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THEMATIC ISSUE

Drought promoted the disappearance of civilizations along the ancient Silk Road

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Abstract Understanding the reasons of the disappearance of oasis civilizations along the ancient Silk Road will provide useful references for human's adaptation to environmental changes in the extreme arid regions in the nowadays and future. Although some studies have associated the demise of complex societies with deteriorating climate in the world, the demise of the civilizations along the ancient Silk Road has remained unresolved. Here, this paper used the nearly 2000 years of climate characteristics revealed by Guliya ice cores, combined with the reconstruction of temperature from tree rings located in the west Kunlun Mountains around the Tarim Basin to examine the climate variations in the Northwestern China in the historical periods. Then this paper compared the demise time of the ancient oases civilizations along the ancient Silk Road from the relevant annals of states and counties. The results showed that climate change may be responsible for the rise and demise of past oasis civilizations in the ancient Silk Road. The periods of fourth to fifth centuries and the seventh to eighth centuries were characterized by long-term drought accompanied by cold climate; five ancient oases and seven ancient oases were demised, respectively, during these periods. Cold–dry climate could cause a deficiency in water resources for irrigation; thus, agricultural production fell and the society was destabilized. Recently, creation of a new "Silk Road economic belt" is realized. Modern oases will face more serious threat under the climate change. The region's irrigation area increased 67.2 % over the past 30 years. The agricultural sector consumes 93 % of regional renewable water resources. Once the drought occurred, many modern oases—like their ancient counterparts—may well trigger more civil uprising and violent conflict in the already water-stressed regions.

Keywords Climate change · Oases civilizations · Societal collapse · Ancient Silk Road

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Introduction

The empires like the Maya in Mexico, the ancient Egyptians along the Nile River, and the Babylonians along the Euphrates and Tigris Rivers disappeared thousands of years ago, yet only today people are learning that their disappearance is the legacy of environmental disasters exacerbated by human activities (Davidson et al. 2012; Shephard 2015). Although the development of human societies had their own internal evolution rules, the influences of natural factors could not be ignored (Sandweiss et al. 1999). Several studies have now documented the role of regional climate variation in contributing to the eventual demise of

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societies in the world (Buckley et al. 2010; Bohannon 2013). However, the demise of the oases civilizations in the famous ancient Silk Road has remained unresolved, only rarely considered the role played by environment and climate in the historical period (Zhang et al. 2013).

The consistency between climate change and ancient cultural changes attracted many scholars' attention (Sandweiss et al. 1999). Some studies have linked the demise of complex societies with deteriorating climate conditions (Weiss et al. 1993; Buckley et al. 2010). For example, Decades-long drought interspersed with intense monsoons in the fourteenth and fifteenth centuries that contributed to the Angkor's (capitol of the Khmer Empire in Cambodia) eventual demise (Buckley et al. 2010). Warm and persistently wet regional climate promoted the conquests of Chinggis Khan's (Genghis Khan's) in the Mongol Empire; however, dry climatic conditions from the 1180 s to the early 13th century coincided with extreme political instability in Mongolia (Pederson et al. 2014). During the last 2485 years, the downfall of most major dynasties in China coincides with intervals of low temperature (Liu et al. 2009). A recently published study suggested that warming could lead to escalating violence (Hsiang et al. 2013) and that increasingly hot summers could lead people to become more aggressive. Researchers have also fingered extreme precipitation—floods and droughts—for promoting violence (Hsiang et al. 2013). Many human conflicts, ranging from interpersonal violence to intergroup violence and further to political instability, will finally lead to the breakdown of civilizations (Bohannon 2013; Hsiang et al. 2013).

Although studies have associated the demise of complex societies with deteriorating climate in different regions (Weiss et al. 1993; Buckley et al. 2010; Davidson et al. 2012), few have investigated the comprehensive connection between history and ancient climatology research in the ancient Silk Road due to the lack of textual records. The ancient Silk Road, established over 2100 years ago to promote trade between China and Europe (Xu et al. 2010), provided a stimulus for cultural growth and economic prosperity along its entire route. The famous ancient civilizations along the ancient Silk Road in China were rimmed by the Taklimakan Desert, which is the world's second largest sandy desert. Within this extremely arid wasteland, when the climate shifts even slightly toward the dry, it means dramatic changes in water availability, leaving ecosystems and agricultural productivity at risk in the extreme arid regions. Many old oases civilizations in the history had been engulfed by the desert.

