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RESEARCH ARTICLE

Spatial distribution of an ancient agricultural oasis in Juyan, northwestern China

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Abstract Activities related to agricultural cultivation are some of the major human drivers of landscape change on the Earth's surface. Archaeological remains can provide qualitative evidence for studies of past agricultural development and environmental conditions. The ancient Juyan Oasis, which once flourished along the historic Silk Road, was a typical oasis of downstream inland river basins in the arid zone of northwestern China. Historical records and archaeological discoveries have qualitatively shown that the oasis supported extensive agricultural activities in this historical period from the Han Dynasty to the early Ming Dynasty (B.C. 202–A.D. 1375), which can be traced back to 2,000 years ago. In this study, different types of archaeological remains (including archaeological sites, ground surface artifacts, ancient cultivation ruins, and agricultural irrigation canals) that were obtained and identified from previous archaeological reports, field inspections, and remote sensing imagery were used to determine the spatial extent of the agricultural oasis in the historical period of interest. Our approach used multiple data sources in order to increase the accuracy and reliability of the results compared to previous studies. Our results distinctly suggested that much of the oasis was cultivated during the historical periods considered. Additionally, the arable land area in the historical period considered was roughly estimated to be approximately (3.39–4.75) $\times$ 10^4 ha. These findings regarding the spatial distribution of this ancient agricultural oasis and its arable land were reasonably determined to represent the ancient agricultural development that occurred in the Juyan Oasis better than results obtained from single sources of data.

Keywords archaeological remain, arable land, remote sensing, Juyan Oasis, Silk Road

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1 Introduction

The Earth's surface has been altered by human efforts to acquire resources (i.e., food, fiber, and fresh water) since the dawn of civilization, with agriculture as one of the most important human drivers of landscape change (Ramankutty and Foley, 1999; Goldewijk and Ramankutty, 2004). In China, large areas of the country are arid, and the environmental and land use characteristics of these regions have changed greatly over time as a result of physical environmental changes and human activities (Fang and Liu, 1992; Yang, 2001; Miao et al., 2002; Zhang et al., 2003; Zu et al., 2003; Cheng et al., 2006; Zhang et al., 2008; Liu et al., 2010a; Zhang et al., 2012). Because the oases offered suitable environments that are unique in arid zones, they acted as heartlands that supported agricultural communities in the historical period from the Han Dynasty to the Qing Dynasty. As a result of agricultural development, natural oases had evolved into agricultural oases that are characterized by irrigated agriculture dependent on local water resources, and are distributed throughout the arid desert region. Agricultural oases comprise a large system that includes many factors (e.g., cities, villages, houses, roads, forests, irrigation facilities, and cultivated farmlands), and cultivated farmland is just one of the elements of the system. Extensive agricultural activities in these oases have sustained human needs for thousands of years (Zhu et al., 1983; Zhang, 2001; Xie et al., 2009; Liu et al., 2010b; Qin et al., 2012; Zhang et al., 2012). As the regional populations grew in the inland river basins of many arid areas, the demand for water for drinking and agricultural purposes also increased (Kang et al., 2008; Nouri et al., 2010; Yang et al., 2011; Zhang et al., 2012). Studies of historical agricultural activities in the ancient oases of arid inland river basins are important for understanding past agricultural development and the processes and mechanisms of environmental evolution in arid zones. These studies could provide insights into the sustainable development of inland river basins and oases in arid regions. Furthermore, archaeological investigation of past agricultural activities can improve our understanding of modern societies as well.

Major changes have occurred in the arid oases environments. First, the original environments have completely changed in most of the oases due to many factors; particularly that oases desertification is severe and the landscapes of historical agricultural activities have vanished. There are nothing but numerous nebkhas and sand dunes in these oases. Second, agricultural activities in the oases were complex in different historical periods, but there are no direct observations of past farming practices during previous long-term periods. Only certain descriptive records could be found in historical documents for different historical periods. So, it is generally difficult to reconstruct the original agricultural landscapes of this historical period because of the above major changes over the past 2,000 years. Although it is impossible to observe previous farming practices directly, information that reflects human agricultural activities in this historical period can be obtained indirectly from the remaining ruins. In particular, the spatial distribution of archaeological remains provides evidence of the extent of past agricultural activities (Turner, 1974; Alizadeh et al., 2004; McAllister, 2008; Nelson et al., 2010), and archaeological remains can act as a direct record of the development of ancient agriculture on a regional scale (Yu et al., 2012). At present, although some ancient oases have undergone desertification, a large number of the archaeological remains were preserved by the extremely arid climate and the low precipitation and high evapotranspiration. These archaeological remains, which reflect historical farming practices, are important data sources for research on the spatial extent and area of ancient agricultural cultivation.

Historical literature and archaeological discoveries suggest that there were thriving communities in the ancient Juyan Oasis, which is downstream of the Heihe River Basin (Sommarstrom, 1956–1958; Ban, 1962; Fang, 1974; Li, 1983; Li, 1991; CCEC, 1998; Sohma et al., 2009). The Heihe is a major river in the arid region located along the Silk Road in northwestern China. Long-term agricultural development played an important role in several dynasties before the Ming Dynasty. The spatial extent of the ancient agricultural oasis and its arable land are direct evidences of how past human activities have changed the surrounding landscapes and environments. These metrics of cultivation practices can clearly characterize the historical agricultural activities of the study area. However, there is no specific record of the scale of cultivation in historical documents for this area, and only descriptive information on past agricultural activities is available. With a series of archaeological surveys and discoveries over the past 100 years, there have been descriptions of the extent and area of past agricultural cultivation based on historical documents. These documents include wooden tablets from the Han Dynasty (B.C. 202–A.D. 220), and paper manuscripts from the Western Xia (A.D. 1038–1227) and Yuan Dynasties (A.D. 1271–1368) that were excavated from the archaeological remains (Li, 1991; CCEC, 1998; Wu, 2002; Li, 2003). In addition, several studies have been conducted in recent years using the evidences of archaeological remains, field investigations, or image features in remotely sensed data (Zhu et al., 1983; Cheng, 2007; Kubota, 2010). However, because researchers have employed different methods and data in each study, their estimates of the spatial extent of the ancient agricultural oasis and the cultivated farmland area are conflicting. In this study, we investigated the extent of the agricultural oasis and the arable land area in the Juyan Oasis by combining archaeological data from the historical period of interest with remote sensing images and field surveys. The principal objective of this research was to provide more reliable and accurate estimates of historical cultivation in order to establish a better understanding of ancient agricultural activities.

