Vegetation Dynamics in the Lower Tarim River and Its Response to Ecological Water Conveyance from 2013 to 2018?Postprint

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Abstract

Desert riparian vegetation plays an extremely important role in maintaining ecological stability in extremely arid regions. Investigating the response of desert riparian vegetation to ecological water conveyance and its change processes in arid areas is of great significance for ecological conservation and restoration as well as the formulation of water conveyance policies. This study takes desert riparian vegetation in the lower reaches of the Tarim River basin as the research object, utilizing Landsat 8 OLI, Sentinel-2A, and other data to construct vegetation cover datasets and time-series vegetation index data for typical monitoring cross-sections, analyzing the spatiotemporal variation characteristics of desert riparian vegetation from 2013 to 2018, and examining the response of desert riparian vegetation to ecological water conveyance in conjunction with groundwater level data. The results indicate that from 2013 to 2018, the vegetation area in the lower reaches of the Tarim River exhibited a continuous increasing trend, with shrub area showing the greatest recovery. Populus euphratica and herbaceous vegetation are located closer to the riverbank, with vegetation restoration areas distributed within 1.0 km and 2.5 km from the river channel, whereas under the influence of dual-channel water conveyance measures and groundwater rise, shrub restoration areas showed varying degrees of increase in shrubs within 11 km along the riverbank. Growth analysis of three main vegetation types at different ecological cross-sections demonstrates that when groundwater depth is greater than -5.75 m, vegetation in the lower reaches of the Tarim River exhibits significant improvement.

Full Text

Preamble

Vegetation Change During 2013-2018 and Its Response to Ecological Water Conveyance in the Lower Reaches of the Tarim River

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Abstract

Desert riparian vegetation plays an extremely important role in maintaining ecological stability in extreme arid regions. Understanding the response of desert riparian vegetation to ecological water conveyance and its changing processes is of great significance for ecological conservation, restoration, and water conveyance policy formulation. This study focuses on desert riparian vegetation in the lower reaches of the Tarim River, utilizing multi-source data including Landsat 8 OLI and Sentinel-2A to construct vegetation cover datasets and time series of vegetation indices at typical monitoring sections. We analyzed the spatiotemporal variation characteristics of desert riparian vegetation from 2013 to 2018 and examined its response to ecological water conveyance in conjunction with groundwater level data. The results show that vegetation area in the lower Tarim River exhibited a continuous increasing trend during 2013–2018, with the largest recovery observed in shrubland area. Populus euphratica forests and herbaceous vegetation were distributed relatively close to the river channel, with vegetation recovery primarily occurring within 1.0 km and 2.5 km of the riverbank. In contrast, shrubland recovery, influenced by dual-channel water conveyance measures and rising groundwater levels, showed varying degrees of increase across a range of up to 11 km from the riverbank. Analysis of growth trends for three dominant vegetation types at different ecological sections revealed significant improvement when groundwater depth was greater than -5.75 m.

Keywords: vegetation; spatiotemporal distribution; dynamic change; ecological water conveyance; response; lower reaches of the Tarim River

Introduction

The lower Tarim River region, extending from the Daxihaizi Reservoir to Lake Taitema, represents a typical extreme arid area in western China with an extremely fragile ecological environment. Desert riparian vegetation dominated by Populus euphratica, Tamarix shrublands, and wetland herbs constitutes an ecological corridor under extreme arid conditions, playing a vital role in windbreak and sand fixation and maintaining ecosystem balance in arid regions. The lower Tarim River experienced flow interruption in the 1990s, resulting in severe vegetation degradation. Since the implementation of the ecological water conveyance project in 2000, particularly after 2011, regional vegetation has effectively recovered [1-2]. Understanding and quantifying the ecological changes in desert riparian vegetation and assessing the ecological effects of water conveyance projects provide crucial scientific foundations for conservation, restoration, and ecological water resource management in arid desert regions.

