Postprint: Impacts of Ecological Water Conveyance on Spatial Patterns of Vegetation Carbon Source/Sink in the Lower Tarim River

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Abstract

Based on ecological water transfer data, meteorological data, and land use/cover change data in the lower reaches of the Tarim River since 2000, combined with the modified CASA (Carnegie-Ames-Stanford Approach) model and the soil microbial respiration model (Heterotrophic respiration, RH), we estimated the Net Ecosystem Productivity (NEP) of vegetation from 2001 to 2019, analyzed the spatial distribution changes of vegetation carbon source/sink, and discussed the impact of ecological water transfer in the lower Tarim River on vegetation carbon source/sink changes.

The results show that: (1) With the ecological water transfer in the lower reaches of the Tarim River since 2000, the degraded ecosystem in the lower reaches has recovered to a certain extent, and the vegetation carbon sink area shows an expanding trend. From 2001 to 2019, NEP showed an increasing trend at a rate of 0.541 g $C \cdot m^{-2} \cdot a^{-1}$, with the largest increase rate in summer at 0.406 g $C \cdot m^{-2} \cdot a^{-1}$. The increased areas are mainly located north of the Daxihaizi Reservoir, Yingsu, Bozikule Wetland, Ka' erdai Wetland, and Taitema Lake. The carbon sink area increased from 71 km^2 in 2001 to 355 km^2 in 2019, a fourfold increase.

(2) In terms of seasonal variation, the summer carbon sink area is 109 km^2, accounting for the largest proportion among the four seasons, followed by spring and autumn, with no obvious carbon sink area in winter.

(3) The order of carbon sink area change in the lower Tarim River ecosystem is: grassland > forestland > cropland > unused land > water area > construction land. In addition, forestland and grassland have the highest annual average change rates at 2.69 $km^2 \cdot a^{-1}$ and 3.57 $km^2 \cdot a^{-1}$, respectively. There is a good linear relationship between ecological water transfer

volume and carbon sink area, and the carbon sink area change exhibits a lag effect of approximately 1 a.

Full Text

Effects of Ecological Water Conveyance on the Spatial Pattern of Vegetation Carbon Sources/Sinks in the Lower Reaches of Tarim River

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Abstract

Based on ecological water conveyance data, meteorological data, and land use/cover change data for the lower reaches of Tarim River since 2000, combined with the modified Carnegie-Ames-Stanford Approach (CASA) model and soil microbial respiration model (RH), this study analyzed the spatial distribution changes of vegetation net ecosystem productivity (NEP) and carbon sources/sinks from 2001 to 2019, and investigated the impacts of ecological water conveyance on vegetation carbon source/sink dynamics. The results indicate that: (1) Since the implementation of ecological water conveyance to the lower reaches of Tarim River in 2000, the degraded ecosystem has recovered to a certain extent, with vegetation carbon sink areas showing an expansion trend. Specifically, NEP exhibited an increasing trend at a rate of 0.541 g $C \cdot m^{-2} \cdot a^{-1}$, with the most significant increase occurring in summer at 0.406 g $C \cdot m^{-2} \cdot a^{-1}$. Areas of carbon sink increase were primarily located north of Daxihaizi Reservoir, Yingsu, Bozikule Wetland, Kaldayi Wetland, and Taitema Lake. The carbon sink area expanded from 71 km^2 in 2001 to 355 km^2 in 2019. (2) Seasonally, summer carbon sink area reached 109 km^2, representing the largest proportion among the four seasons, followed by spring and autumn, while no significant carbon sink area was observed in winter. (3) The magnitude of carbon sink area changes across different ecosystems followed the order: grassland > woodland > cultivated land > unused land > water body > construction land. Woodland and grassland showed the highest annual average change rates at 2.69 $km^2 \cdot a^{-1}$ and 3.57 $km^2 \cdot a^{-1}$, respectively. A strong linear relationship existed between ecological water conveyance volume and carbon sink area, with approximately a 1-year lag effect in carbon sink area response.

