Water Storage Variations and Oasis Ecological Security Assessment in the Tarim River Basin: Postprint

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Abstract

Oases are the most ecologically sensitive and unique landscape types in arid and semi-arid regions, serving as critical areas that sustain human survival and socio-economic development. However, under the dual influence of climate change and human activities, water resources and oasis habitats in arid regions are undergoing dramatic changes. Based on MODIS and GRACE satellite data, land use data, and meteorological observation records from 2000-2020, this study systematically analyzed the dynamic changes in terrestrial water storage and oases in the Tarim River (hereinafter referred to as the Tarim River) basin over the past 20 years and conducted an ecological security assessment of oasis areas by calculating vegetation coverage, estimating Net Primary Productivity (NPP) and Remote Sensing Ecological Index (RSEI). The results show that: (1) From 2002-2020, terrestrial water storage in the Tarim River basin decreased at a rate of 0.27 $\text{mm} \cdot \text{month}^{-1}$; spatially, terrestrial water storage decreased significantly in the northern and western regions of the basin, while increasing significantly in the southern region. (2) From 2000-2020, the oasis area in the Tarim River basin increased significantly by 6.49% (0.42$×10^{4}$ km^2). The overall ecological environment of the basin showed an improving trend, with the ecological grade shifting from relatively poor to medium. Ecological improvement areas accounted for 69% of the total basin area, while ecological degradation areas accounted for less than 5%. The Normalized Difference Vegetation Index (NDVI) in the Tarim River basin increased from 0.13 in 2000 to 0.16 in 2020, vegetation coverage increased by 36.79% over the past 20 years, and NPP increased by 31.55%. (3) While temperature rise and precipitation increase were accompanied by increased downstream river runoff, which further exacerbated the spatiotemporal heterogeneity of terrestrial water resource storage in the Tarim River basin, human activities remain the most fundamental cause of the significant oasis expansion.

Full Text

Preamble

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Changes in Terrestrial Water Storage and Evaluation of Oasis Ecological Security in the Tarim River Basin

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Abstract: Oases represent the most ecologically sensitive and distinctive landscape types in arid and semi-arid regions, serving as critical areas that sustain human survival and socioeconomic development. However, under the dual influence of climate change and human activities, water resources and oasis habitats in dryland regions are undergoing dramatic transformations. Based on MODIS satellite data, GRACE data, land use data, and meteorological observations, this study systematically analyzed the dynamic changes in terrestrial water storage and oases in the Tarim River Basin over the past two decades by calculating vegetation coverage, estimating vegetation net primary productivity (NPP), and employing the remote sensing ecological index (RSEI). The results indicate that: (1) Terrestrial water storage in the Tarim River Basin decreased at a rate of 0.27 $\mathrm{mm} \cdot \mathrm{month}^{-1}$, with significant spatial heterogeneity—showing notable declines in the northern and western regions while increasing significantly in the southern region. (2) Oasis area in the basin expanded substantially from 2000 to 2020, with the overall ecological environment showing improvement trends, transitioning from poor to moderate ecological grade. The area of ecological improvement zones accounted for 69% of the total basin area, while degradation areas comprised less than 5%. The normalized difference vegetation index (NDVI) increased from 0.13 to 0.16, vegetation coverage increased by 36.79%, and NPP expanded by 31.55% over the 20-year period. (3) While rising temperatures and increased precipitation contributed to greater downstream river runoff, they also exacerbated the spatiotemporal variability of terrestrial water resources in the Tarim River Basin. Nevertheless, human activities remain the fundamental driver of significant oasis expansion.

Keywords: terrestrial water storage; oasis dynamic change; ecological security assessment; Tarim River Basin

Introduction

Oases are complex geographical landscapes with high ecological sensitivity within the fragile ecosystems of arid and semi-arid regions. They support human production, livelihood, and economic activities in dryland areas and constitute vital spaces for human survival and development. Oases also serve as natural ecological barriers against desert encroachment and drought, exhibiting significant cooling and humidifying effects, wind shielding, precipitation enhancement, and inverse humidity effects. Climate change has accelerated global desertification processes in dryland regions, making water resource issues increasingly prominent and causing drastic changes to oasis habitats that further damage ecosystem structure and functional integrity. These changes pose substantial challenges to oasis development, regional water resource allocation, and ecological security.

