Heliyon 9 (2023) e22690

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

The evolution of artificial oasis over two millennia in Hexi corridor, China

Xia Tang [a,b,*], Linshan Yang [a,b], Hao Qu [a], Qi Feng [a,b]

[a] Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[b] Key Laboratory of Ecohydrology of Inland River Basin, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Science, Lanzhou 730000 China

A R T I C L E I N F O

Keywords:
Artificial oases development
Driving factors
Structural equaion model
Human-land relationship
The Hexi corridor

A B S T R A C T

Artificial oasis is an important geographical unit that is formed by the combination of natural disturbances and human interventions in a fragile ecosystem of arid regions. Therefore, there are important theoretical and practical significance to estimate long term artificial oasis changes and its driving mechanism. We took Hexi Corridor in northwest of China as a case study, based on multi-types of data included documentary reconstruction records, historical archives data and published articles to quantitative analyze the relationship between artificial oasis evolution and a set of natural and human factors over the past two millennia (0-1990 AD). Results showed that artificial oases had a tortuous evolutionary history, experienced three periods of rapid development in the Hexi Corridor. The structural equation model revealed that two human related factors (population density and grain yield) have a significantly greater influence on artificial oasis development than natural variables (temperature). According to current conditions, paradigm shift in human behavior are the prerequisite for oasis evolution and its transition. Furthermore, assessment the scale of artificial oasis based on the human-land relationship is a future direction for research and practice, for allocating water and soil resources rationally, improving the quality of oasis, and controlling the scale of oasis.

1. Introduction

Transitioning from hunter-gatherers to primitive agriculture, human-land relationship has taken about ten thousand years, but the man-made environments were gradually developed over the past two millennia [1]. The artificial oases are the main places for human activities in arid regions, thereby providing precious fertile soil, living space and ecological services for the local people at present as well as in ancient times [2,3]. In China, oasis comprise less than 5 % of the total area of arid and semi-arid regions, however, it holds more than 90 % of the population and 95 % of social wealth, respectively [4–6]. Historically, the abnormality of arid climate and irrationality of human activities could easily lead to oasis land degradation and expansion of desertification in arid regions [7,8]. Human wellbeing in these areas may be seriously compromised if we exceed a critical threshold that oasis ecosystem into irreversible degradation in future [9]. Therefore, studying the artificial oasis evolution under driving forces can help to understand the feedback mechanism between the human-land relationship and its critical point to ensure sustainable development of oasis.

Systematically revealing the oasis evolution process and its driving forces in long-term is an important prerequisite to future oasis

* Corresponding author. Northwest Institute of Eco-Environment and Resources, Chinese Academy of Science, Lanzhou, 730000, China.
E-mail address: tangxia@llas.ac.cn (X. Tang).

https://doi.org/10.1016/j.heliyon.2023.e22690
Received 16 August 2023; Received in revised form 15 November 2023; Accepted 16 November 2023
Available online 22 November 2023

management [10,11]. However, most studies focus on oasis evolution trajectory from century to millennial scales, using only qualitative methods [5,12–14], which is difficult to reveal the stage characteristics of artificial oasis evolution. With the rapid development of remote sensing technology and availability of instrumental data on the climate and hydrology in the past several decades, more studies for recent periods were carried out with the quantitative approach which focus on the decadal-scale relationships between oasis system and driving factors [15–17]. In many driving force analysis cases, rapid expansion of cultivated oasis is related to economic indicators, such as farming policies, population growth, agricultural technologies, and animal husbandry development [18–21]. Of particular interest, some studies quantitatively investigated the natural and human drivers for the oasis development by using remote sensing data since 1950s [22–24]. However, quantitative studies on the artificial oasis evolution process and its driving forces over the last 2000 years have been few studied.

The Hexi Corridor is a string of oases along the northern edge of the Tibetan Plateau in the Northwest China of Gansu province and represents a typical arid and semiarid region. The Hexi Corridor as the famous transportation hub of Ancient Silk Road, which has been an important route for northern nomadic and southern agricultural cultures interchange over the past millennia, it has historically hosted both farming and nomadic civilizations by oasis ecosystems [25]. Competing for limited space and resources, a series of invasions and conflicts have created severe challenges for these societies, meanwhile, the alternate development of agriculture and husbandry leads to land use changes frequently. The prosperity and decline of civilizations has been bind up with the development of oasis in the Hexi Corridor [26–28]. As an ecological fragile region, the relationship between human, land and water remains a primary constraint for its socioeconomic development today in the region [29]. Analysis of understanding the dynamics and evolution of a complex oasis system underpins sustainable arid land management. Early studies focus on oases changes were mainly based on qualitative methods. The influence of economic, population, policy and climate change on oasis evolution were qualitative investigated through documentary records at several temporal scales of decades, centuries and thousands of years in the Hexi Corridor [30–32]. Studies in recent decades showed that the reconstruction of the cultivated oases and natural oases in historical period using the remote satellite images, maps, archaeological data, and historical documents based on 3S technology [33,34]. Studies on oasification processes have been reported from the reclamation perspective, desertification perspective and human activities perspective, but an important limitation in current reports is lack of analysis to quantify the driving factors of artificial oases system over long term historical periods [12,35–37].

This study attempts to investigate the evolutionary characteristic of artificial oasis in different stages and its relationship with human activities and natural disturbances in the Hexi Corridor last approximately two millennia (0-1990 AD). We applied the methods that integrate quantitative and qualitative approaches to reveal systemically how each driving factors affect the artificial oasis evolution. Multiple data sources including archaeological data, historical documents and reconstruction data were all used. The results will provide a historical case study for decision-makers who participated in sustainable oasis management practices in both the Hexi Corridor and similar arid areas worldwide.

2. Materials and methods

2.1. Study area and period

The Hexi Corridor is located in northwest of Gansu province, China, which distance from east to west is up to 1100 km, and 100–200 km from the south to the north, comprises a total area of approximately 276,000 km^2 (Fig. 1). The Hexi Corridor is the source of three inland water systems, Shule, Heihe and Shiyang Rivers, and many oases are shaped along these rivers, which has been harboring both nomadic and farming civilizations since the early history. The annual precipitation has obvious regional differences,

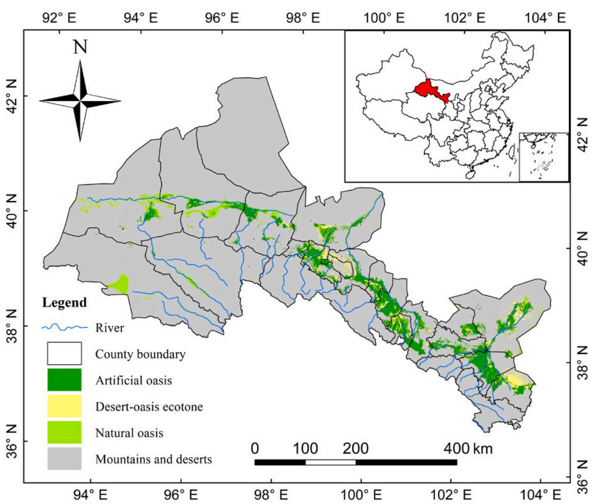

Fig. 1. Location of the Hexi corridor.

from 50 mm northwest in to 550 mm in southeast, while the annual evaporation in most areas is 2000–3000 mm [38]. Due to the scarce precipitation and strong evaporation, this region is a fragile ecosystems and susceptible to external disturbances resulting from changing natural and human stresses. The Hexi Corridor is one of the areas where the ruins of ancient cities are the richest in quantity, the most diverse in type, the most integrated in dynasties, and most complete in preservation. In the light of these ruins of ancient cities and their historical relics, we can restore the flourishing appearance of the ancient cultivated oases in those days, and can explain the artificial oasis expansion and evolution processes. The artificial oasis has been heavily expanded by environment changes, population growth, irrigation technologies, and socioeconomic development over the past 2000 years [27,39]. The study period ranges from 0 to 1990 AD, covering the Han Dynasty to the People's Republic of China. The regime change was more frequent in some time periods, such as the Southern and Northern Dynasties between the Wei-Jin Dynasty and Sui-Tang Dynasties, and it was difficult to collect data. So we reconstructed the evolutionary processes of oasis based on eight main periods by more adequate historical documents in Hexi Corridor (Table 1) [40].