Keywords: ecological water conveyance; carbon sources/sinks; net ecosystem productivity (NEP); lower reaches of Tarim River

1 Introduction

The Tarim River, the largest inland river in China, is known as the "Mother River"of southern Xinjiang. The basin's arid natural environment determines its extremely fragile ecological conditions. Under the continuous impact of large-scale water and soil resource development, the main stream of Tarim River experienced flow interruption and drying in the 1970s, with the lower 400 km of the river channel drying up. This led to declining groundwater levels and large-scale death of riparian Populus euphratica forests, causing severe damage to the desert riparian forest ecosystem that was on the verge of collapse. The terminal lake, Taitema, dried up and wetlands disappeared, threatening the healthy development of the oasis economy. In this context, the State Council approved comprehensive management of the Tarim River Basin. Since 2000, approximately 84.45$×10^{8}$ m^3 of ecological water has been released to the lower reaches, reaching Taitema Lake and alleviating environmental degradation.

Previous studies have examined ecosystem changes before and after water conveyance, oasis evolution responses to ecological water transfer, impacts on plant community composition, groundwater depth changes, and water transformation processes. Important conclusions have been drawn: as water conveyance progressed, groundwater levels in the lower reaches continuously rose, vegetation response range expanded, natural vegetation recovered to some extent, oasis area generally increased, and plant community stability improved. However, research on spatial changes in ecosystem carbon sources/sinks before and after water conveyance remains limited. The study area features a temperate continental climate with annual precipitation of only 17.4–42.0 mm and annual evaporation potential of 2500–3000 mm, creating a strong contrast between precipitation and evaporation and an extremely fragile ecological environment. Ecological water conveyance can directly and effectively improve this vulnerable environment, triggering vegetation recovery and oasis expansion that transforms carbon source areas into carbon sinks. Quantitative assessment of carbon source/sink changes in terrestrial ecosystems is crucial for monitoring the Earth system' s carbon cycle. Net ecosystem productivity (NEP), defined as the difference between net primary productivity (NPP) and heterotrophic respiration (RH), accurately estimates regional carbon source/sink variations. This study employs the CASA model and soil microbial respiration model to analyze NEP changes from 2001 to 2019, exploring the influence of ecological water conveyance on the spatiotemporal pattern of vegetation carbon sources/sinks to provide scientific support for ecological restoration and management decisions in the Tarim River Basin.

2 Study Area, Data, and Methods

2.1 Study Area Overview

The lower reaches of Tarim River are located between the Taklamakan Desert and the Kuruktag Desert, with extensive desert riparian forests along both banks preventing the convergence of these two deserts. The study area begins at Daxihaizi Reservoir, passes through Qiwenkuoer River and the old Tarim River channel, and terminates at Taitema Lake. Between the Yingsu and Alagan ecological monitoring sections lie the Kaldayi and Bozikule wetlands. The region features a typical continental arid climate with annual precipitation of only 17.4–42.0 mm and annual evaporation potential of 2500–3000 mm. The mean annual temperature ranges from 10.7-11.5°C with an annual range of 35.7-35.9°C, indicating an extremely fragile ecological environment.

2.2 Data Sources and Processing

Normalized Difference Vegetation Index (NDVI) data were obtained from NASA' s MOD13Q1 product (http://ladsweb.nascom.nasa.gov) covering 2000–2019, with a temporal resolution of 16 days and spatial resolution of 250 m × 250 m. Due to sensor performance and weather-related noise, ArcMap software was used for preprocessing, denoising, and compositing datasets at various temporal scales.

Meteorological data were sourced from the China Meteorological Data Network (https://data.cma.cn) for 2000–2019. To match the NDVI data resolution, monthly temperature, precipitation, and total solar radiation were spatially interpolated using inverse distance weighting (IDW) and resampled to 250 m × 250 m raster format with consistent projection for subsequent model calculations.

Ecological water conveyance data for the lower reaches of Tarim River were obtained from the Tarim River Basin Administration. **Land use/cover data** were acquired from the Chinese Academy of Sciences' Resource and Environmental Science Data Center (http://www.resdc.cn). Other geographic data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn). Land use types were classified into six primary categories.

2.3 Calculation Methods

2.3.1 Net Ecosystem Productivity Calculation Net ecosystem productivity (NEP) is a critical indicator for regional carbon balance estimation and is commonly used to quantify carbon source/sink magnitude at regional scales. When NEP > 0, vegetation carbon storage exceeds soil microbial respiration emissions, indicating a carbon sink. When NEP < 0, soil microbial respiration exceeds vegetation carbon storage, indicating a carbon source. NEP is calculated as:

$$NEP = NPP - R_H$$

where NPP is net primary productivity and R_H is heterotrophic respiration.

