Ambio 2020, 49:1412–1422
https://doi.org/10.1007/s13280-019-01287-7

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

RESEARCH ARTICLE

The hidden costs of desert development

Lihui Luo, Yanli Zhuang, Wenzhi Zhao, Quntao Duan, Lixin Wang

Received: 3 May 2019 / Revised: 8 October 2019 / Accepted: 31 October 2019 / Published online: 20 November 2019

Abstract Economic benefits and ecological restoration are the leading drivers of desert development through man-made oasis expansion. However, the sustainability of oasis expansion in combating desertification while promoting economic growth remains unclear, though such knowledge is critical for future desert development across the globe. To address this knowledge gap, a comprehensive assessment integrating meteorological, groundwater and remote-sensing data as well as groundwater simulation datasets was conducted to evaluate the spatial–temporal changes in the desert-oasis ecotone of northwest China over the past six decades. Desert development causes a rapid decline in the surrounding groundwater table, increases pollution in soil and groundwater and is associated with an increased frequency of strong sandstorms. Desert development seems to have improved the environment and promoted the economy, but there is a huge cost for the overexploitation of water resources and the transfer of pollution from surface to underground, which could cause deserts to degrade further.

Keywords Desert development · Groundwater · Oasis expansion · Pollution · Water resources

INTRODUCTION

Deserts and oases are independent but interacting ecosystems (Li et al. 2016). Oasis is a type of small- or medium-sized non-zonal and unique natural geographical landscape that is common within desert regions around the world and is mainly distributed in the tropical and subtropical regions of the middle and low latitudes (Ling et al. 2013; Xue et al. 2019a). These areas are controlled by the subtropical high, with rare precipitation and a dry climate (Fan et al. 2002). Oases rely heavily on the water supply, the reason for the existence of the oases, and the ecosystem processes and patterns are related to the status of water resources (Hao et al. 2016). Human activities are concentrated in oasis areas. Oases have become important places for human beings to engage in various material production and economic and social activities (Marx 1999). With the shortage of fertile land resources and the pursuit of economic benefits and ecological restoration, the expansion of the oases has been undertaken on a large scale in recent decades. China, Israel, Egypt and other Middle Eastern countries are reclaiming desert lands to enlarge artificial oases for desert greens (Nativ 2004; Clery 2011; Sarant 2017).

Superficially, desert development presumably enhances economic and ecosystem health. However, with the expansion of oases, several issues related to their sustainability have arisen; many oases have experienced severe pressures of surface water (Liu et al. 2018), falling water tables (Feng et al. 2007; Marlet et al. 2009; Kamel et al. 2010), degradation of water quality (Dassi et al. 2018), and soil salinization (Zammouri et al. 2007; Alhammadi and Glenn 2008; Bouksila et al. 2013; Haj-Amor et al. 2017). Oases are also the main agro-ecological environment suitable for malaria transmission, promoting the spread of malaria northward in the Sahara Desert (Deida et al. 2019). Moreover, the disappearance of naturally growing palm forests in oases has been reported (Salama et al. 2018; Lamqadem et al. 2019), indicating the depletion of aquifers. These problems of severe groundwater decline, soil salinization and groundwater pollution caused by desert development can trigger deepening cycles of overexploitation and degradation of groundwater and soil, which will lead to the occurrence of desertification.

In China, oases are mainly scattered in the arid and semi-arid desert areas to the west of Helan Mountain and north of the Qinghai-Tibet Plateau. Many desert regions are characterized by the extensive poverty of their inhabitants. Some desert margins have been reclaimed into farmlands through national programmes and projects, such as “Learn from Tachai in Agriculture” (1964–1978), “Chinese Economic Reform and Opening Up” (1979–present), “Three-North Shelterbelt Development Program” (1979–2050) and “National Program on Combating Desertification” (1991–2000), which has promoted the development of many man-made oases. Consequently, man-made oases have continued to grow in number and in area in northwest China. In northwest China, there is a very large area of arid and semi-arid regions, where ecosystems are extremely vulnerable and sensitive to human disturbance due to severe water scarcity. Groundwater has become the most important source of water in oasis areas because rainfall cannot support a stable water supply in the oasis (Zhao et al. 2018). Oases and deserts are the typical and representative landscapes of the arid and semi-arid regions of northwest China (Zhao and Chang 2014; Li et al. 2017). Oases cover approximately 5% of the total area in the arid and semi-arid regions of China but support over 95% of the total population, making them the foundation for human life and economic development (Li et al. 2016). In addition to administrative measures, the Chinese government allows and encourages private capital to be invested in the reclamation and management of deserts, including new agricultural activities based on cash crops and desert tourism. Furthermore, deserts have become an important location of industrial land due to the sparse population and low price of land. Many enterprises from the southeast coast of China have moved to deserts. Economic benefits and ecological restoration are the leading drivers of desert development, which makes northwest China one of the most influential regions for desert development. In the past few decades, human activities have greatly changed the distribution and allocation of limited water and land resources, which has boosted economic development (Cheng et al. 2014).

Over the past 60 years, because of the “making the desert green” movement, a large number of oases have been reclaimed in the deserts of China, which has been considered an achievement in desert development. However, the sustainability and effectiveness of man-made oasis expansion in combating desertification while promoting economic growth and prosperity remain unclear (Wang et al. 2015). Such knowledge is critical for future desert development in other parts of the world. To address this important knowledge gap, a typical desert-oasis ecotone in northwest China was selected. Comprehensive meteorological, hydrogeological and multisatellite remote-sensing datasets of the desert-oasis ecotone, as well as groundwater simulations, were used to examine the spatial–temporal dynamics of the desert-oasis ecotone and evaluate the long-term impact of man-made oases on the desert environment. Decades of observations in the desert-oasis ecotone provide a unique window to enhance our understanding of how desert and oasis interact and how to achieve sustainable development of desert ecosystems.

MATERIALS AND METHODS

Study region

The study area is located in the middle reach of the Heihe River Basin (HRB), administrated by Linze County, and the northern part of the study are is the Badain Jaran Desert (Fig. 1). The Badain Jaran Desert is China’s second largest shifting desert and covers an area of 50 000 km^2, which continually erodes the oasis while the oasis continues to expand (Dong et al. 2004). The annual precipitation in this region is approximately 108 mm, but the potential evaporation is as high as 2200 mm (Zhuang and Zhao 2014). From the 1960s to the present, the area of the oasis in the study area has increased by 100 km^2 and the population has expanded. China has planted a large number of forests or sand-fixing vegetation, such as *Haloxylon ammodendron*, *Calligonum mongolicum* and *Populus* in the desert, among them *H. ammodendron* is the most dominant (Zhuang and Zhao 2017). Oases are the most important vegetable- and grain-growing areas in the region. Alfalfa, barley, maize and wheat are not desert plants, but they are economically important crops grown in the desert-oasis ecotone with the support of irrigation.