Understanding the reasons of the disappearance of oasis civilizations along the ancient Silk Road will provide useful references for human's adaptation to climate changes in the nowadays and future. Recently, creation of a new period "Silk Road economic belt" is realized. Its rebirth will inevitably bring immense commercial benefits to the Asia, Europe and Africa. It is not to be ignored to ensure that the new period of Silk Road is built in a sustainable way, e.g., need adequate attention to dealing with hydro-climatic challenges to insure the water and ecological security.

Materials and methods

Data

This paper used the nearly 2000 years of climate characteristics (temperature and precipitation) revealed by Guliya ice cores (Shi et al. 1999), combined with the reconstruction of temperature from tree rings over the past 2485 years (Liu et al. 2009) located in the Qinghai–Tibet Plateau around the Tarim Basin to examine the climate variations in the Northwestern China in the historical periods. The time of oasis demise is collected from the relevant annals of states and counties based on the archaeological excavations.

The land use/cover data, reflecting the characteristics of modern oasis, were derived from TM imageries in August in the 1990, 2000 and 2013 at http://earthexplorer.usgs.gov/, which is at the USGS website. The TM imageries include Landsat band 5, 4, and 3. We selected the particular imageries because of their good quality (spatial resolution of 30 m, and without much cloud).

PDSI, as a measurement of surface moisture conditions, is estimated to measure the impact of drought on the modern oasis. The required calculated gridded data of temperature and precipitation collected from Climatic Research Unit 3.23 (https://crudata.uea.ac.uk/cru/data/hrg/). Database of pressure, relative humidity, U-wind, V-wind, soil moisture, net shortwave radiation, net longwave radiation were collected from NCEP/NCAR Reanalysis (http://www.esrl.noaa.gov/psd/data/ gridded/data.ncep.reanalysis.html). The global dry areas were defined as PDSI <-3.0, while the wet areas were defined as PDSI $>+3.0$.

Methods

Considering the relatively simple land uses and landscapes in the study area, we adopted a six-type classification system, including water body, cultivated land, forestland, grassland, residential and industrial land, and unused land. Based on the geographic information extracted in 2014, and combined with the fieldwork data and high-resolution images from Google Earth, this paper established 200 random points to verify feature attributes (e.g., mountains, oases, deserts, etc.) in the study area and create the confusion matrix.

PDSI drought is estimated by the difference between the observed monthly precipitation and required "precipitation" that is estimated under climatically appropriate for existing conditions for each month (Palmer 1965).

$$\widehat{p} = \widehat{E}_{\mathrm{T}} + \widehat{R} + \widehat{R}_{\mathrm{O}} - \widehat{L} \quad (1)$$

$$\widehat{E}_{\mathrm{T}} = \alpha \mathrm{PE}, \quad \alpha = \frac{\bar{E}_{\mathrm{T}}}{\overline{\mathrm{PE}}} \quad (2)$$

$$\widehat{R} = \beta \mathrm{PR}, \quad \beta = \frac{\bar{R}}{\overline{\mathrm{PR}}} \quad (3)$$

$$\widehat{R}_{\mathrm{O}} = \gamma \mathrm{PR}_{\mathrm{O}}, \quad \gamma = \frac{\bar{R}_{\mathrm{O}}}{\overline{\mathrm{PR}_{\mathrm{O}}}} \quad (4)$$

$$\widehat{L} = \delta \mathrm{PL}, \quad \delta = \frac{\bar{L}}{\overline{\mathrm{PL}}} \quad (5)$$

Penman–Monteith reference evaporation:

$$\mathrm{PE} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{\mathrm{mean}}+273} U_2(\mathrm{vps} - \mathrm{vp})}{\Delta + \gamma(1 + 0.34U_2)} \quad (6)$$