Current approaches for analyzing desert riparian vegetation changes primarily include remote sensing monitoring and ecological plot observations. Remote sensing methods mainly employ multi-temporal classification comparison [3-5] and change trajectory analysis [6-8] to monitor vegetation changes following ecological water conveyance. Most scholars have utilized medium-resolution remote sensing data such as Landsat TM to analyze vegetation changes in the lower Tarim River since 2000 [9-10]. These studies indicate that vegetation has effectively recovered after water conveyance, with significant improvements in vegetation coverage and density [11]. However, due to the sparse distribution characteristics of desert riparian vegetation and limitations in image spatial resolution, few studies have conducted comparative analyses of water conveyance effects on different vegetation types.

Ecological plot observation methods primarily investigate changes in ecological characteristics of desert vegetation (such as tree height, diameter at breast height, and leaf area) [12-14] to quantitatively assess vegetation responses to water conveyance. Nevertheless, due to difficulties in data collection and limited observation periods, ecological approaches struggle to analyze regional-scale spatiotemporal change processes.

To address these limitations, this study utilizes Landsat 8 OLI, Sentinel-2A, and domestic GF-1 (Gaofen-1) data, combined with existing datasets and remote sensing information extraction methods, to obtain maps of major land cover types and desert vegetation changes from 2013 to 2018. Based on these data, we analyze the spatiotemporal characteristics of desert riparian vegetation change in the lower Tarim River and examine vegetation responses to ecological water conveyance through growth trend analysis of different desert vegetation types, thereby providing a scientific basis for evaluating the effectiveness of ecological water conveyance and restoration efforts.

1.1 Study Area and Data

The study area is located in the lower reaches of the Tarim River from Daxihaizi Reservoir to Kuergan, representing the most ecologically vulnerable region of the Tarim River. The river experienced flow interruption from the 1970s to the early 21st century, leading to large-scale die-off and area contraction of desert vegetation such as Populus euphratica, Tamarix, Apocynum venetum, and Alhagi sparsifolia [17], along with severe ecosystem degradation. Since the implementation of ecological water conveyance in 2000, groundwater levels have gradually risen, and vegetation and ecological environments along the Tarim River have recovered. The main vegetation types include Populus euphratica as the dominant tree species, Tamarix-dominated shrubs, and herbaceous plants such as Phragmites australis, Glycyrrhiza inflata, Apocynum venetum, and Alhagi sparsifolia. Influenced by physiological characteristics and water use strategies, Populus euphratica is distributed in narrow strips along both riverbanks, Tamarix shrublands are interspersed and primarily distributed in the periphery of Populus forests, and herbaceous vegetation mainly occurs in wetland areas along the river channels [18].

To analyze spatiotemporal changes in riparian desert vegetation in the lower Tarim River, we first extracted annual change information on desert vegetation and water bodies using September Landsat 8 data from 2013-2018 (Table 1). Additionally, we used domestic high-resolution GF-1 2m/8m data from September 24, 2013, and September 28, 2018, to extract information on forests, shrubs, and grasslands. Finally, for typical areas of vegetation change, we used monthly Landsat 8 data from 2013-2018 to monitor growth changes of different vegetation types before and after water conveyance (Table 1). To avoid cloud and dust effects, we primarily selected images from the growing season months of June, July, August, and September [19-20]. After radiometric and geometric correction, mosaicking, and clipping, we obtained annual growing season image datasets. To analyze relationships between vegetation change and water conveyance/groundwater variation, we also compiled water conveyance data from Daxihaizi to the lower Tarim River for 2013-2018 (Table 2) and monthly average groundwater level data from the Yingsu and Alagan ecological monitoring sections.

1.2 Research Methods

To obtain the distribution and changes of riparian vegetation in the lower Tarim River for 2013 and 2018, we used September GF-1 2m fusion data from both years, combined with 1,672 field sample points of Populus euphratica, shrubs, and herbs. We applied a multivariate decision tree classification method for desert vegetation [20] to extract classification maps of Populus euphratica, shrubs, and herbaceous vegetation (Figure 1 [Figure 1: see original paper]), which were subsequently manually edited and accuracy-assessed using high-resolution Google Earth imagery as a base map. The classification accuracy reached 92.7%, meeting the requirements for change analysis.