Vegetation greenness

The normalized difference vegetation index (NDVI) is an indicator of vegetation activity or greenness that can be used to assess the presence of green vegetation on land (Luo et al. 2018a). To analyse the changing trends of vegetation during the growing season (May–September), the NDVI was used to characterize vegetation activity. NDVI data were derived from observations by two satellite datasets: Global Inventory Modeling and Mapping Studies (GIMMS) and the Moderate Resolution Imaging Spectroradiometer (MODIS). The GIMMS NDVI dataset covering the period 1982–2015 was produced at spatial and temporal resolutions of 5 km and 15 days, respectively (https://ecocast.arc.nasa.gov/data/pub/gimms/) (Nemani et al. 2009). The MODIS NDVI dataset for the period 2000–2015 had a 16-d composite and a 1-km spatial resolution (https://modis.gsfc.nasa.gov) (Stefanov and Netzband 2005). Averages of the monthly NDVI data during

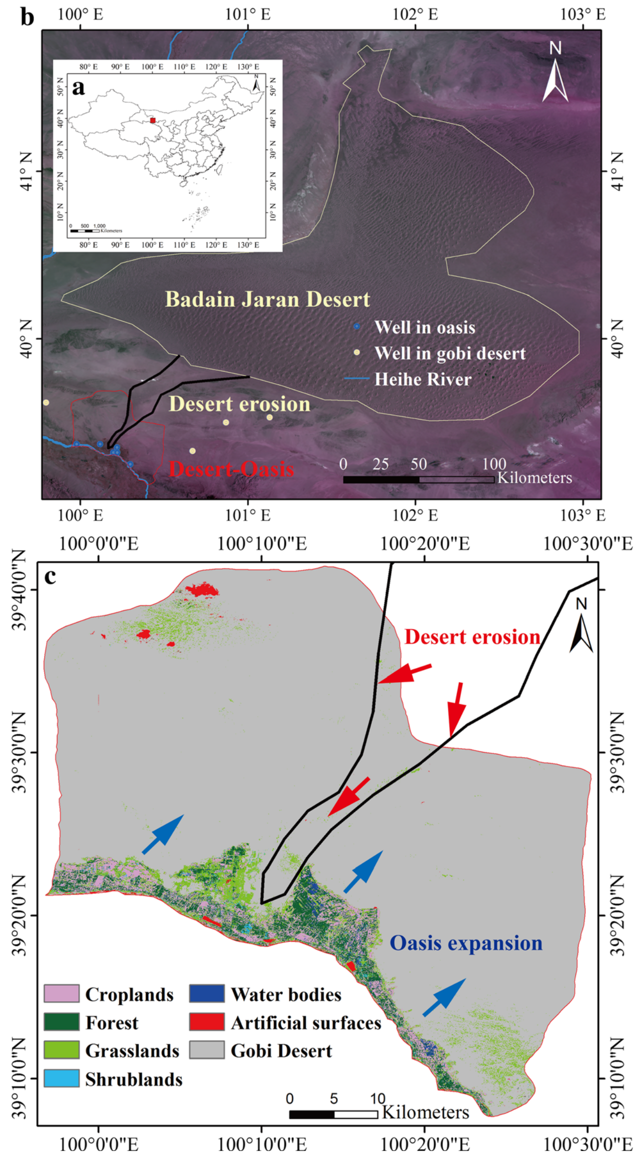

Fig. 1 Geography of the study area. **a** Location of the study area; **b** desert-oasis zone using data from the GaoFen-4 satellite, the red area is the study area; and **c** land cover of the desert-oasis zone in 2015

the growing season (May–September) were used to infer vegetation growth.

Meteorological data

Meteorological data, including air temperature and precipitation, were used to evaluate the regional climate change of the study area, while variables such as visibility, wind speed and the start and end time of sandstorms were employed to analyse the changing trend and the possible inhibition of sandstorms in this area. Meteorological and sandstorm observation data were obtained from the China Meteorological Administration (http://www.cma.gov.cn/) from permanent meteorological stations with daily meteorological records for the period 1953–2015.

Soil and groundwater

A major research plan entitled "Integrated research on eco-hydrological process of the Heihe River Basin", also known as the "Heihe Plan" was launched in 2010, describing a comprehensive eco-hydrological experiment to observe and collect long-term historical data in the basin (Li et al. 2013). Surface and groundwater observations were acquired from the Heihe Plan (http://heihedata.org/) (Li et al. 2017). Spatial distribution data of the groundwater table, with an approximate spatial resolution of 1 km, were simulated using the stream-aquifer water interaction scheme CLM_LTF (Zeng et al. 2016a) to represent the processes involved in surface and groundwater interaction. The current study coupled this model with the Community Land Model CLM 4.5 and integrated the schemes of human water regulation and the groundwater lateral flow processes during 1981–2013 (http://heihedata.org/data/7b9b177c-2c07-491a-bbd8-78a5e84a12a4) (Zeng et al. 2016b). The input data of the model are derived from measurements of wells, eddy covariance, weather stations and evapotranspiration remote-sensing data of the Heihe Plan (Li et al. 2013).

Monthly equivalent water heights were derived from the Center for Space Research (CSR) Gravity Recovery and Climate Experiment (GRACE) RL05 Mascon Solutions dataset during 2002–2015 to evaluate the groundwater depletion (http://www2.csr.utexas.edu/grace/RL05_mascons.html) (Save et al. 2016).

To assess soil and groundwater contamination, soil nitrate accumulations and nitrate concentrations from groundwater observations during 2000–2015 were derived from the Chinese Ecosystem Research Network (CERN, http://www.cern.ac.cn) (Fu et al. 2010). These data are derived from the average of multiple samplings in soil groundwater from observation wells between 2000 and 2015.

Statistical and trend test

Linear and LOESS regression analysis methods were performed to quantify the changes in satellite, climate and observation data. The sequential Mann–Kendall (MK) trend test was used to statistically assess whether there was a trend shift in the climate data (Fraile 1993). The original MK trend test can be calculated using Eqs. (1) and (2):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}\left(x_j - x_i\right), \quad (i = 2, 3, 4 \ldots n) \tag{1}$$

$$\operatorname{sign}(x_j - x_i) = \begin{cases} 1 & if\ x_j - x_i > 0 \\ 0 & if\ x_j - x_i = 0 \\ -1 & if\ x_j - x_i < 0 \end{cases} \tag{2}$$

Two series for the MK trend test, a progressive test (uf_i) and a backward test (ub_i), were established. The sequential progressive series uf_i was calculated using Eq. (3):

$$uf_i = \frac{S_i - E(S_i)}{\sqrt{Var(S_i)}}, \quad (i = 1, 2, 3 \ldots n) \tag{3}$$

where uf_i = 0, $E(S_i)$ represents the mean, and $Var(S_i)$ represents the variance of S_i. The sequential backward (ub_i) analysis of the sequential MK trend test is calculated starting from the end of the time series data. If the values cross each other, diverge beyond a specific threshold value and exceed the 95% confidence level, then there is a statistically significant trend shift point.