2 Geographical setting

The Heihe River Basin is located between 97°E and 102°E and 37°N and 42°N within the arid inland region of northwestern China (Fig. 1). The river originates in the Qilian Mountains in the northern part of the Qinghai-Tibetan Plateau, flows across the Zhangye Basin of Gansu Province, and enters the Ejin Banner of Inner Mongolia. Downstream the Heihe River is divided into two deltas that do not overlap: the modern Ejin Oasis, and the ancient Juyan Oasis (Fig. 1). The Ejin Oasis is the terminal oasis of the modern river, while the Juyan Oasis was that of the ancient river. The latter oasis is the study area of this research. It is located southeast of the modern Ejin Oasis and northwest of the Badain Jaran Desert. In the historical period studied, the Juyan Oasis's lush vegetation and ample water supported thriving agriculture. Today, however, this area is a desert, with numerous nebkhas and sand dunes (Wang et al., 2008, 2010; Liu et al., 2010b). It is a typical oasis of the downstream reaches of the inland river basins of the arid region. Downstream of the Heihe River is an extremely arid region with a mean annual precipitation of 35 mm and a potential evapotranspiration of 3,755 mm (1961–2011).

3 Materials and methods

3.1 Data sources

The data used in this study were derived from previously reported archaeological documents and discoveries, remote sensing imagery, and field surveys (Table 1).

The archaeological materials include most of the

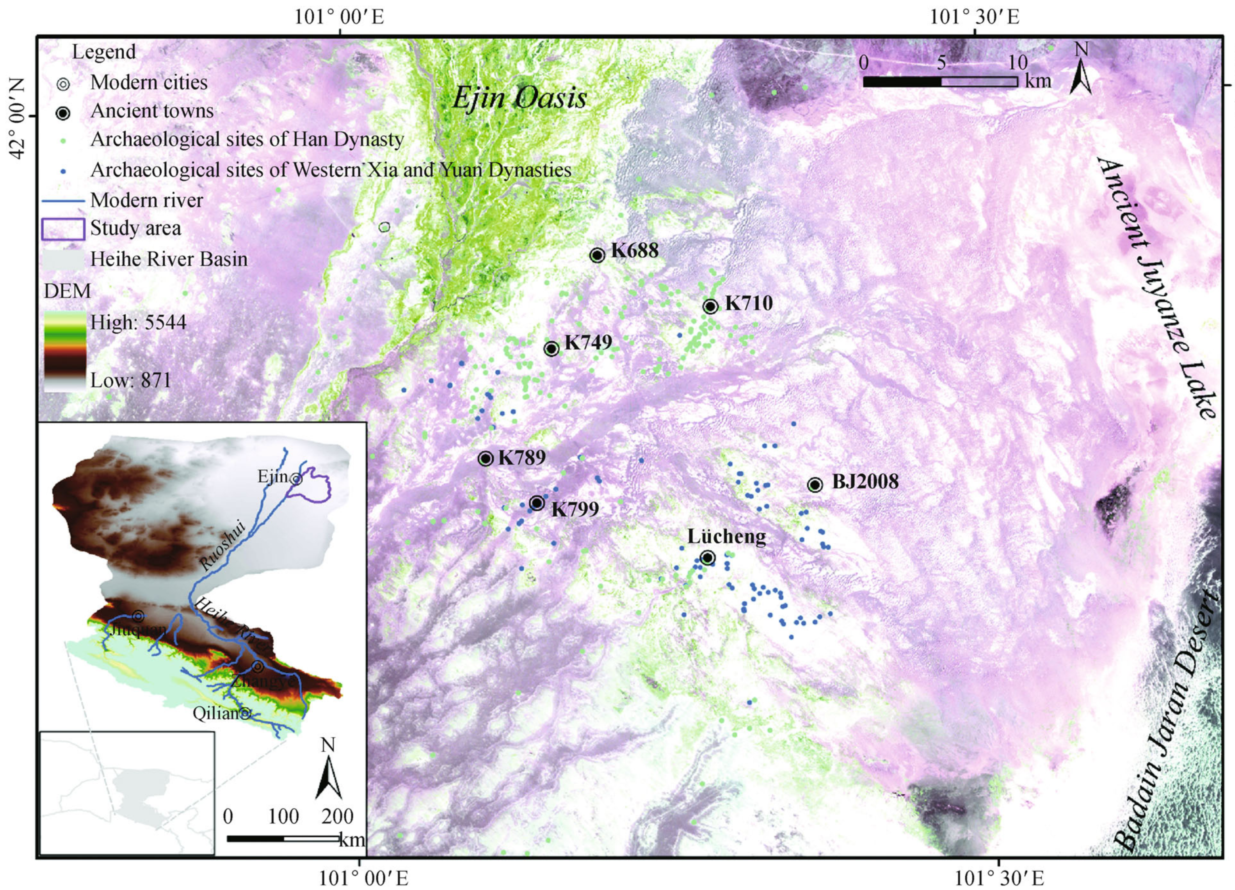

Fig. 1 Map of the Heihe River Basin in northwestern China. The purple polygon shows the study area, which is located downstream of the Heihe River and in the northwestern part of the Badain Jaran Desert.

relevant reports and excavations from the 1900s to the 2000s in the Juyan region. This information includes detailed reports from explorations in central Asia, Kan-su (Gansu), and eastern Iran (Stein, 1928); observations of the Sino-Swedish Expedition in northwestern China in the 1930s (Sommarstrom, 1956–1958); archaeological reports from surveys of the Han Dynasty in the downstream region of the Ejin River in the 1970s (Yue, 1984); archaeological documents from the Han Dynasty excavations in the Juyan region in the 1990s (Luo, 2003); details of the previously unreported wall-surrounded ruins that were discovered in the Juyan Oasis in 2008 (Sohma et al., 2009); and information from the Cultural Relics Atlas of China (Branch of Inner Mongolia Autonomous Region) (SBCR, 2003).

