Impacts of Ecological Water Transfer in the Tarim River on Changes in Vegetation Gross Primary Productivity over the Past 20 Years: Postprint

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Abstract

Vegetation Gross Primary Productivity (GPP) is a critical component of terrestrial ecosystem carbon cycling and is essential for maintaining global carbon balance. Based on the Google Earth Engine platform and utilizing the MOD17A2H product released by NASA LP DAAC, this study analyzed the changes in GPP of terrestrial ecosystems during the growing season in the Tarim River ecological water conveyance period. The results show that: (1) After ecological water conveyance, the ecological environment of the Tarim River was improved overall. In the early stage of water conveyance, the average growing season GPP of the Tarim River was 3675.51 g $C \bullet m^{-2} \bullet season^{-1}$; in the middle stage, the growing season GPP increased to 4024.09 g $C \bullet m^{-2} \bullet season^{-1}$; and in the later stage, this value jumped to 4896.61 g $C \bullet m^{-2} \bullet season^{-1}$. From 2000 to 2020, the growing season GPP of the Tarim River showed a significant increasing trend, with an increase of approximately 90.25 g $C \bullet m^{-2}$ per growing season. After 2010, the increase in daily GPP in the upper, middle, and lower reaches was also more pronounced, increasing by 2.54 g $C \bullet m^{-2}$, 2.17 g $C \bullet m^{-2}$, and 1.74 g $C \bullet m^{-2}$ per 10 a, respectively. (2) The daily GPP variation in terrestrial ecosystems of the Tarim River during the growing season (May-October) showed significant differences across different regions. The daily GPP variation in the upper reach area generally exhibited a unimodal trend of first increasing and then decreasing, while the lower reach area was dominated by a bimodal variation trend. (3) The Tarim River ecological water conveyance project is beneficial to the variation of growing season GPP, with a more significant impact on GPP changes in June and August.

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Full Text

Effects of Ecological Water Conveyance on Vegetation Gross Primary Productivity Changes in the Tarim River over the Past 20 Years

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Abstract

Gross primary productivity (GPP) represents a critical component of the terrestrial ecosystem carbon cycle and is essential for maintaining global carbon balance. Based on the Google Earth Engine platform and MOD17A2H products released by NASA LP DAAC, this study analyzed GPP changes in the Tarim River terrestrial ecosystem during the growing season throughout the ecological water conveyance period. The results demonstrate that the ecological environment of the Tarim River has improved significantly following ecological water conveyance. During the early water conveyance period, the average growing season GPP was 3675.51 g $C \cdot m^{-2} \cdot season^{-1}$. In the middle period, this value increased to 4024.09 g $C \cdot m^{-2} \cdot season^{-1}$, and in the later period, it rose substantially to 4896.61 g $C \cdot m^{-2} \cdot season^{-1}$. From 2000 to 2020, GPP exhibited a pronounced increasing trend during the growing season, with an increment of approximately 90.25 g $C \cdot m^{-2}$ per growing season. After 2010, the daily GPP increase became more pronounced across the upper, middle, and lower reaches, rising by 2.54 g $C \cdot m^{-2}$, 2.17 g $C \cdot m^{-2}$, and 1.74 g $C \cdot m^{-2}$ per decade, respectively. The diurnal GPP variation patterns differed markedly among regions. The upper reaches displayed a single-peak trend (increasing then decreasing), while the lower reaches showed a predominantly bimodal pattern. The ecological water conveyance project has demonstrably benefited GPP changes during the growing season, particularly in June and August.

Keywords: gross primary productivity (GPP); ecological water conveyance project; spatiotemporal distribution; *Populus euphratica* key conservation areas; Tarim River

1.2.1 MODIS GPP Dataset

This study utilized the MOD17A2H GPP product provided by NASA LP DAAC (https://lpdaac.usgs.gov/products/mod17a2hv006/). This product is calculated using a radiation use efficiency model based on MODIS data at 500 m spatial resolution, incorporating the fraction of photosynthetically active radiation absorbed by vegetation (FPAR), leaf area index (LAI), an updated biome property look-up table, and daily global modeling and assimilation meteorological data. The dataset has undergone rigorous quality control and can be directly used for model input, finding widespread application in studies of terrestrial energy, carbon, and water cycles, as well as vegetation biogeochemical processes. Using the Google Earth Engine platform, we performed preprocessing steps including radiometric calibration, atmospheric correction, spatial projection, data conversion, image clipping, and statistical analysis to obtain GPP data for the Tarim River mainstream area. Based on vegetation growth characteristics in the study area, combined with existing research and the timing of each ecological water conveyance event, the growing season was defined as May through October and divided into three sub-seasons: spring (May–June), summer (July–August), and autumn (September–October).