Evaluation of long-term trend change

Trend analysis was conducted to calculate the long-term spatial trend of NDVI and groundwater table, shown in Eq. (4). The *Ind* in Eq. (4) represents these variables, Ind_i represents the variable in year i, and n represents the total number of years. Using the groundwater table as an example, a positive slope value denotes that the groundwater table is increasing, which indicates an improvement in groundwater, while a negative value denotes that the groundwater table is decreasing, which represents a depletion in groundwater; a slope of zero suggests that there is no change (Chen et al. 2014). Quantitative data were estimated with a two-sample Student's t test, where $P < 0.05$ is considered statistically significant.

$$\text{Trend} = \frac{n \times \sum_{i=1}^{n} (i \times Ind_i) - \left(\sum_{i=1}^{n} i\right) \times \left(\sum_{i=1}^{n} ind_i\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{4}$$

RESULTS

Meteorological factors and vegetation greenness

Surface air temperature of the study area significantly increased by 0.24 °C per decade from 1953 to 2015 ($P < 0.001$, Fig. 2a). Total precipitation levels exhibited a slight increase of 2.15 mm per decade (Fig. 2b). The study area experienced a warming and wetting phenomenon.

Oasis retreats were observed mainly in the 1970s, and the retreat area was mainly distributed along the edge of the river oasis. The large-scale expansion of the oasis began in the 1960s and the late 1980s, and the oasis area tended to stabilize after 2000. The oasis area has increased at a rate of 2.01 km^2 $year^{-1}$, more than doubling since 1963. New oases also formed in the southeast and northwest corners of the study area. The "Heihe River Water Allocation" programme (2000–present), which aims to increase the supply of water for the downstream of the Heihe River, has slowed the expansion of oases due to the decline in surface water supply (Fig. 2c).

The NDVI generally increased, especially along the edge of the oasis away from the river. In the Gobi, changes in vegetation activity slightly increased. Severe vegetation deterioration was observed near the river within the oasis (Fig. 2d). The NDVI of the growing season exhibited a significant and positive increasing trend of 0.0017 and 0.0038 $year^{-1}$ based on GIMMS and MODIS datasets, respectively, during 2000–2015 ($P < 0.001$). During 1982–2000, the increase in NDVI was 0.0001 $year^{-1}$, which indicated a significant increase in the oasis area since 2000 (Fig. 2e).

Sandstorms

Severe and widespread sandstorms in the study area mainly occur from March to May, especially in April. Based on meteorological observations within the oasis (Zhou 2003; Fu et al. 2010), the average sandstorm frequency and duration were 10.55 events and 833 min annually, respectively. The maximum frequency and duration occurred in 1966, which experienced a frequency of 28 sandstorm events and a duration of 3411 min (Fig. 3a, b). The frequency and duration of sandstorms significantly decreased by 0.35 events $year^{-1}$ and 23.07 min $year^{-1}$ ($P < 0.001$), respectively. A strong sandstorm was defined as a visibility level ≤ 1 during 1954–1979 and visibility distance < 200 m during 1980–2015. Strong sandstorms occurred 7 times in 32 years and 11 times in 30 years during 1954–1986 and 1986–2015, respectively (Fig. 3c, d).

Water resources

Water withdrawals from both surface and groundwater were considerable in this area, and the mean annual surface water and groundwater extractions during 1984–2015 were approximately 180 and 20 million m^3, respectively. Irrigation accounted for approximately 80% of the total water use. The withdrawal of surface water significantly decreased by 3.1 million m^3 $year^{-1}$ ($P < 0.001$) after the "Heihe River Water Allocation Scheme" plan was implemented in 2000 by local authorities. To compensate for the restriction in surface water use, there was a significant increase in groundwater irrigation of 1.4 million m^3 $year^{-1}$

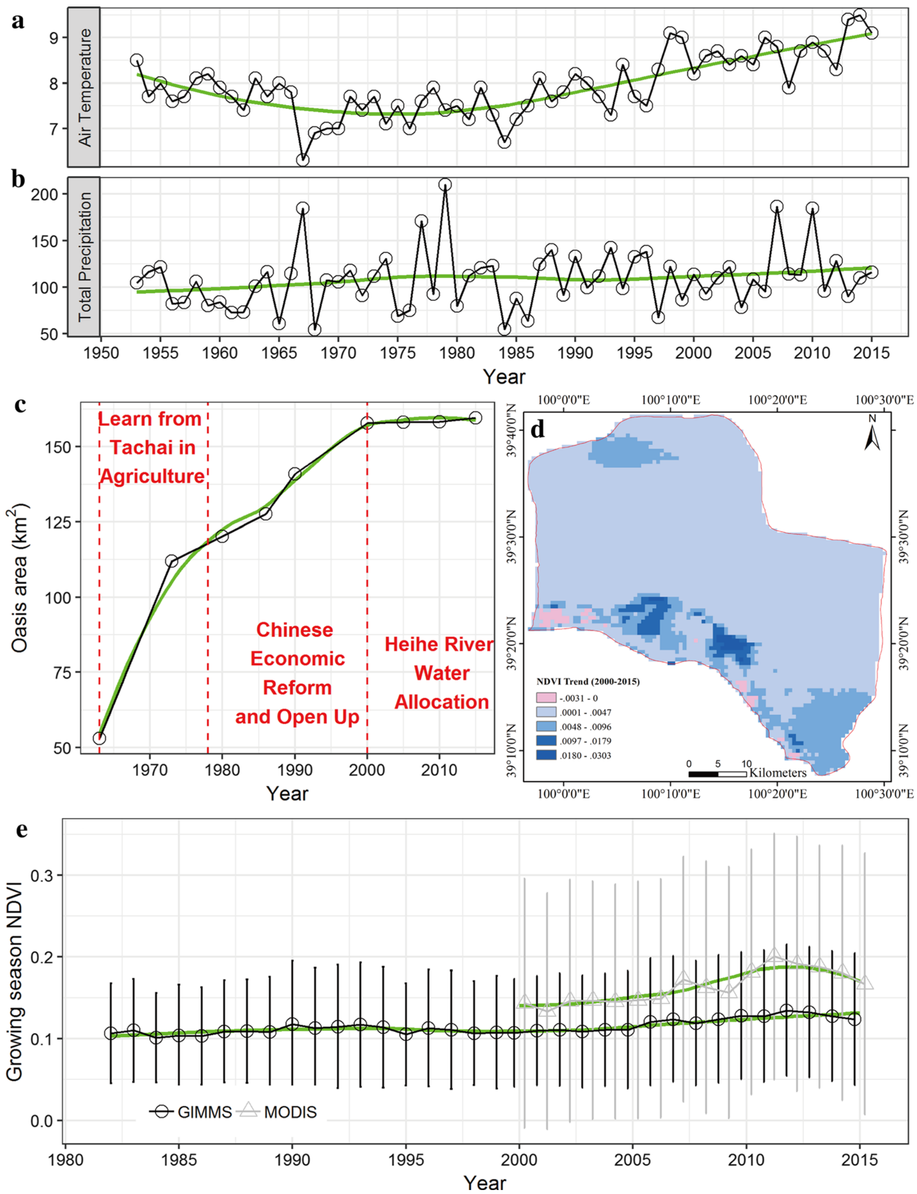

Fig. 2 Annual mean air temperature, total precipitation, oasis area and NDVI changes in the study area. **a** Annual mean air temperature during 1953–2015 (unit: °C); **b** annual total precipitation during 1953–2015 (unit: mm); **c** oasis area changes during 1963–2015. There are three major periods: (1) "Learn from Tachai in Agriculture", starting in 1963; (2) "Chinese Economic Reform and Open Up", starting in 1978; (3) "Heihe River Water Allocation", starting in 2000. **d** Spatial trends in the growing season NDVI from May to September during 2000–2015 (MODIS); **e** growing season NDVI trends from May to September during 1982–2015 (GIMMS) and 2000–2015 (MODIS)

(Fig. 4a). Overall, the groundwater level in the study area during 1984–2015 decreased on average by 1.0–3.0 m but reached 18.5 m in some areas (Fig. 4b). The agricultural water demand increased the number of wells by 95% between 2000 and 2010, most of which were concentrated in the man-made oasis and desert ecotone. Over the last 30 years, groundwater exploitation has lowered the groundwater table by approximately 4.13 and 10.69 m in the oasis and the Gobi Desert, respectively. The groundwater table has significantly and linearly dropped at average rates of 0.13 and 0.36 m year^{-1} in the oasis and the Gobi Desert, respectively ($P < 0.001$) (Fig. 4c–d). Compared to the early period (1981–2000), the groundwater table in the later period (2000–2015) has been declining in the Gobi Desert zone. The groundwater table rose in certain areas near the Heihe River but fell in the Gobi Desert.

