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LETTER

Natural and semi-natural land dynamics under water resource change from 1990 to 2015 in the Tarim Basin, China

Fang Liu , Zhuxiao Yu , Erqi Xu , Dajing Li , Hongqi Zhang and Yuanwei Qin

1 Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China
2 Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China
3 University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
4 Department of Microbiology and Plant Biology, University of Oklahoma, Norman, OK 73019, United States of America

* Authors to whom any correspondence should be addressed.
E-mail: zhanghq@igsnrr.ac.cn and yuanwei.qin@ou.edu

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Abstract
The Tarim Basin is a typical arid area and has the world’s most severe desertification of natural and semi-natural land due to limited water resources. However, knowledge about the impacts of changes in water resources on the spatio-temporal dynamics of natural and semi-natural land is still limited. We analyzed the spatio-temporal changes in natural and semi-natural land and the associations with desertification in the Tarim Basin during the period 1990–2015. We then investigated the changes in water resources and the consequent impacts on the spatio-temporal changes of natural and semi-natural land by integrating Gravity Recovery and Climate Experiment territorial water storage data and field observations. The results showed that a total area of $10.32 \times 10^3$ km$^2$ of natural and semi-natural land was converted to desert during the period 1990–2015. Desert vegetation type and saline type were the natural and semi-natural land types most sensitive to conversion to desert. The area of natural and semi-natural land decreased by 0.83% every year, and the proportion of desertified land was 34.79% on average during the period 2000–2010; this is less than for the period 1990–2000 (1.14% yr$^{-1}$ and 52.01%) due to increased availability of water resources from the water conveyance program. However, the rate of decrease of natural and semi-natural land area (0.93% yr$^{-1}$) and the proportion of desertified land (58.88%) rose again during the period 2010–2015 due to the rapid decrease in water resources. During the period 2000–2015, the rate of loss of natural and semi-natural land area (7.89%) in the region with decreased water resources was about twice that in the region with increased water resources (3.88%), highlighting the critical role of water resources in maintaining natural and semi-natural land and slowing desertification.

1. Introduction

Natural and semi-natural land is defined as land covered by natural and semi-natural vegetation or water bodies, which receives little influence from human activities and provides crucial ecosystem support services. Spontaneous ecological processes primarily determine natural vegetation, and semi-natural vegetation is influenced by human activities but retains its spontaneous ecological processes (Faber-Langendoen et al. 2014). Natural and semi-natural land mainly includes (a) the oasis–desert ecotone with sparse vegetation dominated by perennial species, for example *Populus euphratica*, *Tamarix ramosissima*, *Alhagi sparsifolia* and *Phragmites australis* (Amuti and Luo 2014), (b) riparian forests, for example *Populus euphratica* and *Populus pruinose* (Thevs 2011, Thomas and Lang 2021), and (c) wetlands.

Desertification is the main ecological and environmental crisis in the northwestern arid area of China. Natural and semi-natural land serves as a
natural barrier for slowing desertification and plays a vital role in maintaining the stability of the oasis ecosystem (Shi et al., 2004, Sivakumar and Stefanski, 2007, Ma et al., 2009, Ling et al., 2015, Mamat et al., 2019); for example, riparian forest (Chen et al., 2003, Hao et al., 2010, Yu et al., 2012, Liu et al., 2014a, Ling et al., 2015, Halik et al., 2019) and vegetation between oases and the desert ecotone (Xu et al., 2007, Ye et al., 2009, Chen et al., 2010, Wang and Li, 2013, Amutii and Luo, 2014, Peters et al., 2020). However, the area and quality of natural and semi-natural land have declined significantly due to the overexploitation of soil and water resources for the expansion of artificial oases (Shi et al., 2004, Huang and Pang, 2010, Thevs et al., 2011, Chen, 2014, Peng et al., 2014), resulting in a substantial decrease in ecosystem services and increased desertification (Zhang et al., 2010, Feng et al., 2015, Xiao et al., 2019, Thomas and Lang, 2021). For example, the weakened ability of the degraded natural vegetation to control sand has resulted in desertification (Sivakumar and Stefanski, 2007). Several ecological restoration projects have been carried out to help the sustainable development of the Tarim Basin. Recovery of natural and semi-natural vegetation was demonstrated to be an effective approach for slowing desertification (Zhang et al., 2018, Zeng et al., 2020). Previous studies have mainly focused on one or several specific vegetation types. Thus, there is a need to investigate the linkage between natural and semi-natural land dynamics and desertification across the Tarim Basin.

