Quantifying the impacts of river hydrology on riparian vegetation spatial structure: case study in the lower basin of the Tarim River, China

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Abstract:

River hydrology largely determines the species composition and spatial distribution of riparian vegetation. However, it is difficult to determine the riparian vegetation spatial pattern that is only influenced by river hydrology due to the complex impacts of other influencing factors in field environments. We investigated the spatial structure of riparian vegetation in the lower basin of the Tarim River in hyper-arid western China, where distinct geomorphic and climatic features exclude the influences of factors other than river hydrological factors on the spatial structure of riparian vegetation. Landsat 8 OLI remotely sensed data were used to identify the different vegetation types and obtain the vegetation leaf area index (LAI) in the study area. Our results showed that the overall vegetation LAI exhibited a negative exponential declining trend with distance from the river, but this relationship was different for the different vegetation types, exhibiting a negative exponential relationship for the *Populus* woodlands and a Gaussian-type relationship for the *Tamarix* shrublands. The average width of the riparian vegetation decreased along the river by a negative power function. The average vegetation LAI decreased linearly along the river. The quantitative data we obtained regarding the river-induced variation in the riparian vegetation cover with the distance from the river channel would particularly be useful for modeling riparian vegetation dynamics and distributions.

Keywords:

Riparian vegetation, Vegetation spatial pattern, Hyper-arid region, Tarim River, Remote sensing, River-induced vegetation
1. Introduction

Rivers can foster one special vegetation type, riparian vegetation. Although riparian areas are geographically small portions of the landscape, riparian vegetation is one of the most important ecosystems on the Earth’s surface. It supports diverse plant and animal communities and maintains a range of important ecosystem services such as biodiversity, flood retention, river channel stabilization, nutrient sinks, pollution control, groundwater recharge, timber production, and recreation (Dzubakova et al. 2015). Because of its remarkable environmental, engineering, and management implications, riparian vegetation has attracted the interest of many researchers. Members of the scientific community such as hydrologists, geomorphologists and fluvial engineers have usually only considered riparian vegetation as a critical influencing factor on the fluvial and geomorphological processes of rivers (Tooth & Nanson 2000, Tooth 2000). However, ecologists and biogeographers have focused on the dynamics of riparian vegetation and its spatial distribution (Camporeale et al. 2013). Many field investigations have been carried out to describe and demonstrate riparian vegetation dynamics and spatial patterns (see the review by Camporeale et al. 2013), while some other studies have further developed some modeling approaches to simulate and predict riparian vegetation dynamics and distributions (Garcia-Arias & Frances 2016, Tealdi et al. 2013, García-Arias et al. 2013, Camporeale & Ridolfi 2007, Camporeale & Ridolfi 2006, Muneepeerakul et al. 2007, Benjankar et al. 2011, Gurnell et al. 2016, Corenblit et al. 2007, Corenblit et al. 2015, Perucca et al. 2006a, Coulthard & Van De Wiel 2007, Crouzy et al. 2016).

The role of rivers is key in understanding riparian vegetation dynamics and spatial structure.
River hydrology, including floodplain morphology and the river flow regime, largely determines the species composition and spatial distribution of riparian vegetation (Osterkamp & Hupp 2010, Garcia-Arias et al. 2014, Camporeale et al. 2006, Stromberg 2001). However, the dynamics and spatial structures of most riparian vegetation communities around the world are not determined only by river hydrology. Climate, geomorphology, soil texture and plant eco-physiological characteristics can also influence these processes. Different floodplains and river flow regimes as well as different plant responses to disturbances caused by flooding and water stress under different climatic and geomorphological conditions can cause variations in the spatial structure of riparian vegetation. In existing studies, the spatial distributions and structures of riparian vegetation have usually been investigated for specific areas or rivers in terms of how they are influenced by different factors other than river hydrology (Bashforth et al. 2011, Dunn et al. 2011, Fernandes et al. 2011, Greet et al. 2011, Yang et al. 2011, Sunil et al. 2012, Dzubakova et al. 2015, Blanco et al. 2016, Douda et al. 2016, Robertson & Augspurger 1999, Carr 1998, Fernandez-Alaez et al. 2005). Therefore, these studies have not been able to identify the riparian vegetation spatial patterns that are only induced by the river. Identification of the riparian vegetation spatial patterns that are influenced only by river hydrology can demonstrate the characteristics of the spatial distribution of vegetation types along the river (at the longitudinal scale) and perpendicular to the river (at the transverse scale) and provide the quantitative relationships between vegetation biomass or coverage and the distance to the river channel. Revealing these spatial patterns of riparian vegetation can improve our understanding of the influences and roles of river hydrology on riparian
vegetation dynamics. Particularly, these quantitative relationships can provide a useful tool to separate the influence of river hydrology from the influences of other factors and thus improve simulations of riparian vegetation dynamics and distributions.

In hyper-arid regions, desert riparian vegetation grows along river banks where rain is very scarce, usually less than 60 - 100 mm per year (Noy-Meir 1973); therefore, rain and rain-induced factors are not the drivers that influence the dynamics of riparian vegetation and its spatial distribution in such areas. River and river-induced factors are usually the only controlling factors forming the desert riparian vegetation. These natural environments in hyper-arid regions provide desirable conditions to analyze the role of rivers in the formation of riparian vegetation spatial structure.