Groundwater changes were also estimated from the Gravity Recovery and Climate Experiment (GRACE)-derived equivalent water height (Save et al. 2016). The rates of groundwater depletion based on GRACE in the oasis and the desert zone were 0.13 and 0.21 cm year^{-1}, respectively (Fig. 4e). The groundwater storage in the

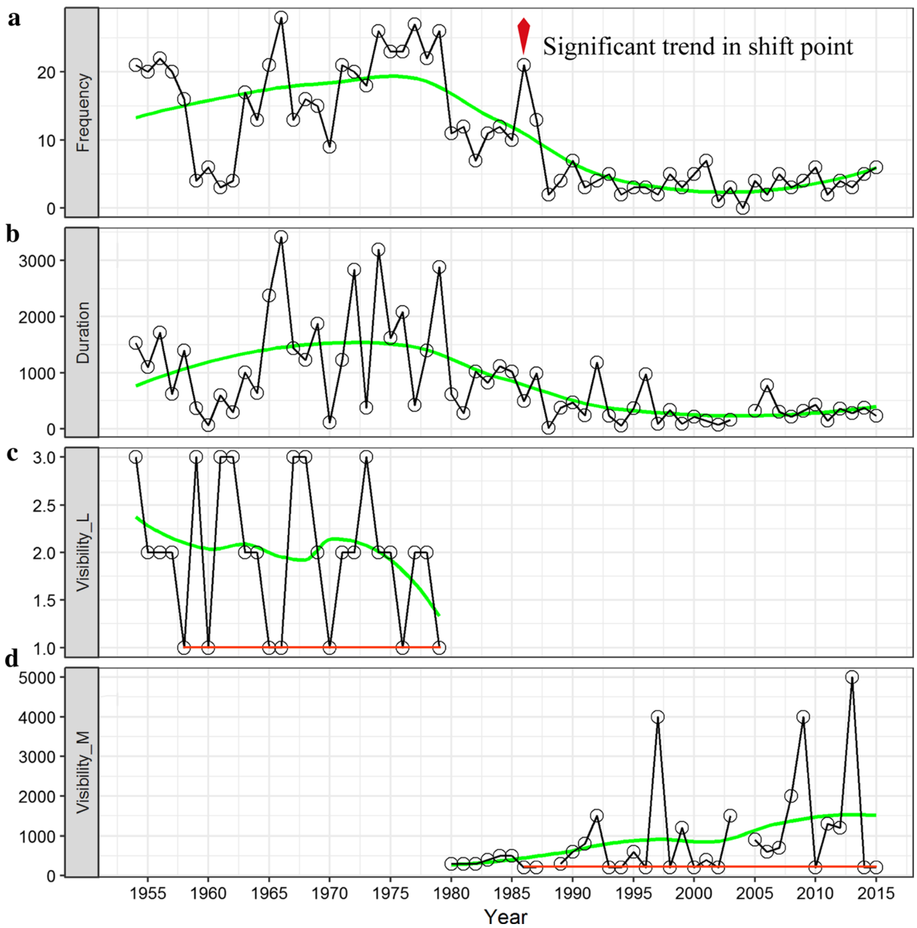

Fig. 3 Sandstorm statistical data in the study area during 1954–2015. **a** Frequency of sandstorms; **b** total duration of sandstorms (unit: min); **c** minimum visibility of sandstorms during 1954–1979 (unit: level); and **d** minimum visibility of sandstorms during 1980–2015 (unit: m). The two red lines in (**c**, **d**) indicate that a strong sandstorm occurred in that year (i.e., 1958, 1960, 1965, 1966, 1970, 1976, 1979, 1986, 1987, 1993, 1994, 1996, 1998, 2000, 2002, 2010, 2014 and 2015)

study area was significantly reduced ($P < 0.001$), which was consistent with the simulation result. In particular, the decreasing rate of groundwater in the desert was greater than that of the oasis.

Soil and water pollution

For the development of farmlands in the desert, the application of nitrogen fertilizer is required due to insufficient soil fertility. Nitrate (NO_3^-) concentrations from soil and groundwater situated in three different oasis zones (i.e., typical old croplands, newly cultivated sandy croplands and the sand-fixing belt of the oasis) were assessed using data collected between 2000 and 2015 (Fig. 5a). Most of the observed traditional croplands are closer to the Heihe River, and the observed newly cultivated sandy croplands and the sand-fixing belt are near the centre of the oasis. Although 78% of sampled groundwater nitrate concentrations were lower than those of the Class 3 Chinese national drinking water standard ($\leq$ 20 mg/L), the results indicated that nitrate concentrations increased in response to the increased use of nitrogen fertilizer. After decades of cultivation, soil nitrate accumulation was much higher in the old oasis than those in the new-cultivated sandy croplands (i.e., the new oasis). As a consequence, the new oasis requires more fertilizer supplies, and the nitrate concentrations in its groundwater were higher than those in the old oasis. The relationship between nitrate concentrations and depths showed that the groundwater nitrate concentrations were significantly and negatively correlated with depth ($r = -0.40$, $P < 0.05$). It is clear from these data that contaminated groundwater was ubiquitous with high variability in deep aquifers and shallow groundwater (Fig. 5b).

