Postprint: Impact of Ecological Water Transfer on Natural Vegetation NPP in the Lower Tarim River

Authors: Zhang Jingjing, Hao Haichao

Date: 2021-06-17T00:00:00+00:00

Abstract

Net primary production (NPP) is a key parameter of carbon cycle and energy flow in terrestrial ecosystems that characterizes ecosystem quality. Based on MOD13A1, MCD12Q1, TERRACLIMATE, and other datasets from 2001-2019, the CASA model was used to estimate the spatiotemporal variation trend of natural vegetation NPP in the lower reaches of the Tarim River under ecological water conveyance conditions over the past 20 years. Through Slope trend analysis and Pearson correlation analysis, the influence of the ecological water conveyance project on the growth status of natural vegetation in the lower Tarim River was analyzed from the perspectives of spatiotemporal distribution, different vegetation types, and different cumulative water conveyance volumes. The results indicate: (1) Over the past 20 years, natural vegetation NPP in the lower Tarim River has exhibited an overall upward trend, with areas showing extremely significant and significant increases accounting for 31.93% ($P<0.01$) and 11.49% ($P<0.05$) of the total area, respectively, and the average increase rate was 0.40 g C m-2 a-1. (2) In the transverse direction, natural vegetation NPP in the lower Tarim River decreases with increasing distance from the river channel; in the longitudinal direction, from upstream to downstream along the river channel, natural vegetation NPP displays the following pattern: upper section (28.21 g C m-2) > middle section (18.70 g C m-2) > lower section (13.55 g C m-2). (3) Regarding NPP across different vegetation types, the ranking is: Tamarix community (57.37 g C m-2) > Populus euphratica community (29.29 g C m-2) > herbaceous community (23.23 g C m-2), with the Tamarix community also showing the largest NPP increase during the ecological water conveyance process at 350.20%. (4) Both groundwater depth and natural vegetation NPP are significantly correlated with the cumulative 3-year ecological water conveyance volume, with correlation coefficients of -0.70 ($P<0.01$) and 0.62 ($P<0.01$), respectively; the correlation between total annual water conveyance volume and groundwater depth in the following year is significantly higher than that with groundwater depth in the current year; furthermore, as groundwater depth continuously and stably recovered, the correlation between natural vegetation NPP and groundwater depth also significantly strengthened during 2010-2019 (R2=0.62).

Full Text

Effects of Ecological Water Conveyance on NPP of Natural Vegetation in the Lower Reaches of Tarim River

ZHANG Jingjing[1,2,3], **HAO Haichao**[1,2,3], **HAO Xingming**[1,2], **FAN Xue**[1,2,4], **LI Yuanhang**[1,2,4]

[1]State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
[2]National Field Scientific Observation and Research Station of Akesu Oasis Farmland Ecosystem, Aksu 843017, Xinjiang, China
[3]University of Chinese Academy of Sciences, Beijing 100049, China
[4]College of Life Sciences, Xinjiang Normal University, Urumqi 830054, Xinjiang, China

