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River flow is critical for vegetation dynamics: Lessons from multi-scale analysis in a hyper-arid endorheic basin

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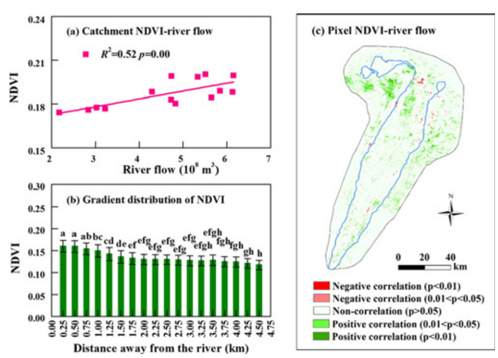
HIGHLIGHTS

- The spatio-temporal variations and influential factors of vegetation cover in a hyper-arid endorheic basin were studied.
- NDVI and hydro-climatic factors showed different relationships at catchment and pixel scales.
- The river flow mainly affected the vegetation cover within 2 km distance and had a 1-yr lag effect.
- The water diversion project should be adjusted based on spatio-temporal lagged hydro-ecological connections.

GRAPHICAL ABSTRACT



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ABSTRACT

Knowledge of the spatio-temporal responses of vegetation dynamics to hydro-climatic factors is important to assess ecological restoration efforts in arid and semiarid areas. In this study, the vegetation dynamics during 2000–2015 were investigated in the downstream area of the Heihe River Basin (HRB) in Northwest China where an ecological water diversion project (EWDP) commenced in 2000. The spatio-temporal relationships between vegetation cover and climatic factors (precipitation and temperature) and available water resources (river flow and groundwater) were determined. The results indicated that the mean growing season NDVI increased significantly during the period of 2000–2015, and the area of East Juyan Lake (EJL) enlarged to 36.4 km^2 in 2010. The scale effect of the relationships between NDVI and hydro-climatic factors was obvious. At the catchment scale, changes of NDVI were not significantly correlated with climatic factors, but significantly related with the antecedent 1-year river flow. River flow played an important role in vegetation growth within approximately 2000 m distance from the river bank. At the pixel scale, the changes of NDVI were significantly positive with temperature and river flow in 17.40% and 7.14% of the study area, respectively, whereas significant relationship between NDVI and precipitation occurred in only 0.65% of study area. The suitable water table depth for vegetation growth was between 1.8 and 3.5 m. The increased river flow and recovered groundwater due to the EWDP were critical for the improvement of vegetation cover, whereas the riparian vegetation degraded along some parts of the river bank. It is important to improve integrated watershed management with consideration of spatio-temporal lagged hydro-ecological connections in the study area.

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1. Introduction

The shortage of water resources makes arid and semiarid ecosystems the most susceptible biomes to land degradation and global climate change (James et al., 2013). Ecological restoration of degraded arid and semiarid ecosystems has received much attention worldwide due to the accelerated desiccation, salinization and groundwater degradation (King, 2011). Natural vegetation in arid and semiarid regions acts an important role in biodiversity conservation and desertification reduction. Vegetation growth is strongly influenced by climate change, and it is more sensitive to climate droughts in drier regions than wetter regions (Zhang et al., 2016). Air temperature and precipitation are two critical climatic factors, and have been widely considered as the important influencing factors of vegetation growth. Higher temperatures associated with deficiency of precipitation had negative consequences on plant growth, especially in semi-arid ecosystems (Lotsch et al., 2005). However, shallow groundwater replenished by snowmelt in the form of river flow was critical for natural oases to maintain much higher productivity with respect to the other ecosystems supported by local rainfall in arid regions (Jobbagy et al., 2011). Severe reduction in river flow resulted in notable degradation of riparian vegetation while the increase of extreme rainfall could benefit hydrological connectivity between river flow and surrounding floodplains (Fernandes et al., 2016). Furthermore, human activities have an important effect on riparian ecosystems. Major human activities include alteration of river flow through dam construction and groundwater withdrawal, urbanization, and modification of biotic conditions through agriculture, grazing and introduction of non-native species (Patten, 1998).

In the arid and semiarid endorheic basin, the contradiction between enlarged irrigated agriculture in the midstream area and degraded natural ecosystem in the downstream area has become increasingly prominent (Schlüter et al., 2005; He et al., 2012). Greater consumption of water in the midstream area implies less available water in the downstream area, i.e., human activities in the midstream area benefit at the expense of degradation in downstream area. Therefore, it was a critical issue to determine the optimal level of water diversion between midstream and downstream areas in the endorheic basin (Barbier, 2003). The responses of ecosystem in the downstream area to river flow regulation caused by water diversion from the midstream involve many complex hydrological processes (Zhao et al., 2016). Understanding the vegetation change before and after water diversion, and investigating the hydrological linkages between midstream and downstream areas are essential for water resources planning in endorheic basins (Nepal et al., 2014). Many pre-date readily available remotely sensed data provided important approaches for analysis of vegetation change before and after water diversion to better reallocate limited water resources for ecosystem conservation or restoration in arid and semiarid regions, such as the Central Asia (Imentai et al., 2015) and Northwestern China (Cheng et al., 2014; Zhu et al., 2016).