Remote sensing data include CORONA images with four scenes from 1969, Geoeye images with four scenes from 2010, and Landsat ETM + images with one scene from 2002. The spatial resolution of the CORONA images is approximately 3.0 m, while those of the Geoeye and ETM + images are approximately 0.5 m and 15 m, respectively. Taken together, the remotely sensed data provides complete coverage of the study area.

3.2 Field surveys

Two field surveys were conducted in August 2010 and May 2012. Ground surface artifacts, farmlands, agricultural irrigation canals, important sites, and paleo-channels were surveyed, and their geometries and locations were measured. These field surveys were conducted to identify the characteristics of ancient farmlands and to ground-truth the remotely sensed data. In addition, the investigation and collection of ground surface artifacts from past human activities was another objective during the field work. The ground surface artifacts included bricks and tiles, mills and rollers, porcelains and earthen wares, and metal objects.

3.3 Methodology

Ancient farmlands were distributed between the numerous nebkhas and sand dunes. Information about ancient farmland is generally connotative and is therefore not easily discerned from a single source. This research used data from multiple sources to analyze and determine the spatial extent of an ancient agricultural oasis. Remotely sensed data were used to identify the historical agricultural irrigation canals and to extract the spatial extent of ancient

Table 1 Different types of archaeological remains used in this study

Different types of data	Archaeological remains				
	Archaeological sites	Ground surface artifacts	Ancient cultivation ruins	Sample canal points	Agricultural irrigation canals
Total number	418	190	40	115	—
Obtained sources	Previously archaeological reports, remotely sensed imagery	Field inspections	Remotely sensed imagery	Field inspections	Remotely sensed imagery
Remarks	Including ancient towns, fort ruins, beacon towers, housing sites, pagodas, temples, and tombs	Including fragments of bricks and tiles, mills and rollers, porcelains and earthen wares, and metal objects	Including Daitian cultivation ruins, and Qutian cultivation ruins	Positioned by GPS	Total cumulative length of the main and sub canals is more than 390 km

agriculture. Previously reported archaeological documents and discoveries were used to map the spatial distribution of archaeological sites. Field surveys were used to obtain the spatial distribution of ground surface artifacts and to validate the locations of the agricultural irrigation canals that had been identified in remote sensing images. Artifacts can be seen as one source of strong evidence because of less post-depositional disturbance in the Juyan Oasis, according to the history of human activities that was introduced before. Previous studies have found that using remote sensing data and archaeological remains is a useful approach to studying human agricultural activities (Turner, 1974; Alizadeh et al., 2004; McAllister, 2008; Xie et al., 2009; Nelson et al., 2010; Qin et al., 2012; Yu et al., 2012).

As is shown in Table 1, all of the archaeological remains in the study area can be divided into several categories according to their different functions and sources. The majority of the 418 archaeological sites used for this analysis were obtained from previous archaeological reports, although 70 were newly identified using remote sensing. All of the ground surface artifacts and sample canal points were inspected and identified in the field surveys. 190 locations of ground surface artifacts and 115 positions of sample canal points were collected using GPS. Ground characteristics of the ancient farmlands were also collected from field surveys. More than 390 km of irrigation canals (total cumulative length of the main and sub canals) provided another important dataset for this research. The irrigation canals were observed via remote sensing imagery and carefully validated with sample canal points from our previous work. Forty additional locations of ancient cultivation ruins were distinguished from remote sensing images. The information about the ancient cultivation ruins was drawn from the testimonies of people who, developed agricultural production with advanced cultivation methods (e.g., Daitian cultivation, Qutian cultivation), as described in historical documents.

The approximate extent of the ancient agricultural oasis in the study area was first interpreted through the image features and field characteristics of the imagery. The extent of cultivation was further evaluated and visually digitized based on the spatial distribution of archaeological remains in the area. Furthermore, the results from this research were compared with those of previous studies (Zhu et al., 1983; Cheng, 2007; Kubota, 2010). The portion of the Gobi Desert that overlapped the boundaries of this oasis was excluded from the delineation of the cultivated farmland because crops were difficult to maintain in these areas.

3.4 Data processing and analysis

Because different data sources were used in the current research, it was necessary to preprocess the selected materials. Images and information on the historical sites described in archaeological reports were saved using information finding, graph scanning, graph splicing, geometric correction, and digitization processes. The locations of archaeological sites and past cultivation ruins extracted from remotely sensed images were geometrically corrected and digitized, and the ground surface artifacts and sample canal points located during field surveys were transformed into the same storage formats. All datasets were saved as shapefiles for use in a geographic information system. Related graphs from archaeological reports were scanned with a color scanner. The ground control points (GCPs) collected during the field surveys included important sites and obvious features (e.g., intersections of rivers or canals) that were used for the geometric correction of remote sensing data and related graphs. Images were mosaicked and graphs were spliced using image processing software. Standard deviations and histogram equalizations were conducted for all of the images to highlight important image features. Finally, the locations of all archaeological sites, ground surface artifacts, and sample canal points were digitized and transformed as point datasets. All preprocessing was conducted using a color scanner, Photoshop, ENVI, ERDAS, and ArcGIS.

Then, by comparing the image features from remotely sensed data with in-situ observations, we established standards for interpretation and extracted the ancient agricultural oasis. Its spatial extent was ultimately determined according to the information from image features and archaeological remains (e.g., archaeological sites, ground surface artifacts, cultivation ruins, and irrigation canals). The accuracy of the image interpretation of ancient agricultural irrigation canals was validated using the sample canal points obtained during field surveys. The spatial extent of historical agricultural activities as proposed in this study was carefully compared with estimates from previous works.