2.2. Data

2.2.1. Artificial oasis areas data

In this study, an artificial oasis is developed from natural oasis, which area suitable for human occupation and agriculture by human management, such as cultivated land and residential area. The reconstruction historical artificial oasis areas were based on abundant land use information, which lead to limitations in developing a contiguous oasis areas data set over the past 2000 years. Therefore, the land use data of Hexi Corridor in the historical period has been extremely scarce. We reconstructed artificial oasis areas based on the assumptions about the reclamation of cultivated oases based on previous results [41–43]: due to people selected natural oases (with better water and soil conditions) rather than desert for reclamation in the historical periods, we can assume that the oasis area remains unchanged during the same research period. Xie et al. [33,44] developed the most comprehensive assessment of the areas of oases in the Heihe River basin during historical periods by multidisciplinary approach, based on remote sensing images, document literature, historical atlas and ancient sites information. The reconstruction method introduced by them has been adopted in many studies for other regions and is considered to be reliable [7,45]. We adopt Xie's results and extended it to Hexi Corridor, based on Xie's theory and the grid model established [44].

2.2.2. Construction of potential driving factors

With increasing desertification, river drying-up, the stability of oases decreased, and climate change, it is recognized that oasis systems are coupled human-land systems, which are influenced by both the human and natural drivers [46]. According to historical literature accessibility and data availability, the choices of the potential driving factors have imposed a certain degree of interventions on artificial oasis development in the long term [7]. In particular, the Hexi Corridor was controlled and influenced by multiple regimes during the historical period, how these changes influenced the intensity of human activities and thus the oasis evolution. Here, four natural indicators and eight human indicators were selected. Natural indicators including precipitation, temperature, flood events, and drought events, human indicators are migration, population density, conflicts, famines, wages, crop yield, agricultural policy, and water infrastructure. The selected variables and data sources are listed in Table 2.

Because the relevant data on various factors that were analyzed was discontinuous, it was impossible to obtain complete data from 0 to 1990 AD. Instead, we summarized the available data to provide the mean values for a total of 40 periods (each 50 years of length). Where no data were available for a 50-year period, we used interpolations between adjacent periods to impute the missing data. The selected data was standardized before analysis to eliminate the effects of dimension and orders of magnitudes.

2.2.2.1. Temperature (T) and precipitation (P).

Temperature (T) and precipitation (P) reconstructed in historical periods based on instrumental data in the most recent period and changes in paleoclimatic conditions. The reconstruction of a decadal temperature and precipitation have been used to integrating ring-width series from living trees and archaeological wood specimens for wood from the Qilian Mountains [63,48]. The instrumental temperature and precipitation data in the recent period (1955–1990 AD) were obtained from the China Meteorological Data Service Website (http://data.cma.cn/). We obtained T and P continuous records, which were high consistent with similar research in north-west China over the last 2000 years [64–66].

2.2.2.2. Drought (DT) and flood (FD) events.

We adopted drought and flood frequency data from records in historical documents, such

Table 1
Eight periods selected in the historical periods.

Periods	Selected time	Main production
Han Dynasty	206 BC-220 AD	Agriculture
Wei-Jin Era	220 AD-420 AD	Agriculture
Sui-Tang Dynasty	581 AD -907 AD	Agriculture
Yuan Dynasty	1271AD- 1368 AD	Animal husbandry
Ming Dynasty	1368 AD-1644 AD	Agriculture
Qing Dynasty	1644 AD-1912 AD	Agriculture
The Republic of China	1912 AD-1949 AD	Agriculture
The People's Republic of China	1949 AD-1990AD	Agriculture

Table 2
Selected factors reflecting natural and human dynamics in the Hexi Corridor during the study period.

	Name of variables	Value units	Data sources
Natural factors	Mean annual temperature (*T*)	°C	[8,47]
	Mean annual precipitation (*P*)	mm	[48]
	Number of floods per decade (*F*)	times/yr	[49,50,51]
	Number of droughts per decade (*D*)	times/yr	[49,50,51]
Human factors	Population density (*PD*)	per/km^2	[43]
	Migration (*M*)	No./50 yr	[52,53]
	Conflicts (*C*)	No./50 yr	[54,55]
	Famines (*FM*)	No./50 yr	[49,56,57]
	Wages (*W*)	10^3RMB	[58,59]
	Grain yield per unit area (*G*)	kg/ha	[60,61]
	Agricultural policy (*AP*)	0 = negative influence 1 = positive influence	[7,62]
	Water infrastructure (*WI*)	0 = negative influence 1 = positive influence	[24,62]

as "The Chorography of Hexi" [62] and "Encyclopedia of China's Meteorological Disasters; Gansu Volume" [67]. Furthermore, we investigated and verified by literature, including "the History of Disaster and Famine in Northwest China [49], "the China Meteorological Disaster Encyclopedia: Gansu Fascicule (718 BC-2000 AD)" and "The Atlas of Drought and Flood Distribution over Northwest China in the Past 500 Years" [50].

2.2.2.3. Population density (PD). Population density (***PD***) was regarded as most representation influence variables for agricultural production. Many crises, from crop failures to warfare, can cause drastic population decreases, such population density reductions also decrease the workforce, and so large areas of artificial oasis may also remain abandoned for long periods. Cheng et al. [43] provided relatively high reliability for long term population record, which has been widely accepted for social studies. The population density was calculated by population size (per) divided into the Hexi Corridor area (km^2).

2.2.2.4. Migration (M). The migration of population plays a dual role in the oasis development [68]. Migration might encourage many people to survive from the Central Plains pouring into the Hexi Corridor, however, long-range movements of people between large areas (regions or nations) during clashes and social disturbance. To identify migrations with significant impacts on socioeconomic or large-area artificial oasis evolution, we identified events in the literature [52,53] that described large movements of people with a clear purpose, e.g., to escape conflict/war, severe drought, flooding, plagues, or earthquakes. By examining population data in the literature, the population of migrants was obtained.

2.2.2.5. Conflicts (C). As a multi-ethnic region, in order to competition for oasis resources, the conflicts in Hexi Corridor are mainly dominated by the nomad invasion process and the domestic rebellions conflicts in historical periods. The military clashes might promote artificial oasis expansions to meet the demands of grain supply for the military. However, frequent wars might not be helpful to oases reclamation. Based on historical documents and local chronicles, such as Chinese Military History [54] and the multi-volume compendium *Tabulation of Wars in Ancient China* [55], we obtained data including conflicts between different ideologies, different ethnic groups, and different religions.

2.2.2.6. Famines (FM). Despite the lack of a widely accepted definition of famine, in the present study, it refers to a situation where an entire village had no food or when all family members or their animals faced a serious shortage of food that could eventually lead to increase the frequency of mortality. In the stages of a famine, people's may not be to inevitable the loss of land and livestock. Famines have been recorded in historical documents about the Hexi Corridor, and the famine events were described such as wasting, edema, starving people, countless people hungry, severely hungry, hungry people everywhere, deaths of hunger everywhere, the dead lying in disorder, or similar descriptions [49,56,57].

2.2.2.7. Wages (W). The locals lived mainly on agriculture. We analyzed changes in wages of the ordinary labor, which was possible to influence on the ability of households to mobilize the enthusiasm for grain production. To perform this analysis, we estimated any changes in a typical worker's ability to purchase food over time, which reflects the balance between the simultaneous changes in a worker's income and the grain prices. Therefore, accounts for the effects of inflation without actually requiring a calculation of inflation rates [58]. The research literature suggests that the wages of the most common workers (farmers, craftsmen, and laborers) reflected the wages of 90–95 % of the population [59]. So the wages represented the overall standard of living during a given period.