Abstract

Vegetation net primary production (NPP) is a key parameter of the carbon cycle and energy flow in terrestrial ecosystems that characterizes ecosystem quality. Based on the CASA model, this study estimated the spatiotemporal variations of natural vegetation NPP in the lower reaches of the Tarim River under ecological water conveyance conditions over the past 20 years. Using slope trend analysis and Pearson correlation analysis, we examined the impacts of ecological water conveyance projects on natural vegetation growth from three perspectives: spatiotemporal distribution, different vegetation types, and cumulative water transfer volumes. The results show that: (1) The NPP of natural vegetation in the lower reaches of the Tarim River showed an overall upward trend, with areas of extremely significant increase, significant increase, and insignificant change accounting for 31.93% ($P<0.01$), 11.49% ($P<0.05$), and 52.03% of the total area, respectively. (2) Horizontally, NPP decreased with increasing distance from the river channel, following the pattern: 0-1000 m > 1000-2000 m > 2000-10000 m. Longitudinally, from upstream to downstream, NPP generally increased, with average growth rates of 28.21 g $C \cdot m^{-2}$, 18.70 g $C \cdot m^{-2}$, and 13.55 g $C \cdot m^{-2}$ in the upper, middle, and lower sections, respectively. (3) Among vegetation types, NPP values ranked as: tamarisk community (57.37 g $C \cdot m^{-2}$) > Populus euphratica community (29.29 g $C \cdot m^{-2}$) > herbaceous community (23.23 g $C \cdot m^{-2}$), with the tamarisk community showing the largest increase (350.20%) during ecological water conveyance. (4) Groundwater depth and natural vegetation NPP were significantly correlated with cumulative ecological water volume over three years, with correlation coefficients of -0.70 ($P<0.01$) and 0.62 ($P<0.01$), respectively. The correlation between annual water conveyance and groundwater depth in the following year was significantly higher than that with the current year' s groundwater depth. Moreover, as groundwater depth continued to rise stably, the correlation between NPP and groundwater depth strengthened significantly (R^2=0.62). This study systematically analyzes NPP variations in the lower Tarim River since the implementation of ecological water conveyance and provides scientific guidance for future water conveyance and ecological restoration efforts.

Keywords: inland river basins; groundwater depth; CASA model; desert riparian forest

---

1.2 Data Sources

Natural vegetation NPP in this study was calculated using the Google Earth Engine (GEE) platform. MOD13A1 and MCD12Q1 data products were employed, with the Normalized Difference Vegetation Index (NDVI) data having been corrected for atmospheric gases, thin clouds, and aerosol effects at a temporal resolution of 16 days and spatial resolution of 500 m$×500m.Landsat5imagerywithcloudcoverlessthan10×$0.1° and temporal resolution of one month. Water conveyance data for the lower Tarim River were provided by the Tarim River Basin Authority. Groundwater depth data came from monitoring by our research team and the Tarim River Basin Authority at nine cross-sections: Akedun, Yahepumahan, Yingsu, Abudale, Kaerdayi, Tugemailai, Alagan, Yiganbujima, and Kaogan (Figure 1). Land use data were obtained from the Western Environmental Science Data Center at a scale of 1:100000.

Note: This map is based on the standard map downloaded from the Standard Map Service website of Xinjiang Uygur Autonomous Region Surveying and Mapping Geographic Information Bureau (Approval No.: Xin S (2019) No. 022), with no modifications to the base map. Letters in the figure represent the distribution of groundwater and ecological monitoring sections.

[Figure 1: see original paper]

1.3.1 CASA Model

This study employed the widely used Carnegie-Ames-Stanford Approach (CASA) model to estimate NPP of the lower Tarim River vegetation from 2000 to 2019. NPP depends primarily on absorbed photosynthetically active radiation (APAR) and light use efficiency ( ). The calculation formula is as follows:

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

where x represents the pixel, and t represents the time period (month).

The APAR calculation formula is:

$$APAR(x,t) = SOL(x,t) \times FPAR(x,t) \times 0.5$$

where $SOL(x,t)$ is the total solar radiation, $FPAR(x,t)$ is the proportion of photosynthetically active radiation absorbed by vegetation, and the constant 0.5 represents the fraction of solar effective radiation that vegetation can absorb relative to total solar radiation.

Light use efficiency ε characterizes photosynthetic production efficiency and is calculated as:

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{\max}$$

where $T_{\varepsilon 1}$ and $T_{\varepsilon 2}$ are temperature stress coefficients, W_{ε} is the water stress coefficient, and $\varepsilon_{\max}$ is the maximum light use efficiency. The stress factors were determined based on existing research, with maximum light use efficiency values for different vegetation types shown in Table 1.