4 Results

4.1 Evidence of the ancient agricultural oasis

Both nomadic and agricultural activities took place in the ancient Juyan Oasis during different historical periods. The most important difference between the nomadic and agricultural activities is whether there are settlements. Permanent buildings for long-term settlement, household artifacts of daily life, and irrigation canals for developing agricultural production can serve as criteria for distinguishing agricultural from nomadic oases in arid regions. The nomadic activities could also leave behind certain ruins, but the quantity of nomadic remains, particularly the permanent buildings and irrigation canals are very few. The construction styles and materials of nomadic settlements should be easily obtained and built (e.g., tent with cloth or stone) in order to support the convenient movement of these buildings for nomadic activities, which are quite different from permanent buildings with complex and hard construction styles for long-term settlements. A most important issue is that permanent buildings could cost much time and labor to build, which is an inconvenience for those with nomadic life styles. All of the archaeological sites discovered in the oasis and used in this research belong to the sedentary settlements. Their construction styles were inspected during the fieldwork. Furthermore, sedentary administration offices that have been established and developed with long periods during different dynasties suggested many sedentary settlements should have existed and developed around them. According to historical documents, the construction styles, the quantity and spatial distribution of archaeological sites and irrigation canals, and some agricultural instruments, agricultural production was the dominant activity in the study area, and most of the remains pertain to historical agricultural activities. Different types of archaeological sites (e.g., cities, forts, beacon towers, houses, temples, pagodas, tombs, and irrigation canals) and ground surface artifacts (e.g., fragments of brick, tile, iron, porcelain, earthenware, stone mills, and stone rollers) were distributed throughout the ancient agricultural region (Fig. 2). Most of the archaeological sites (more than 300) belong to ancient town sites, housing sites, pagodas, and temples, which were used to support human settlement and daily activities. These archaeological sites can be seen as direct and qualitative evidence that can be used to assess historical agricultural activities. A large number of archaeological sites and ground surface artifacts related to past agricultural activities were obtained and seemed to have been employed in ancient agricultural activities.

Furthermore, evidence of the ancient cultivation was captured in remotely sensed images based on spectral features, which manifested the sand erosion and wind erosion. The primary interpretations of ancient cultivation from remotely sensed images could be classified into certain categories, i.e., adamant white land, ruins of ancient cultivation methods, eroded-trips land and uneven land, and land enclosed with extensive nebkhas or sand dunes, which were caused by severe wind and sand erosion and the extremely arid climate in this region. Ruins of the ancient cultivation methods (e.g., Daitian cultivation, Qutian cultivation) are clear indicators of past agricultural activities (Zhong et al., 2011). Daitian and Qutian are the two cultivation methods of the advanced agricultural techniques that were introduced into the Juyan Oasis to improve the agricultural development in the historical period of interest, improving the efficiency and increasing the yield of agricultural production. Daitian is an ancient farming method that was defined as: crop on the same land and change the field ribbing every year, which was created by a person named Zhaoguo in the Western Han Dynasty. Qutian is another ancient farming method that was defined as: divide land into several sub areas, and then conduct cultivating and sowing, concentrated fertilization, and irrigation for sub-lands one by one. Additionally, there were many archaeological remains distributed around the farmlands, which aided the interpretation of the image features of the ancient agricultural oasis. The ultimate interpretation standards of ancient farmlands in remote sensing images were determined by combining image features primarily distinguished from remotely sensed data with the spatial distributions of different archaeological remains. Finally, the locations with abundant archaeological remains that overlapped with the agricultural areas, as determined from remote sensing, confirmed the image interpretation (Fig. 3). In summary, the features captured in remote sensing images can act as another important data source for distinguishing the spatial extent of the ancient agricultural oasis.

4.2 Spatial distribution of the ancient agricultural oasis

The extent of agriculture in the Juyan Oasis was determined and mapped according to the spatial distribution of sufficient archaeological sites, ground surface artifacts, cultivation ruins, and agricultural irrigation canals, as well as image features from remotely sensed data (Fig. 4). Historical agricultural activities were distributed throughout this oasis; large pieces of farmlands were cultivated on both sides, which were divided into

Fig. 2 Examples of different types of archaeological remains found in the Juyan Oasis.