Available moisture stored in soil system:

$$\mathrm{PR} = \mathrm{AWC} - (S_{\mathrm{s}} + S_{\mathrm{u}}) \quad (7)$$

$$\mathrm{PR}_0 = \mathrm{AWC} - \mathrm{PR} = (S_{\mathrm{s}} + S_{\mathrm{u}}) \quad (8)$$

Moisture loss (where AWC indicated the available capacity of the soil system):

$$\mathrm{PL} = \mathrm{PL}_{\mathrm{s}} + \mathrm{PL}_{\mathrm{u}} \quad (9)$$

$$\mathrm{PL}_{\mathrm{s}} = \min(\mathrm{PE} + S_{\mathrm{s}}) \quad (10)$$

$$\mathrm{PL}_{\mathrm{u}} = \frac{(\mathrm{PE} - \mathrm{PL}_{\mathrm{s}})S_{\mathrm{u}}}{\mathrm{AWC}}, \quad \mathrm{PL}_{\mathrm{u}} \le S_{\mathrm{u}} \quad (11)$$

$$d = P - \widehat{P} \quad (12)$$

$$Z = K_j d_j \quad (13)$$

Palmer drought severity index:

$$\mathrm{PDSI}_i = 0.897\mathrm{PDSI}_{i-1}\frac{1}{3}Z_i \quad (14)$$

Results and analysis

Cold–dry conditions bred demise of oases civilizations

Climate variations in Northwestern China in the nearly 2000 years were got based on the climate characteristics revealed by Guliya ice cores, combined with the reconstruction of temperature from tree rings located in the west Kunlun Mountains around the Tarim Basin. Periods marked by extreme low precipitation occurred in the sixth, ninth, tenth and twelfth centuries, while periods of extreme cold occurred around 550 and 1220 AD (Fig. 1). Climate change and its consequent impacts on hydrology and water resources are significant and will expose how deeply the economy, geopolitics and the water–energy–food nexus are intertwined.

In ancient oases civilizations, there was relatively little ability to withstand extreme weather and abrupt climate changes. They periodically faced the major dilemma of limited water resources. Almost all the water resources came from the natural river, so productivity declined significantly whenever cold and dry climate patterns occurred. In contrast, when the climate was in the warm–wet phase, the abundant water resources came from mountains that easily met agricultural irrigation needs. Land productivities were increased, leading to population growth, oasis expansion, and social stability, along with increasing demand for food and energy. When the climate was in the cold–dry period again, there was a deficiency in water resources for irrigation. Rivers dried up, soil desertification intensified and agricultural production fell, leading the society to be destabilized. The demise periods of the 21 ancient oases civilizations along the ancient Silk Road were mainly concentrated in the fourth and fifth centuries (five oases)[1] and the seventh and eighth centuries (seven oases)[2] (Fig. 2). These time periods were characterized by long-term drought accompanied by cold climate. A lack of precipitation and glacier meltwater intensified the desertification process, which caused the water-based oasis ecosystem to become increasingly fragile and eventually to "die." It can be surmised that the worsening dry conditions would have been an important contributing factor in the collapse of the established order in the demise of civilizations along the ancient Silk Road.

It is also noteworthy that a portion of the residents in the ancient countries along the ancient Silk Road are Indo-European (Comas et al. 1998); the actual historical evidence is extremely scarce, but it indicates that a population displacement and migration likely spurred by climate change occurred in ancient times.

Modern oases will face more serious threat under the climate change

The famous ancient Silk Road civilizations of Kroran (Loulan) and Jingjue have long been lost to the desert hinterland. Ironically, even though historical records show that the Kroran (Loulan) instigated the world's first environmental laws, these people still fell victims to climate change (Kasim et al. 2009). It should be learned from the

[1] Kara mound; Jingjue; Zileke; Niya; Kroran.

[2] Mazartag; Mairicavate; Majianleke; Dandanuilik; Heihas; Andil; Old Qiemo.