1.3.2 Analysis Methods

Linear regression analysis was used to calculate the slope trend of NPP changes, reflecting spatial distribution differences in vegetation NPP at the pixel scale in the lower Tarim River from 2000 to 2019. The formula is:

$$\text{slope} = \frac{n \times \sum_{i=1}^{n} i \times NPP_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} NPP_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where slope is the trend line slope reflecting the interannual change rate; NPP_i is the NPP value in year i; and n is the number of years. When slope > 0, NPP increases, and vice versa.

2.1 Spatial Distribution Characteristics and Change Trends of NPP

From 2000 to 2019, the spatial distribution of average annual NPP of natural vegetation in the lower Tarim River showed significant heterogeneity, generally characterized by high values along both banks of the river channel and low values in areas far from the river and around lakes (Figure 2). The multi-year average NPP values within 1000 m, 1000-2000 m, and 2000-10000 m from the river channel were 27.48 g $\mathrm{C \cdot m^{-2}}$, 18.27 g $\mathrm{C \cdot m^{-2}}$, and 16.52 g $\mathrm{C \cdot m^{-2}}$, respectively, decreasing gradually with distance from the river. Overall, NPP values in the lower Tarim River were relatively low, ranging from 0.72 to 183.88 g $\mathrm{C \cdot m^{-2}}$. Longitudinally, the multi-year average NPP values in the upper section (Daxihaizi Reservoir-Yingsu), middle section (Yingsu-Alagan), and lower section (Alagan-Taitema Lake) were 28.21 g $\mathrm{C \cdot m^{-2}}$, 18.70 g $\mathrm{C \cdot m^{-2}}$, and 13.55 g

$C \cdot m^{-2}$, respectively, with the upper section significantly higher than the middle and lower sections.

During 2000-2019, NPP of natural vegetation in the lower Tarim River showed an overall upward trend with obvious spatial differences (Figure 2). Statistics indicate that since the implementation of ecological water conveyance, areas with decreasing NPP in the lower Tarim River covered 132 km^2, accounting for only 2.07% of the study area, mainly distributed near the Kuruk Desert in the upper section and below Taitema Lake. Areas with significant decreases covered 157 km^2 (2.47% of the study area), with small distributions in the upper, middle, and lower sections. Areas with insignificant changes covered 3310.75 km^2 (52.03% of the study area), primarily showing insignificant increases and distributed mainly in areas far from the river channel in the upper and middle sections. Areas with significant increases covered 731.25 km^2 (11.49% of the study area), distributed mainly along both banks of the river. Areas with extremely significant increases covered 2031.75 km^2 (31.93% of the study area), concentrated along river banks and in some areas above Taitema Lake.

[Figure 2: see original paper]

2.2 Interannual Variation Characteristics of NPP

From 2000 to 2019, the average annual NPP of natural vegetation in the lower Tarim River ranged from 16.05 to 24.08 g $C \cdot m^{-2}$, with a multi-year average of 20.81 g $C \cdot m^{-2}$. Interannual fluctuations were obvious (Figure 3). NPP increased significantly from 2000 to 2005, with a growth rate of 29.48%. It decreased significantly from 2005 to 2008, with a decline of 47.35%. From 2008 to 2010, NPP fluctuated and decreased slightly, with a decline of 14.30%. NPP increased continuously from 2010 to 2019, with a growth rate of 28.30%. After 2010, the average annual NPP values were generally greater than 20 g $C \cdot m^{-2}$, indicating that vegetation growth conditions improved substantially after 2010.