2.3.2 CASA Model NPP was estimated using the modified CASA model, a light use efficiency model that calculates NPP based on meteorological and remote sensing data. The model inputs include monthly mean temperature, precipitation, solar radiation, vegetation type, and NDVI. The calculation follows:

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

where SOL(x, t) represents total solar radiation, calculated using the western region formula based on astronomical radiation; FPAR(x, t) is the fraction of photosynthetically active radiation absorbed by the vegetation canopy; and (x, t) is light use efficiency, calculated as:

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

where _{max} is the maximum light use efficiency under ideal conditions (0.389 g C $\cdot$ MJ^{-1}), T_ 1 and T_ 2 represent the effects of low and high temperatures on light use efficiency, and W_ is the water stress coefficient calculated as the ratio of actual evapotranspiration to potential evapotranspiration.

2.3.3 Soil Microbial Respiration Model Heterotrophic respiration was estimated using an empirical model based on monthly precipitation and temperature data from Tieganlike and Ruoqiang meteorological stations, interpolated using IDW. The model has been successfully applied in northwestern arid regions and Gansu Province, demonstrating its applicability to this study area:

$$R_H = 0.22 \times [\exp(0.0912 \times T) + \ln(0.3145 \times P + 1)] \times 30 \times 46.5\%$$

where T is monthly mean temperature (°C) and P is monthly mean precipitation (mm).

2.3.4 Trend Analysis A unary linear regression method was applied for pixel-by-pixel temporal analysis of NEP from 2001 to 2019. This approach effectively characterizes interannual variation while eliminating anomalies and reflecting true long-term trends:

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

where Slope represents the linear regression slope, n is the number of years, NEP_i is the NEP value for year i, and i is the year index. A positive Slope indicates an increasing trend, while a negative Slope indicates a decreasing trend.

3 Results

3.1 Spatiotemporal Variation of NEP

3.1.1 Interannual Variation Based on the spatial distribution characteristics of NEP in the lower reaches of Tarim River from 2001 to 2019, the spatial pattern was found to be strongly influenced by water availability. Areas with better moisture conditions, such as the eastern and southeastern parts of Daxihaizi Reservoir and southeastern Yingsu, showed higher NEP values, while other areas exhibited lower values. The multi-year average NEP was -17.91 g $C \cdot m^{-2} \cdot a^{-1}$, with the minimum anomaly of -87.66 g $C \cdot m^{-2} \cdot a^{-1}$ occurring in 2001 and the maximum anomaly of 18.20 g $C \cdot m^{-2} \cdot a^{-1}$ in 2016, indicating gradually increasing fluctuations. Overall, NEP showed an upward trend with an average rate of change of 0.541 g $C \cdot m^{-2} \cdot a^{-1}$, primarily distributed in Bozikule Wetland, Kaldayi Wetland, and Taitema Lake near water bodies, while most other areas showed decreasing trends.

3.1.2 Seasonal Variation Seasonal NEP trends showed considerable consistency across the lower reaches of Tarim River. Increasing areas were mainly located in the eastern and southeastern parts of Daxihaizi Reservoir and southeastern Yingsu, while areas farther from water bodies generally showed decreasing trends. Summer NEP values were notably higher, while spring and autumn showed similar distribution patterns but with lower values. Winter NEP was negative across most areas. The contribution rate to annual NEP followed the order: summer > spring > autumn > winter.

3.2 Vegetation Carbon Source/Sink Changes

Analysis of carbon sink areas revealed that the average annual carbon sink area in the lower reaches of Tarim River was 175 km^2, with summer showing the largest area at 109 km^2, followed by spring (47 km^2) and autumn (71 km^2), while winter showed no significant carbon sink area. Ecological water conveyance primarily occurs in summer and autumn when temperatures rise and precipitation increases relatively, creating positive feedback for vegetation carbon source/sink dynamics. The temporal correspondence between water conveyance and seasonal carbon sink area variations is evident, with larger carbon sink areas occurring during the frequent conveyance periods of summer and autumn.

From 2001 to 2019, carbon sink areas expanded significantly, particularly after 2005. In 2001, carbon sink areas were limited, but by 2005, a carbon sink zone emerged in southeastern Yingsu. Although this area showed slight carbon sink activity in 2001, it became more pronounced subsequently. In 2009, a carbon sink area first appeared near Taitema Lake and increased annually, indicating improving ecological conditions at the terminus of the water conveyance. Overall, carbon sink areas expanded southward, demonstrating that ecological water conveyance promoted the transformation from carbon source to carbon sink zones.