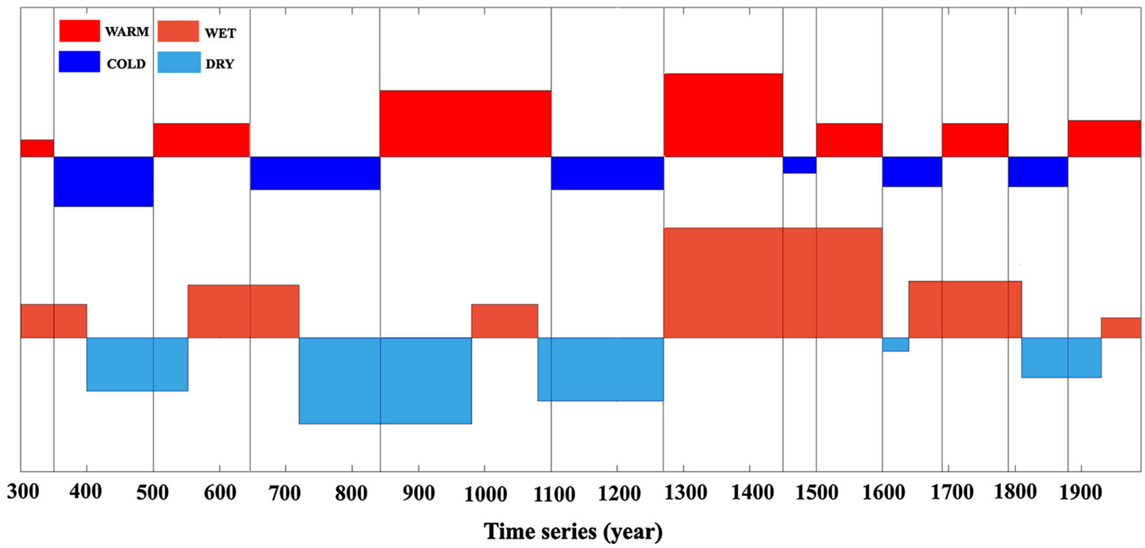

Fig. 1 Nearly 2000 years of climate characteristics (temperature and precipitation) revealed by Guliya ice cores, combined with the reconstruction of temperature from tree rings over the past 2485 years in the mid-eastern of Qinghai–Tibet Plateau, i.e., relatively high temperature indicates warm period and abundant precipitation indicates wet period