Scarcity of water is the biggest threat to social activities, agricultural production and ecosystems in arid areas. To support cropland expansion (Qin et al., 2013, Liu et al., 2014b), considerable amounts of both groundwater and river water in the Tarim Basin (Thevs et al., 2015b) and the Aral Sea Basin (Qadir et al., 2009) are exploited for agricultural irrigation. The change in water resources is the main factor driving desertification. Recent studies have shown that continuous access to groundwater is critical for the growth of Populus euphratica in Tarim Basin or the Amu Darya (Thevs et al., 2015a, Thomas and Lang, 2021). Previous studies on water resource conditions have focused on glacial lake areas (Wang et al., 2016), streamflow trends (Tao et al., 2011), terrestrial water storage (Yang et al., 2017, Zhao and Li, 2017), groundwater change (Chen et al., 2006, Feng et al., 2018) and the balance between water demand and groundwater level threshold (Hao et al., 2010, Hoppe et al., 2020). Furthermore, changes in the area and the physiological responses of natural vegetation were analyzed under different water conditions (Chen et al., 2003, 2013, Thevs et al., 2008, Chipman et al., 2016, Thomas and Lang, 2021). The direct linkage between natural vegetation and water resources has mostly been studied at a site scale based on observations (Thomas et al., 2006, Thevs et al., 2007, Hao et al., 2010, Buras et al., 2013, Keyimu et al., 2017). The impacts of water resources on natural and semi-natural land and desertification on a broad scale have rarely been reported. Therefore, it is important to explore the spatio-temporal interactions among changes in natural and semi-natural land, desertification and water resources, which could provide support for policymaking and achieve sustainable development of the oasis ecosystem.

In this study, based on multiple remote sensing data products and field observations, we aim to (a) analyze the spatio-temporal changes in natural and semi-natural land and associations with desertification and (b) explore the impacts of changes in water resources on natural and semi-natural land in the Tarim Basin during the period 1990–2015. This study will provide scientific guidance for natural and semi-natural land protection policies and water resource management in the Tarim Basin.

2. Materials and methods

2.1. Study area

The Tarim Basin, located in arid northwestern China, is China’s largest inland basin and has the longest inland river, the Tarim River, and the largest desert, the Taklamakan Desert, in China (figure 1). According to the UN Food and Agriculture Organization, the soil types in this region mainly include Arenosols, Solonchak, Fluvisols and Gleysols (Thevs et al., 2008). Comprising typical and fragile mountain–oasis–desert ecosystems (Li et al., 2015), the Tarim Basin is mainly characterized by sporadic oases and widespread deserts. Natural vegetation includes riparian forests, shrub vegetation and grassland, which are highly dependent on groundwater when river run-off is low (Thevs, 2011). Annual rainfall is low (<50 mm yr−1), but potential evaporation is high (>2000 mm yr−1). Glaciers and snowmelt are the major sources of surface and groundwater in the Tarim Basin (Feng et al., 2000, Rumbaur et al., 2015). Irrigation agriculture and settlements compete with natural vegetation for the use of water. The Tarim Basin contains nine large watersheds (www.fao.org/water/drought/article-278, including the Aksu River, Kashgar River, Yarkant River, Hotan River, Weigan River, Kaidu–Kongque River, Keriya River and Qarqan River basins and the main stream of the Tarim River (figure 1).

2.2. Data

We collected and combined datasets from multiple sources to identify and map natural and semi-natural land and desertification in the Tarim Basin. Table 1 provides a summary of the datasets used in this study. Land cover and land use maps, the Global Inventory Monitoring and Modeling System (GIMMS) Normalized Difference Vegetation Index–3rd generation (NDVI 3g) product and a geomorphological distribution map were used for identifying and mapping
natural and semi-natural land. NDVI data were also used for monitoring desertification. Terrestrial water storage (TWS) data from the Gravity Recovery and Climate Experiment (GRACE) satellites indicated the water resources in the Tarim Basin. Digital elevation model (DEM) data from the Shuttle Radar Topography Mission (SRTM) were collected for watershed segmentation. We collected the strong dust event data for 16 meteorological stations across the Tarim Basin (figure 1) between 1990 and 2007. Strong dust storm events included a dust storm with a visibility distance of less than 200 m and extreme wind speed higher than 20 m s$^{-1}$ (according to the China Meteorological Data Service Center). We counted the frequency of dust storm events every year and calculated the multi-year average frequency in each period (1990–2000 and 2000–2007) for each station. We carried out two field surveys and collected a total of 813 ground samples in the Tarim Basin in 2010 and 2013, including 663 ground samples in the middle and upper reaches of the Tarim Basin in 2010 and 150 ground samples in the lower reaches of the Tarim Basin in