Monitoring oasis dynamic changes and their influencing mechanisms in arid regions has long been a research focus. Most studies have employed multi-source remote sensing data for oasis dynamic monitoring. For instance, some researchers have used multi-source remote sensing data to monitor vegetation dynamic changes in Inner Mongolia and Xinjiang. Others have analyzed vegetation dynamics using land use dynamic models and transition matrices, such as studies on land cover changes in Jiangsu Province. Markov models have been used to predict vegetation dynamics in the desert-oasis ecotone of the Tarim River Basin, while the Carnegie-Ames-Stanford Approach (CASA) model has been applied to calculate net primary productivity (NPP) reflecting vegetation ecological conditions in Central Asian arid regions. Remote sensing ecological security assessments have also been developed to evaluate vegetation conditions, such as studies using the remote sensing ecological index (RSEI) and standard deviation ellipse algorithms to assess ecological quality in the Hami oasis region, and research on spatiotemporal dynamics of ecological environmental quality in the Aral Sea region.

In terms of ecological security assessment, scholars have evaluated oasis ecological security using improved three-dimensional ecological footprint models or constructed dynamic evaluation models for oasis urban land ecological security using weighted average methods. While current research has addressed oasis dynamic changes and ecological security in arid regions, more investigation is needed from systematic and water resource impact perspectives to analyze oasis dynamic change processes.

Therefore, this study selected the Tarim River Basin oasis area—a region sensitive to climate change and human activities and a core area of the Silk Road Economic Belt—as the research target. Based on GRACE gravity satellite data and multi-source remote sensing data, we analyzed the spatiotemporal dynamic evolution characteristics of terrestrial water storage and oases in the Tarim

River Basin over the past two decades using multiple oasis dynamic indices, and assessed ecological security through indicators including NDVI, vegetation coverage, NPP, and RSEI. This research holds significant importance for ecological conservation and restoration management, healthy oasis development, and the construction of the national Silk Road Economic Belt in arid desert regions.

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1. Materials and Methods

1.1 Study Area Overview

The Tarim River Basin is located in the hinterland of the Eurasian continent, in southern Xinjiang, northwestern China (Fig. [Figure 1: see original paper]), representing China' s largest inland basin. Surrounded by the Tianshan, Kunlun, and Altun Mountains, the basin covers an area of approximately 92.60\$×10^{4}\$ km^2. The basin originally comprised nine major water systems (Kaidu River, Kongque River, Dina River, Weigan River, Aksu River, Kashgar River, Yarkant River, Hotan River, and Qarqan River), which eventually converged into Taitema Lake (Table). Currently, only four tributaries supply the main Tarim River: the Yarkant River, Hotan River, Kaidu River, and Aksu River. Water supply primarily originates from glacier and snow meltwater in surrounding high mountains, forest precipitation in mid-mountain zones, and bedrock fissure water in low mountain areas. The basin elevation ranges from 773 to 8,323 m, comprising high mountains, snow-capped peaks, valley grasslands, Gobi deserts, and lowland oases, with deserts dominating the landscape. The region experiences year-round aridity with scarce rainfall, with an average annual precipitation of 53 mm and mean annual temperature of 3.9 °C.

1.2 Data Sources

This study utilized the following datasets: Normalized Difference Vegetation Index (NDVI) data from MOD13Q1 products at 250 m spatial resolution; vegetation coverage and NPP data calculated from MOD13A1, MOD15A2H, and MCD15A3H remote sensing products; land use data from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.gscloud.cn) providing 1 km\$×1*kmChinaLandUseData*;*meteorologicalstationtemperatureandprecipitationdatafromtheChinaMete*
//cdc.cma.gov.cn);*andterrestrialwaterstoragedataderivedfromGRACEgravitysatellitedata*(*RL*06*Mascons*
*//www2.csr.utexas.edu/grace/RL*06$_{mascons}$.*html*)*at*0.25°×\$0.25° spatial resolution. Missing data were filled using multi-year cumulative averages for missing months and adjacent month averages. Water storage changes were obtained using the Mascons method, with the anomaly baseline period set as the complete time series. Additional data used in RSEI calculations included MOD09A1 and MOD11A2 products, as well as Terraclimate data.

