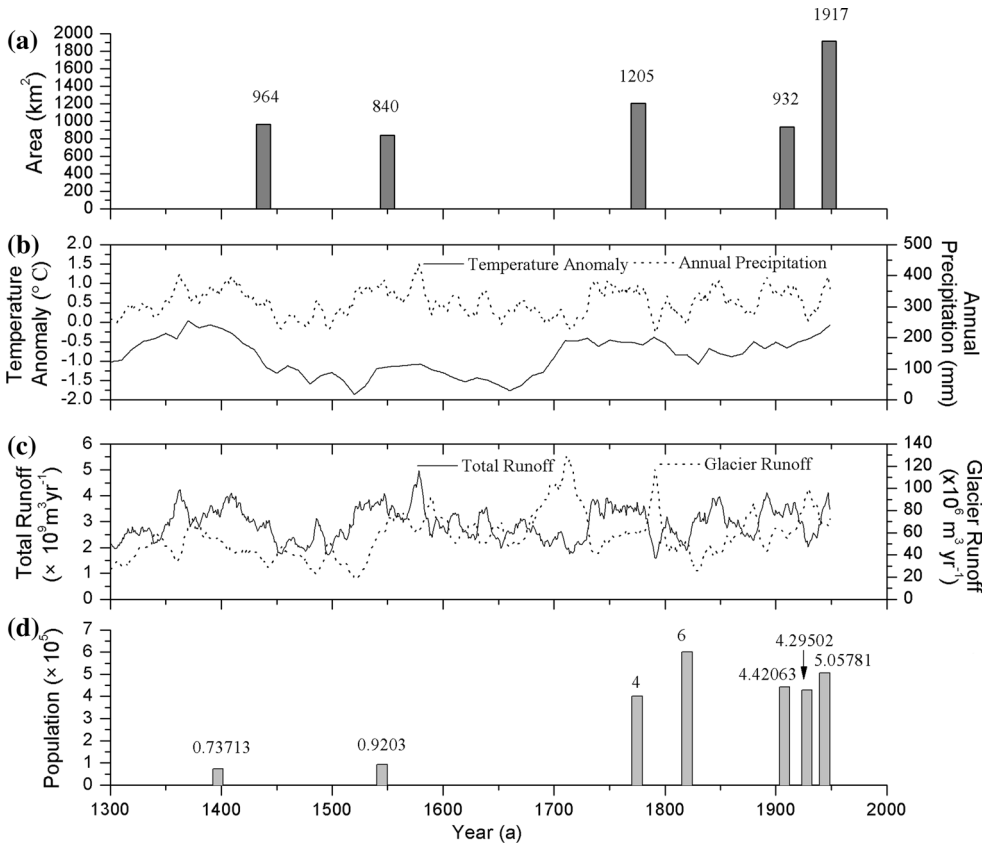

Fig. 8 The oasis area change and its driving factors. **a** Change of oasis area in each period. **b** Change of annual mean temperature anomaly and annual precipitation. **c** Change of the total annual catchment runoff, annual glacier runoff. **d** Change of population number

several places changed obviously, although the overall pattern unchanged. First, the oasis in core regions such as Zhangye, Gaotai, and Linze expanded outward from the existing range, but only within a relatively limited range since available land and water resources were limited by topography, soil, and production technology. Second, the oasis in Jiuquan expanded to the east because of the abundant resources of water and land and dense river system. Lastly, the oases in Shandan and Minle, which were near the mountains, were randomly scattered in small scale. The trend of expansion outwards and connecting pieces of large blocks was observed. Similar events were observed in the oasis south of Gaotai and Jiuquan near the mountains. Besides, particularly remarkable about the oasis is the region in Jinta Basin, which is located in the downstream of Taolai River. Its range has expanded rapidly since the Qing Dynasty, and reached a considerable range until the Republic of China.

On the whole, the spatial variation of cultivated oasis in the Heihe River basin showed an expansion trend, which included radiating expansion and extension upstream and downstream. On the one hand, the oasis in the south of Gaotai and east of Jiuquan expanded from the existing range. On the other hand, the oasis began to emerge in the upstream, which coincided with the downstream in the regions along the mainstream of Heihe and around the small rivers near mountains, which indicated an expansion trend to upstream and downstream.