![Spatial distribution map of distribution of natural and semi-natural land in 2015, meteorological stations and ground samples.](image-url)
2013 (figure 1). We recorded the geo-locations, land cover types and field photos for these ground samples. We used these ground samples to assess the accuracy of the natural and semi-natural land cover map. Additionally, four locations of the 2 m Global Land Cover Validation Reference Dataset in 2010 derived from very high spatial resolution imagery (e.g. Quick-Bird) (Olofsson et al. 2012, Stehman et al. 2012, Pengra et al. 2015) were used to demonstrate the potential of NDVI to calculate the fractional vegetation cover (FVC) in low-vegetation areas. These four locations were the only pixels with vegetation coverage less than 50% in Central Asia, where the vegetation is similar to the Tarim Basin.

2.3. Methods

We first analyzed the spatio-temporal changes in natural and semi-natural land for the periods 1990–2000, 2000–2010 and 2010–2015. Secondly, we analyzed the changes in natural and semi-natural land under the impacts of water resource change observed from the long-term field site and the GRACE TWS data in the Tarim Basin (Wiese 2015). Thirdly, we analyzed the spatio-temporal changes in dust storm events between 1990–1999 and 2000–2007 in the Tarim Basin. Fourthly, we discussed the impacts of natural and semi-natural land, cotton production, aeolian erosion, water resources and grazing activities on desertification. We used satellite-based products at different spatial resolutions. To change the coarse spatial resolution images into medium spatial resolution images, we used the nearest neighbor assignment resampling technique using the Resample tool in the Data Management Toolbox in ArcGIS 10.2. To change the very high spatial resolution images and medium spatial resolution images into medium or coarse spatial resolution images, we used the aggregation approach and calculated the area percentage of each land cover type based on the original spatial resolutions. The workflow is shown in figure 2.

2.3.1. Natural and semi-natural land mapping method

We developed a two-step approach and extracted the spatial distribution of natural and semi-natural land (Liu et al. 2016) based on a combination of multi-source information, including land cover and land use visually interpreted from Landsat images (Liu et al. 2014b), vegetation coverage retrieved from GIMMS 3g NDVI images (Fensholt and Proud 2012) and geomorphological distribution (Li et al. 2009). First, we identified and mapped four ecological zones in the Tarim Basin considering the FVC (Carlson and Ripley 1997), including artificial oases (agricultural area and built-up land with FVC > 30%), natural oases (areas outside of artificial oasis, with FVC > 30%), the oasis–desert ecotone (areas with 5% < FVC < 30%) and desert (areas with FVC < 5%). Second, we derived five natural and semi-natural land types (artificial oasis, high-cover vegetation, wetland, desert vegetation and saline type) based on the combination of land cover, spatial location and ecological service functions for each ecological zone. The artificial oasis type included forest and grassland in artificial oases. The high-cover vegetation type and wetland type included forest and grassland, and water bodies and wetlands in natural oases, respectively. The desert vegetation type and saline type included vegetation in the oasis–desert ecotone and saline land in the desert, respectively. We generated natural and semi-natural land maps for the Tarim Basin in 1990, 2000, 2010 and 2015. The natural and semi-natural land map in 2010 had an overall accuracy of 87% based on 813 ground samples (figure 1).
2.3.2. Identification and mapping of desertification
Desertification generally begins with degradation of vegetation (Li et al. 2004) and then leads to a substantial decline in ecosystem productivity (Hellden and Tottrup 2008). NDVI has a strong relationship with vegetation coverage (Carlson and Ripley 1997) and was used to calculate vegetation coverage at a global scale (Gutman and Ignatov 1998) and in the Tarim Basin (Hao et al. 2010). In this study, we separated each 2 m land cover map into vegetation cover (trees and other vegetation) and non-vegetation cover. Using the 8 km NDVI pixels as a reference, we then aggregated the 2 m land cover maps into 8 km spatial resolution and calculated FVC. We analyzed the linear relationship between NDVI and vegetation coverage. Although their spatial extent did not completely match, the strong linear relationship ($R^2 = 0.98$) between FVC and NDVI data (figure 3) showed the potential of using NDVI to calculate FVC.