1.3 Methods

1.3.1 Vegetation Coverage Fraction This study employed a pixel binary model to calculate vegetation coverage, assuming each pixel comprises vegetation and soil components. The formula is as follows:

$$NDVI = f_{veg} \times NDVI_V + (1 - f_{veg}) \times NDVI_S$$

where f_{veg} represents vegetation coverage fraction, $NDVI_V$ denotes NDVI values for fully vegetated pixels, and $NDVI_S$ represents NDVI values for bare soil or non-vegetated pixels. Based on MOD13Q1 imagery, the maximum NDVI value in the study area was used as $NDVI_V$ and the minimum as $NDVI_S$ to calculate vegetation coverage. According to vegetation characteristics, basin vegetation coverage was classified as: high coverage (>75%), relatively high coverage (50%-75%), moderate coverage (25%-50%), and low coverage (0%-25%).

1.3.2 CASA Model This study adopted the modified Carnegie-Ames-Stanford Approach (CASA) model, a light use efficiency model that combines Google Earth Engine with big data modeling. Input data included monthly mean temperature, monthly precipitation, monthly solar radiation, vegetation types, and NDVI. The expression is:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t)$$

where $NPP(x,t)$ represents net primary productivity ($\mathrm{g\ C \cdot m^{-2} \cdot month^{-1}}$) at pixel x in month t, $APAR(x,t)$ is photosynthetically active radiation ($\mathrm{MJ \cdot m^{-2} \cdot month^{-1}}$), and $\varepsilon(x,t)$ is actual light use efficiency ($\mathrm{g\ C \cdot MJ^{-1}}$).

1.3.3 Remote Sensing Ecological Index (RSEI) The RSEI integrates four evaluation indicators: greenness, wetness, heat, and dryness, derived from NDVI, wetness index (WET), land surface temperature (LST), and normalized difference built-up and soil index (NDBSI). Through principal component analysis, the remote sensing ecological index is obtained as:

$$RSEI_0 = 1 - PC_1[(NDVI, WET, LST, NDBSI)]$$

$$RSEI = \frac{RSEI_0 - RSEI_{min}}{RSEI_{max} - RSEI_{min}}$$

where PC_1 represents the first principal component of the four indicators, and $RSEI_{min}$ and $RSEI_{max}$ are the minimum and maximum values of $RSEI_0$, respectively. The RSEI was classified into five grades: poor [0.0, 0.2), relatively poor [0.2, 0.4), moderate [0.4, 0.6), good [0.6, 0.8), and excellent [0.8, 1.0). RSEI difference values were similarly divided into five grades: severe degradation [-∞,

-0.2), slight degradation [-0.2, -0.05), stable [-0.05, 0.05), slight improvement [0.05, 0.2), and significant improvement [0.2, $+\infty$).

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2. Results

2.1 Terrestrial Water Storage Change Characteristics

From April 2002 to December 2020, terrestrial water storage anomaly (TWSA) in the Tarim River Basin showed a significant decreasing trend ($P < 0.01$) at a rate of -0.27 mm$\cdot$month^{-1}. Seasonally, all four seasons exhibited significant declines ($P < 0.01$), with decreasing rates of -3.26 mm$\cdot$a^{-1} in spring, -3.25 mm$\cdot$a^{-1} in summer, -3.17 mm$\cdot$a^{-1} in autumn, and -1.04 mm$\cdot$a^{-1} in winter. Most regions showed water storage reduction rates of less than -1 mm$\cdot$month^{-1}, while the northern Tianshan and western Pamir Plateau areas experienced sharp decreases of -3 to -1 mm$\cdot$month^{-1}.

Spatially, from 2002 to 2020, the northern Kongque River, Dina River, Weigan River, Kuqa River, and Aksu River basins showed significant decreasing trends ($P < 0.01$), with reduction rates of -0.36 mm$\cdot$month^{-1}, -0.13 mm$\cdot$month^{-1}, -0.25 mm$\cdot$month^{-1}, and -0.21 mm$\cdot$month^{-1}, respectively. The western Kashgar River basin decreased at -0.13 mm$\cdot$month^{-1}, while the southwestern Yarkant River basin showed a reduction rate of -0.25 mm$\cdot$month^{-1}. In contrast, the southern and southwestern Qarqan River, Keriya River, and Qarqan River basins exhibited significant increasing trends ($P < 0.01$), with growth rates of 0.21 mm$\cdot$month^{-1} and 0.15 mm$\cdot$month^{-1}, respectively. The Hotan River basin overall showed a stable water storage trend (Fig. [Figure 2: see original paper]).