The Heihe River is the second largest endorheic rivers in Northwestern China. With the population expansion and the rapid economic development in the upper and mid-catchment of the Heihe River Basin (HRB), water consumption increased rapidly and the water available for ecological processes was reduced. A series of severe ecological disasters appeared, for example, the dry up of terminal lakes including the East Juyan Lake (EJL) and West Juyan Lake (WJL), the death of desert riparian vegetation and the frequent occurrence of sandstorms (Cheng et al., 2014). In order to restore the degraded ecosystem, the Chinese government carried out an ecological water diversion project (EWDP) since 2000 to reduce river flow consumption for irrigation in the mid-catchment, and more water has been delivered from the midstream to the downstream area of the HRB. However, more water has been used for the development of economy in the downstream area of HRB, including the expansion of the cultivated land and tourism. In this way, the ecological water was squeezed by economic water. Therefore, the ecological water used by natural oases should be evaluated, and the core task was to understand the responses of vegetation dynamics to water resource availability at varying temporal and spatial scales, which made it possible to assess ecological restoration effect of the EWDP. Previous studies about the vegetation dynamics in the downstream area of HRB usually concentrated on single respect, such as the relationship between NDVI and river flow (Jin et al., 2010; Zhao et al., 2016), and that between NDVI and groundwater (Wang et al., 2011; Zhu et al., 2012). The spatio-temporal patterns and influencing factors of vegetation dynamics needed further investigation. In this study, the relationship between vegetation dynamics and hydro-climatic factors was systematically explored at catchment and pixel scales, which was vital for water resource management and determination of appropriate area for the oases in the endorheic basin.

The objectives of this study were to (1) detect the spatio-temporal variations of vegetation cover in the downstream area of the HRB during 2000–2015, (2) determine the spatio-temporal patterns of the relationships between vegetation dynamics and hydro-climatic factors, and (3) discuss the effects of the water diversion project on vegetation dynamics in the study area.

2. Materials and methods

2.1. Study area

The downstream area of the HRB is located in Inner Mongolia, Northwest China (100°00′–101°30′ E, 41°00′–42°30′ N) (Fig. 1). The area has a continental arid temperate climate with an average annual precipitation of 34 mm and an average annual potential evaporation of 3220 mm. The average annual temperature is 9.0 °C, with the highest temperature of 41 °C in July and a lowest of −36.4 °C in January. The lower reach of Heihe River branches into two rivers at Langxinshan (LXS), which are the East River and the West River. The two rivers ultimately flow into the EJL and the WJL, respectively. However, the two lakes dried up in 1992 and 1961, respectively, due to huge water consumption along the river by human activities. The Ejina oasis, at the downstream area of HRB, encompassed by peripheral desert regions, including sand deserts and the Gobi, is distributed along the rivers on the alluvial fan. The predominant natural vegetation is *Populus euphratica*, *Tamarix ramosissima*, and *Sophora alopecuroides*. Sparse vegetation, including *Nitraria tangutorum* and *Haloxylon ammodendron*, also exists in the desert regions (Zhang et al., 2011). In this study, the EJL was separated from the downstream area of HRB, and the remaining part was called the Ejina oasis.

2.2. Data sources

NDVI is the normalized reflectance difference between the visible red and near infrared bands (Rouse et al., 1974). It is recognized as an indicator of vegetation coverage and greenness, and has been commonly used for spatial vegetation assessments (Kawabata et al., 2001). The Moderate Resolution Imaging Spectroradiometer (MODIS) maximum value composite (MVC) value NDVI with resolutions of 250-meter and 16-day was used to evaluate surface vegetation conditions. These MODIS vegetation index data (MOD13A1) were derived from the Earth Observing System (EOS) Terra MODIS surface reflectance for the period of 2000–2015. The MVC method was used to minimize atmospheric effects, solar zenith angle effects, scan angle effects and cloud contamination. In this study, monthly NDVI was calculated by the MVC method.

Land use and cover data of three years (1990, 2000, and 2010) were obtained from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. These maps were derived from Landsat remote sensing images and the Chinese Huan Jing (HJ) satellite with a ground resolution of 30 m. The algorithm of hierarchical classification was employed to follow step-by-step procedures that effectively controlled classification quality. The independent validation indicated that the overall accuracy reached 86% (Zhang et al., 2014). Land use was divided