Discussion

Possible drivers for oasification process

Besides the natural factors that restrict the maximum range of oasis, several different and complicated mankind's activities could explain the changes in the cultivated oasis. Natural factors can be considered as the natural environment that supports the existence of oasis, including climate and its changes, geological structure and terrain, water resource, soil condition as well as some natural hazards. Among these elements, geological structure and terrain, which laid the basic geographical conditions kept the characters of stability in the historical periods. Meanwhile, agriculture is the most sensitive department to climate change in the socioeconomic system (Zhang et al. 2003b). The climate changes can not only affect the growth of vegetations, but also drives the distribution of water resource, then influence the oasis finally, which become the main natural factor. Therefore, it can be regarded as the most important element. Aside from the natural factors, the changes are closely related to

human factors such as political situation, policy, and population.

Climate changes

A large number of researches suggested that events, such as agricultural yields, outbreak of wars, population changes, regime changes, and so forth, were closely related to climate change in historical periods (Zhang et al. 2007; Xu 1998; Wang et al. 1996; Ge and Wang 1995; Li 1999). For historical climatology, the Little Ice Age began from the 13th or 14th century and ended in the beginning of the 20th century (Grove 1988). In China, it was deemed as the period from the end of the 15th century to the end of the 19th century, which covered almost the total times of the Ming and Qing Dynasties (1368–1911 AD) (Wang et al. 1998). The trend of climate change in the Heihe River basin had three much colder periods from 1428 to l537, 1622 to l740, and l797 to l870, respectively, among which the middle one between the Ming and Qing Dynasties was comparatively obvious (Dong 1993). Moreover, the rainfall change, which is one of the most important aspects of climate change, has profound effects on water resource supply. The main water source in this river basin is obtained from the rainfall, accounting for 90.2 % of the total (Pan et al. 2012). In recent years, the temperature anomaly and annual precipitation were reconstructed by using the tree rings as Fig. 8b (Yang et al. 2002; Zhang et al. 2003a).

The temperatures were lower than modern times and represented an overall increase trend from 1368 to 1949, while the annual precipitation kept the similar trend but was less obvious, which approximately matched the evolution of cultivated oasis. The peaks of temperature and rainfall could be observed in the Republic of China, which is consistent with the peak of oasis area. In addition, the trough appeared in the year around 1550 and 1625, which are the year of the Late Ming with the lowest oasis area and dynasty subrogation between the Ming and Qing without reconstruction due to limit materials,

Water resources

Since oasis is a production of irrigation, the distribution of water resources played a leading role in restricting the oasis distribution (Fan et al. 2006). The main water resources were provided by a large number of branches and the main stream. Although there were several lakes and springs, they were seldom used to irrigate directly (*New Rehabilitation Suzhou Chronicle*). According to the tree rings, the total runoff and the glacier runoff of the whole river basin was reconstructed as Fig. 8c (Sakai et al. 2012).

As it is shown in the figure, the average value of the total was about 3×10^9 m^3 and the trend of total runoff accord with that of glacier runoff. There were three peak periods of total runoff from 1400 to 1445, from 1520 to 1585, from 1730 to 1785 and from 1940 to 1949, which corresponded with the periods of boom years of the oasis. In the Qing Dynasty, the agricultural water consumption in the middle reaches reached to 1.3×10^9 m^3 to 3.0×10^9 m^3, which almost consume the total of water (Xiao and Xiao 2008). Therefore the river gradually dried up in the down reaches.

Political situation and policy

The exploitation of oasis in this region had strong political and social background, especially for the key roles in consolidating the national defense. Since the boundary between agriculture and stock rising crossed the region, a series of military conflicts had happened for the controls of limited water resources. Peaceful environment was the basis for oasis development, while military clashes not only damage the crops and conservancy projects, but also impacted on the population and policy.

In the Ming Dynasty, the government faced huge military pressures from Timur Empire, Turban Kingdom and the tribes of Qinghai-Tibet Plateau especially the Tartar of Mongolia from the north. Therefore, intense needs of military defense to meet the supplements became the most essential force for developing cultivated oasis. Therefore, the oasis range was limited under the threats. When it comes to the Qing Dynasty, the relationship between the Qing and the Mongolia was improved through marriage and the conflicts between nomads and the Central Government of China reduced. Not until the outbreak of War against Japan (1937 AD) did the political situation tended towards stability in the Republic of China. For the periods between them, the region was in chaos because of the military conflicts led by regime changes. Therefore, the oasis area expanded when the situation is stable, which represented by the reconstruction.