1.2.2 Ecological Water Conveyance Data

Ecological water conveyance data from May 2000 to October 2020, including conveyance frequency, methods, timing, and volumes, were obtained from the State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. The Tarim Basin serves as a core area of China's "Silk Road Economic Belt" and possesses an extremely fragile ecological environment, with average annual precipitation of approximately 51.2 mm and annual evaporation reaching 2300–3000 mm. Water resources primarily consist of high-altitude snowmelt, mid-mountain forest precipitation, and low-mountain bedrock fissure water. The Tarim River basin comprises nine major water systems and 144 rivers surrounding the Tarim Basin, with a total area of 102$\times10^{4}$ km^{2} and total surface runoff of 398$\times10^{8}$ m^{3}. The mainstream extends from the confluence of three source streams at Xiaoqiaoke to Lake Taitema, spanning 1321 km. The mainstream is divided into upper (Xiaoqiaoke–Yingbaza), middle (Yingbaza–Daxihaizi Reservoir), and lower reaches (Daxihaizi Reservoir–Lake Taitema). The study area includes the upper, middle, and lower reaches of the Tarim River, as well as two key *Populus euphratica* forest conservation areas (Shaya and Luntai) belonging to the upper and middle reaches.

1.3.1 GPP Interannual Variation Analysis

Based on 500 m resolution MODIS GPP data, we extracted and calculated the annual growing season GPP totals for the study area. The relative change rate index was employed to compute annual changes and relative change rates for the entire Tarim River mainstream and its upper, middle, and lower reaches. The calculation formula is as follows:

$$\delta = \frac{\Delta GPP_i}{GPP_m}$$

where δ represents the relative change rate (%), i denotes the year (2000–2020), ΔGPP_i is the absolute change in GPP for subregion m in year i (g $C \cdot m^{-2} \cdot$ season^{-1}), and GPP_m is the multi-year average growing season GPP for subregion m (g $C \cdot m^{-2} \cdot$ season^{-1}).

1.3.2 GPP Seasonal Variation Analysis

Using the acquired GPP data and established seasonal divisions within the growing season, we calculated seasonal GPP values for the Tarim River from 2000 to 2020. The calculation formula is:

$$GPP_s = \sum_{i=1}^{n} (GPP_i \times m)$$

where GPP_s represents GPP for a specific season (spring, summer, or autumn) (g $C \cdot m^{-2}$), s denotes the season, i represents the year (2000-2020), m indicates the number of months corresponding to the specified season, and n is the total number of years (21).

1.3.3 Impact Analysis of Ecological Water Conveyance on GPP

The Pearson correlation coefficient method was used to measure correlations between variables, with larger r values indicating stronger relationships. Considering potential time lags between ecological water conveyance and GPP response, we analyzed correlations between cumulative water conveyance and GPP at time lags of 0–3 months. The correlation coefficient formula is:

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}}$$

where r represents the correlation between ecological water conveyance and GPP, x_i is the water conveyance volume in year i (10^8 m^3), y_i is the growing season GPP in year i (g $C \cdot m^{-2} \cdot$ month^{-1}), $\bar{x}$ is the multi-year average water conveyance volume, and $\bar{y}$ is the multi-year average monthly GPP. The analysis also considered time lags of 1–3 months between water conveyance and GPP response.

2.1 Daily GPP Variation Characteristics of the Tarim River Terrestrial Ecosystem

Daily GPP during the growing season (May-October) exhibited distinct variation trends across different regions of the Tarim River [Figure 2: see original paper]. In the upper reaches, daily GPP showed a single-peak trend (increasing then decreasing), while the lower reaches displayed a predominantly bimodal pattern. With the progression of ecological water conveyance, daily GPP peaks also varied significantly among years. The study divided the 20-year water conveyance period into three stages: early (2000-2007), middle (2008-2014), and late (2015-2020). During the early stage, upper reach peaks occurred in July-August, with daily GPP reaching 13.00 g $C \cdot m^{-2}$. In the middle stage, the peak shifted to June-July, increasing to 17.47 g $C \cdot m^{-2}$. By the late stage, the peak further advanced to May-June, reaching 21.39 g $C \cdot m^{-2}$. In the lower reaches, bimodal patterns were evident, with the first peak shifting from July (8.07 g $C \cdot m^{-2}$) in the early stage to June (10.57 g $C \cdot m^{-2}$) in the late stage, and the second peak shifting from September (12.69 g $C \cdot m^{-2}$) to August (17.47 g $C \cdot m^{-2}$). These results clearly indicate that the Tarim River Basin comprehensive management project has produced positive ecological impacts, with the maximum daily vegetation primary productivity increasing and its timing shifting earlier.

To further examine daily GPP variation patterns from 2000 to 2020, we analyzed multi-year daily GPP changes across the upper, middle, and lower reaches, with particular focus on two key *Populus euphratica* forest conservation areas (Shaya in the upper reaches and Luntai in the middle reaches) [Figure 3: see original paper]. The results show that the Tarim River ecosystem has improved overall, with daily GPP in all reaches exhibiting increasing trends. The upper reaches showed the greatest increase at 2.35 g $C \cdot m^{-2}$ per decade, followed by the middle (1.69 g $C \cdot m^{-2}$) and lower reaches (0.90 g $C \cdot m^{-2}$). After 2010, these increases became more pronounced, reaching 2.54 g $C \cdot m^{-2}$, 2.17 g $C \cdot m^{-2}$, and 1.74 g $C \cdot m^{-2}$ per decade, respectively. The daily GPP changes in the Shaya and Luntai conservation areas showed high consistency with these patterns.