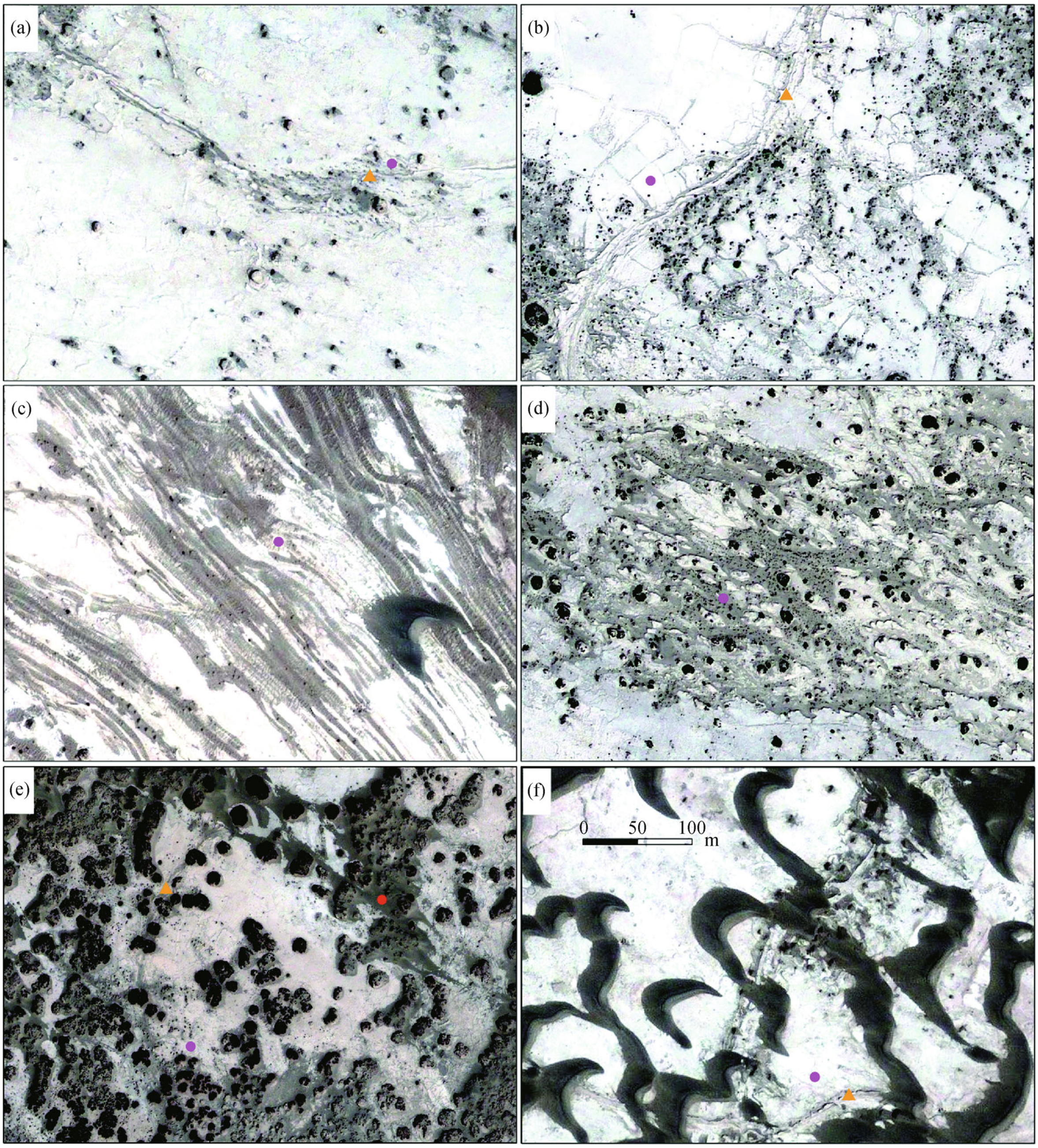

Fig. 3 Features of ancient cultivation as captured in remotely sensed imagery and confirmed by fieldwork. Labels represent the archaeological remains with different types (yellow triangles, pink dots, and red dots represent sample canal points, ground surface artifacts, and archaeological sites, respectively). Further, (a) adamant white land, (b) ancient cultivation ruins, (c) land in severely wind-eroded strips, (d) uneven land with severe wind erosion, (e) land enclosed by extensive nebkhas, and (f) land enclosed by extensive sand dunes.

northern and southern regions by the paleo-channel. Each ancient town site in the oasis contained many scattered archaeological sites and ground surface artifacts, which were direct evidences of extensive cultivation within the town. Archaeological discoveries suggest that the most prosperous period for the communities within the Juyan Oasis was during the Han Dynasty (B.C. 202–A.D. 220), which was a time of peak agricultural activity in the study area. Historical literature from *Hanshu* and *Shiji* recorded many strategies being established and implemented in the Juyan region during the Han Dynasty, particularly in the reign of *EmperorWu* (B.C. 156–B.C. 87). These included the establishment of military and civil administration, encouragement of immigration, introduction of advanced agricultural instruments and techniques, development of water conservation facilities and irrigated agriculture, and construction of fortresses (Ban, 1962; Zhu et al., 1983; CCEC, 1998; Li, 2003).

In addition, irrigation canals are another direct evidence for ancient agricultural activities. The spatial distribution of ancient irrigation canals was consistent with the estimated range of the ancient agricultural oasis (Fig. 4). In the southern part of the oasis, the extensive distribution of ancient irrigation canals suggests that these regions were important sites of historical cultivation. However, irrigation canals were sparsely distributed in the northern region, particularly in the eastern and northern regions of ancient town sites K710 and K688. The difference in the distribution of ancient irrigation canals between the northern and southern regions of the oasis could be related to the age and intensity of usage, and to the current conditions of the remaining irrigation canals.

4.3 Estimation of arable land

The spatial distribution of the ancient agricultural oasis is indicative of the amount of farmland on which historical agricultural activities were developed. However, the actual area of arable land was likely less than the estimated extent of the agricultural oasis. In calculations of the extent of the ancient agricultural oasis, the areas of both arable and non-arable lands, as well as villages, buildings, irrigation canals, roads, forests, and grasslands, were included. For estimates of the arable land area in the study region, these non-arable features should be excluded. Because it is impossible to observe the original land conditions and land use patterns that were prevalent nearly 2,000 years ago due to landscape changes and oasis desertification, the arable land coefficient can be used to calculate this estimate, as has been proposed and employed in studies of modern land use change (Shi et al., 1993). The arable land coefficient for the ancient agricultural region in the Juyan Oasis was estimated by assuming that modern tracts of non-arable land in the arid irrigated agricultural regions of inland China were similar to those of the historical period in this oasis.

The total proportion of construction land for irrigation canals, buildings and roads in the ancient Juyan Oasis might be roughly equivalent to that of modern agricultural regions when only agricultural activities are taken into account. However, the proportions of forest and grassland in the study area were likely larger during historical periods of interest compared to modern times. Evidences showed that there was a large area of forest in the ancient Juyan Oasis when ample water resources flowed into the oasis (Zhu et al., 1983; Wang et al., 2008). Similarly, shrubs and grasses likely thrived in the ancient oasis, and archaeological surveys discovered that a large volume of shrubs and grasses were used to construct human structures and for fire warnings in fire beacons (Zhu et al., 1983). In addition, historical records inscribed on wooden tablets of the Han Dynasty indicate that soldiers were punished when they did not locate enemies in the surrounding vegetation (Zhu et al., 1983), implying that vegetation was abundant in the area during the Han Dynasty (B.C. 202–A.D. 220). According to the results of previous studies conducted in multiple irrigation districts in Xinjiang and the mid and downstream reaches of the Heihe River Basin, the average non-arable land coefficient for irrigated agriculture in inland arid regions of China was estimated at 15%–25% (Yu et al., 2009; Hu, 2012). In view of the abovementioned discussion and analysis, it is likely that forests and grasslands covered a larger proportion of the ancient Juyan Oasis, and the proportion of non-arable land in the study area is at least two times the amount of the proportion in the modern irrigated agricultural oasis. The non-arable land coefficient of the study area was roughly conservatively estimated at a minimum of 30%–50% for an estimated area of arable land of $(3.39–4.75) \times 10^4$ ha.