[Figure 3: see original paper]

2.3 Changes in NPP of Different Vegetation Types

The growth season variation trends of NPP for Populus euphratica, tamarisk, and herbaceous communities were similar from 2000 to 2019. NPP decreased from April to the lowest point of the growing season in July, with minimum values of 0.92 g $C \cdot m^{-2}$, 1.36 g $C \cdot m^{-2}$, and 0.70 g $C \cdot m^{-2}$, respectively. Thereafter, NPP increased continuously, reaching maximum values of 10.29 g $C \cdot m^{-2}$, 4.33 g $C \cdot m^{-2}$, and 3.51 g $C \cdot m^{-2}$ in September, then decreased in October. The interannual variation characteristics of NPP in the upper, middle, and lower sections of the lower Tarim River were similar. As shown in Figure 3, April-October represents the growth period for natural vegetation, with the fastest growth occurring in July-September. During this period, the average monthly growth rates of NPP for P. euphratica, tamarisk, and herbaceous communities were 6.47 g $C \cdot m^{-2}$, 3.34 g $C \cdot m^{-2}$, and 2.66 g $C \cdot m^{-2}$, respectively.

However, the annual growth season variation trends were not consistent. As shown in Figure 3, larger NPP values typically appeared in September, while the largest values usually occurred in July in the middle section. Analysis revealed that the actual temperature in the lower Tarim River in July was close to the optimal growth temperature for P. euphratica, tamarisk, and herbaceous communities (Figure 3). The average temperature difference between actual and optimal growth temperatures was 3.83°C in July, 3.35°C in August, and 4.63°C in September. This indicates that NPP is constrained more significantly by water conditions than by temperature.

From 2000 to 2019, the NPP values of P. euphratica, tamarisk, and herbaceous communities increased substantially but showed different interannual variations. The multi-year average NPP values ranked as: tamarisk (57.37 g C • m^{-2}) > P. euphratica (29.30 g C • m^{-2}) > herbaceous community (23.23 g C • m^{-2}). NPP values in the upper section ranged from 20.36 to 30.97 g C • m^{-2}, with a multi-year average of 26.70 g C • m^{-2}. In the middle section, values ranged from 17.96 to 21.96 g C • m^{-2}, with a multi-year average of 18.70 g C • m^{-2}. In the lower section, values ranged from 13.60 to 11.70 g C • m^{-2}, with a multi-year average of only 13.55 g C • m^{-2}. The increases in the upper, middle, and lower sections were 43.75%, 61.39%, and 42.44%, respectively, with the middle section showing the most significant increase.

2.4 Impact of Groundwater Depth and Ecological Water Conveyance on NPP

The ecological water conveyance process can be roughly divided into three stages (Figure 5). From 2000 to 2009, continuous but small-volume water conveyance totaled 19.20$×10^{8}$ m^3, during which groundwater depth recovered slowly. From 2010 to 2013, intermittent and extremely small-volume conveyance totaled only 0.25$×10^{8}$ m^3, causing groundwater depth to decline year by year. From 2014 to 2019, continuous and medium-volume conveyance totaled 23.71$×10^{8}$ m^3, leading to rapid groundwater recovery. From 2017 to 2019, large-volume continuous conveyance reached 35.16$×10^{8}$ m^3. Overall, the average groundwater depth in the lower Tarim River ranged from 3.91 to 7.47 m, with an average rise of 1.38 m, though groundwater depth showed fluctuating recovery due to inconsistent water delivery.

Groundwater depth showed a lagged response to annual total water conveyance. The deepest groundwater depth (7.47 m) appeared at the end of the small-volume intermittent conveyance period (2013), while the shallowest depth (4.20 m) appeared at the end of the large-volume stable conveyance period (2019). The correlation between water conveyance and current-year groundwater depth was weak (rho=-0.29), while the correlation with the following year’ s groundwater depth was significantly higher (rho=-0.68). From 2000 to 2019, the correlation between groundwater depth and NPP was weak (R^2=0.23). However, as groundwater depth rose steadily due to continuous conveyance since 2010, the correlation between NPP and groundwater depth strengthened significantly

(R^2=0.62).