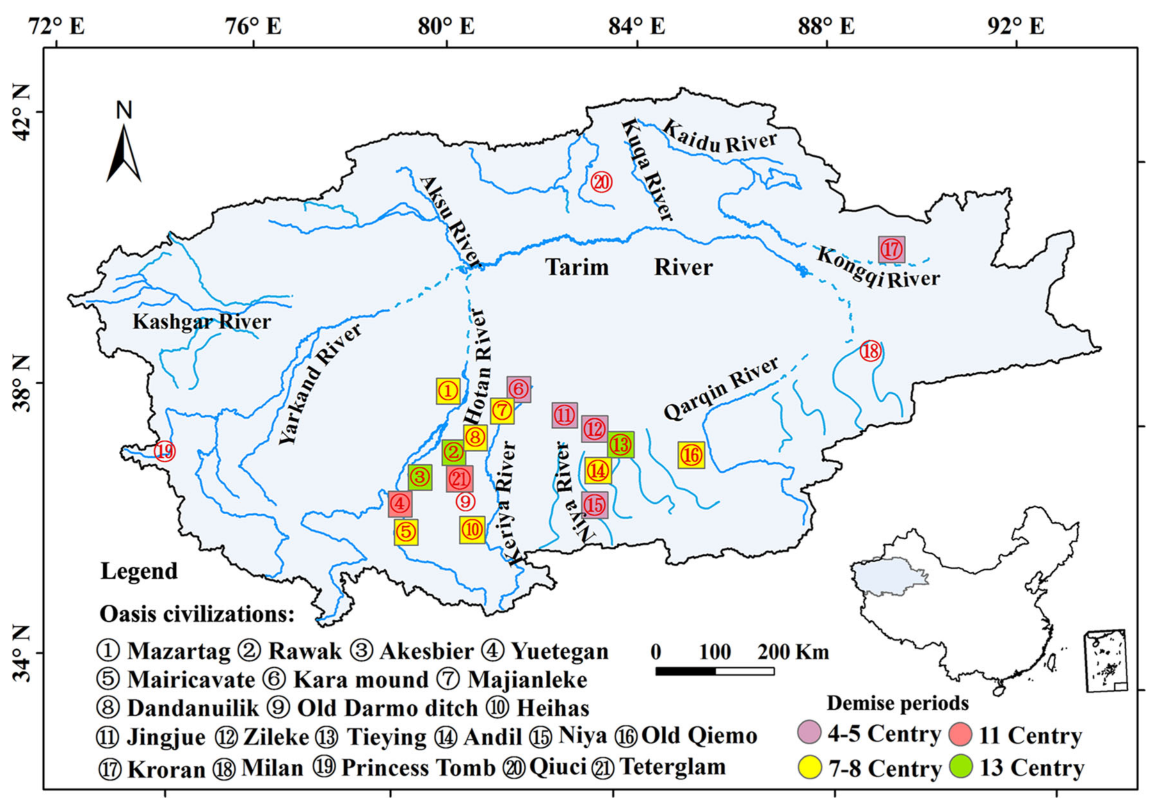

Fig. 2 Spatial distribution and demise periods of the 21 oasis civilizations, i.e., the demise periods of the ancient oases along the ancient Silk Road were mainly concentrated in the fourth and fifth centuries (five oases of No. *6*, *11*, *12*, *15*, *17*) and the seventh and eight centuries (seven oases of No. *1*, *5*, *7*, *8*, *10*, *14*, *16*); three oases of No. *2*, *3*, *13* demised in the thirteenth century; and two oases of No. *4*, *21* demised in the eleventh century

mistakes and victories of these ancient civilizations, because climate change is alive and well and still claiming victims.

Understanding how the climate changes and its impact on water supplies may be the first step toward the future maintenance. The Tarim Basin's oasis economy is agricultural-based, and the economy is presently lagging far behind most parts of eastern China. Human economic and social activities are strongly dependent on water resources for production, life and ecology in the Tarim Basin area. Water, mostly formed at the high mountain areas, is the critical factor to drive the energy and mass circulation in the arid region and exhibited sensitive response to climate change.

Climate change is alive and well and still claiming victims in the modern times, even more complicated and mutable. Over the past half-century, almost all regions of the world have experienced a marked warming process (IPCC 2013). Abrupt increases around 1986 in both the temperature and precipitation time series occurred in the Tarim River Basin (Chen et al. 2006), then the temperature experienced a much more "sharply" increase in 1997, since then has been in a high volatility (Chen et al. 2015). The calculated PDSI according to the Eqs. (1–14) reveals that the average PDSI after 1986 is 0.38 higher (wetter) than before; however, it reversed to decline trend again in the recent 15 years (Fig. 3). If future warming overwhelms increased precipitation, episodic heat droughts will similarly occur, and their social, economic, and political consequences will likely become more common, and will finally lead to the contradiction of water resources supply and demand in the oasis and desert to much more acute.

People are accustomed to the warm and wet climate since 1986, but ignore the slightly decreased (drier) PDSI in the nearly 15 years. In fact, the Tarim Basin's irrigation area increased by 67.2 % over the past 30 years (1990–2013), and especially in the past 15 years, the oases in the Tarim River Basin expanded about 1.5×10^4 km^2, while the grassland decreased about 10 % and unused land expanded about 4 % (Fig. 4). Almost all of the water resources are used for irrigation in the extreme arid region, seizing the ecological water seriously. Potential changes in these limited water resources generate huge concerns about further degradation of vegetation and expansion of the desert intrusion. Some regions are becoming overly dependent on groundwater, consuming the resource faster than it can naturally replenish and thus causing the natural vegetation downstream experience serious degradation and land salinization (Chen 2014, 2015; Li 2016). Because the gap between supply and demand is routinely bridged with non-renewable groundwater, groundwater supplies in some major aquifers will be depleted in a matter of decades, especially in the extreme regions (Feng et al. 2013; Famiglietti 2014). Under the impact of global climate change, the vulnerability of ecology system and uncertainty of water resources are increasing. Once the cold–dry climate reestablishes itself, or extreme warming overwhelms increased precipitation, many modern oases—like their ancient counterparts—may well trigger more civil uprising and international violent conflict in the already water-stressed regions, and face certain demise.