The coefficient of variation (CV) of NDVI can detect changes in vegetation growth stages and has been used to identify land degradation in Saudi Arabia (Weiss et al. 2001) and Xinjiang in China (Gong 2007). The trend analysis of annual NDVI CV maps was calculated by the following two steps (Hellden and Tottrup 2008): first, the annual NDVI CV map was calculated based on the monthly NDVI maps in 1 year at pixel level; then, the Mann–Kendall test was applied to calculate the trend in annual CV values in the Tarim Basin from January 1990 to December 2015 to map desertification. The Mann–Kendall test statistic ($S$) is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn} \left( x_j - x_i \right)$$

$$\text{sgn} \left( x \right) = \begin{cases} +1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases}$$

where $n$ is the length of the time series data ($x_1, x_2, \ldots, x_n$) and $x_i$ and $x_j$ represent the data at times $i$ and $j$, respectively.

The statistical significance of the $S$ value is tested based on the $Z$ value

$$Z = \begin{cases} \frac{S-1}{\sqrt{\sigma^2}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\sigma^2}} & S < 0 \end{cases}$$

where $\sigma^2$ is calculated as

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18}$$

where $m$ is the number of tied groups and $t_i$ is the size of the $i$th tied group.

2.3.3. Linkage of desertification to natural and semi-natural land
Sub-watershed was used as the basic unit generated from the segmentation of nine watersheds using Arc Hydro 2.0 (Djokic et al. 2011). Arc Hydro, an ArcGIS-based system, can be effectively used for stream segmentation and watershed delineation by incorporating actual stream and watershed vector data. The process included DEM reconditioning, fill sinks, flow direction, flow accumulation, stream definition, stream segmentation and catchment delineation. We chose the ‘Agree’ algorithm to modify raw DEM by integrating the local river network. Agree parameters were set, including the Sharp drop/raise parameter of 10, which was different from the default value of 1000. There were 241 sub-watersheds in total in the Tarim Basin. Furthermore, we categorized all the sub-watersheds into oasis-dominated, oasis–desert ecotone-dominated and desert-dominated watersheds according to the area making up the largest proportion of the ecological zones.

The binning method was used for data smoothing to remove the noisy data to analyze associations between natural and semi-natural land and desertification. First, we created bins from 0–0.1, 0.1–0.2, 0.2–0.3, … and 0.9–1.0 based on equal intervals for the proportion of the area subject to desertification. Then we calculated the average value of the proportion of natural and semi-natural land area in each 10% bin.
2.3.4. Terrestrial water storage analysis

The TWS data, an important indicator of water resource change (Rodell et al. 2018), was used for analyzing the impact of water resource changes on natural and semi-natural land. The monthly GRACE TWS data at a spatial resolution of 0.5° for 2002–2015 were downloaded from the NASA Jet Propulsion Laboratory (JPL, http://grace.jpl.nasa.gov). The missing values in the data were filled by linear interpolation. The monthly data were aggregated to annual average values based on the Mascon set of 0.5° gain factors (Wiese 2015). Annual GRACE TWS data in the Tarim Basin for 2002–2015 were analyzed to represent the spatio-temporal dynamics of water resources. To assess the reliability of GRACE TWS observations, we also used one field site with long-term observation of groundwater depth in Yengisu (87.95° E, 40.42° N) in the Tarim Basin for 1989–2011. Yengisu is a monitoring section along the lower reaches of the Tarim River. The monitoring wells were dug in this section to measure the changes in groundwater depth. The monthly groundwater depth data were provided by the Tarim River Basin Bureau for 1989, 1997, 1999–2007 and 2009–2011 and were then aggregated to the annual average. We overlaid the Yengisu site to the GRACE TWS data and extracted annual GRACE TWS values during the period 2002–2015. We then analyzed the linear relationship between annual GRACE TWS and annual groundwater depth during the period 2002–2011.