For mapping desert riparian vegetation and water bodies, this study employed a "global-local" dynamic threshold method to extract water information [21] and used the Soil Adjusted Vegetation Index (SAVI) to extract sparse desert vegetation information [22]. The SAVI calculation method is as follows:

$$SAVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red} + L} \times (1 + L)$$

where ρ_{NIR} is the zenith reflectance of the near-infrared band, ρ_{Red} is the zenith reflectance of the red band, and L is the soil adjustment coefficient with a value between [0,1]. For sparsely distributed vegetation with low density, SAVI introduces a soil adjustment factor L to reduce soil interference in vegetation information retrieval; the sparser the vegetation, the larger the L value. According to experimental results from desert vegetation in the lower Tarim River by Liu et al. [23], $L = 0.5$ yields the best extraction effect for desert vegetation, and this value was adopted in this study. Based on this approach, we used six periods of Landsat 8 data from September 2013–2018 to extract riparian vegetation and water bodies, obtaining the overall trend of vegetation and water changes over six years.

To evaluate and compare growth changes of typical vegetation at six ecological sections from Yingsu to Kuergan in the lower Tarim River, we used monthly Landsat 8 time series data from June–September 2013–2018. We selected typical vegetation patch units of Populus euphratica, Tamarix, and Phragmites at each ecological section and extracted their 24-month SAVI time series curves. By constructing these time series for the three typical vegetation types, we compared growth trends across different vegetation types and ecological sections, and analyzed vegetation responses to ecological water conveyance at different spatial locations in conjunction with water conveyance volumes and groundwater depth.

2.1 Vegetation Area Change Analysis in the Lower Tarim River

Land cover types in the lower Tarim River from Daxihaizi Reservoir to Kuergan are dominated by vegetation, water bodies, and bare land. To analyze riparian vegetation changes, we extracted vegetation and water information from Landsat data for 2013-2018, with area change information shown in Figure 2a [Figure 2: see original paper]. The results indicate that vegetation in the lower Tarim River showed an increasing trend over the past five years, with vegetation area in 2018 increasing by nearly 249.74 km^2 compared to 2013. Except for 2014, vegetation exhibited continuous growth, while water area fluctuated considerably during the same period. Combined with ecological water conveyance data from Table 2, we found that years with larger water conveyance volumes corresponded to larger water areas. Increased water area in the lower Tarim River facilitated vegetation growth and recovery. The relationship between cumulative ecological water conveyance over six years and vegetation area change shows a significant linear correlation, with a Pearson correlation coefficient of 0.949. Spatially, water increase areas were mainly distributed in the lower river channel and newly added wetland areas between the Yingsu and Alagan sections, while vegetation expanded outward along both banks of the Tarim River, most notably between Yingsu and Alagan, where wetland recovery was particularly robust.

2.2 Spatial Distribution of Different Vegetation Types

The main vegetation types in the lower Tarim River include Populus euphratica, Tamarix shrubs, and desert herbaceous vegetation. Using the river channel centerline as a baseline, we calculated the distribution area of different vegetation types at 0.5 km intervals along the river in 2018 (Figure 3 [Figure 3: see original paper]). The results show that Populus euphratica had the highest concentration along the riverbank, followed by herbaceous vegetation, with shrubs showing the lowest concentration. The vast majority of Populus euphratica was distributed within 1.5 km of the river channel. The distances from the river centerline covering 90% of total area for Populus euphratica, herbaceous vegetation, and shrubs were 2.5 km, 7.0 km, and 8.5 km, respectively. This indicates that shrubs could be distributed farthest from the river centerline, followed by herbaceous vegetation, with Populus euphratica closest to the river. The relationship between vegetation area and distance from the river centerline follows a power exponential function (Figure 3).

To analyze spatial changes in the three main vegetation types from 2013-2018, we used high-resolution interpreted area change maps for 2013 and 2018 (Figure 4 [Figure 4: see original paper]) and calculated area change rates at 0.5 km intervals along the river centerline (Figure 5 [Figure 5: see original paper]). Statistical results reveal several key patterns. First, in 2018, the recovered areas of Populus euphratica, shrubs, and herbaceous vegetation were 0.89 km^2, 228.56 km^2, and 7.15 km^2, respectively, with shrubland showing the most significant net recovery, followed by herbaceous vegetation, and Populus euphratica showing the smallest recovery. Second, Populus euphratica recovery was mainly distributed east of Yingsu, west of Alagan, and north of Yiganbujima, primarily within 0-1.0 km and 4.5-6.0 km from the river channel, accounting for 56% and 39% of total recovery area, respectively. The 4.5-6.0 km range mainly occurred between Yingsu and Alagan. Compared with shrubs and herbs, Populus euphratica showed the smallest recovery area and the most stable rate of area change across different distances from the river.