2.2 Oasis Dynamic Change Characteristics

From 2000 to 2020, the total oasis area in the nine source regions of the Tarim River Basin showed a significant expansion trend ($P < 0.01$), with an expansion area of approximately 0.42$\times10^{4}$ km^2 (6.49%). Specifically, the Bosten Lake, Kongque River, Dina River, Weigan-Kuqa River, and Aksu River oasis areas expanded by 274 km^2 (6.35%), 1,138 km^2 (9.77%), 880 km^2 (8.37%), 240 km^2 (3.90%), and 282 km^2 (7.01%), respectively. The western Kashgar River oasis area expanded by 91 km^2 (1.46%). The southern Yarkant River, Hotan River, Keriya River, and Qarqan River oasis areas expanded by 965 km^2 (38.68%), 553 km^2 (3.98%), 179 km^2 (5.71%), and 24 km^2 (6.82%), respectively (Fig. [Figure 3: see original paper]).

2.2.1 Oasis NDVI Changes From 2000 to 2020, NDVI in the nine source oasis regions of the Tarim River Basin showed a significant increasing trend ($P < 0.01$). The Bosten Lake, Kongque River, Dina River, Weigan-Kuqa River, and Aksu River oasis areas increased by 55.25%, 50.89%, 51.61%, 38.42%, and

91.15%, respectively. The Kashgar River oasis area decreased by 17.18%, while the southern Yarkant River, Hotan River, Keriya River, and Qarqan River oasis areas increased by 51.48%, 66.42%, 49.56%, and 32.02%, respectively. Hurst index analysis indicates that the Dina River and Kongque River oasis areas will continue to show increasing trends in the future, while the Hotan River oasis area will decrease (Fig. [Figure 4: see original paper]).

2.2.2 Oasis Vegetation Coverage Changes Vegetation coverage in the Tarim River Basin oasis areas showed a significant upward trend from 2000 to 2020 ($P < 0.01$), with an overall increase of 36.79%. The northern Bosten Lake, Kongque River, Dina River, Weigan-Kuqa River, and Aksu River oasis areas showed the highest increase rates at $0.85\% \cdot a^{-1}$ and $1.20\% \cdot a^{-1}$, respectively. The southern Yarkant River, Hotan River, Keriya River, and Qarqan River oasis areas showed relatively slower increase rates of $0.21\% \cdot a^{-1}$ ($P < 0.01$). Areas with high, relatively high, and moderate vegetation coverage all showed significant upward trends ($P < 0.05$), with expansion rates of $8.28\% \cdot a^{-1}$, $2.53\% \cdot a^{-1}$, and $7.26\% \cdot a^{-1}$, respectively. Conversely, low vegetation coverage areas showed significant decreasing trends ($P < 0.01$), with reduction rates of $-0.25\% \cdot a^{-1}$ in the Yarkant River oasis area, $-37.48\ km^2 \cdot a^{-1}$ in the Hotan River oasis area, $-11.10\ km^2 \cdot a^{-1}$ in the Keriya River oasis area, and $-19.49\ km^2 \cdot a^{-1}$ in the Qarqan River oasis area. Hurst index analysis reveals that most areas of the Tarim River Basin will improve in the future, with 54%-75% of the Bosten Lake, Aksu River, Yarkant River, Weigan-Kuqa River, Kashgar River, Keriya River, and Qarqan River oasis areas showing persistent increasing trends (Fig. [Figure 5: see original paper]).