To analyze the response of NPP to cumulative water conveyance, we extracted the average NPP values and cumulative water volumes for the entire lower Tarim River and its upper, middle, and lower sections from 2000 to 2019. The correlations between different cumulative water volumes and NPP are shown in Figure 6. The correlation coefficients between cumulative water volume over three years and NPP for the entire lower Tarim River, upper section, and middle section were 0.62 ($P<0.01$), 0.69 ($P<0.01$), and 0.61 ($P<0.05$), respectively, all passing significance tests. However, the correlation between annual water conveyance and NPP did not pass significance tests. This indicates that natural vegetation shows a clear cumulative response to ecological water conveyance, with the most obvious cumulative response occurring at the three-year scale. The correlations between NPP and annual conveyance duration or daily water volume were weak and insignificant, possibly due to variable timing of water delivery initiation. Groundwater depth showed a similar cumulative response to water conveyance, with correlation coefficients of -0.69 ($P<0.01$), -0.71 ($P<0.01$), and -0.66 ($P<0.05$) for the entire river, upper section, and middle section, respectively.

[Figure 5: see original paper]

[Figure 6: see original paper]

3 Discussion

Remote sensing-based monitoring of vegetation in the lower Tarim River indicates significant vegetation recovery and fluctuating increases in vegetation coverage since ecological water conveyance began. Studies on land use changes after water conveyance show a net increase of 382.85 km^2 in vegetation area from 2000 to 2018, with 明显改善的植被生长状况. Vegetation recovery is closely related to groundwater depth, and our NPP calculations align with actual conditions. Research shows that groundwater depth responds to ecological water conveyance with some lag, which matches our findings. However, our study analyzed the correlation between annual total water conveyance and the following year’ s groundwater depth, ignoring the impact of conveyance timing—a relationship that requires further investigation.

Correlation analysis between precipitation, NPP, and groundwater depth revealed weak correlations (Figure 7). Although temperature and precipitation in the lower Tarim River have changed in recent years, the magnitude has been small, while human activities have had greater impacts. Therefore, compared with ecological water conveyance, precipitation has minimal influence on NPP and groundwater depth. This indicates that NPP decline in the lower Tarim River is primarily driven by water conveyance volume, and ecosystem restoration has achieved phased progress through ecological engineering implementation.

[Figure 7: see original paper]

4 Conclusions

This study systematically analyzed variations in natural vegetation NPP in the lower Tarim River since the implementation of ecological water conveyance, yielding the following conclusions:

(1) From 2000 to 2019, natural vegetation NPP in the lower Tarim River showed an overall upward trend. Areas with extremely significant increase, significant increase, and insignificant change accounted for 31.93% ($P<0.01$), 11.49% ($P<0.05$), and 52.03% of the total area, respectively. Horizontally, NPP decreased with increasing distance from the river channel, following the pattern: 0-1000 m > 1000-2000 m > 2000-10000 m. Longitudinally, multi-year average NPP values ranked as: upper section (28.21 $\mathrm{g\,C \cdot m^{-2}}$) > middle section (18.70 $\mathrm{g\,C \cdot m^{-2}}$) > lower section (13.55 $\mathrm{g\,C \cdot m^{-2}}$), with the middle section showing the largest increase (61.39%).

(2) The NPP change characteristics of tamarisk, Populus euphratica, and herbaceous communities were similar during the growth season (April-October): NPP increased slowly from April to July, then rose rapidly from July to September. However, their interannual variation trends differed. Multi-year average NPP values ranked as: tamarisk community (57.37 $\mathrm{g\,C \cdot m^{-2}}$) > P. euphratica community (29.30 $\mathrm{g\,C \cdot m^{-2}}$) > herbaceous community (23.23 $\mathrm{g\,C \cdot m^{-2}}$). The tamarisk community showed the greatest increase (350.20%) during ecological water conveyance, followed by P. euphratica (66.46%) and herbaceous communities (55.34%).