2.2.2.8. Grain yield (G). The grain yields were obtained from published literature, representing grain production or agricultural development level in the Hexi Corridor. The average *G* data included the region's main grain crops: corn (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum æstivum L.*), and proso millet (*Panicum miliaceum* L.) [60]. Grain production was recorded in Chinese units (jin/ha) was converted to international units (kg/ha) for the present analysis [61].

2.2.2.9. Agricultural policy (AP) and water infrastructure (WI). Agricultural management and its relevant irrigated technologies were the main components of the impacts on artificial oasis development in the Hexi Corridor [69]. Although it was difficult to identify the influences of management and technologies factors on oasis change, this study assumed agricultural policy and irrigation infrastructures as the two key human drivers. To explore the government policy of oasis land reclamation has played a role in different periods, the recorded policies or infrastructures with positive and negative, assigned with 1 and 0 respectively. We obtained a description of the evolution of these recorded in historic documents during the corresponding period (Table 3).

2.3. Statistical analyses

Structural equaion model (SEM) was considered to be a more effective method for establishing the correlation between multiple variables in the system, to give the strength of the relationship between each factor through the path coefficient [70], Based on the hypothesized mechanisms and data available, SEM model was constructed to quantify the multivariate causal network in which artificial oasis evolution, natural and human factors are involved. Model construction procedures involved the following two stages. Firstly, the models contain two composite variables that potentially represent collections of variables in terms of the natural change and human activity. We screened for a set of indicators of natural change and human activity effects on twelve driving factors. Pearson correlations were used to select the indicators that exhibited significant correlations with driving factors. The natural change factors include the *P*, *T*, *DT* and *FD*. Human activity variables included the *G*, *W*, *FM*, *C*, *M*, *PD*, *AP* and *WI*, which is an indicator of intense human disturbance on artificial oasis evolutions (Fig. 2). Secondly, SEMs were developed from the fully conceptual model using $\chi 2$ tests with maximum likelihood estimation. The insignificant paths ($P > 0.10$) were eliminated gradually until all links significantly contributed to the final model. The Pearson's correlation analysis was performed and visualized using the "cor" function and "corrplot" package, in R software. The SEM analysis was conducted using AMOS 20.0 software (IBM Corp., Armonk, USA).

3. Results

3.1. Analysis of changes in the area of artificial oasis

The artificial oasis areas showed significant fluctuations changes over two millennia. The artificial oasis decreased from 2939 km^2 to 1949 km^2, 1199 km^2, and 757 km^2, in the periods of the Han, Wei-Jin Era, Sui-Tang and Yuan dynasties, respectively. The area of artificial oasis started to increase to 1401 km^2 and 3200 km^2 during the Ming and Qing dynasties, but decreased to 2275 km^2 in the Republic of China period. With expanding artificial oases in arid regions since from 1949 AD, the area peaked at 13733 km^2 in 1990 AD (Fig. 3). Based on the artificial oasis changes, the evolutional processes of artificial oasis in the Hexi Corridor can be divided into three stages of rapid development: "start-up" (from the Han Dynasty to the Sui-Tang Dynasty), "recovery stage" (during the Ming and Qing Dynasties) and "booming development" (after the People's Republic of China).

Table 3
Influence directions of agricultural policy and water infrastructure on oasis development [7,62].

Periods	Agricultural policy (*AP*)	Influence direction[a]	Water infrastructure (*WI*)	Influence direction
Han Dynasty	Transition of nomadic herding into agriculture; immigration and cultivation of farmland were encouraged to supply food to the garrison	1	Qianjin channel construction (about 100 km)	1
Wei-Jin Era	Armed conflict happened; there was no new agricultural policy	0	No new infrastructure, as the region was in a state of upheaval	0
Sui-Tang Dynasty	Large-scale garrison reclamation supported by the presence of military units	1	Canals including the Yingke and Jiaguan canals were constructed	1
Yuan Dynasty	Returned to nomadic lifestyles	0	Damage to water facilities and irrigation systems due to long-term warfare	0
Ming Dynasty	Agricultural development along with defence; introduction of better seeds, cattle, and steel farm implements	1	Irrigated channels increased massively	1
Qing Dynasty	Tax according to the size of farmland; Manchu nobility forbidden from excessive land occupation; retired soldiers commanded to participate in agricultural production	1	Abandoned river channels reactivated, and irrigated channels increased massively	1
The Republic of China	The government attached great importance to the development of Northwest Territory of China	1	No marked changes in the irrigated channels and other water facilities	0
The People's Republic of China	The implementation of the 'Food Security Program' policy,'Reform and Opening' policy and family contract responsibility system; the construction of farmland irrigation enhanced	1	Reservoirs and water diversion projects, the length of the total water channels increased and the numbers of extraction wells drilled peaked	1

[a] Positive influences of agriculture policy or water infrastructure were assigned with 1, and negative influences were assigned with 0.

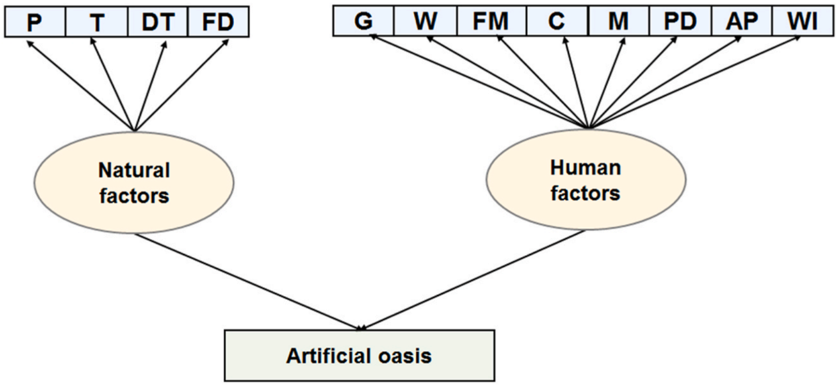

Fig. 2. Conceptual model of the effects of natural and human factors on artificial oasis evolutions. The arrows in the model indicate relationships to overall effects (e.g., natural and human factors) and not individual components of those variables (e.g., *P* and *G*).

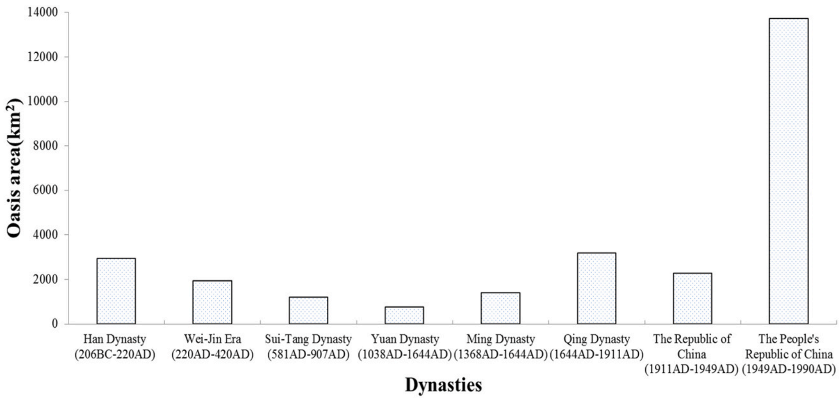

Fig. 3. Changes of artificial oasis areas in the Hexi corridor.

3.2. *Temporal change in the potential driving factors*

3.2.1. *Characteristics of natural factors*

T was around 2 °C from 0 to 1990 AD, with certain extent of variation (Fig. 4a). According to the reconstructed temperature data, *T* change was divided into four periods: from cold to warm conditions (380-600 AD), correspondingly to the Han, Wei-Jin Dynasties; the Medieval Warm Period (800-1100 AD), correspondingly to the Tang, Song Dynasties; the Little Ice Age (1550-1770 AD) during the Ming and Qing Dynasties; rapid warming stage after the Republic of China (1920–1990 AD). There was obviously annual variation in the average *P* over the last 2000 years, and the *P* had increase tendency (Fig. 4b). The occurrence of relatively high *P* was observed in the Sui-Tang Era to early Yuan Dynasty (580-1100 AD) and The People's Republic of China (1949–1990 AD). According to reconstructed records, the full time series showed that there were the most frequent occurrence droughts than floods in the Hexi Corridor [51]. The highest *FD* (Fig. 4c) and *DT* (Fig. 4d) frequencies recorded in the Qing Dynasty (1644-1911 AD), secondly by the Yuan and Ming Dynasties (1271-1368 AD).