5 Discussion

5.1 Reliability of the extent and area of ancient farmland

Archaeological remains are the most obvious evidence of the ancient agricultural oasis in the study area. In particular, hundreds of buildings that were documented in archaeological reports and the plentiful ground surface artifacts mapped during fieldwork reflected the spatial distribution of past agricultural activities. Also, the remotely sensed spatial distributions of the irrigation canals are the exact footprint of the ancient agricultural boundary. In addition, further information about the historical agricultural remains could be obtained from remote sensing images and the aerial observation of desertification areas. The spatial distribution of the ancient agricultural oasis as determined by the multi-source data in this paper is reasonable and reliable. Detailed discussion and comparison will be conducted in Section 5.2.

Additionally, a comparison of the proportions of arable land to non-arable land factors distributed in irrigated agricultural districts was made between the study area in the historical period and the inland arid regions of China. The farmland area in the oasis was estimated using the arable land coefficient, and the area is approximately 3.4×10^4 ha. However, the ancient farmland area of the oasis was 2.8×10^4 ha according to the per capita cropland area of the middle stream of the Heihe River, and the population of the study area in the Han Dynasty (Xie et al., 2013). This value is smaller than the estimate in this paper, potentially for two reasons. First, as an important frontier position to defend against the Huns' invasion, this region had been developed to be the largest agricultural district in the Hexi Corridor during the Han Dynasty according to the records of wooden tablets (Yang, 2006). Additionally, the per capita cropland area in the Juyan Oasis was larger than that in the middle stream of the Heihe River. Second, the arable land proportion might be smaller than our estimate because of flourishing vegetation due to the abundant river

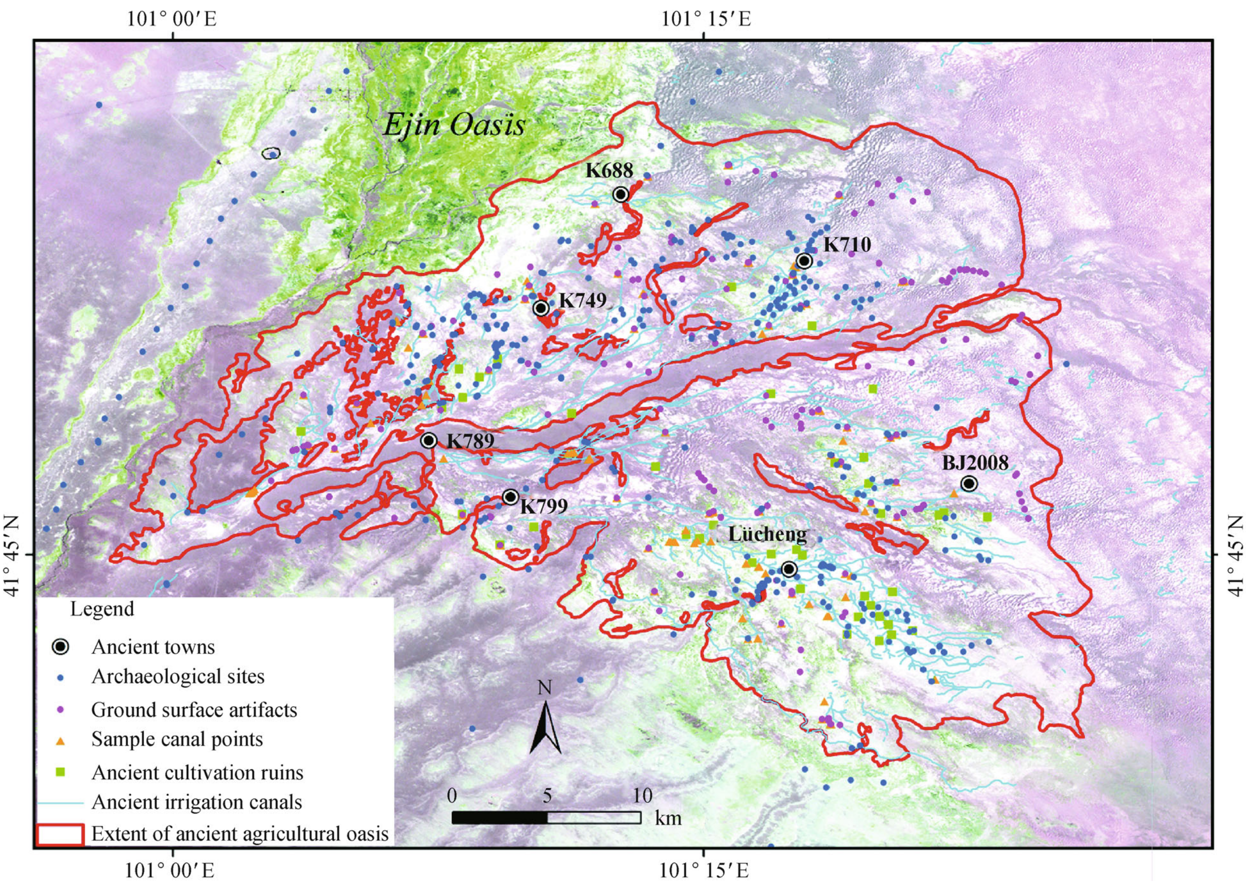

Fig. 4 Spatial distribution of archaeological remains and estimated extent of the ancient agricultural oasis in the Juyan Oasis.

water flowing into the oasis during this historical period. Stronger and more logical evidence is needed to support and conduct the estimation of arable land area in a future study.