2.2.3 Interannual NPP Variation Characteristics NPP in the nine source oasis regions of the Tarim River Basin showed significant increasing trends from 2000 to 2020 ($P < 0.01$). The northern Bosten Lake, Kongque River, Dina River, Weigan-Kuqa River, and Aksu River oasis areas showed increase rates of $2.38\ g\ C \cdot m^{-2} \cdot a^{-1}$, $2.26\ g\ C \cdot m^{-2} \cdot a^{-1}$, $1.39\ g\ C \cdot m^{-2} \cdot a^{-1}$, $3.12\ g\ C \cdot m^{-2} \cdot a^{-1}$, and $4.30\ g\ C \cdot m^{-2} \cdot a^{-1}$, respectively, with 20-year NPP increases of 71.28%, 82.12%, 56.13%, 98.51%, and 219.06%, respectively. The western Kashgar River oasis area showed an increase rate of $0.86\ g\ C \cdot m^{-2} \cdot a^{-1}$ (12.67%). The southern Yarkant River, Hotan River, Keriya River, and Qarqan River oasis areas showed 20-year increase rates of $2.03\ g\ C \cdot m^{-2} \cdot a^{-1}$, $0.46\ g\ C \cdot m^{-2} \cdot a^{-1}$, $2.86\ g\ C \cdot m^{-2} \cdot a^{-1}$, and $3.42\ g\ C \cdot m^{-2} \cdot a^{-1}$, with increases of 66.42%, 49.56%, 90.86%, and 123.32%, respectively. Hurst index analysis indicates that the Bosten Lake, Aksu River, Yarkant River, Kongque River, Dina River, Weigan-Kuqa River, Kashgar River, Keriya River, and Qarqan River oasis areas will continue to show increasing trends in the future, while the Aksu River, Kongque River, and Dina River oasis areas have Hurst values of 0.27, suggesting decreasing trends, particularly in the Hotan River oasis area where 75.96% will show decreasing trends (Fig. [Figure 6: see original paper]).

2.3 Oasis Ecological Effect Evaluation

From 2000 to 2020, the overall ecology of the Tarim River Basin improved (Fig. [Figure 7: see original paper]). The RSEI increased from 0.32 in 2000 to 0.50 in 2020, with the ecological grade shifting from poor to moderate. The area of poor and relatively poor ecological conditions decreased by 22.26% and 27.57%, respectively, while the area of good and excellent ecological conditions increased by 86.87% and 140.02%, respectively. In 2020, the area of ecological degradation (severe and slight degradation) accounted for approximately 6.23% of the total basin area, stable areas comprised 26.08%, slight improvement areas accounted for 62.69%, and significant improvement areas represented 5.00%. Oasis areas in the Tarim River Basin were concentrated in stable and slight improvement zones, covering 88.77% of the total basin area. The southern Kunlun and Karakoram mountain regions showed the most significant improvement, with severe degradation areas not exceeding 0.5% of the total area in each basin (Fig. [Figure 7: see original paper]).

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3. Discussion

3.1 Natural Factors

From 2000 to 2020, temperature and precipitation in the Tarim River Basin showed significant spatial heterogeneity. Temperature increased significantly in the Weigan-Kuqa River and Aksu River basins, while decreasing in the northern Kaidu River basin and western Pamir Plateau. Precipitation changes were predominantly increasing, with 66.67% of stations showing upward trends, particularly in the southwestern basin. These climate variations significantly influenced interannual water storage changes. Rising temperatures in the northern Tianshan Mountains accelerated glacier retreat and snowmelt, reducing mountain water storage. Most meteorological stations are distributed in low-altitude areas below 1,500 m, with few stations above 2,000 m. Although station data indicated decreasing temperatures in low-altitude areas over the past 20 years, field monitoring revealed that temperatures in the Tianshan region showed significant upward trends with increasing altitude, particularly above 3,000 m, where warming was more pronounced. Glacier accumulation serves as an important factor for increased water storage in this region.

Correlation analysis between water storage changes and temperature/precipitation revealed significant relationships between water storage and temperature in the Weigan-Kuqa River and Aksu River basins ($P < 0.05$), confirming that temperature rise is a crucial cause of water storage decline in these basins. Precipitation in the Tarim River Basin is concentrated in mountainous areas, which have become wetter since the 1980s, partially replenishing regional water resources. The vast majority of stations showed increasing annual precipitation, especially in high-altitude zones. In the southern Karakoram region, precipitation occurs primarily as snowfall, accumulating mainly above 5,000

m. The unique geographical location and altitude create favorable conditions for glacier development. Research shows that while summer mean temperature and minimum temperature in the Karakoram region have decreased in recent decades, increased summer and winter precipitation has gradually accumulated moisture over the Karakoram, causing cooling anomalies and forming abundant solid precipitation. Increased snowfall and low temperature sensitivity are primary reasons for glacier growth or stability in the region. Consequently, terrestrial water storage in the southern Tarim River Basin has remained stable with an overall increasing trend, as the region receives abundant glacier meltwater from the Kunlun Mountains.