3.2.2. *Characteristics of Human factors*

Humans as participants, organizers, and output consumers can adjust the oasis systems through production technology and activities. During the Han Dynasty (0-220 AD) the *PD* in the Hexi Corridor was about 1.16 per/km^2, but it decreased to about 0.74 per/km^2 in the Sui-Tang Dynasty (581-907 AD), then a slight growth in the Qing Dynasty (1644-1912 AD, Fig. 5a). In the Republic of China, the explosion of population in the Hexi Corridor increase to 6.6 per/km^2, and finally reached 20.5 per/km^2 in the period of New China (Fig. 5a). The migration, conflict and famine in different stages were determined through interpreting the historical data to reflect the trajectory of social stability change in ancient China [7,71]. By comparing the social stability evolution with change in migration, conflict and famine during the same periods, it was found that there exist highly consistent relationships [25]. The findings show that there existed three peak value: the "Five Hu" period of the Eastern Jin dynasty (290–400 AD), on five occasions, famine in Mongolia led to migrations of large populations of Mongolian nomads, in turn, conflicts by the nomad invasion; from this flourishing Tang to Song Dynasties (690-960 AD), frequent conflicts between ethnic minorities and dynastic changes, led to an increase in the number of famines and migrations within the Hexi Corridor; the coldest of the Little Ice Age (1640-1700 AD), a significant increase in famines and

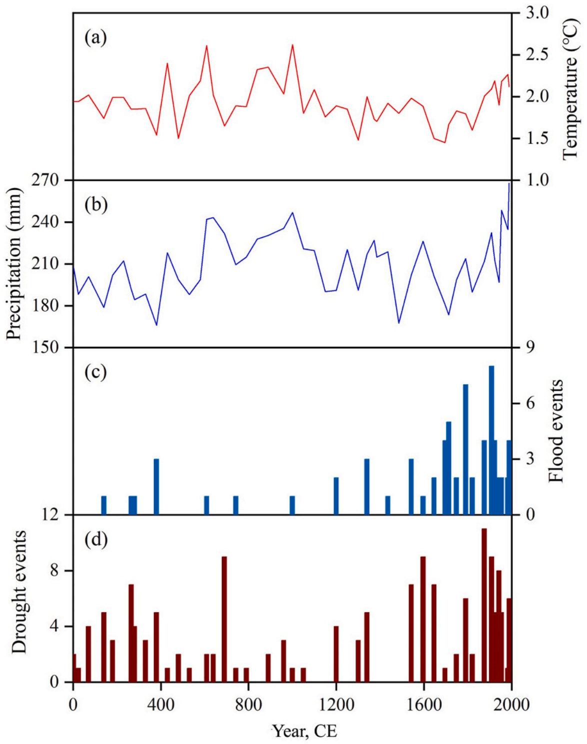

Fig. 4. Temporal variations of natural factors including (a) annual mean temperature (*T*), (b) annual mean precipitation (*P*), (c) flood events (*FD*), and (d) drought events (*DT*) in the Hexi corridor from 0 to 1990 AD.

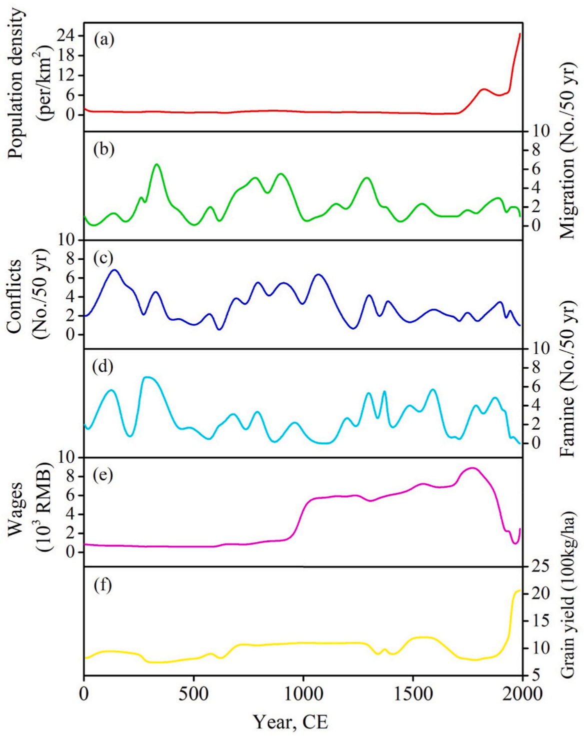

Fig. 5. Trends in human factors variables in the Hexi Corridor from 0 to 1990 AD. (a) population density (*PD*), (b) migration (*M*), (c) conflicts (*C*), (d) famine (*FM*), (e) wages (*W*), and (f) grain yield (*G*).

conflicts occurred frequently (Fig. 5b, c, 5d).

The system of prefectures and counties was set up in the 121 BCE, for defense needs, an unprecedented expansion of artificial oases occurred in the Hexi Corridor. After 1000 AD, the natural oasis of this region was gradually replaced by artificial oasis, also promoted establishment of towns and the agricultural technology growth, the *W* increase with socioeconomic development (Fig. 5e). If there were agricultural productivity stability, enough artificial oases and the state of irrigated technology, which may be sufficient to increase crop yields [27]. The *G* in the Hexi Corridor fluctuated in some periods. The *G* increased from Han Dynasty until Ming Dynasty, a slight decreased in Qing, then keeping increased again in the Republic of China period and in 1990 AD (Fig. 5f). Irrigated agricultural had a twisted evolutionary history in the Hexi Corridor, influenced by a diverse range of environmental and socioeconomic factors. The *AP* and *WI* have shifted from the focuses on development of new farming tools and cultivation methods to modernized, water-saving irrigation methods and water diversion infrastructures (Table 3).

3.3. Analyzing the potential driving factors

The artificial oasis areas was significantly positively correlated with population density (correlation coefficient = 0.9), grain yield (0.68) and precipitation (0.34), agricultural policy (0.32) and water infrastructure factors (0.32), while negatively correlated with conflicts (-0.24) (Fig. 6). Specifically, population density in the Hexi Corridor exerted significantly positive influences, indicating that food consumption need was one of the most important drivers of artificial oasis expansion; grain yield increase, probably due to the advance in technologies, also positively affected artificial oasis evolution; the positive effects of precipitation might reflect the increasing water for farming activities in arid region; the positive influence of agricultural policy and water infrastructure factors indicated that these policies might have encouraged people to reclaim surrounding lands for agriculture; conflicts had a negative effect over cultivated oasis evolution, which might indicate that population was decreasing and therefore, agricultural development was compromised. Meanwhile, Grain yield showed correlations with population density (correlation coefficient = 0.79), precipitation (0.51) and temperature (0.26). Drought showed correlations with famine (correlation coefficient = 0.51) and flood (0.5).

To quantify the relative importance factors influencing artificial oasis evolution, we established SEMs based on the relationships between artificial oasis and their critical drivers over the past two millennia in the Hexi Corridor (Fig. 2). The final model explained 81.6 % of the variation in the artificial oasis evolution (Fig. 7). Human factors had direct positive effects on drivers of artificial oasis expansion, whereas natural factors had direct negative effect over artificial oasis evolution. Comparing with the standardized path coefficients (β), as for natural factors (β=-0.08), which was deeply influenced by human factors (β=0.94), the results showed the artificial oasis has been strongly impacted by human beings. In addition, the effect of the precipitation (*P*) on artificial oasis was not significant ($P > 0.05$), but the temperature (*T*) as natural factors showed a significant effect on artificial oasis ($P < 0.001$). Similarly, population density and grain yield had an indirect effect on artificial oasis by positively impact on human factors (Fig. 7). Other variables, including *DT, FD, W, FM, C, M, AP* and *WI*, were eliminated during the analysis due to they had very limited influence on oasis.