(3) Groundwater depth and natural vegetation NPP showed significant correlations with cumulative ecological water volume over three years, with correlation coefficients of -0.70 ($P<0.01$) and 0.62 ($P<0.01$), respectively. The correlation between annual water conveyance and groundwater depth in the following year was significantly higher than that with the current year' s depth, demonstrating a lagged groundwater response to water conveyance. Additionally, due to continuous water conveyance since 2010, the correlation between NPP and groundwater depth strengthened significantly as groundwater depth recovered steadily.

(4) Although ecological water conveyance has improved NPP, vegetation in the study area remains sparse. Research indicates that vegetation response to water conveyance is limited to areas within 1000 m of the river channel. Populus euphratica may revert to pre-restoration conditions or worse after dry years or flow interruption. Therefore, continuous water conveyance with stable volumes should be maintained at the interannual scale. At the intra-annual scale, the optimal conveyance timing should be advanced to April-May, and the conveyance method should shift from single linear delivery to multi-channel distribution.

References

[1] Field C B, Behrenfeld M J, Randerson J T, et al. Primary production of the biosphere: Integrating terrestrial and oceanic components[J]. Science, 1998, 281(5374): 237-240.

[2] Valerie M D, Zhai P, Pörtner H O, et al. An IPCC special report on the impacts of global warming of 1.5 ℃ above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty[R]. World Meteorological Organization, Geneva, Switzerland, 2018.

[3] Zhao M S, Running S W. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009[J]. Science, 2010, 329(5994): 940-943.

[4] Cheng Chunxiao, Xu Zongxue, Zhang Shurong, et al. Response of NPP to climate change and human activities in the Heihe River Basin[J]. Journal of Beijing Normal University (Natural Science), 2016, 52(5): 571-579.

[5] Li J, Wang Z L, Lai C G, et al. Response of net primary production to land use and land cover change in mainland China since the late 1980s[J]. Science of the Total Environment, 2018, 639: 237-247.

[6] Liu Yangyang, Wang Qian, Yang Yue, et al. Spatial-temporal dynamics of grassland NPP and its driving factors in the Loess Plateau, China[J]. Chinese Journal of Applied Ecology, 2019, 30(7): 2309-2319.

[7] Qin Jingxiu, Hao Xingming, Zhang Ying, et al. Effects of climate change and human activities on vegetation productivity in arid areas[J]. Arid Land Geography, 2020, 43(1): 117-125.

[8] Zhao Peng, Chen Tao, Wang Qian, et al. Quantitative analysis of the impact of climate change and human activities on grassland ecosystem NPP in Xinjiang[J]. Journal of University of Chinese Academy of Sciences, 2020, 37(1): 51-62.

[9] Ouyang Ling, Ma Huiyao, Wang Zongming, et al. Impacts of climate change and human activities on net primary productivity of grassland in the eastern Inner Mongolia[J]. Acta Ecologica Sinica, 2020, 40(19): 6912-6924.

[10] Zhou Yanyan, Zhu Minxiang, Guo Xiaojuan, et al. Relative effects of climate change and human activities on net primary productivity in Shule River Basin[J]. Acta Ecologica Sinica, 2019, 39(14): 5127-5137.

[11] Li Chuanhua, Cao Hongjuan, Fan Yeping, et al. Remote sensing estimation and analysis of net primary productivity (NPP) based on corrected CASA model: A case study of Hexi Corridor[J]. Acta Ecologica Sinica, 2019, 39(5): 1617-1625.

[12] Yang Huijin, Li Xiaoyu, Liu Lijuan, et al. Estimation of net primary productivity in arid region based on coupling model[J]. Chinese Journal of Applied Ecology, 2016, 27(6): 1750-1758.

[13] Nayak R K, Patel N R, Dadhwal V K. Estimation and analysis of terrestrial net primary productivity over India by remote-sensing-driven terrestrial biosphere model[J]. Environmental Monitoring and Assessment, 2009, 170(1-4): 195-213.