3. Results

3.1. Desertification of natural and semi-natural land in the Tarim Basin during the period 1990–2015

The conversion of natural and semi-natural land to desert is an essential part of desertification. Between 1990 and 2015, a total area of 10,320.43 km² of natural and semi-natural land was converted to desert, accounting for 8.79% of the total natural and semi-natural land area in 1990 (figure 4). The main stream of the Tarim River had the largest area of natural and semi-natural land converted to desert (2090.09 km², 20.25% of the total natural and semi-natural land area converted to desert), followed by the Kaidu–Kongque River Basin (1997.05 km², 19.35%). The Weigan and Yarkand River Basins had the smallest areas (<100 km²) of natural and semi-natural land converted to desert. In terms of the natural and semi-natural land types converted to the desert, about 80.77% of the desert area was derived from the desert-vegetation type, followed by the saline type (15.87%). This indicated that the desert-vegetation type and saline type are more fragile than other types of natural and semi-natural lands. A similar pattern was also found in each watershed except in the Aksu and Yarkand River Basins. The saline type contributed the largest share of the natural and semi-natural land converted to desert in the Aksu River Basin (71.38%) and the Yarkand River Basin (41.81%).

3.2. Spatio-temporal changes in natural and semi-natural land and associations with desertification

We analyzed the spatio-temporal changes of natural and semi-natural land at the sub-watershed scale...
Figure 5. Spatial distribution of the changes in proportion of natural and semi-natural land by area ((a) 1990–2000, (b) 2000–2010, (c) 2010–2015) and in the proportion of desertified land by area ((d) 1990–2000, (e) 2000–2010, (f) 2010–2015) at the sub-watershed scale in the Tarim Basin. (g) Average percentage area of natural and semi-natural land shrinkage and land desertification during the three periods.

in the Tarim Basin during the periods 1990–2000, 2000–2010 and 2010–2015. About 57.26% of 241 sub-watersheds experienced a decrease in the proportion of natural and semi-natural land by area (by 1.14% yr\(^{-1}\) on average) between 1990 and 2000, mainly in the eastern Tarim Basin, such as the lower reaches of the Tarim River and the Kaidu–Kongque River Basin (figure 5(a)). Desertification was more serious in the southern and eastern Tarim Basin, for example in the lower reaches of the Tarim River and the Kaidu–Kongque River Basin (figure 5(d)). The increase in the proportion of natural and semi-natural land by area mostly occurred in the watershed’s middle reach, such as the Aksu River Basin (figure 5(a)).

Compared with the period 1990–2000, more sub-watersheds (73.44%) experienced a decrease in the proportion of natural and semi-natural land by area but had a smaller loss of actual area of natural and semi-natural land (0.83% yr\(^{-1}\)) during the period 2000–2010 (figures 5(b) and (f)) due to the continuous expansion of cropland into natural and semi-natural land (Qin et al 2013, Liu et al 2014b) and improved water allocation (Chen et al 2017). Similarly, less desertification was observed during the period 2000–2010, with the proportion of the area desertified being 34.79%, while the corresponding figure for the period 1990–2000 was 52.01% (figures 5(e)–(g)). For the eastern Tarim Basin, in the low reaches of the Tarim River, the decline in
natural and semi-natural land and the occurrence of desertification during the period 2000–2010 period were less than during the period 1990–2000 owning to the water conveyance program launched in 2000 (figures 5(b) and (e)) (Chen et al 2017).

During the period 2010–2015, a decrease in the area of natural and semi-natural land occurred in 68.88% of sub-watersheds with an average rate of decrease of 0.93% yr$^{-1}$; this was slightly higher than in the period 2000–2010. Correspondingly, more areas suffered desertification in this period, with an average percentage of 58.88% by area, which was also higher than that during 2000–2010 (figure 5(g)).

As a natural barrier in arid regions, the change in natural and semi-natural land is also related to the desertification of the whole land cover types. Therefore, we then analyzed the associations between the proportion of natural and semi-natural land by area and desertification for the three types of sub-watersheds (oasis-dominated, oasis–desert ecotone-dominated and desert-dominated watersheds). The oasis–desert ecotone-dominated sub-watersheds had the largest average proportion of natural and semi-natural land by area (70.08%), followed by the oasis-dominated sub-watersheds (51.95%). Desert-dominated sub-watersheds had the largest proportion of desert by area (58.77%) and the smallest proportion of natural and semi-natural land by area (23.28%), where the land faced a high risk of desertification. Figure 6 shows and compares the linear relationships between the proportion of natural and semi-natural land by area and the proportion of desertification by area during the periods 1990–2000, 2000–2010 and 2010–2015 for each type of sub-watershed. During the period 1990–2000, the proportion of natural and semi-natural land by area had a significantly negative linear relationship with the proportion of desertification by area in each type of sub-watershed. During the period 1990–2000, the proportion of natural and semi-natural land by area had a significantly negative linear relationship with the proportion of desertification by area in each type of sub-watershed (P < 0.05), indicating more natural and semi-natural land and less desertification. During the period 2000–2010, the linear relationships between the proportion of natural and semi-natural land by area and the proportion of desertification by area were not significant in the desert-dominated and oasis–desert ecotone-dominated sub-watersheds, but we can see the desertification rate declined substantially, compared to that for 1990–2000. A negative linear relationship between the proportion of natural and semi-natural land by area and the proportion of desertification by area was also identified in the third period (2010–2015), especially in the desert-dominated sub-watersheds.