DISCUSSION

Two national programmes and projects, “Learn from Tachai in Agriculture” and “Chinese Economic Reform and Opening Up”, which were implemented to “modify

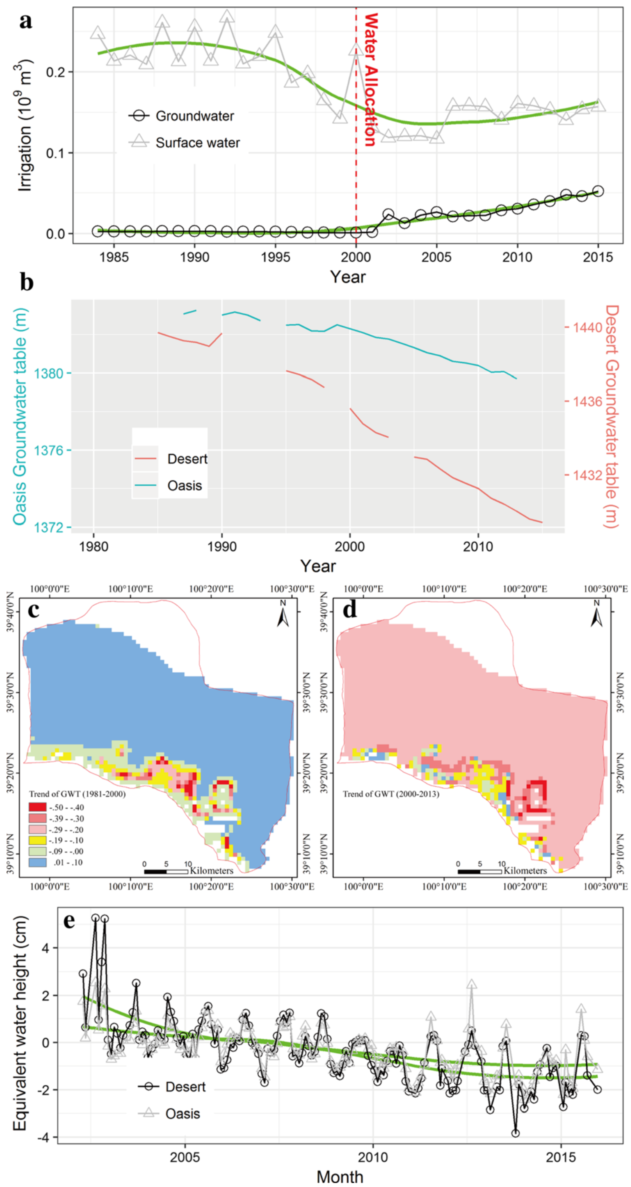

Fig. 4 Water resource dynamics. **a** Surface and groundwater use during 1984–2015 in the study area; **b** mean water table changes in wells during 1980–2015 in the oasis (left *y*-axis) and desert (right *y*-axis) zones; **c** spatial trends in the water table using the CLM_LTF model during 1981–2000; **d** spatial trends in the water table during 2000–2013 using the CLM_LTF model; and **e** monthly equivalent water heights using GRACE data during 2002–2015 in the oasis and desert zones

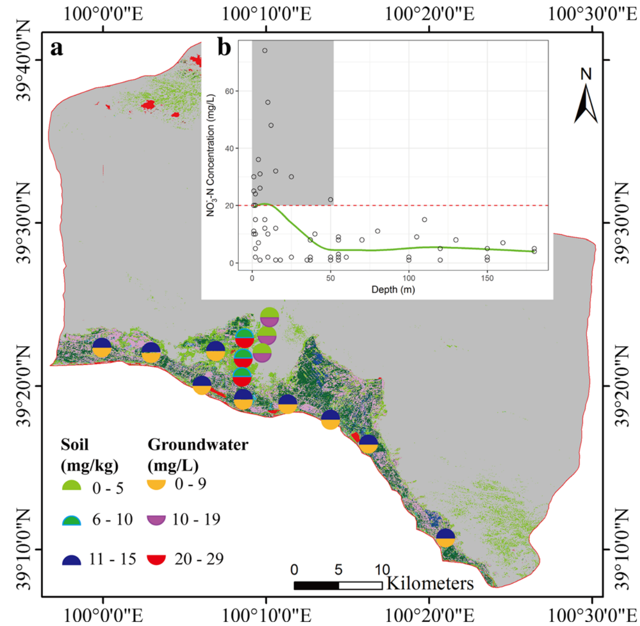

Fig. 5 Soil nitrate accumulation and groundwater nitrate contamination in the oasis and the Gobi Desert zones of the study area. **a** Soil nitrate accumulation (top-coloured semicircles) and groundwater nitrate contamination use (bottom-coloured semicircles); **b** the relation between groundwater NO^{3-}-N concentrations and sample depths of wells; the water quality in the shaded area exceeds the Class 3 Chinese national drinking water standard (above the red dashed line)

the mountains, deserts and lakes to create farmland", facilitated the massive expansion of oases through administrative measures. Socioeconomic and environmental factors were the main driving force in the promotion of oasis development in this study area. As a consequence of desert development, the area of oasis continues to expand and the desert intrusion has been limited. Vegetation activity and air quality have been improved to a certain extent, the frequency and duration of sandstorms have decreased, and the local economy continues to develop. At the same time, potential costs of desert development are also emerging.

Growing strong sandstorms

Sandstorms are disastrous weather events that occur most commonly in the desert and adjacent areas and are often associated with major agricultural disruption and environmental issues. The occurrence and development of sandstorms are important causes for the acceleration of land degradation and, to a certain extent, result in the expansion of desert erosion. Local Chinese histories have documented sandstorms in the study area since AD 351 (Sivakumar 2005). Northwest China is a region where severe sandstorms occur frequently and cause serious economic and environmental damage in the affected areas (Xu et al. 2017). The Badain Jaran Desert is one of the main sources of sandstorms (Liu et al. 2017).

A number of national programmes and projects for combating desertification have been launched. China has been advocating the planting of suitable trees and other plants in the desert to limit the effects of dryland degradation and contain desert expansion. Vast belts of vegetation have been planted across the northwest arid lands of China, known as the "Great Green Wall", the largest afforestation programme undertaken in human history (Parungo et al. 1994; Su et al. 2007). The Great Green Wall, which includes planted sand-fixing vegetation and crops in the oasis, can reduce wind from the desert and resist sandstorms (Meng et al. 2012; Xue et al. 2019b). With the continued expansion of the oasis and the continued advancement of desertification control efforts, sandstorms seem to have been alleviated and suppressed in the study area. However, although the duration of the sandstorm season in the study area has diminished to some extent since the late 1990s, the frequency of strong sandstorms has increased.

Rising water resource exploitation

Water resources play a crucial role in the development of desert-oasis ecosystems, but northwest China suffers from a serious shortage of water resources. An increasingly serious problem arises through the rapidly increasing water demands of agricultural irrigation and industrial use. The "Heihe River Water Allocation Scheme" plan required that the upstream and midstream regions of the HRB provide more surface water to the downstream regions of the HRB, which has led to the overexploitation of groundwater and has resulted in a decline in the groundwater table due to the substantial decline in surface water acquisition. The April–October period is the annual irrigation period when groundwater overexploitation becomes serious, resulting in a continuous decrease in the groundwater table. This type of groundwater table is dynamically distributed because the groundwater aquifer is permeable and groundwater and surface water interactions are strong (Zeng et al. 2016a). According to the spatial variation trend of the groundwater table obtained from regional groundwater simulation (Zeng et al. 2016a), deepened groundwater table depths occurred in the oasis zone and away from the river area, which corresponded with groundwater exploitation. Although groundwater can be replenished from surface water recharge close to the Heihe River, the decline in the water table indicates that groundwater extraction has created a deficit in the water budget surrounding Gobi Desert groundwater, and this water resource is unsustainable in regions of intensive oasis development.

The expansion of the cultivated area is mostly concentrated in the man-made oasis and desert ecotone, away from the surface water supply source, without a conveyance system of irrigation; thus, the system relies on groundwater for irrigation, which results in the decrease of the water table (Cheng et al. 2014; Li et al. 2016). Many sand-fixing desert shrubs, such as *Haloxylon ammodendron*, the most common desert vegetation in the desert-oasis ecotone, obtain water mainly from groundwater. A lowered water table affects the water source of this sand-fixing vegetation, which will face more severe water limitation in the future (Zhou et al. 2017).