Third, shrubland recovery was the most extensive, with increased areas widely distributed along both banks from Daxihaizi to Kuergan. The main area increase occurred within 1.0-11.0 km of the river centerline, with the maximum increase rate at 2.0 km from the river, where recovered shrub area accounted for 51% of total shrub recovery. Fourth, herbaceous vegetation recovery was mainly distributed within 2.5 km of the river channel. Increased herbaceous areas primarily appeared north of Yingsu, at Qiwenkule Lake, and in the lower section of the old Tarim River, located 2 km and 10.5 km from the river centerline in wetland and waterlogged areas with increased areas of 4.88 km^2 and 4.93 km^2, respectively. The herbaceous vegetation in these areas was mainly riparian wetland herbs. Analysis of the curve showing herbaceous area change with distance from the river (Figure 5) revealed that vegetation reduction within 1.0 km was related to Populus euphratica increase, as the recovery of Populus euphratica canopy cover shaded substantial herbaceous vegetation, resulting in reduced herbaceous area interpreted from remote sensing data. Finally, dual-channel water conveyance from Daxihaizi greatly expanded the vegetation recovery area in the lower reaches. Except for 2014, dual-channel, braided river, and sheet flow conveyance methods were implemented from 2013–2018 [10], increasing the benefited area in the upper sections and adding substantial shrub and wetland herbaceous vegetation near the dual channels. As shown in Figure 4, vegetation recovery in dual-channel conveyance areas was significantly better than in areas below Alagan, with an influence distance more than twice that of single-channel conveyance.

3.1 Comparison of Vegetation Growth Across Different Sections

Monthly growth change curves from June–September 2013–2018 for typical Populus euphratica, shrub, and herbaceous vegetation samples near five sections (Yingsu, Bozikule [no Populus euphratica], Alagan, Yiganbujima [no Populus euphratica], and Kuergan) show that all three vegetation types exhibited stable growth states (Figure 6 [Figure 6: see original paper]). The same vegetation type showed consistent trends across different sections, though with some variation in magnitude. Shrub growth showed little difference across ecological sections, while Populus euphratica and herbaceous vegetation gradually improved from upstream to downstream. Different distances from the river centerline were the main reason for these differences. As shown in Figure 4, Populus euphratica and herbaceous sample plots were distributed in riparian wetland areas close to the river, where ecological water conveyance directly affected their growth, and groundwater levels became shallower further downstream. Herbaceous vegetation in riparian wetlands showed particularly robust growth. Shrubs were mainly distributed farther from the river channel, and groundwater changes responded more slowly to water conveyance, resulting in less pronounced growth changes compared to Populus euphratica and herbaceous vegetation.

From the perspective of vegetation growth habits, seasonal herbaceous vegetation was more sensitive to water conveyance volume. With shallow root systems and annual life cycles, herbaceous growth was directly affected by water amount within the year. Before 2016, when water conveyance was relatively small, intra-annual variation in herbaceous vegetation was limited but still higher than that of Populus euphratica and shrubs. After 2016, with abundant water supply, herbaceous vegetation showed the largest seasonal variation, followed by shrubs, with Populus euphratica showing the smallest variation. This corresponds to the growth habits of shrubs and herbs in arid regions, which grow and wither rapidly under water-sufficient and water-deficient conditions. As a tree species, Populus euphratica has deeper root systems, and groundwater depth remained within its suitable growth range. Consequently, Populus euphratica experienced less water stress than herbs and shrubs, showing smaller seasonal variation.

Vegetation growth changes showed significant correlation with ecological water conveyance volume, with growth curves showing a notable increase after 2016. As shown in Table 2, water conveyance volumes were relatively small during 2013-2015, reaching a minimum in 2014 in terms of both volume and duration. During this period, vegetation SAVI indices fluctuated below 0.2, with flat growth curves or only slight increases. After 2016, however, ecological water conveyance remained at high levels, particularly in 2017 when it exceeded 12\$×10^{8}\$ m^{3}. During this period, SAVI indices for Populus euphratica, shrubs, and herbs rapidly increased from 0.2-0.3 in 2016-2017 to 0.3-0.5 in 2017, showing clear upward trends.