5.2 Comparison of results with previous studies

It is impossible to validate these estimates directly because there is no optimal approach for obtaining the effective cultivation area that occurred 2,000 years ago. The results from previous studies regarding ancient agricultural activities in the Juyan Oasis can be used for comparison (Zhu et al., 1983; Cheng, 2007; Kubota, 2010).

As illustrated in Fig. 5, the spatial extent of the ancient agricultural oasis in the study area reported in Zhu et al. (1983) and Cheng (2007) was smaller than that estimated in this paper. The main geographical differences between the studies include those surroundings of the Lücheng, BJ2008, K710, and K688 sites. A large number of archaeological sites, ground surface artifacts, and irrigation canals were distributed in these areas, which highly suggests that these regions were important farmlands during various historical periods. In addition, sites K710 and K688 were the Juyan County and the Juyan Commandery Office, respectively, during the Han Dynasty, (Hedin and Bergman, 1944; Yue, 1984; Xue, 1991; Luo, 2003). There were extensive farmland activities in the surroundings of these two important town sites. Comparing with the above two results, the larger estimate of this study is more reasonable. However, the extent of the ancient agricultural oasis estimated in Kubota (2010) through remote sensing images was larger than that estimated in this paper. The main dispute region is the large areas between the eastern portions of the sites BJ2008 and K710 and the ancient Juyanze Lake. According to our results, this region was not likely to have an ancient farmland for two reasons. First, we did not find any archaeological remains in this region during a series of field surveys. Second, previous research has suggested that some areas of this region were impacted by severe desertification during the Han Dynasty, making these areas unsuitable for cultivation (Zhu et al., 1983; Li, 2003). So we conclude that the extent of the ancient agricultural oasis is much smaller than that result from Kubota (2010). In summary, compared with previously reported results, the estimate of the spatial extent of the ancient agricultural oasis in this study demonstrates highly improved reliability and accuracy. This estimate was based on high-resolution remote sensing with the aid of a number of archaeological remains. The evidences are also more plentiful than those

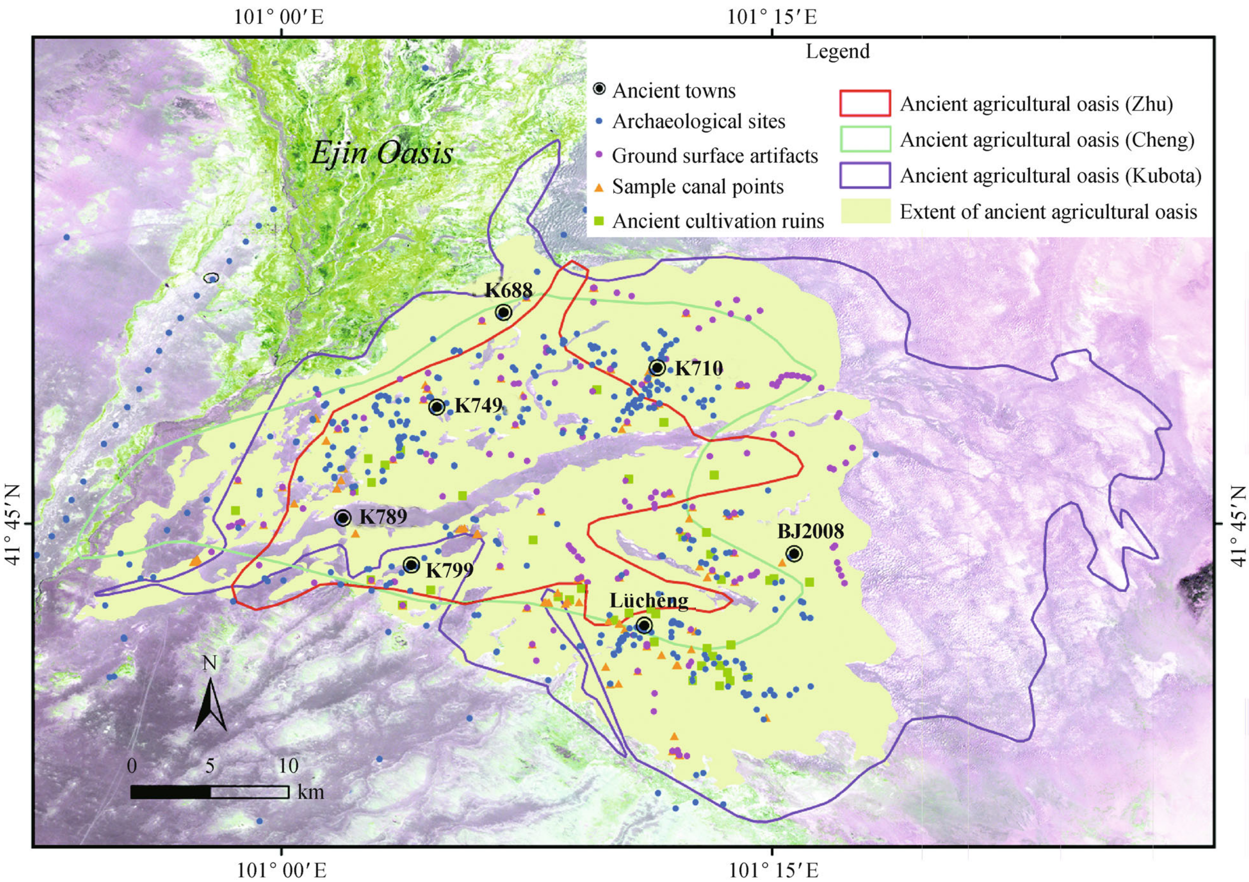

Fig. 5 Estimates for the extent of the ancient agricultural oasis in the Juyan Oasis calculated in this study compared to those calculated in Zhu et al. (1983), Cheng (2007), and Kubota (2010).

of previous studies. In particular, cultivated farmlands were likely developed in the areas surrounding the ancient towns (e.g., Lücheng, BJ2008, K710, and K688) because of their historical importance, which is further supported by the ample archaeological remains found there.