Vegetation in the Tarim River Basin is distributed across mountainous zones, oases, and oasis-desert ecotones. Recent temperature increases accompanied by precipitation growth have contributed to ecological improvement, including increases in NDVI, vegetation coverage, and NPP. Compared with Central Asian arid regions where intensified desertification has created significant carbon sources, the ecological improvement in the Tarim River Basin will reduce carbon source areas, with some regions potentially becoming carbon sinks.

3.2 Anthropogenic Factors

As an important human-environment system in arid regions, oases are strongly influenced by human activities. Since 2000, cultivated land in the Tarim River Basin has expanded by 56.95% (15,324 km^2), with the most significant expansion occurring in the Kongque River and Qarqan River oasis areas at 130.81% and 142.13%, respectively. Forest and grassland areas decreased by 7.28% and 8.36%, respectively, with Bosten Lake forest area decreasing by approximately 1,150 km^2 (2.91%) and Kongque River grassland area decreasing by 1,763 km^2 (7.28%). Unutilized land area (primarily desert and bare land) decreased by 5.71%, except in the Dina River and Keriya River basins where it slightly increased. The continuous expansion of cultivated land in oasis areas, encroaching upon desert-oasis transition zones, is a primary cause of transition zone shrinkage and vegetation degradation.

According to the Xinjiang Statistical Yearbook, over 1,100$×10^{4}$ hm^2 of agricultural land and over 2,819$×10^{4}$ people face water resource pressure. The southern slopes of the Tianshan Mountains in the northern Tarim River Basin are primary oasis distribution areas. Recent rapid expansion of cultivated land scale has caused river channel dry-up and excessive groundwater exploitation, leading to reduced terrestrial water storage in the region. Since 2000, the Chinese government has intensified ecological protection efforts in the Tarim River Basin, delivering ecological water conveyance to the lower reaches 88 times with a total volume of 45.45$×10^{8}$ m^3. Since the water conveyance began, natural forest vegetation in the lower reaches has recovered significantly, groundwater levels have risen by approximately 4-5 m, and vegetation coverage in inundated areas has increased at rates up to 0.40 $g\ C \cdot m^{-2} \cdot a^{-1}$ higher than in non-inundated areas. Under human activity influences, surface vegetation coverage in the lower Tarim River has increased in recent years, and the ecological degradation trend has been essentially controlled.

4. Conclusions

This study investigated changes in terrestrial water storage and oasis ecological security in the Tarim River Basin from 2000 to 2020, reaching the following conclusions:

(1) Terrestrial water storage in the Tarim River Basin decreased at a rate of 0.27 $\text{mm} \cdot \text{month}^{-1}$, with significant spatial heterogeneity—declining notably in northern and western regions while increasing significantly in southern regions. Accelerated mountain ice and snow melt caused by rising temperatures is the primary reason for water storage reduction in northern basin areas, while significantly increased mountain precipitation accompanied by cooling has replenished terrestrial water resources in southern basin areas to some extent.

(2) Oasis area in the Tarim River Basin increased by 6.49% (0.42\$×10^{4}\$ km^2) from 2000 to 2020, with the overall ecological environment showing improvement. The ecological grade shifted from poor to moderate, with improvement zones accounting for 69% of the total basin area and degradation areas less than 5%. NDVI increased from 0.13 to 0.16, vegetation coverage increased by 36.79%, and NPP expanded by 31.55% over the 20-year period. Spatially, all river basins in the Tarim River showed significant increases in NDVI, vegetation coverage, and NPP, with the most pronounced increases in northern Tianshan region basins and the western Kashgar River basin oasis areas.

(3) Human activities are the main driving force behind oasis dynamic changes in the Tarim River Basin. With increased upstream water supply, humans have intensified water resource allocation, converting other land types to cultivated land and urban construction land, developing unutilized land in oasis areas, and promoting significant oasis area growth.

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Note: Figure translations are in progress. See original paper for figures.

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