3.2 Response of Vegetation Growth to Groundwater Depth

Comparing growth change curves for Populus euphratica, shrubs, and herbs at the Yingsu and Alagan sections with monthly average groundwater variation curves from 2013-2017 reveals vegetation growth responses to groundwater depth in the lower Tarim River (Figure 7 [Figure 7: see original paper]). Within the same section, different vegetation types showed similar trends, with all vegetation demonstrating improved growth. The year 2016 was a significant turning point for vegetation improvement. During 2013-2015, vegetation growth changes were relatively flat, while after 2016, growth curves rose noticeably, with shrubs showing the most obvious improvement.

Analysis of groundwater depth change curves indicates that the significant improvement node occurred in July 2016. After July 2016, the minimum groundwater depth was -5.75 m in August 2016, and groundwater depth remained above -5.75 m thereafter. Vegetation at both Yingsu and Alagan ecological sections showed clear improvement during this period. Before July 2016, groundwater levels were below this value except in September 2013, during which vegetation index changes were slow with only large seasonal fluctuations. Although groundwater depth rose to -5.56 m in September 2013, vegetation was in a withering period during this time, and groundwater levels subsequently dropped rapidly, resulting in no obvious improvement in vegetation growth. This demonstrates that -5.75 m is a critical turning point for groundwater depth; when groundwater depth is above this value, vegetation shows significant improvement. Further analysis reveals that after groundwater rise, shrubs in the lower Tarim River improved most significantly. From 2013-2018, shrub area recovered by 228.56 km^{2}, covering almost all areas along the Tarim River banks, indicating that when groundwater levels recover to an ecologically suitable depth for shrubs, shrublands—the dominant vegetation type in the lower Tarim River—can substantially improve the local ecological environment.

Integrated analysis shows that both ecological water conveyance and groundwater depth significantly influence vegetation in the lower Tarim River. The temporal process of vegetation improvement over the past six years demonstrates the importance of sustained ecological water conveyance. Although water conveyance was implemented during 2013–2015, the volume in 2014 was only 0.07$×10^{8}$ m^3, and groundwater levels did not continue the rising trend from 2013 but instead declined continuously until rising again after water conveyance in 2015. After 2016, annual water conveyance exceeding 6.0$×10^{8}$ m^3 rapidly raised groundwater levels above -6.0 m, and vegetation condition improved dramatically. Therefore, annual sustained ecological water conveyance is crucial for maintaining groundwater levels. To continuously improve riparian vegetation in the lower Tarim River, sustained and appropriately scaled annual water conveyance is needed to maintain groundwater levels suitable for riparian vegetation growth.

4 Conclusions

(1) During 2013–2018, vegetation in the lower Tarim River showed a continuous increasing trend, with vegetation area increase exhibiting a significant linear relationship with cumulative ecological water conveyance over the six-year period.

(2) Based on high-resolution remote sensing interpretation for 2013 and 2018, the three main vegetation types—Populus euphratica, herbaceous plants, and shrubs—were distributed at distances of 2.5 km, 7.0 km, and 8.5 km from the river centerline, respectively. In 2018, the primary recovery areas for the three types were located 1.0 km, 2.5 km, and 11.0 km from the river channel, respectively. Shrubland recovery was most evident along both riverbanks under the influence of dual-channel water conveyance and rising groundwater.

(3) Vegetation growth at six ecological sections along the lower Tarim River showed significant correlation with annual water conveyance volume. After 2016, ecological water conveyance increased substantially, and growth curves for different ecological sections rose markedly. Populus euphratica and herbaceous vegetation grew better further downstream, while shrub growth was relatively consistent across sections.

(4) Changes in groundwater level and vegetation growth before and after 2016 demonstrate that sustained ecological water conveyance can maintain groundwater levels suitable for riparian vegetation growth. After July 2016, groundwater depth remained above -5.75 m, vegetation area increased continuously, and growth conditions improved steadily.

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