5.3 Implication for water resource management

Certain experiences and lessons of past agricultural activities are potentially valuable resources for the sustainable development of the Heihe River Basin, where efficient water management is essential for solving problems related to rapid population growth and the extensive expansion of farmland in this drainage region. The area of the agricultural oasis in the ancient Juyan Oasis is larger than that in the modern Ejin Oasis, which has an area of approximately 2.08×10^4 ha (Hu, 2012). Natural and human-associated factors caused the difference. Particularly, human activities used more water in the up- and middle stream areas of the river basin after the Ming and Qing Dynasties, causing extensive decrease of river water flowing downstream. Water resources are the key to maintaining the structure of oasis landscapes in arid regions and to implementing the sustainable development of oasis agriculture (Wang and Cheng, 1999; Zhang et al., 2012). When human activities were weak in the up- and midstream areas, sufficient water resources should flow into the downstream area to support agricultural production and development in the historical period studied. In fact, some studies also found that there was sufficient river water entering the ancient oasis before the *Hongwu's Reign* of the Ming Dynasty (A.D. 1368–1644) due to wars and the disappearance of surface water (Zhu et al., 1983; Xiao et al., 2005; Wang et al., 2008; Sakai et al., 2012). And records describing a suitable environment with lush vegetation and ample water resources were also found in the wooden tablets of the Han Dynasty and the manuscripts of the Yuan Dynasty that were obtained from archaeological excavations (Zhu et al., 1983; Li, 1991).

To optimize the utilization of limited water resources, ancient agricultural practices (i.e., cultivation methods, irrigation systems, and water usage for human and ecological needs) could be used to guide the sustainable development of arid regions. Particularly, it is important to resolve conflicts in water use needs between up-, middle, and downstream regions, as well as between agriculture and ecosystem. Population and farmland are the two key factors that affect the needs of water resources among the up-, middle, and downstream of the Heihe River Basin. Ancient people could solve water problems easily in arid inland river basins. Because of smaller populations and less farmland, they were less dependent on river water in farming practices and daily needs. According to Cheng (2007), the population and farmland area were strongly overburdened in the modern Heihe River Basin, which broke the natural balance and exceeded its carrying capacity. Controlling population and reducing cultivated farmland may be efficient ways to address the water resource conflicts between the different regions in the river basin. Although modern water conservancy facilities are more advanced than those of the historical period studied, other techniques (e.g., water-saving irrigation methods, canal lining) should be introduced in order to improve the utilization efficiency of the limited water resources. Additionally, many reservoirs and dams were built in the up- and middle stream of the Heihe River during the past 100 years (Wang and Cheng, 1999). Much river water is kept in the reservoirs, which causes the drying up of some branches (e.g., Beida River). The decrease or closing up of some reservoirs in the up- and middle stream could also be very useful for protecting the deteriorated environments of the downstream region. The water distribution of the historical period of interest in the study area could also guide the sustainable development of the modern Ejin Oasis, where water availability is extremely limited.

5.4 Uncertainties and future study

The spatial distribution of the archaeological remains of human activities directly affects the estimation accuracy of the spatial extent of the ancient agricultural oasis. Although ample archaeological sites and ground surface artifacts were collected from archaeological reports, remote sensing images, and field surveys, archaeological remains in certain sub-regions are rare, particularly to the north and east of site K710, to the east of site BJ2008, and in the zone between the Juyan and Ejin oases. Due to severe desertification and re-cultivate in certain sub-regions, it is difficult to conduct field surveys. More evidences should be collected in these areas in future investigations. In addition, although it was possible to approximate the proportions of forest and grassland within the agricultural region based on historical records, archaeological discoveries, and field surveys, it was impossible to estimate the exact extent of these features because of desertification; only small numbers of forest and vegetation ruins remain today. Stronger evidence and a more logical estimation method (e.g., forecast model) should be developed to support and validate this estimation in a future study.

Furthermore, historical documents and archaeological discoveries suggest that agricultural activities were developed throughout different dynasties, but the absolute dates and the exact dynasties during which these areas were cultivated were not proposed because of the complex cultivation during the historical period of interest and the inadequate evidence for each dynasty in this study. It is difficult to determine the chronology of different periods for the past agricultural activities using only available data. Given the spatial distribution of archaeological sites (Fig. 1) and the ages of their foundations recorded in the previously surveyed reports (Sommarstrom, 1956–1958; Yue, 1984; Li, 1991; Luo, 2003; Sohma et al., 2009), most historical agricultural activities were believed to have occurred during the Han Dynasty (B.C. 202–A.D. 220). In addition, it is also believed that most of the southern region and certain parts of the northern region of the oasis were once again cultivated during the Western Xia and Yuan Dynasties (A.D. 1038–1368). Several studies have also indicated that the southern region of the oasis was cultivated at least during the Western Xia and Yuan Dynasties based on the preliminary results of ^{14}C dating for certain wheat seeds and nebkha leaves in the oasis (Qi et al., 2007; Lan et al., 2009; Wang et al., 2010). The ages of wheat seeds are approximately A.D. 1160, and those of nebkha leaves are A.D. 1475–1580. Although there have been a few dating works conducted in this region, the sampling points for the dating research are very few in such a large and complex area. In the future, adequate chronological evidence (e.g., archaeological excavations, various dating methods, and more sample dating points) should be collected to better estimate the chronological control of agricultural activities that were developed in this oasis during the different historical periods.

6 Conclusions

In this study, archaeological and remote sensing imagery datasets were combined in order to study the historical agricultural activities in the ancient Juyan Oasis. The evidences described in this study provided more reliable and direct proof that agricultural activities were well developed in the ancient Juyan Oasis. The results were more accurate and reliable compared to previous works. A new finding was that cultivated farmlands were most likely developed in the areas surrounding the ancient towns of the Lücheng and BJ2008 sites. This was not reported in previous work. Despite some limitations, a combination of archaeological remains of past human activities with remote sensing could offer an effective approach for assessing the spatial extent of historical agricultural activities. This work provides a rare glimpse of the extent of cultivation and arable land area that offers not only intuitive evidence of past agricultural activities, but is also potentially valuable for determining the best way to distribute limited water resources and promote sustainable development in a region.

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