[14] Potter C S, Randerson J T, Field C B, et al. Terrestrial ecosystem production: A process model based on global satellite and surface data[J]. Global Biogeochemical Cycles, 1993, 7(4): 205-210.

[15] Wang Jiuzhong, Wu Mingquan. Spatio-temporal analysis about the primary productivity of Mentougou District in Beijing from 2003 to 2014[J]. Journal of East China Normal University (Natural Science), 2018(1): 163-170.

[16] Zhang Meng, Zeng Yongnian. Net primary production estimation by using fusion remote sensing data with high spatial and temporal resolution[J]. Journal of Remote Sensing, 2018, 22(1): 143-152.

[17] Zhu Wenquan, Pan Yaozhong, He Hao, et al. Simulation of maximum light utilization of typical vegetation in China[J]. Chinese Science Bulletin, 2006, 51(6): 700-706.

[18] Guan Xiaobin, Shen Huanfeng, Gan Wenxia, et al. Estimation and spatiotemporal analysis of winter NPP in Wuhan based on Landsat TM/ETM+ Images[J]. Remote Sensing Technology and Application, 2015, 30(5): 884-890.

[19] Sheng Hao, Li Junli, Yang Liao, et al. MODIS time-series data analysis methods: A case study on the 7th autumn ecological water conveyance in the lower reaches of Tarim River[J]. Arid Land Geography, 2007, 30(2): 251-256.

[20] Deng Mingjiang, Yang Pengnian, Zhou Haiying, et al. Water conversion and strategy of ecological water conveyance in the lower reaches of the Tarim River[J]. Arid Zone Research, 2017, 34(4): 717-726.

[21] Bai Yuan, Xu Hailiang, Zhang Qingqing, et al. Evaluation on ecological water requirement in the lower reaches of Tarim River based on groundwater restoration[J]. Acta Ecologica Sinica, 2015, 35(3): 630-640.

[22] Liao Shumin, Xue Lianqing, Chen Jiacheng, et al. Cumulative ecological response of ecological water transmission in Tarim River[J]. Water Resources Protection, 2019, 35(5): 120-127.

[23] Tursun Kasim, Manisahan Tursun, Han Guihong, et al. Analysis on impact factors of land desertification in lower reaches of Tarim River in past 50 years[J]. Journal of Desert Research, 2019, 41(3): 591-600.

[24] Huang Yue, Bao Anming, Wang Shifei, et al. Eco-environmental change in the lower Tarim River under the influence of intermittent water transport[J]. Acta Geographica Sinica, 2013, 68(9): 1252-1262.

[25] Wang Shanshan, Wang Jinlin, Zhou Kefa, et al. Response of land use/land cover change to ecological water transmission in the lower reach of Tarim River[J]. Water Resources Protection, 2021, 37(2): 69-74, 80.

[26] Zhao Junhong, Zhou Huarong, Lu Yayuan, et al. Temporal-spatial characteristics and influencing factors of the vegetation net primary production in Tarim from 2000 to 2015[J]. Arid Zone Research, 2020, 43(1): 190-200.

[27] Chen Yaning, Li Weihong, Chen Yapeng, et al. Ecological response and ecological regeneration of transfusing stream water along the dried-up watercourse in the lower reaches of the Tarim River, Xinjiang[J]. Arid Zone Research, 2006, 23(4): 521-531.

[28] Cui Yongxiang, Liu Hailong, Wang Chuanjian. Analysis of sand desertification change in the lower reach of Tarim River Basin during 2000–2018 based on support vector machine and remote sensing: Taking the area of Daxihaizi Reservoir as an example[J]. Journal of Shihezi University (Natural Science Edition), 2021, 39(1): 46-53.

[29] Zhu Changming, Li Junli, Shen Zhanfeng, et al. Spatio-temporal dynamics of vegetation activities in the lower reach of the Tarim River based on MODIS intensive time series data[J]. Resources Science, 2009, 29(6): 1029-1034.

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