3.3. Spatio-temporal dynamics of water resources in the Tarim Basin

Water resources are a critical factor sustaining the natural and semi-natural land and the oasis system in the Tarim Basin. The year 2000 was considered the transition year of accelerated warmer–wetter trends in the mountains of the Tarim Basin (Wang et al 2016). The average runoff from the record of hydrological stations was also higher in the 2000s than in the 1990s (figure 7(a)). A greater increment in the surface water area in the Hotan oasis was detected in the 2000s than in the 1990s (Amuti and Luo 2014). Thus, more water supplies were available in the Tarim Basin in the 2000s than in the 1990s. We also used GRACE TWS data, an independent satellite observation, to monitor the inter-annual changes in water resource availability in the Tarim Basin. GRACE TWS clearly showed that more water resources were available in the 2000s, especially between 2002 and 2007 (figure 7(b)). However, to our surprise, water resources, retrieved from the GRACE TWS data, decreased significantly (P < 0.01) during the period 2010–2015, and the rate of decrease also became faster (figure 7(b)), challenging the sustainable development of natural and semi-natural land and oasis ecosystems. Spatially, an obvious decrease in water storage occurred in the Weigan River, the main stream of the Tarim River and Qarqan River basins, especially from 2010 to 2015 (figures 7(c)–(e)). Monitoring of well observations in Korla and Kashgar in the region also showed a declining trend for groundwater tables between 2007 and 2013 (Feng et al 2018). The lower reaches of the Tarim River with water shortages and degraded ecosystems are regarded as the most vulnerable region in the study area. Using
the lower reaches of the Tarim River as an example, we analyzed the water resource changes by combining satellite observations from the GRACE TWS during the period 2002–2015 and the groundwater depth field observations during the period 1989–2011. The GRACE TWS data showed consistent variations ($R^2 = 0.93; P < 0.01$) in groundwater depth observations during the period 2002–2011. There are three phases of water delivery (Chen et al 2017). About $2.3 \times 10^9$ m$^3$ of water was transported to the lower reaches of the Tarim River, increasing the groundwater depth from about 10 m to about 4 m during the first phase (2000–2006) (figure 8). In contrast, much less water ($0.03 \times 10^9$ m$^3$) was delivered to the Tarim River’s lower reaches during the second phase (2007–2009). Thus, GRACE TWS
values decreased from 0.7 cm in 2006 to $-0.9$ cm in 2009, and groundwater depth decreased from 4 m in 2006 to 7 m in 2009. Then much more water ($2 \times 10^9$ m$^3$) was transported to the lower reaches of the Tarim River, but GRACE TWS values and groundwater depth were relatively stable during the third phase (2010–2012). To our surprise, GRACE TWS data showed faster and faster decreasing rates between 2012 and 2015, indicating a more and more serious water resource crisis in this region.

### 3.4. Impacts of water resource change on natural and semi-natural land

Water storage increased in the second period (2000–2010) and then decreased in the third period (2010–2015) (figures 7 and 8); correspondingly, the rates of loss of natural and semi-natural land declined between 2000 and 2010 and then increased from 2010 to 2015 (figure 5(g)). This showed that the improved water conditions were favorable for the recovery and growth of natural and semi-natural land in the whole basin in the 2000s compared with the 1990s. The decline in water storage after 2010 sped up the shrinkage of natural and semi-natural land area between 2010 and 2015.

Spatially, based on the annual GRACE TWS data in 2002 and 2015, we identified the areas with increased and decreased water storage in the Tarim Basin (figure 9). In the region with decreased water storage, the area of natural and semi-natural land decreased by 7.89% (7297.42 km$^2$) as a proportion of the total area of natural and semi-natural land area during the period 2000–2015, about twice that in the region with increased water storage (3.88% decrease, 570.23 km$^2$). We also calculated the relationship between water storage and changes in the area of artificial/semi-artificial land (including cropland, built-up land and orchards) in the Tarim Basin. Our results indicated that the decrease in water storage was also associated with the expansion of artificial/semi-artificial land (figure 9). The expansion of artificial/semi-artificial land would lead to a decline in water storage and the area shrinkage of natural and semi-natural land. Our results confirm the important role of water resources in supporting natural and semi-natural land in the Tarim Basin.