4. Discussion

The SEM analyses showed that the population density, grain yield, and temperature factors could generally explain 81.6 % of the influencing artificial oasis development. The SEM model convectively explained that population density was the primary driving force to greatest influence on reclaim the oases. This finding is corresponded with other civilizations in the world including other arid area in

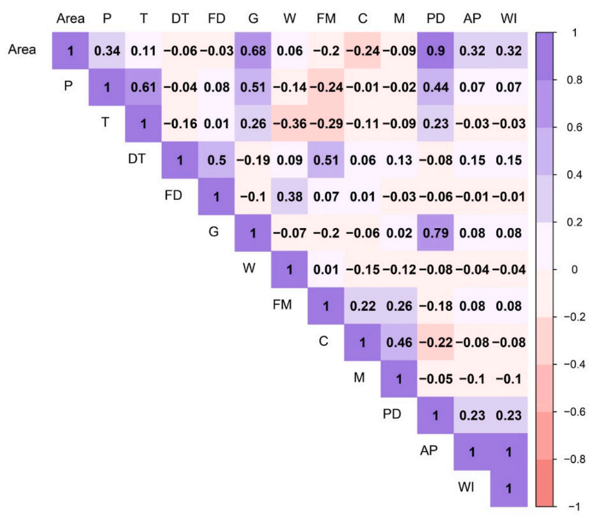

Fig. 6. Pearson correlation coefficients (*r*) for the artificial oasis and potential driving factors.

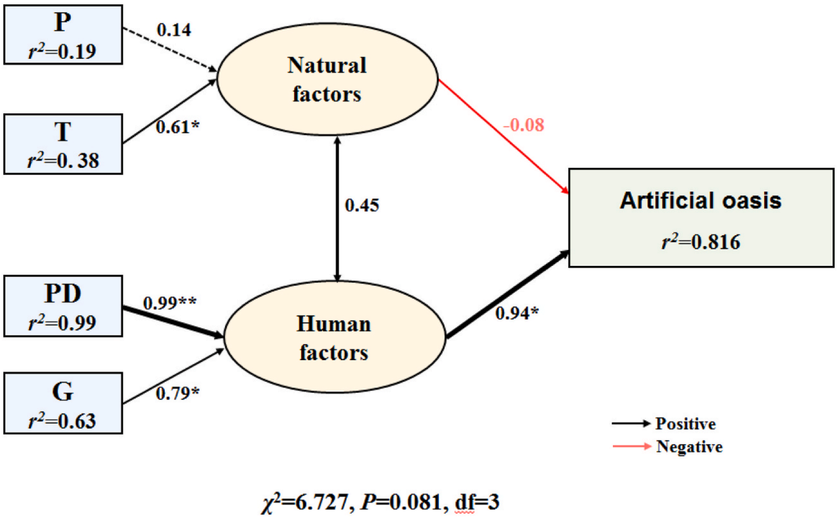

Fig. 7. Structure equation modelling (SEM) examining the natural and human drivers on artificial oasis. Single-headed arrows represent the hypothesized direction of causation. Numbers next to single-headed arrows are standardized path coefficients, which indicate the effect size of the relationship. Double-headed arrows indicate covariance between related variables. Red and black arrows indicate negative and positive relationships, respectively, and arrow width is proportional to the strength of the relationship. The proportion of variance (r^2) explained appears below each response variables in the model.

ancient China [19,69,72,73]. The difference is that artificial oasis appeared to a similar of U shape in the Hexi Corridor. This was due to the artificial oasis reclamation activities experienced three rapid development stages: from the Han Dynasty to the Sui-Tang Dynasty—the central government controls then reclamation of oasis for defense needs; during Ming and Qing dynasties—artificial oasis development due to the population increased drastically and the basic agricultural production conditions by the government; and after the People's Republic of China—artificial oasis for food demand increasing quickly and economic development [24,41,43,74]. On the other hand, three processes of migration occurred in Han dynasty, Ming and Qing dynasties, and 1949 to 1990 AD, respectively, have greatly changed the land cover, and, as a whole, the natural vegetation of this region was gradually replaced by artificial oasis [75]. In addition, crop yield has more positive influence on artificial oasis, which coincides with previous findings that agricultural production increase in this region was primarily determined by the size of cultivated oases [18,19,24]. As a result, the Hexi Corridor is located in a pastoral-agricultural area: the government could adopt an oasis reclamation policy to boost crop yield, not only meet the population growth need but also using local agricultural production to army provisions supply.

Understandably, temperature as a natural force had negatively influence on artificial oasis, because it is the most important element for farming [76]. In nomadic and dry-farming regions, the fragile of societies is widely dependent on the production of complementary land and food, which might further promote oasis reclamation intensity [47,77,78]. However, long-term of the cold combined with diminished rainfall, the water resources are relatively scarcity region intensified desertification, causing downstream oasis abandoned [79,80]. Furthermore, a lot of the ruins of ancient cities were left over the regions, such as Souyang City in Anxi, Camel City in Gaotai, Shazhou City and Shouchang City in Dunhuang, Liancheng City in Minqin, Heishui City in Zhangye, etc [41]. Floods, droughts, wages, famine, conflicts, migration, agricultural policy and water infrastructure have no obvious correlated with artificial oasis development. One of the reasons may be that a growing population provides more agricultural laborer to reclaim the oasis, which can produce more food to offset the crisis effects [81].

The quantitative historical analysis supported the realist assumption that the artificial oasis evolution was triggered by a range of factors and facilitated increased predictions of

its possible future changes [82]. Over the past 2000 years, as human activity intensified, natural oasis pattern driven by the natural forces was replaced by the artificial oasis in which irrigated agriculture played a leading role in combination with grassland livestock in the Hexi Corridor [83–85]. Particularly, after the People's Republic of China, the total artificial oases area showed a 75 % increase from 2275.09 km^2 to 8982.21 km^2. The government promoted water-saving and adjusted the plantation patterns, which had improved the continuous expansion of artificial land production. Nevertheless, with increasing desertification, groundwater depletion, natural vegetation degradation, climate change and biodiversity loss, it is gradually realized that further measures are still needed to decrease water use in agriculture and increase ecological water use [86–88]. It is becoming essential to assess the scale of artificial oasis in the Hexi Corridor based on the human-land relationship and human-environment relationship. Above all, the resource reallocation policies should the optimized to improve the balance between natural oases and artificial oases for sustainable development of this region [89].

This study reconstructed the evolutionary-process of artificial oasis by using the multiple sources data including the paleo-climates, historical atlas and local historical ethnographies spanning the last two millennia (0-1990 AD). It is necessary to point out some limitations when the research results from this paper are applied. Firstly, inconsistency between the data extracted from the different proxy materials, and limitations of the data represented discontinuous time periods. Furthermore, due to the use of multiple data sources, low resolutions and co-linearity of data may occur. For instance, some co-linearity may exist between artificial oasis areas and population as the oasis area was reconstructed. Finally, the SEM model that was established may over-simplify to description of the evolution of the oasis. In addition, the comparative analysis of potential driving factors of artificial oases in different stages is insufficient. The spatial distribution of artificial oasis area in each historical period is significantly different, so it is necessary in the future to separate different stages and build structural equation models to compare the driving factors.

5. Conclusions

Artificial oasis evolution trajectory reconstruction is the key to study oasification, natural changes and development of human society in historical periods, the basis of understanding the evolutionary processes of the natural environment in different time scales and its relationship with human activities, and the way to improve the current land sustainable management and the future against desertification. We examined the area of artificial oasis and the potential driving factors changes from 0 to 1990 AD to observe the evolution of artificial oasis and driving mechanism in the Hexi Corridor. A structural equaion model (SEM) was established using historical literatures, historical atlases, and reconstructed data to identify the impact on natural driving factors (temperature, precipitation, flood events, and drought events) and the human driving factors (grain yield, wages, famine, conflicts, migration, population density, agricultural policy, and water infrastructure) on the artificial oasis.