Adequate and comprehensive plans

Future climate change is inevitable, and the driving force of human activities will increase the probability of adverse effects, just as they did in years gone by. Given this scenario, government must make adequate and comprehensive plans to actively respond to climate change, especially in extreme arid regions. These plans include:

1. Implicit in this first step is accurately estimating the extent of future climate change and appropriately preparing for it. Coordinating water use between production and ecology and resolving or mitigating the conflicts arising from the uneven distribution of water resources among regions would improve the coping capacity and adaptability to future climate change. Screening areas should be done to identify current and future climate impacts and establishing water conservancy project in areas that are extremely sensitive to climate change in order to avoid massive climate migration due to floods, drought, etc. For

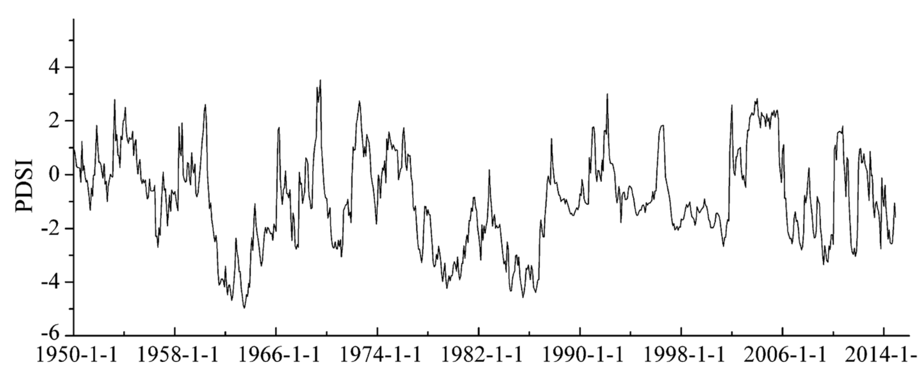

Fig. 3 Changes of monthly mean Palmer drought severity index in the Tarim River Basin over 1950–2014