### 4. Discussion

#### 4.1. Uncertainties in the mapping for natural and semi-natural lands and desertification

High-accuracy land cover and land use maps, generated through visual interpretation of Landsat images in 1990, 2000, 2010 and 2015 at a spatial resolution of 30 m, were used to identify and generate the natural and semi-natural land in the whole basin in the 2000s compared with the 1990s. The decline in water storage after 2010 sped up the shrinkage of natural and semi-natural land area between 2010 and 2015.

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Thus, GIMMS 3g NDVI are valid data for identifying
The Tarim Basin is a typical region suffering severe and extensive aeolian erosion, leading to substantial land degradation and a reduction in biodiversity, vegetation production and ecosystem function (Ravi et al. 2010). According to the field experiment in the Tarim Basin, water resources and natural and semi-natural vegetation can reduce sand-drift (Betz et al. 2015). We analyzed the frequency of dust storm events based on the records of 16 meteorological stations during two periods: 1990–1999 and 2000–2007 (figure 10). The average frequency of dust storms in the north Tarim Basin (4.1 days yr$^{-1}$, 2.9 days yr$^{-1}$) was lower than that in the south Tarim Basin (12.9 days yr$^{-1}$, 11.2 days yr$^{-1}$) in both periods, probably because the north Tarim Basin has more natural and semi-natural vegetation land (figure 1) and water resources (figure 7) than the south Tarim Basin. We further compared the frequency of dust storm events in the two periods. Most meteorological stations (except Tazhong and Minfeng) had a relatively higher frequency of dust storms in 1990–1999 than in 2000–2007. A decreasing frequency of dust storms occurred after 2000, accompanied by the decreased rate of loss of natural and semi-natural land (figure 5) and increasing water storage (figure 7). This suggested that increasing water storage and decreasing the rate of loss of natural and semi-natural land could reduce the frequency of dust storm events.

4.3. Desertification under multiple driving factors

Desertification occurred under multiple driving factors, including natural and semi-natural land, aeolian erosion, water resources and grazing activities (Okin et al. 2018). Natural and semi-natural land provides a wind erosion prevention service by controlling sand (Guo et al. 2018). The shrinkage and degradation of natural and semi-natural vegetation usually weaken ecological function and lead to accelerated aeolian erosion and a high potential for sand-dust storms (Wang et al. 2012, Chi et al. 2019). Increased aeolian erosion causes grassland communities to shift from grass dominance to shrub dominance, a typical feature of land degradation (Alvarez et al. 2012).

Water availability is the decisive factor for the presence of natural and semi-natural vegetation and the desertification process. The large area of natural and semi-natural land converted into the desert was mainly a result of imbalanced water allocation due to the excessive use of water resources to support oasis expansion (e.g. for cotton) (Han et al. 2011, Liu et al. 2014b). For example, the Aksu River Basin, one of the most important cotton-producing areas globally, consumed more water than its water quota and caused extensive expansion of saline soils (Zhao et al. 2015, Thevs et al. 2015b). Increasing consumption of water for agricultural production (cotton) in the upper and middle Tarim River Basin reduced groundwater depth substantially to about 8–12 m, below the groundwater depth threshold (4–6 m) for desert riparian vegetation (Hao et al. 2010, Rumbaur et al. 2015, Liu et al. 2016, Yang and Jiang 2019), causing...
aeolian desertification along the lower reaches of the Tarim River (Wang et al 2012). As one of the major freshwater sources in the Tarim Basin, glacial lake areas expanded four times faster in 2000–2013 than in 1990–2000 (Wang et al 2016). The water conveyance project implemented in 2001 drained over $4 \times 10^7$ m$^3$ of water and further improved water conditions, especially in the lower reaches of the Tarim Basin (Chen et al 2010, 2017). The underground water depth increased to 4 m, and the groundwater salinity decreased to 1–5 g l$^{-1}$; thus, natural vegetation substantially increased, and the desertification trend was reversed (Sun et al 2011, Zhang et al 2013, Chen et al 2017). Based on the transect observations in the field and remote sensing imagery, several studies showed the recovery of vegetation in the lower reaches of the Tarim Basin. For example, the area of the endangered tree species Populus euphratica increased in the regions where water supply was abundant (Zhang et al 2013, Peng et al 2014). During the period 2001–2013, transformation from unused land to natural and semi-natural land was the major type of land cover change, and the average FVC was increased by 150% (Bao et al 2017).