Policy based on political and social background was one of the most important factors that affect oasis evolution. Whether the policy of military cultivation during the Ming Dynasty or "Tax According to Farmland" during the Qing Dynasty, they had the same effects on promoting the oasification process. The military cultivation was a kind of collective and coordinative farm work with compulsory and submissiveness. "Tax According to Farmland" relieved the peasants of their backbreaking labor and raised the production enthusiasm greatly. After 1937 AD in the Republic of China, the government attached great importance to developing Northwest Territory of China, which also helped to forward the expansion of the oasis.

Changes of population

Population is the main basis for agricultural development in the historical periods, with its number and distribution affecting the oasis directly or indirectly. The increasing population provides labors for cultivation, and increases demand for agricultural products, which, in turn, made the oasis expand objectively. According to records in the historical documents, the agricultural people were estimated (Fig. 8d).

It is indicated that population increased dramatically in the Qing Dynasty and kept a high value to the Republic of China. More cultivated lands were needed in order to feed the growing world. However, as good water and land resources along the rivers were almost fully developed, it was inevitable to search new lands. Under these circumstances, besides exploding outward in exhibiting range, newly developed oasis began to blow up at mountainous regions in the south and some plant land in the north. Consequently, the change in population distribution was the direct reason for oasis evolution.

Since cultivation activates mainly centered round the settlements or cities, the distribution of settlements was consistent with the distribution of the oasis. The distribution of settlements was restricted in south of the Great Wall in the Ming Dynasty, while enlarging to the Jinta Basin in the north during the Qing Dynasty. Meanwhile, the density of settlements increased during the whole period which indicated the expansion of population distribution. As the reconstruction result, the cracked polygon of oasis linked together gradually during the whole period.

Effects of landscape change

Land-use practices are inherently a trade-off between increasing ecosystem services with immediate benefits to human beings while potentially degrading long-term ecosystem function (Foley et al. 2005). The oasis evolution produced profound ecological consequences. As one of the most essential breadbasket in China, the increase of oasis provided more supplies to the people so that the national defense was enhanced. In addition, microclimate condition was improved, with the reduction of evaporation and a slight rise of rainfall. The soils were also improved so that the land productivity was enhanced, which heightened land carrying capacity of oasis (Fan 1996).

Nevertheless, there were several negative influences. More forests had been cut or burned to provide additional cropland with the increase of population (Dang 2001; Wang 1999). Early in the Ming Dynasty, the main stream usually dried up due to the use of water resources in midstream according to the records in the *Ganzhen Chronicle* (Liu et al. 2008). Under this condition, the oasis in downstream was abandoned combined with the wars. With the rise of population and oasis, cases about the water resources tangle in the Qing Dynasty, which never recorded ever before reflected the over-exploitation of water resources (Li 2002; Wang 2004). *The secret territory map for the Qing Dynasty* showed that the whole Juyan Lake in the downstream had departed into two parts (Liu 1992; Gong et al. 2002), which were associated with the rising intensity of water utilization in the middle reaches.

Implications of oasis exploitation and evolution

Some implications can be learned from the oasis exploitation and evolution, among which the most important one is observing the natural principle and proceeding from reality first. The over exploration of natural resources may lead ecological disasters, especially in the arid regions with fragile ecosystems. Therefore, promoting the organic connection of ecological construction and district economic development should be emphasized to realize mutual benefits.

Agriculture consumes the largest amount of the world's fresh water in most countries, accounting approximately 70 % of the total per year (UNESCO 2001; Pimentel et al. 2004; Chaves and Oliveira 2004; Rosegrant et al. 2009). Since water consumption for agriculture land is far more than other types of land cover such as grass and forest, arid regions shall focus on the readjustment of industrial structure to avoid uncontrolled oasification. It is also necessary to make laws to regulate the water resource utilization and practice unified management so that the water resource can be allocated efficiently. Specific measures for implementing the licensing system for water usage shall be implemented to ensure the basic water supply of life and production in different regions. Meanwhile, the development of water-saving technology is essential for agriculture in arid regions and to solve the water resource shortage.