Increasing soil and water pollution

Since the 1980s, China's consumption of nitrogen fertilizer and plastic mulching, including greenhouse film, has increased substantially. Film mulching technology can remarkably improve crop yields by effectively maintaining soil moisture and temperature and reducing water evaporation, which is of particular importance and has wide use in the arid and semi-arid regions of China (Zhang et al. 2016; Luo et al. 2018b). Because the study area belongs to primary production areas for vegetables and grains, plastic mulching is widely used in agriculture for its instant economic benefits (Luo et al. 2018b). Based on the first agricultural census of pollution sources in 2008, more than 80% of the agricultural area has been covered with plastic mulching technology in the study area. Residual plastic film also showed an upward trend due to ineffective recycling mechanisms and policies (Zhang et al. 2016).

Although plastic mulching and nitrogen fertilizer have significantly increased productivity, high nitrogen application rates and residual plastic film may increase soil and groundwater pollution (Steinmetz et al. 2016). For example, with the increase of the residual plastic mulching in the soil, the negative effects of the residual film due to its resistance to degradation are becoming increasingly prominent, such as soil fertility degradation, decline in crop yield and increased environmental pollution. Fertility degradation requires more fertilizer to be used for crop growth, and fertilizers are identified as the main source of nitrate in soil and groundwater in heavily cultivated areas of China (Han et al. 2016). Excessive NO_3^- input has been more pronounced in desert ecosystems, leading to an increase in serious nitrate groundwater pollution (Gates et al. 2008; Gu et al. 2015). Fertilizer and crop residues are also considered to contribute significantly to nitrate in groundwater (Zhang et al. 2013; Zhai et al. 2017). Sandy soils have a lower water-holding capacity and, therefore, a greater potential to lose nitrate from leaching when compared with silt loam or clay loam soils (Li et al. 2018). The newly reclaimed oasis is mainly composed of sandy soil, in which pesticides and fertilizers are capable of entering and polluting groundwater (Zhang et al. 2013, 2019). If new oases are to be reclaimed, organic manure needs to be used to reduce groundwater pollution (Sun et al. 2012). Addressing the issue of groundwater pollution is urgent to stop further contamination of deep aquifers, which are the most important irrigation and drinking water sources in arid and semi-arid areas. Improving nitrogen fertilizer and irrigation management practices in the desert-oasis zone is key to managing groundwater NO_3^- concentrations.

In recent years, many industries in China have moved to northwest China, which has caused pollution to migrate to China's rural areas and even desert zones. Under the double pressure of China's economic development and environmental protection, the desert has become a preferred location for sewage disposal. Deserts are relatively difficult to regulate, providing an attractive location for polluting emissions. Due to multiple factors, such as pollution cleaning cost, and the difficulty of regulating and monitoring large areas, many enterprises have minimally invested in sewage facilities and have discharged waste water into the desert (e.g., the Tengger Desert pollution incident (Miao et al. 2015). The drainage of pollution into the desert is a new trend; however, wastewater can easily infiltrate into the sand, which eventually pollutes the groundwater and is highly detrimental to the ecosystem. Local environmental bureaus are not able to withstand pressure due to economic interests. According to the survey, there are more than 40 wells with a depth of 180 metres in the desert zone of the study area. These wells are all used by local enterprises. Furthermore, a large amount of groundwater is pumped by these enterprises, causing a drop in the water table in the desert. At present, although air quality and the frequency of sandstorm events have exhibited a certain reduction, the loss of life and property is still serious (Zhu et al. 2016).

CONCLUSIONS

The costs of desert development have included a series of environmental problems in the desert-oasis ecotone, with increasing frequency of strong sandstorms and severe decline in groundwater. Pollution has been diverted from the atmosphere to the underground and from the city to the remote areas, including deserts. Moreover, deterioration of water quality endangers the future use of existing water in oasis areas and may cause severe ecological and environmental problems. These problems seriously threaten the sustainable development of oases, the living environments of local residents and the quality of life. This comprehensive regional-scale assessment can help improve the understanding of the unique features and resources of fragile ecosystems, maximize the benefits of and reduce the environmental pressures upon the desert-oasis ecotone, and therefore sustain the precious oasis ecosystems distributed in arid and semi-arid regions. It is necessary to strengthen the supervision of the industrial pollution and improve the utilization of organic fertilizer and water in order to ensure that the greening of China's deserts is sustainable. Developing desert into oasis has benefits, but maintaining healthy ecosystem services is a great challenge.

Acknowledgements We are grateful to Wolfgang Kinzelbach for valuable feedback on the manuscript. This research was jointly supported by the Key Research Project of Frontier Science of Chinese Academy of Sciences (QYZDJ-SSW-DQC040), and the National Natural Science Foundation of China (41877545, 41871065). Lixin Wang acknowledges partial support from Division of Earth Sciences of National Science Foundation (NSF EAR-1554894) and the President's International Research Awards from Indiana University.

REFERENCES

Alhammadi, M.S., and E.P. Glenn. 2008. Detecting date palm trees health and vegetation greenness change on the eastern coast of the United Arab Emirates using SAVI. *International Journal of Remote Sensing* 29: 1745–1765.

Bouksila, F., A. Bahri, R. Berndtsson, M. Persson, J. Rozema, and S.E.A.T.M. Van der Zee. 2013. Assessment of soil salinization risks under irrigation with brackish water in semiarid Tunisia. *Environmental and Experimental Botany* 92: 176–185.

Chen, B.X., X.Z. Zhang, J. Tao, J.S. Wu, J.S. Wang, P.L. Shi, Y.J. Zhang, and C.Q. Yu. 2014. The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. *Agricultural and Forest Meteorology* 189: 11–18.

Cheng, G., X. Li, W. Zhao, Z. Xu, Q. Feng, S. Xiao, and H. Xiao. 2014. Integrated study of the water–ecosystem–economy in the Heihe River Basin. *National Science Review* 1: 413–428.

Clery, D. 2011. Greenhouse-power plant hybrid set to make Jordan's Desert Bloom. *Science* 331: 136–136.

Dassi, L., M. Tarki, H. El Mejri, and M. Ben Hammadi. 2018. Effect of overpumping and irrigation stress on hydrochemistry and hydrodynamics of a Saharan oasis groundwater system. *Hydrological Sciences Journal* 63: 227–250.

Deida, J., R. Tahar, Y.O. Khalef, K.M. Lekweiry, A. Hmeyade, M.L.O. Khairy, F. Simard, H. Bogreau, et al. 2019. Oasis Malaria, Northern Mauritania1. *Emerging Infectious Diseases* 25: 273–280.

Dong, Z., T. Wang, and X. Wang. 2004. Geomorphology of the megadunes in the Badain Jaran Desert. *Geomorphology* 60: 191–203.

Fan, Z., X. Xia, Y. Shen, K. Alishir, R. Wang, S. Li, and Y. Ma. 2002. Utilization of water resources, ecological balance and land desertification in the Tarim Basin, Xinjiang. *Science in China, Series D: Earth Sciences* 45: 102–108.