3.3 NEP Distribution Patterns Under Land Use/Cover Change

Land use change is a key factor influencing regional ecosystem carbon source/sink spatial patterns. Analysis of carbon sink areas across different land use types revealed that after ecological water conveyance, total carbon sink area increased from 71 km^2 in 2001 to 355 km^2 in 2018. Grassland showed the largest increase (295 km^2), followed by woodland (2.69 $km^2 \cdot a^{-1}$), cultivated land (0.67 $km^2 \cdot a^{-1}$), unused land (0.98 $km^2 \cdot a^{-1}$), water bodies (0.15 $km^2 \cdot a^{-1}$), while construction land showed a decrease (-0.15 $km^2 \cdot a^{-1}$). Correspondingly, carbon source areas decreased from 4,479 km^2 to 4,255 km^2, with grassland showing the most significant reduction (703.9 km^2), followed by woodland (528.8 km^2) and water bodies (16.3 km^2), while unused land and cultivated land showed slight increases.

3.4 Impacts of Ecological Water Conveyance

3.4.1 Effects on NPP The spatial distribution and interannual variation of NPP means indicated that increasing areas were primarily located in the eastern and southeastern parts of Daxihaizi Reservoir and southeastern Yingsu. Overall, NPP showed an upward trend with an increase rate of 0.541 g $C \cdot m^{-2} \cdot a^{-1}$, mainly distributed near Daxihaizi Reservoir, Yingsu, Bozikule Wetland, Kaldayi Wetland, and Taitema Lake, while most areas distant from water bodies showed decreasing trends. During the initial stage of ecological water conveyance (2000–2005), carbon sink areas increased but not significantly. Since 2005, with increased water conveyance volumes, carbon sink areas expanded substantially, reaching a maximum increase of 350 km^2, demonstrating the effectiveness of ecological water conveyance in improving the ecological environment.

3.4.2 Effects on Vegetation Carbon Sources/Sinks Comparison of water conveyance volumes and carbon sink area statistics revealed a strong correlation. While carbon sinks in the lower reaches of Tarim River are predominantly low-carbon sink zones (NEP < 300 g $C \cdot m^{-2} \cdot a^{-1}$), the relationship between water conveyance and carbon sink area showed approximately a 1-year lag effect. Linear fitting of cumulative water conveyance and cumulative carbon sink area yielded a strong correlation ($R^2 = 0.95$), with all data points falling within the 95% prediction interval, indicating a positive response of carbon sink areas to increased water conveyance.

4 Conclusion

This study analyzed the spatiotemporal variation patterns of NEP in the lower reaches of Tarim River from 2001 to 2019 and examined the influence of ecological water conveyance on ecosystem carbon source/sink patterns. The main conclusions are: (1) NEP showed an overall increasing trend at a rate of 0.541

$g\ C \cdot m^{-2} \cdot a^{-1}$, with increasing areas primarily distributed in the central and southern parts of the lower reaches. (2) Seasonally, NEP in autumn and summer showed upward trends with rates of 0.057 $g\ C \cdot m^{-2} \cdot a^{-1}$ and 0.406 $g\ C \cdot m^{-2} \cdot a^{-1}$, respectively, while spring and winter showed decreasing trends at rates of -0.022 $g\ C \cdot m^{-2} \cdot a^{-1}$ and -0.154 $g\ C \cdot m^{-2} \cdot a^{-1}$, respectively. (3) Carbon sink area increased from 71 km^2 to 355 km^2, with the magnitude of change across ecosystems following the order: grassland > woodland > cultivated land > unused land > water body > construction land. A 1-year lag effect existed between annual water conveyance volume and carbon sink area changes, and a strong linear relationship was observed between cumulative water conveyance and carbon sink area.

This study demonstrates that ecological water conveyance has produced considerable ecological benefits in the lower reaches of Tarim River. However, remote sensing data, while effective for reflecting spatial changes, contain inherent uncertainties. Additionally, the CASA and R_H models have regional applicability limitations and uncertainties. Therefore, improving model applicability and data accuracy is essential when analyzing carbon source/sink patterns in different regions. Notably, the lower reaches of Tarim River are dominated by deserts and sparse vegetation, characterized by low-carbon sink zones. The results are supported by survey data and statistical analysis, confirming that the ecological benefits from water conveyance are substantial.

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