Analysis found the artificial oasis has experienced three rapid evolutionary periods: "start-up" from the Han Dynasty to the Sui-Tang Dynasty, "recovery stage" followed during Ming and Qing dynasties, and then "booming development" after the People's Republic of China. The SEM analyses suggested the population density and crop yield showed significant relationship with the artificial oasis development over the past 2000 years in the Hexi Corridor Moreover, temperature was considered as a leading role control of growing conditions, are negatively correlated the associated large-scale artificial oasis development. Through comparing with most recent studies in the arid region, our study show that the oasis evolution process and its driving forces are important for assess the sustainable scale of artificial oasis based on the human-land relationship in the Hexi Corridor. These findings will make contribution to sustainable oasis management practice in arid region with similar backgrounds.

Funding statement

This work was funded by the National Natural Science Foundation of China (No. 41801079).

Data availability statement

The authors do not have permission to share data.

CRediT authorship contribution statement

Xia Tang: Writing – review & editing, Writing – original draft, Investigation, Data curation.**Linshan Yang:** Analyzed and interpreted the data. **Hao Qu:** Writing – original draft, Data curation. **Qi Feng:** Project administration.

Declaration of competing interest

Xia TANG reports financial support was provided by the National Natural Science Foundation of China. Authors declare no conflicts of interests. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We also thank the editorial office of Heliyon and anonymous reviewers for their valuable comments and suggestions which were useful to improve the presentation of our paper.

References

[1] M.L. Han, On the accommodation between human and environment during the last 2 000 Years and scientific inspiration, Geogr. Res. 19 (3) (2000) 324–331 (In Chinese).
[2] H. Wahap, T. Tiyip, H. Yimit, H.G. Xiong, Study on human driving mechanisms of the oasis land use changes in arid region, J. Arid Land Resour. Environ. 21 (6) (2007) 1–6 (in Chinese).
[3] D. Gui, J. Xue, Y. Liu, J. Lei, F. Zeng, Should oasification be ignored when examining desertification in Northwest China? Solid Earth Discussions 2017 (2017) 1–24, https://doi.org/10.5194/se-2017-59.
[4] X. Tang, Z.Q. Zhang, A bibliometrical analysis of oasis research, Acta Ecol. Sin. 36 (2016) 3115–3122, https://doi.org/10.5846/stxb201501120091 (In Chinese).
[5] T. Wang, X. Xue, L.H. Zhou, J. Guo, Combating aeolian desertification in northern China, Land Degrad. Dev. 26 (2015) 118–132, https://doi.org/10.1002/ldr.2190.