Feng, S., S. Kang, Z. Huo, S. Chen, and X. Mao. 2007. Neural networks to simulate regional ground water levels affected by human activities. *Ground Water* 46: 80–90.

Fraile, R. 1993. On the statistical analysis of series of observations. *Atmospheric Research* 29: 274.

Fu, B.J., S.G. Li, X.B. Yu, P. Yang, G.R. Yu, R.G. Feng, and X.L. Zhuang. 2010. Chinese ecosystem research network: Progress and perspectives. *Ecological Complexity* 7: 225–233.

Gates, J.B., J.K. Böhlke, and W.M. Edmunds. 2008. Ecohydrological factors affecting nitrate concentrations in a phreatic desert aquifer in northwestern China. *Environmental Science and Technology* 42: 3531–3537.

Gu, B., X. Ju, J. Chang, Y. Ge, and P.M. Vitousek. 2015. Integrated reactive nitrogen budgets and future trends in China. *Proceedings of the National academy of Sciences of the United States of America* 112: 8792–8797.

Haj-Amor, Z., T. Tóth, M.-K. Ibrahimi, and S. Bouri. 2017. Effects of excessive irrigation of date palm on soil salinization, shallow groundwater properties, and water use in a Saharan oasis. *Environmental Earth Sciences* 76: 590.

Han, D., M.J. Currell, and G. Cao. 2016. Deep challenges for China's war on water pollution. *Environmental Pollution* 218: 1222–1233.

Hao, X., W. Li, and H. Deng. 2016. The oasis effect and summer temperature rise in arid regions—case study in Tarim Basin. *Scientific Reports* 6: 35418.

Kamel, S., L. Dassi, and K. Zouari. 2010. Approche hydrogéologique et hydrochimique des échanges hydrodynamiques entre aquifères profond et superficiel du bassin du Djérid, Tunisie. *Hydrological Sciences Journal* 51: 713–730.

Lamqadem, A.A., G.M. Afrasinei, and H. Saber. 2019. Analysis of Landsat-derived multitemporal vegetation cover to understand drivers of oasis agroecosystems change. *Journal of Applied Remote Sensing* 13: 014517.

Li, B., L. Wang, K.F. Kaseke, R. Vogt, L. Li, and M.K. Seely. 2018. The impact of fog on soil moisture dynamics in the Namib Desert. *Advances in Water Resources* 113: 23–29.

Li, X., G.D. Cheng, S.M. Liu, Q. Xiao, M.G. Ma, R. Jin, T. Che, Q.H. Liu, et al. 2013. Heihe Watershed Allied Telemetry Experimental Research (HiWATER): Scientific objectives and experimental design. *Bulletin of the American Meteorological Society* 94: 1145–1160.

Li, X., S. Liu, Q. Xiao, M. Ma, R. Jin, T. Che, W. Wang, X. Hu, et al. 2017. A multiscale dataset for understanding complex ecohydrological processes in a heterogeneous oasis system. *Scientific Data* 4: 170083.

Li, X., K. Yang, and Y. Zhou. 2016. Progress in the study of oasis-desert interactions. *Agricultural and Forest Meteorology* 230–231: 1–7.

Ling, H., H. Xu, J. Fu, Z. Fan, and X. Xu. 2013. Suitable oasis scale in a typical continental river basin in an arid region of China: A case study of the Manas River Basin. *Quaternary International* 286: 116–125.

Liu, F., Y. Chen, H. Lu, and H. Shao. 2017. Albedo indicating land degradation around the Badain Jaran Desert for better land resources utilization. *Science of the Total Environment* 578: 67–73.

Liu, Y., J. Xue, D. Gui, J. Lei, H. Sun, G. Lv, and Z. Zhang. 2018. Agricultural oasis expansion and its impact on oasis landscape patterns in the southern margin of Tarim Basin, Northwest China. *Northwest China. Sustainability* 10: 1957.

Luo, L., W. Ma, Y. Zhuang, Y. Zhang, S. Yi, J. Xu, Y. Long, D. Ma, et al. 2018a. The impacts of climate change and human activities on alpine vegetation and permafrost in the Qinghai-Tibet Engineering Corridor. *Ecological Indicators* 93: 24–35.

Luo, L., Z. Wang, M. Huang, X. Hui, S. Wang, Y. Zhao, H. He, X. Zhang, et al. 2018b. Plastic film mulch increased winter wheat grain yield but reduced its protein content in dryland of northwest China. *Field Crops Research* 218: 69–77.

Marlet, S., F. Bouksila, and A. Bahri. 2009. Water and salt balance at irrigation scheme scale: A comprehensive approach for salinity assessment in a Saharan oasis. *Agricultural Water Management* 96: 1311–1322.

Marx, E. 1999. Oases in south Sinai. *Human Ecology* 27: 341–357.

Meng, X., S. Lu, T. Zhang, Y. Ao, S. Li, Y. Bao, L. Wen, and S. Luo. 2012. Impacts of inhomogeneous landscapes in oasis interior on the oasis self-maintenance mechanism by integrating numerical model with satellite data. *Hydrology and Earth System Sciences* 16: 3729–3738.

Miao, X., Y. Tang, and C.W.Y. Wong. 2015. Environment: Polluters migrate to China's poor areas. *Nature* 518: 483–483.

Nativ, R. 2004. Can the desert bloom? Lessons learned from the Israeli case. *Groundwater* 42: 651–657.

Nemani, R., H. Hashimoto, P. Votava, F. Melton, W. Wang, A. Michaelis, L. Mutch, C. Milesi, et al. 2009. Monitoring and forecasting ecosystem dynamics using the Terrestrial Observation and Prediction System (TOPS). *Remote Sensing of Environment* 113: 1497–1509.

Parungo, F., Z. Li, X. Li, D. Yang, and J. Harris. 1994. Gobi dust storms and The Great Green Wall. *Geophysical Research Letters* 21: 999–1002.

Salama, F.M., M.M. Abd El-Ghani, A.A.E.R. Amro, A.E.S. Gaafar, and A.A.E.M. Abd El Galil. 2018. Vegetation dynamics and species diversity in a Saharan Oasis. *Egypt. Notulae Scientia Biologicae* 10: 363–372.

Sarant, L. 2017. Egypt: Space to grow. *Nature* 544: S14–S16.

Save, H., S. Bettadpur, and B.D. Tapley. 2016. High-resolution CSR GRACE RL05 mascons. *Journal of Geophysical Research: Solid Earth* 121: 7547–7569.

Sivakumar, M. 2005. Impacts of sand/dust storms on agriculture. In *Natural disasters and extreme events in agriculture*, ed. M.V.K. Sivakumar, R.P. Motha, and H.P. Das. Berlin: Springer.

Stefanov, W.L., and M. Netzband. 2005. Assessment of ASTER land cover and MODIS NDVI data at multiple scales for ecological characterization of an arid urban center. *Remote Sensing of Environment* 99: 31–43.

Steinmetz, Z., C. Wollmann, M. Schaefer, C. Buchmann, J. David, J. Tröger, K. Muñoz, O. Frör, et al. 2016. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? *Science of the Total Environment* 550: 690–705.