Over-grazing is another reason for vegetation degradation (Zhang et al 2003, Raiesi and Riahi 2014, Qasim et al 2017, Middleton 2018). The number of livestock in Xinjiang increased from 12,428.9 $\times$ 10$^3$ in 1990 to 36,065.6 $\times$ 10$^3$ in 2010, an increase of 190%. The rise in livestock numbers and concentrated distribution around drinking water (Zhang 1992) will lead to intensive grazing and further intensification of the desertification process.

### 4.4. Implications for land and water resources management

Our study revealed that natural and semi-natural land and desertification dynamics were highly associated with changes in water resources. The water conveyance project drained substantial water from the upper Tarim River and increased water resources in the lower reaches of the Tarim River. However, we also clearly noticed large variability in water volume in different years, challenging natural and semi-natural land growth. The water conveyance project did not achieve delivery of the planned amount of water, mainly due to the overuse of water for cropland expansion in the upper and middle rivers (Chen et al 2017). The Tarim Basin is one of the most important cotton-producing regions globally and the largest cotton production area in China (Thevs et al 2015b). Cotton production in the Tarim Basin accounted for 90% of total cotton production in Xinjiang, where the cotton planting area increased substantially from 4.35 $\times$ 10$^3$ km$^2$ in 1990 to 19.04 $\times$ 10$^3$ km$^2$ in 2015, an increase of 338% (Statistical Bureau of Xinjiang Uyghur Autonomous Region 2020). The water demand for cotton production came from irrigation (Rouzi et al 2018), and over 95% of available water resources was used for agricultural irrigation (mainly cotton) in the Tarim Basin (Zhou et al 2018).

The Aral Sea Basin in Central Asia had a similar situation to the Tarim Basin, with both humans and natural ecosystems competing for river water. Due to the extremely uneconomic water use and policies that did not consider the sustainability of agricultural developments, enormous environmental problems occurred after the 1960s in Central Asia (Varis 2014). About 90% of available water resources in Central Asia were used to irrigate cotton and wheat, and more than 50% of irrigated soils were salt-affected or water-logged (Qadir et al 2009, Varis 2014). Excessive water use and inadequate drainage systems caused large-scale land degradation, the disappearance of the Aral Sea and deterioration in water quality in downstream parts of the basin (Qadir et al 2009, Varis 2014).

To achieve sustainable development in the Tarim Basin, increasing water resources and water use efficiency are strongly recommended. The allocation of water resources must be uniformly regulated from the perspective of the entire basin, taking into account the upper, middle and lower reaches and balancing water use between natural and semi-natural land and agricultural production. The reclamation and expansion of cropland needs to be strictly controlled as cropland use about two times as much water as natural and semi-natural land per unit area (Chen et al 2017). Thus, the lower reaches of rivers can get increased water resources. There is also an urgent need to improve water use efficiency for agriculture production using water-saving irrigation techniques to increase grain and cotton output rate per square water.

### 5. Conclusions

Using multiple independent field and satellite observations, we have quantitatively analyzed the dynamics of natural and semi-natural land, desertification and water resources in the Tarim Basin during the period 1990–2015. A total of 10,320.43 km$^2$ of natural and semi-natural land was degraded to the desert during this period. Due to the increased availability of water resources through the water conveyance program, the rate of loss of natural and semi-natural land and the proportion of desertified land by area decreased in 2000–2010 compared with that in 1990–2000. The rapid decrease in water resources after 2011 led to a high rate of decrease of natural and semi-natural land area during the period 2010–2015. The proportion of natural and semi-natural land by area decreased by 1.14%, 0.83% and 0.93% per year on average during the periods 1990–2000, 2000–2010 and 2010–2015, respectively. The proportion of desertified land by area was 52.01%, 34.79% and 58.88% during the periods 1990–2000, 2000–2010 and 2010–2015. This study urgently suggests improved water management
to support natural and semi-natural land and sustainable agricultural production in the future.

**Data availability statement**

The data that support the findings of this study are available upon reasonable request from the authors.

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**ORCID iDs**

Fang Liu  
https://orcid.org/0000-0003-2692-0924  
Erqi Xu  
https://orcid.org/0000-0002-3255-3959

Yuanwei Qin  
https://orcid.org/0000-0002-5181-9986

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