[6] L.N. Hao, X.L. Su, V.P. Singh, L. Zhang, G.X. Zhang, Suitable oasis and artificial land scales in arid regions based on ecological health, Ecol. Indicat. 102 (2019) 33–42.
[7] X. Tang, Y. Zhao, Z.Q. Zhang, Q. Feng, Y.P. Wei, Artificial oasis evolution in the Heihe River basin over the past 2,000years, Land Degrad. Dev. 29 (8) (2018) 2254–2263, https://doi.org/10.1002/ldr.2991.
[8] B. Yang, A. Braeuning, K.R. Johnson, Y.F. Shi, General characteristics of temperature variation in China during the last two millennia, Geophys. Res. Lett. 29 (2002), https://doi.org/10.1029/2001GL014485, 38-1-38-4.
[9] J.P. Bravard, A. Mostafa, R. Garcier, G. Tallet, P. Ballet, A. Bolo, Y. Chevalier, H. Tronchere, Rise and fall of an Egyptian oasis: artesian flow, irrigation soils, and historical agricultural development in el-deir, kharga depression, western desert of Egypt, Geoarchaeology, An International Journal 31 (2016) 467–486, https://doi.org/10.1002/gea.21566.
[10] A. Maitiniyazi, A. Kasimu, Landscape pattern changes and its driving factors in pishan oasis, xinjiang Uyghur autonomous region, J. Arid Land Resour. Environ. 7 (31) (2017) 55–62 (In Chinese).
[11] M. Sabit, Y. Mamat, N. Nasirdin, Spatio-temporal characteristics analysis of land use/cover changes in Yutian Oasis, Xinjiang during 1991-2011, J. Glaciol. Geocryol. 36 (3) (2014) 582–589 (In Chinese).
[12] L. Shi, Study on the Spatio-Temporal Process of Oasisization and Desertification in the Period of the Ming, Qing Dynasties and Republic of China in the Middle Reaches of Heihe River. MD Thesis, Lanzhou University, Lanzhou, 2010 (In Chinese).
[13] D.J. Mattingly, M.J. Sterry, D.N. Edwards, The origins and development of Zuwīla, Libyan Sahara: an archaeological and historical overview of an ancient oasis town and caravan centre, Azania 50 (1) (2015) 27–75, https://doi.org/10.1080/0067270x.2014.980126.
[14] Z. Muyibul, X. Jianxin, P. Muhtar, S. Qingdong, Z. Run, Spatiotemporal changes of land use/cover from 1995 to 2015 in an oasis in the middle reaches of the Keriya River, southern Tarim Basin, Northwest China, Catena 171 (2018) 416–425.
[15] E.F. Lambin, H. Geist, Land-use and Land-Cover Change: Local Processes and Global Impacts, Springer, 2006, https://doi.org/10.1007/3-540-32202-7_4.
[16] W. Liu, S.K. Cao, H.Y. Xi, Q. Feng, Land use history and status of land desertification in the Heihe River basin, Nat. Hazards 53 (2010) 273–290, https://doi.org/10.1007/s11069-009-9429-5.
[17] P.H. Jiang, R.F. Zhao, H.L. Zhao, J.P. Fan, J.Z. Wang, C. Liu, Spatial-temporal evolution of land use/cover change in middle section of Heihe basin since 1975, J. Ecol. Rural Environ. 28 (2012) 473–479 (in Chinese).
[18] Y.W. Xie, F.H. Chen, J. Qi, Past desertification processes of Minqin Oasis in arid China, Int. J. Sustain. Dev. World Ecol. 16 (2009) 260–269, https://doi.org/10.1080/13504500903132309.
[19] Q.Q. Zhang, H.L. Xu, Y. Li, Z.L. Fan, P. Zhang, P.J. Yu, H.B. Ling, Oasis evolution and water resource utilization of a typical area in the inland river basin of an arid area: a case study of the Manas River Valley, Environ. Earth Sci. 66 (2012) 683–692, https://doi.org/10.1007/s12665-011-1276-5.
[20] T. Amuti, G. Luo, Analysis of land cover change and its driving forces in a desert oasis landscape of Xinjiang, Northwest China, Solid Earth 5 (2014) 1071–1085.
[21] Z.T. Zhang, E.Q. Xu, H.Q. Zhang, Complex network and redundancy analysis of spatial-temporal dynamic changes and driving forces behind changes in oases within the Tarim Basin in northwestern China, Catena 201 (2021), 105216, https://doi.org/10.1016/j.catena.2021.105216.
[22] Y. Hamid, X.L. Pan, T. Taxpolat, G. Ernst, F. Zhang, Water resource development in the Tarim Basin and its eco-environmental effects, Resour. Sci. 24 (2002) 48–54, https://doi.org/10.1007/s11769-002-0038-4.
[23] J. Liao, T. Wang, X. Xue, Oasis evolution in the Heihe River basin during 1956-2010, J. Desert Res. 32 (2012) 1426–1441 (in Chinese).
[24] G.S. Wang, Spatial-temporal Change and Driving Mechanism of the Artificial Oasis in the Heihe River Basin during Historical Periods, PhD Thesis, Lanzhou University, Lanzhou, 2014 (in Chinese).
[25] L.S. Yang, Q. Feng, J.F. Adamowski, R.C. Deo, Z.L. Yin, X.H. Wen, X. Tang, M. Wu, Causality of climate, food production and conflict over the last two millennia in the Hexi Corridor, China, Sci. Total Environ. 713 (2020), 136587, https://doi.org/10.1016/j.scitotenv.2020.136587.
[26] B.C. Li, A Study on the Desertification of Hexi Corridor in Historical Time, Science Press, Beijing, China, 2003 (In Chinese).
[27] Z.X. Lu, Y.P. Wei, H.L. Xiao, S.B. Zou, J.L. Xie, J. Ren, A. Western, Evolution of the human-water relationships in Heihe River basin in the past 2000 years, Hydrol. Earth Syst. Sci. 19 (2015) 2261–2273, https://doi.org/10.5194/hess-19-2261-2015.
[28] Y.P. Li, Q.S. Ge, H.J. Wang, H.L. Liu, Z.X. Tao, Relationships between climate change, agricultural development and social stability in the Hexi Corridor over the last 2000 years, Sci. China Earth Sci. 62 (2019) 1453–1460, https://doi.org/10.1007/s11430-018-9323-3.
[29] S.C. Xiao, H.L. Xiao, Advances in the study of the water regime process and driving mechanism in the Heihe River basin, Adv. Earth Sci. 23 (7) (2008) 748–755, https://doi.org/10.11867/j.issn.1001-8166.2008.07.0748 (in Chinese).
[30] H. Zhang, J.W. Wu, Q.H. Zheng, Y.J. Yu, A preliminary study of oasis evolution in the Tarim Basin, Xinjiang, China, J. Arid Environ. 55 (2003) 545–553.
[31] W. Liu, T. Wang, S.K. Cao, J.H. Si, H.Y. Xi, Evolution and variation of land desertification in Heihe river basin and its effection factors, J. Arid Land Resour. Environ. 23 (2009) 35–43 (in Chinese).
[32] Y.W. Xie, Y. Zhang, D. Qian, J. Gong, Y. Xie, G. Chang, Driving forces of Jintao asis changes based on participatory rural appraisal and principal component analysis, Sci. Geogr. Sin. 36 (2) (2016) 312–320 (in Chinese).
[33] Y.W. Xie, Dataset of Artificial Oasis Distribution in the Heihe River Basin during the Historical Period, Heihe Plan Science Data Center, 2013, https://doi.org/10.3972/heihe.092.2013.db.
[34] X.K. Zhu, F.L. Chen, H.D. Guo, Reconstruction of the water cultivation paleoenvironment dating back to the han and Tang dynasties surrounding the yangguan frontier pass using X- and L-band SAR data, Rem. Sens. 10 (10) (2018) 1536, https://doi.org/10.3390/rs10101536.
[35] B.C. Li, On the Hexi corridor of agricultural development achievement in the Tang period, Development and Research 2 (1989) 63–65 (In Chinese).
[36] J. Liao, Research on Oasis Evolution in Heihe River Basin, PhD Thesis, Cold and Arid Regions Environment and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, 2011 (in Chinese).
[37] D. Zhou, X. Wang, M. Shi, Human driving forces of oasis expansion in northwestern China during the last decade-a case study of the Heihe River Basin, Land Degrad. Dev. 28 (2) (2017) 412–420, https://doi.org/10.1002/ldr.2563.
[38] X.J. Meng, S.F. Zhang, Y.Y. Zhang, The temporal and spatial change of temperature and precipitation in Hexi corridor in recent 57 years, Acta Geograph. Sin. (2012) 1482–1492 (In Chinese).
[39] J.A. Holmes, E.R. Cook, B. Yang, Climate change over the past 2000 years in Western China, Quat. Int. 194 (2009) 91–107, https://doi.org/10.1016/j.quaint.2007.10.013.
[40] X.Y. Zhang, X.M. Wang, P. Yan, Re-evaluating the impacts of human activity and environmental change on desertification in the Minqin oasis, China, Environ. Geol. 55 (2008) 705–715, https://doi.org/10.1007/s00254-007-1022-1.
[41] B.C. Li, An investigation and study on the desertification of the ancient oases from Han to Tang dynasties in the Hexi corridor, Acta Geograph. Sin. 53 (1998) 106–115, https://doi.org/10.11821/xb199802002.
[42] X. Wu, Historical variance of the ecological environment in the inland river area along the Hexi corridor, J. Lanzhou Univ. 28 (2000) 46–49 (in Chinese).
[43] H.Y. Cheng, The Desertification of the Hexi Area in Historical Time, PhD Thesis, Lanzhou University, Lanzhou, 2007 (in Chinese).
[44] Y.W. Xie, Q. Bie, C.S. He, Human settlementand changes in the distribution of river systems in the Minqin Basin over the past 2000 years in Northwest China, Ecosys. Health Sustain. 3 (11) (2017), 1401011, https://doi.org/10.1080/20964129.2017.1401011.
[45] C. Yuan, Y. Ye, X.Q. Fang, Rasterizing cropland data and accuracy comparison in Jiangsu and Anhui provinces in the Mid-Qing Dynasty, Prog. Geogr. 34 (2015) 83–91 (in Chinese).
[46] D.K. Munroe, D. Müller, Issues in spatially explicit statistical land-use/cover change (LUCC) models: examples from western Honduras and the Central Highlands of Vietnam, Land Use Pol. 24 (2007) 521–530, https://doi.org/10.1016/j.landusepol.2005.09.007.
[47] B. Yang, C. Qin, A. Bräuning, I. Burchardt, J. Liu, Rainfall history for the Hexi Corridor in the arid northwest China during the past 620 years derived from tree rings, Int. J. Climatol. 31 (2011) 1166–1176.
[48] B. Yang, C. Qin, J. Wang, M. He, T.M. Melvin, T.J. Osborn, et al., A 3,500-year treering record of annual precipitation on the northeastern Tibetan Plateau, Proc. Natl. Acad. Sci. USA 111 (2014) 2903–2908.