Su, Y.Z., W.Z. Zhao, P.X. Su, Z.H. Zhang, T. Wang, and R. Ram. 2007. Ecological effects of desertification control and desertified land reclamation in an oasis–desert ecotone in an arid region: A case study in Hexi Corridor, northwest China. *Ecological Engineering* 29: 117–124.

Sun, B., L. Zhang, L. Yang, F. Zhang, D. Norse, and Z. Zhu. 2012. Agricultural non-point source pollution in China: Causes and mitigation measures. *Ambio* 41: 370–379.

Wang, T., X. Xue, L. Zhou, and J. Guo. 2015. Combating aeolian desertification in northern China. *Land Degradation and Development* 26: 118–132.

Xu, W., Y. Xiao, J. Zhang, W. Yang, L. Zhang, V. Hull, Z. Wang, H. Zheng, et al. 2017. Strengthening protected areas for biodiversity and ecosystem services in China. *Proceedings of the National Academy of Sciences of the United States of America* 114: 1601–1606.

Xue, J., D. Gui, J. Lei, H. Sun, F. Zeng, D. Mao, Q. Jin, and Y. Liu. 2019a. Oasification: An unable evasive process in fighting against desertification for the sustainable development of arid and semiarid regions of China. *CATENA* 179: 197–209.

Xue, J., D. Gui, J. Lei, H. Sun, F. Zeng, D. Mao, Z. Zhang, Q. Jin, et al. 2019b. Oasis microclimate effects under different weather events in arid or hyper arid regions: A case analysis in southern Taklimakan desert and implication for maintaining oasis sustainability. *Theoretical and Applied Climatology* 137: 89–101.

Zammouri, M., T. Siegfried, T. El-Fahem, S. Kriâa, and W. Kinzelbach. 2007. Salinization of groundwater in the Nefzawa oases region, Tunisia: Results of a regional-scale hydrogeologic approach. *Hydrogeology Journal* 15: 1357–1375.

Zeng, Y., Z. Xie, Y. Yu, S. Liu, L. Wang, B. Jia, P. Qin, and Y. Chen. 2016a. Ecohydrological effects of stream–aquifer water interaction: A case study of the Heihe River basin, northwestern China. *Hydrology and Earth System Sciences* 20: 2333–2352.

Zeng, Y., Z. Xie, Y. Yu, S. Liu, L. Wang, J. Zou, P. Qin, and B. Jia. 2016b. Effects of anthropogenic water regulation and groundwater lateral flow on land processes. *Journal of Advances in Modeling Earth Systems* 8: 1106–1131.

Zhai, Y., X. Zhao, Y. Teng, X. Li, J. Zhang, J. Wu, and R. Zuo. 2017. Groundwater nitrate pollution and human health risk assessment by using HHRA model in an agricultural area, NE China. *Ecotoxicology and Environmental Safety* 137: 130–142.

Zhang, X., Z. Xu, X. Sun, W. Dong, and D. Ballantine. 2013. Nitrate in shallow groundwater in typical agricultural and forest ecosystems in China, 2004–2010. *Journal of Environmental Sciences (China)* 25: 1007–1014.

Zhang, D., H. Liu, W. Hu, X. Qin, X. Ma, C. Yan, and H. Wang. 2016. The status and distribution characteristics of residual mulching film in Xinjiang, China. *Journal of Integrative Agriculture* 15: 2639–2646.

Zhang, Y., W. Zhao, T.E. Ochsner, B.M. Wyatt, H. Liu, and Q. Yang. 2019. estimating deep drainage using deep soil moisture data under young irrigated cropland in a desert-oasis ecotone. *Northwest China. Vadose Zone Journal* 18: 180189.

Zhou, Z. 2003. Typical severe dust storms in northern China during 1954–2002. *Chinese Science Bulletin* 48: 2366–2370.

Zhao, W., and X. Chang. 2014. The effect of hydrologic process changes on NDVI in the desert-oasis ecotone of the Hexi Corridor. *Science China Earth Sciences* 57: 3107–3117.

Zhu, Y., Y. Chen, L. Ren, H. Lü, W. Zhao, F. Yuan, and M. Xu. 2016. Ecosystem restoration and conservation in the arid inland river basins of Northwest China: Problems and strategies. *Ecological Engineering* 94: 629–637.

Zhou, H., W. Zhao, and G. Zhang. 2017. Varying water utilization of *Haloxylon ammodendron* plantations in a desert-oasis ecotone. *Hydrological Processes* 31: 825–835.

Zhao, W., X. Chang, X. Chang, D. Zhang, B. Liu, J. Du, and P. Lin. 2018. Estimating water consumption based on meta-analysis and MODIS data for an oasis region in northwestern China. *Agricultural Water Management* 208: 478–489.

Zhuang, Y., and W. Zhao. 2014. Dew variability in three habitats of a sand dune transect in a desert oasis ecotone, Northwestern China. *Hydrological Processes* 28: 1399–1408.

Zhuang, Y., and W. Zhao. 2017. Dew formation and its variation in *Haloxylon ammodendron* plantations at the edge of a desert oasis, northwestern China. *Agricultural and Forest Meteorology* 247: 541–550.

AUTHOR BIOGRAPHIES

Lihui Luo is an Associate Professor at Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. His main research interests include hydrological and permafrost modelling, ecosystem monitoring and human impact assessment.

Address: Linze Inland River Basin Research Station, Key Laboratory of Inland River Basin Ecohydrology, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China.
Address: University of Chinese Academy of Sciences, Beijing 100049, China.
e-mail: luolh@lzb.ac.cn

Yanli Zhuang is an Associate Professor at Linze Inland River Basin Research Station at Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. Her research interests include Eco-hydrological monitoring and modelling in arid and semi-arid regions.

Address: Linze Inland River Basin Research Station, Key Laboratory of Inland River Basin Ecohydrology, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China.
Address: University of Chinese Academy of Sciences, Beijing 100049, China.
Address: Department of Earth Sciences, Indiana University-Purdue University Indianapolis (IUPUI), 723 W Michigan St, SL 118 M, Indianapolis, IN 46202, USA.
e-mail: zhuangyl@lzb.ac.cn

Wenzhi Zhao (✉) is a professor at Linze Inland River Basin Research Station at Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. His main research interests include Eco-hydrological processes and their interaction.

Address: Linze Inland River Basin Research Station, Key Laboratory of Inland River Basin Ecohydrology, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China.
Address: University of Chinese Academy of Sciences, Beijing 100049, China.
e-mail: zhaowzh@lzb.ac.cn

Quntao Duan is a Master Student at Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. His main research interests include human footprint, ecosystem monitoring and human impact assessment.

Address: Linze Inland River Basin Research Station, Key Laboratory of Inland River Basin Ecohydrology, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China.
Address: University of Chinese Academy of Sciences, Beijing 100049, China.
e-mail: duanqt@lzb.ac.cn

Lixin Wang (✉) is an Associate Professor at Department of Earth Sciences, Indiana University-Purdue University Indianapolis (IUPUI). His main research interests include ecohydrology and biogeochemistry.

Address: Department of Earth Sciences, Indiana University-Purdue University Indianapolis (IUPUI), 723 W Michigan St, SL 118 M, Indianapolis, IN 46202, USA.
e-mail: lxwang@iupui.edu