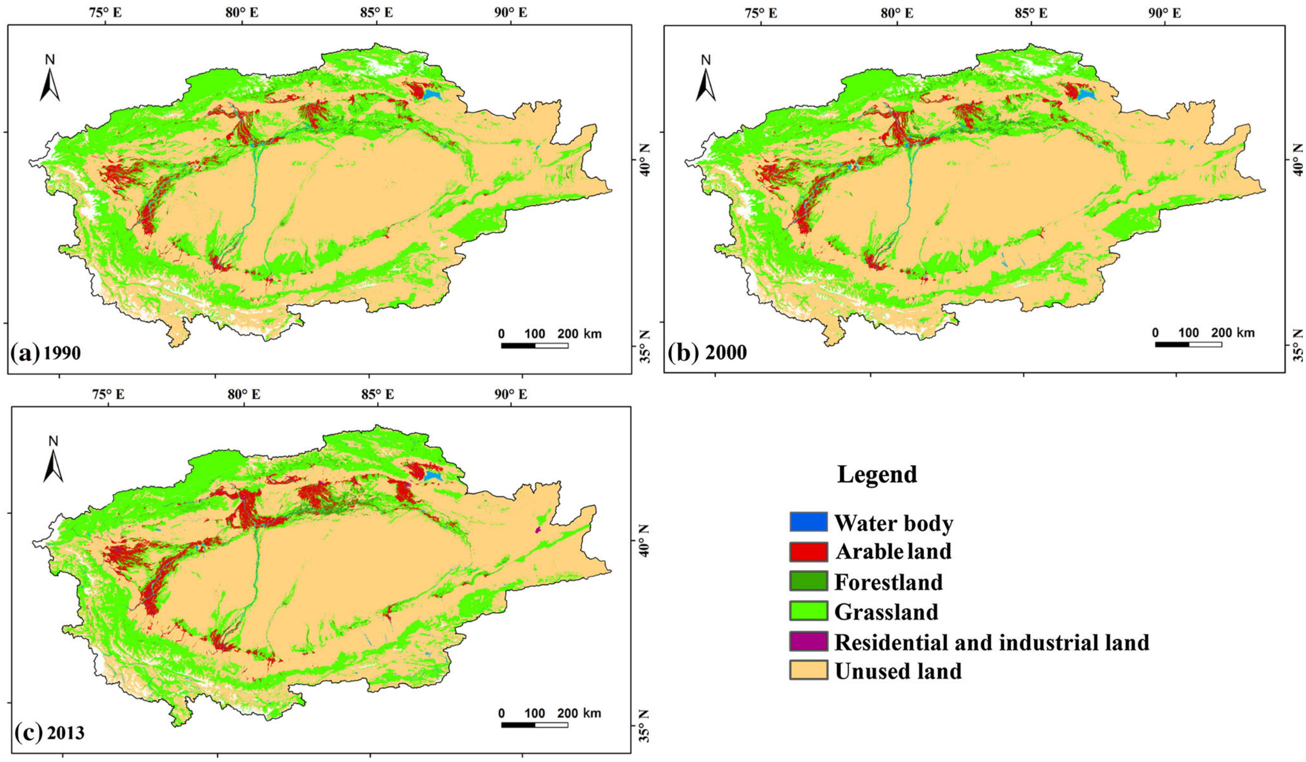

Fig. 4 Land use/cover change in the Tarim River Basin in **a** 1990, **b** 2000, **c** 2013

example, Water Transfer Project aims to channel watery rivers to meet water needs in the dry urban. And the construction of mountain-region controlling and regulating reservoirs should be fast-tracked to resolve issues related to uneven water distribution, water diversion projects, water capacity, alteration of irrigated areas, water supply capacity and water use efficiency.

2. The other key point is the need for far greater agricultural water use efficiency. Most of the key water conservancy projects were built in the 1960s and 1970s and suffer from low standards, poor regulation and imperfect engineering support. And there is a clear lack of controllable mountain regulating reservoirs (Chen 2014). The water use efficiency and effectiveness of these engineering projects are still low and cannot meet the growing water demands of present and predicted economic and social development. Therefore, strict laws need to be established to prohibit excess reclamation. Returning cultivated land to water completely reverses the need for extensive management and diversion of water resources. Ecological function regions and breeding stress-resistant varieties need to be established promote natural ecological restoration.
3. One of the important potential impacts of climate change on human societies is the possibility of changes in human migration patterns (McLeman and Smit 2006). Migration has long been a response to climate variability and environmental change, yet impediments to migration can and should be removed. Identifying the vulnerability of populations to existing environmental and socioeconomic processes of change and then assessing how well such populations could adapt to new conditions imposed by climatic change, such as temporary protected status. Principles and international cooperation should be constructed and lines of responsibility should be cleared to deal with climate migrants. Ultimately, all of these measures would ensure ecological security and sustainable economic and social development.

Conclusions

1. Climate is an important contributing factor in the demise of past oasis civilizations in the ancient Silk Road. The periods of fourth to fifth centuries and the seventh to eighth centuries were characterized by long-term drought accompanied by cold climate, and five ancient oases and seven ancient oases were demised, respectively, during these periods. The results revealed that the social conflicts in the oases along the ancient

Silk Road resulted from a lack of water resources caused by cold and dry climate.

2. Modern oases will face more serious threat under the climate change. The region's irrigation area increased 67.2 % over the past 30 years. But the calculated PDSI reveals a decline trend (drying) in the recent 15 years. Once the cold–dry climate occurred, or if future warming overwhelms increased precipitation leading to similar heat droughts, many modern oases—like their ancient counterparts—may well trigger more civil uprising and violent conflict in the already water-stressed regions.
3. Government must make adequate and comprehensive plans to actively respond to climate change, especially in extreme arid regions: The first step is accurately estimating the extent of future climate change and appropriately preparing for it. The other key point is the need for returning cultivated land and far greater agricultural water use efficiency.

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