2.2 Growing Season GPP Variation Characteristics

From 2000 to 2020, the average growing season GPP of the Tarim River terrestrial ecosystem showed a significant increasing trend, rising from 2950.32 g $C \cdot m^{-2} \cdot season^{-1}$ to 5479.72 g $C \cdot m^{-2} \cdot season^{-1}$, with an increment of approximately 90.25 g $C \cdot m^{-2}$ per growing season ($R^2 = 0.61$) [Figure 4: see original paper]. This trend closely correlates with ecological water conveyance activities. Before 2010, water conveyance primarily used single-channel methods with a cumulative volume of 22.7$×10^{8}$ m³. After 2010, dual-channel conveyance became dominant, with cumulative volume reaching 55.30$×10^{8}$ m³, resulting in more substantial GPP increases.

Seasonal contributions to growing season GPP varied significantly among regions. In the upper reaches, summer contributed most (38.10%), followed by spring (31.42%) and autumn (30.48%). Conversely, in the middle and lower reaches, autumn contributed most (32.42% and 36.84%, respectively), followed by summer (31.00% and 34.17%) and spring (29.37% and 35.33%). To illustrate GPP changes across different water conveyance periods, representative years were selected: 2003 (early), 2011 (middle), and 2019 (late). Growing season GPP increased from 1074.54 g $C \cdot m^{-2} \cdot season^{-1}$ in the early period to 1382.73 g $C \cdot m^{-2} \cdot season^{-1}$ in the middle period and 2040.37 g $C \cdot m^{-2} \cdot season^{-1}$ in the late period. Spatially, significant increases were concentrated along riverbanks [Figure 5: see original paper].

2.3 GPP Variation in Key *Populus euphratica* Conservation Areas

Taking the Shaya *Populus euphratica* forest reserve as an example, analysis of its growing season and seasonal GPP from 2000 to 2020 revealed continuous improvement. Growing season GPP increased from 747.50 g $C \cdot m^{-2} \cdot season^{-1}$ in 2000 to 1132.72 g $C \cdot m^{-2} \cdot season^{-1}$ in 2020. Seasonal GPP also increased, with autumn showing the greatest increase (from 4.14 to 7.17 g $C \cdot m^{-2}$), followed by summer (from 5.67 to 5.69 g $C \cdot m^{-2}$), and spring the smallest increase (from 3.51 to 4.61 g $C \cdot m^{-2}$) [Figure 6: see original paper]. High GPP values were distributed along river courses. Under the influence of ecological water conveyance, seasonal GPP patterns shifted, with autumn values surpassing those of spring and summer in later years.

2.4 Impact of Ecological Water Conveyance on GPP Changes

Correlation analysis between ecological water conveyance and GPP revealed generally positive relationships, with correlation coefficients for cumulative water conveyance versus growing season GPP being significantly greater than those for annual water conveyance [Figure 7: see original paper]. The impact was most significant in June and August, passing the 95% confidence test. Considering potential time lags, we analyzed correlations between 1-, 2-, 3-, and 5-year cumulative water conveyance and GPP with 0–3 month lags. Results showed that water conveyance and GPP were negatively correlated in some areas when considering time lags, particularly in Aksu region. This contrasts with findings from other southern Xinjiang areas where precipitation and GPP showed positive correlations, indicating that while precipitation is important, local topography, microclimate, and vegetation type may be more critical factors influencing GPP responses to water conveyance.

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3 Conclusions

Using Google Earth Engine and MOD17A2H products from NASA LP DAAC, this study calculated GPP in the Tarim River terrestrial ecosystem during the growing season throughout the ecological water conveyance period. The main findings are:

1) Daily GPP variation patterns differed significantly among regions. The upper reaches showed a single-peak trend (increasing then decreasing), while the lower reaches exhibited a bimodal pattern. With continued water conveyance, daily GPP peaks occurred earlier and maximum values increased.

2) Following ecological water conveyance, the Tarim River environment improved overall. Daily GPP in the upper, middle, and lower reaches showed significant increasing trends of 2.35, 1.69, and 0.90 g $C \cdot m^{-2}$ per decade, respectively, with more pronounced increases after 2010 (2.54, 2.17, and 1.74 g $C \cdot m^{-2}$ per decade). Growing season GPP increased significantly from 2000 to 2020, with an increment of approximately 90.25 g $C \cdot m^{-2}$ per growing season. Seasonal contributions varied regionally: summer dominated in the upper reaches, while autumn contributed most in the middle and lower reaches.

3) The ecological water conveyance project showed positive correlations with growing season GPP changes, particularly affecting June and August (passing 95% confidence tests). Time-lag analysis revealed complex relationships, with some areas showing negative correlations at 1-3 month lags, highlighting the importance of local environmental factors.

Terrestrial ecosystem changes are complex processes requiring comprehensive consideration of human activities and climate change. This study focused on water conveyance impacts, though concurrent climate variations (temperature, precipitation) and natural factors (topography, soil organic matter) also affect GPP and warrant further investigation.

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