[49] L. Yuan, Research on the regulation of historical drought occurrence in Gansu, Qinghai and Ningxia, J. Lanzhou Univ. 2 (1994) 111–116 (in Chinese).
[50] H.Z. Bai, A.X. Dong, G.F. Zheng, The Atlas of Drought and Flood Distribution over Northwest china in Past 500 Years: 1470-2000, China Meteorological Press, Beijing, 2010 (in Chinese).
[51] X. Tang, Q. Feng, Analysis of drought and flood disasters during 0-1950 AD in the Hexi Corridor, China, based on historical documents, Front. Environ. Sci. 9 (2021), 781179, https://doi.org/10.3389/fenvs.2021.781179.
[52] R. Fang, R. Zhang, History of Population in Gansu Province, Gansu People's Press, Lanzhou, 2007 (in Chinese).
[53] Q. Jiang, Research on Population in Ancient Hexi Corridor, Inner Mongolia People Press, Inner Mongolia, 2008 (in Chinese).
[54] S. Wang, in: The Military History of China, vol. 2, Committee of Chinese Military History, The People's Liberation Army Press, Beijing China, 1986 (in Chinese).
[55] Editorial Committee of Chinese Military History, Tabulation of Wars in Ancient China, Chinese Peoples Liberation Army Publishing House, Beijing, 2002 (in Chinese).
[56] C.P. Tang, Ancient Gansu drought causes and prevention measurements, Development and Research 6 (1999) 61–63 (in Chinese).
[57] W.G. Ding, M. Liu, The correlation research on pests and drought, famine and policy suggestions in historical Gansu, J. Arid Land Resour. Environ. 25 (2011) 113–117 (in Chinese).
[58] K. Tian, X.W. Gao, Review the system bottlenecks of the ancient Chinese official high salary for a clean government, Tianfu New Idea 21 (2005) 107–110 (in Chinese).
[59] J. Wang, Research and enlightenment on Chinese historical salary system, Review of Economic Research 83 (2003) 2–12 (in Chinese).
[60] B.C. Li, The research of area yield of grain in Hexi area in the history, J. Northwest Norm. Univ. Soc. Sci. (1992) 16–21 (in Chinese).
[61] Y. Su, X. Fang, J. Yin, Impact of climate change on fluctuations of grain harvests in China from the western han dynasty to the five dynasties (206 BC-960 AD), Sci. China Earth Sci. 57 (2014) 1701–1712.
[62] Zhangye Prefectural Committee, The Chorography of Hexi, Gansu Zhengye Press, 1958 (in Chinese).
[63] Y. Liu, Z. An, H.W. Linderholm, D. Chen, H. Song, Q. Cai, et al., Annual temperatures during the last 2485 years in the mid-eastern Tibetan Plateau inferred from tree rings, Sci. China Earth Sci. 52 (2009) 348–359.
[64] X.H. Gou, Y. Deng, L.L. Gao, F.H. Chen, E. Cook, M.X. Yang, F. Zhang, Millennium tree-ring reconstruction of drought variability in the eastern Qilian Mountains, northwest China, Clim. Dynam. 45 (2015) 1761–1770, https://doi.org/10.1007/s00382-014-2431-y.
[65] F.H. Chen, Q.H. Xu, J.H. Chen, H.J. Birks, J.B. Liu, S.R. Zheng, L.Y. Jin, C.B. An, R.J. Telford, X.Y. Cao, Z.L. Wang, X.J. Zhang, K. Selvaraj, H.Y. Lu, Y.C. Li, H. P. Wang, A.F. Zhou, G.H. Dong, J.W. Zhang, X.Z. Huang, J. Bloemendal, Z.G. Rao, East Asian summer monsoon precipitation variability since the last deglaciation, Sci. Rep. 5 (2015), 11186, https://doi.org/10.1038/srep11186.
[66] Z.Y. Wang, B. Yang, A. Deslauriers, A. Brauning, Intra-annual stem radial increment response of Qilian juniper to temperature and precipitation along an altitudinal gradient in northwestern China, Trees (Berl.) 29 (2015) 25–34, https://doi.org/10.1007/s00468-014-1037-7.
[67] K.G. Wen, A.X. Dong, Encyclopaedia of China's Meteorological Disasters: Gansu Volume, China Meteorological Press, Beijing, 2005 (in Chinese).
[68] Y. Ye, X.Q. Fang, M.A.U. Khan, Migration and reclamation in Northeast China in response to climatic disasters in North China over the past 300 years, Reg. Environ. Change 12 (2012) 193–206.
[69] Y.W. Xie, G.S. Wang, X.Q. Wang, P.L. Fan, Assessing the evolution of oases in arid regions by reconstructing their historic spatio-temporal distribution: a case study of the Heihe River Basin, China, Front. Earth Sci. (2017) 629–642, https://doi.org/10.1007/s11707-016-0607-y.
[70] J.B. Grace, Structural Equation Modeling and Natural Systems, Cambridge University Press, Cambridge, UK, 2006, https://doi.org/10.1017/CBO9780511617799.
[71] Z.X. Lu, Q. Feng, S.C. Xiao, J.L. Xie, S.B. Zou, Q. Yang, J.H. Si, The impacts of the ecological water diversion project on the ecology-hydrology-economy nexus in the lower reaches in an inland river basin, Resour. Conserv. Recycl. 164 (2021), 105154, https://doi.org/10.1016/j.resconrec.2020.105154.
[72] X. Yang, The oases along the Keriya River in the Taklimakan desert, China, and their evolution since the end of the last glaciation, Environ. Geol. 41 (2001) 314–320, https://doi.org/10.1007/x002540100388.
[73] X. Yan, Y.L. Cai, Multi-scale anthropogenic driving forces of karst rocky desertification in southwest China, Land Degrad. Dev. 26 (2015) 193–200, https://doi.org/10.1002/ldr.2209.
[74] H.M. Li, F.W. Liu, Y.F. Cui, L.L. Ren, M. Storozum, Z. Qin, J. Wang, G.H. Dong, Human settlement and its influencing factors during the historical period in an oasis-desert transition zone of Dunhuang, Hexi Corridor, northwest China, Quat. Int. 458 (2017) 113–122.
[75] H.Y. Cheng, Y.C. Huang, L.Q. Zhao, The Human Activity in Hexi Corridor during Historical Time, China Science and Technology, Beijing, 2011. Papers Online (in Chinese).
[76] M.V.K. Sivakumar, H.P. Das, O. Brunini, Impacts of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics, Clim. Change 70 (2005) 31–71.
[77] O. Potchter, D. Goldman, D. Kadish, D. Iluz, The oasis effect in an extremely hot and arid climate: the case of southern Israel, Journal of Arid Environment 72 (9) (2008) 1721–1733.
[78] Y.D. Wang, Evolution of Oases under Human Interference in Arid Northwest China, Master thesis, Tsinghua University, Beijing, 2018.
[79] H.D. Wei, X.Y. Xu, F. Ding, L.P. Zhou, Dynamic monitoring of land desertification in Minqin oasis, J. Arid Land Resour. Environ. 10 (2007) 12–17 (in Chinese).
[80] A.I.L. Miguel, W. Jobst, A.C. Oscar, R.V. Eleonora, Deterioration of Oases Subject to Climate Change and Coastal Development: the Case of Todos Santos Oasis, Baja California Sur, vol. 2020, Groundwater for Sustainable Development, Mexico, 2020, 100401, https://doi.org/10.1016/j.gsd.2020.100401.
[81] Q. Feng, L.S. Yang, R.C. Deo, A. AghaKouchak, J.F. Adamowski, R. Stone, Z.L. Yin, W. Liu, J.H. Si, X.H. Wen, M. Zhu, S.X. Cao, Domino effect of climate change over two millennia in ancient China's Hexi Corridor, Nat. Sustain. 2 (2019) 957–961.
[82] A. Abulizi, Y. Yang, Z. Mamat, J. Luo, D. Abdulslam, Z. Xu, A. Zayiti, A. Ahat, W. Halik, Land-use change and its effects in Charchan oasis, Xinjiang, China, Land Degrad. Dev. 28 (1) (2017) 106–115.
[83] N.A. Wang, Climatic and humanistic background of desertification process over the last 2000 Years in Hexi corridor, J. Desert Res. 23 (1) (2003) 95–100 (in Chinese).
[84] Z.H. Zhou, J. Ma, Spatial-temporal evolution mechanism of historical towns in Hexi Corridor: taking cultural relics protection units as an example, Huazhong Archit. 8 (2018) 12–19 (in Chinese).
[85] X. Tang, Q. Feng, Analysis on driving mechanism of land use change in Heihe River basin during historical period, Res. Soil Water Conserv. 3 (2015), 336-340,348 (In Chinese).
[86] J. Bai, X. Chen, L. Li, G. Luo, Q. Yu, Quantifying the contributions of agricultural oasis expansion, management practices and climate change to net primary production and evapotranspiration in croplands in arid northwest China, J. Arid Environ. 100–101 (2014) 31–41.
[87] R.M.S.P. Vieira, J. Tomasella, R.C.S. Alvalá, M.F. Sestini, A.G. Affonso, D.A. Rodriguez, A.A. Barbosa, A.P.M.A. Cunha, G.F. Valles, E. Crepani, S.B.P. Oliveira, M. S.B. de Souza, P.M. Calil, M.A. Carvalho, D.M. Valeriano, F.C.B. Campello, M.O. Santana, Identifying areas susceptible to desertification in the Brazilian northeast, Solid Earth 6 (2015) 347–360.
[88] S.M. Hassan, H. Khosravi, S. Ghasemian, Assessment of combating-desertification strategies using the linear assignment method, Solid Earth 7 (2016) 673–683.
[89] O. Shelef, I. Stavi, P. Zdruli, S. Rachmilevitch, Land use change, a case study from southern Italy: general implications for agricultural subsidy policies, Land Degrad. Dev. 27 (2016) 868–870.