Excess population can lead to the relentless pressures on the oasis land as well as the ecosystem stability. Population growth, accompanied by increased water use, will not only severely reduce water availability per person, but stress all biodiversity in the entire global ecosystem (Vorosmarty et al. 2000). In fact, in the Qing Dynasty, the Hexi Corridor, which covers the midstream of the Heihe River basin, reached a population density of 8.8 people per km^2, passing the critical value of population density in arid regions of 7 people per km^2 (Wang et al. 2003a). Under these circumstances, it is essential to use policy to control population.

Above all, the uncontrolled oasification process is an ecological disaster in arid regions, although it satisfied living demands of mankind in a short time. Water shortage is the challenge in the development, especially in arid

regions (Jiang 2009; Wang et al. 2009). Rational water resource allocation with high efficiency and a fitting area of the oasis are crucial for the development in arid regions.

Methodological and data considerations

A comparison of the results with those of previous studies suggests that a few of progresses have been made. The multi-disciplinary approaches combining with historical geography and geographical information science could heighten the precision and expressive force of oasification process in the historical period, obtaining the results with results in positioning and quantity. The use of multi-source data helps humans open an easy access to all kinds of evidences for oasis exploitation. Relative to the way of literature research or combined with historical map analysis, in addition, the technological route is optimized by using 3S technology, not only obtaining the evidences in fields as well as in remote sensing images but acquiring a platform for oasis restoration. But even so, the reconstruction process is time-consuming due to the complex of determining the ancient sites. The results provide a quantitative view of oasification process in regional scale, but they should not be applied in the isolated interpretation of individual sites or settlements.

However, historical data have certain limitations that influence the application and ecological interpretations (Whitney 1994; McAllister 2008). Most of the historical information in documents is descriptive, scattered and not directly comparable to quantitative data being gathered in modern times. Most of the records which concern only a few flourished periods are choicest and opportunistic, resulting in the data gaps in turbulent times. Even in the records in boom periods, some defects, such as confusions of age, can still be found. Because the name changes of a few settlements and irrigation channels for positing, and because the abandonment of these sites, it is practically impossible to search all of them with all the materials, which inevitably affects the precision of the restoration.

Conclusion

Based on the analysis of historical documents, remote sensing images and maps, the spatial patterns of oasis from the Ming Dynasty to the Republic of China in the Heihe River basin were reconstructed in GIS. The main conclusions obtained are as follows:

1. The cultivated oasis area in the overall study periods represented the fluctuating growth process, with areas of 964, 840, 1205, 932 and 1917 km^2 in the five periods, respectively. Overall, the oasis area reached the maximum value in the Republic of China, and had the smallest value in the Late Ming Dynasty. Meanwhile, massive oasification mainly occurred in the Early Qing Dynasty, and the Republic of China. Declines were observed in the periods between them.
2. The spatial pattern of cultivated oasis in local regions changed dramatically, although the overall distribution pattern did not alter obviously. The oasis in the core regions, including Zhangye, Gaotai, and Linze expanded within a limited extent because of the finite water and land resources. However, the oasis near mountains, including the south of Gaotai and south of Jiuquan expanded evidently. In particular, the oasis in the Jinta Basin, which is located in the downstream of the Taolai River, expanded fleetingly from the Qing Dynasty, and reached a considerable range during the Republic of China.
3. The spatial variation of cultivated oasis in the Heihe River basin shows an overall expansion trend, which includes radiate expansion and extension to upstream and downstream. For instance, the oasis in the south of Gaotai and east of Jiuquan expanded from its existing range, whereas newly developed oasis appeared in the lands near the upstream and downstream of the mainstream and branches such as in the Taolai River, to show an expansion trend in the upstream and downstream.
4. Both the natural and human factors could illustrate the oasification process. Climate change could be regarded as the key natural factor and the water distribution could restrict the oasis distribution. The core human fact is the political situation and policy. Population change is the direct and active aspect of oasis change.
5. Although the oasis expanded during 1368–1949 AD and played an active role in the national defense in ancient China, it had laid the groundwork for ecological problems. However, a large and increasing population with limited resources casts a shadow on mankind's future existence in the Heihe River basin, bringing the adverse effects like cutoff of rivers and reduction of water in downstream.

Today, when exploiting the water and land resources, observing the natural principle and conduct on the practical situation of arid regions is necessary and important. What is needed in arid regions is not the exploitation without limitations, but the utilization with controls and plans based on the resources and environmental carrying capacity. To adjust the industrial structure and to adopt advanced techniques in saving water are effective measures and pressing tasks for raising water and land potentialities in arid regions.

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