In this paper, we report the results of an investigation of the spatial structure of riparian vegetation in the lower reaches of the Tarim River in the Tarim Basin of China, a hyper-arid region with a mean annual precipitation of less than 50 mm. The Tarim River covers most of the Tarim Basin and is one of the world’s largest closed hydrological drainage systems without an outflow. In the lower basin of the Tarim River, the river is enclosed by two large deserts, the Taklamakan Desert in the west and the Kuluk Desert in the east (Fig. 1), and a narrow but long strip of desert riparian vegetation has formed along this river. The terrain is flat, and no obvious highland exists in the lower basin; hence, the formation and development of the spatial structure of the riparian vegetation is not constrained by geomorphology. In addition, the stream flow generally decreases gradually from the Daxihazi Reservoir to the terminal Taitmar Lake (Fig. 1), causing longitudinal changes in the spatial structure of the vegetation along the river. The spatial structure of the riparian
vegetation along the river and perpendicular to the river in the lower basin of the Tarim River is representative of a vegetation spatial pattern that is only induced by floodplain morphology and the river flow regime.

Several studies have explored the spatial distribution of the vegetation in this area on the basis of field investigations (Ye et al. 2009, Li et al. 2013). However, such field investigations are limited in their ability to reveal the spatial patterns of vegetation at the landscape level and basin scale. Remote sensing method is the most effective way to inventory large areas (Congalton et al. 2002). Based on the remotely sensed imageries, the spatial distributions and patterns of vegetation at the landscape level can be more accurately revealed (Glenn et al. 2008). In this study, we used Landsat remotely sensed data to discern the vegetation types, obtain the leaf area index (LAI) of the different vegetation types, and analyze the spatial structures of the riparian vegetation in the lower Tarim River basin, including the spatial distributions of the different vegetation types along the river and perpendicular to the river; and the variations of vegetation coverages, which were expressed by vegetation LAI, at the transverse and longitudinal scales in the riparian area. Our aims were to provide a representative spatial pattern of riparian vegetation that were only induced by the river hydrology and quantify the impacts of river hydrology on the riparian vegetation spatial structure. Our results could improve our knowledge of the river-induced vegetation spatial patterns and provide useful supports to model the impacts of rivers on riparian vegetation dynamics and distributions.
2. Materials and methods

2.1 Site description

The Tarim River locates in the Tarim Basin in Xinjiang Province, China. The Tarim Basin is one of the driest regions in the world. The mean annual potential evaporation is more than 2000 mm but the mean annual precipitation is less than 50 mm. The Tarim River is a typical inland river without runoff yield of itself, and water resources are all supplied by its headstreams. The flow in the mainstream of the river was controlled by both climate and human activities. Due to long history of human occupation, artificial oasis cover the upper and middle reaches of the river, nonetheless, the natural vegetation covers the lower reaches of the river, free from being destroyed by human activities. In the 1980s, particularly after the Daxihaizi reservoir (Fig. 1) was built in 1972, excessive water use in the upper and middle reaches of the river had even led to a gradual drying up of the river’s lower reaches (Feng et al. 2005). This “drying-up” seriously deteriorated the basin’s downstream ecosystems. A water diversion project was being conducted to revive the ecological system of Tarim River starting in May 2000. An approximately average $2 \times 10^8$ m$^3$ volume of water per year was transported from Daxihaizi reservoir to the lower reaches of Tarim River (Tao et al. 2008). The lower reaches of the Tarim River are located between the Taklamakan and Kuluk deserts and extend from the Daxihaizi Reservoir to the terminal Taitmar Lake, with a length of approximately 200 km (Fig. 1). The width of the river channel is approximately 10 – 20 m, and depth is approximately 1 – 2 m. The water diversion usually lasted one to two month every year. During the period of water diversion, the streamflow in the channel usually decreases gradually from the Daxihaizi Reservoir to the terminal Taitmar Lake due to water
consumption by the vegetation and the groundwater recharge in the riparian areas. After the water diversion ceased, the channel usually dried up. More than ten years water diversion project made the riparian ecosystems reviving and groundwater level rising in the riparian zone (Li et al. 2013, Tao et al. 2008).

The narrow but long strip of desert riparian vegetation stretches along the lower Tarim River bank with a width of approximately 5 km or less. The species richness in this desert riparian ecosystem is low (Chen et al. 2006). In this area, the only tree species is *Populus euphratica*, the dominant shrubs are *Tamarix* spp. along with other minor shrubs such as *Lycium ruthenicum* and *Halimodendron halodendron*, and the dominant herbs are *Phragmites communis* along with other minor herbs such as *Apocynum hendersonii, Alhagi sparsifolia, Karelinia caspica,* and *Glycyrrhiza inflata* (Chen et al. 2006).

2.2 Processing of remote sensing images

Landsat 8 OLI images with 30 m × 30 m spatial resolution have temporal and spatial characteristics that are appropriate for many ecological questions, particularly at the landscape level (Kennedy et al. 2014). Here, we used Landsat 8 OLI remotely sensed data to identify and discern the vegetation types in the study area and to retrieve the LAI values of the dominant riparian vegetation types.

Relevant Landsat 8 OLI remote-sensing datasets from June to July 2013 were downloaded from the website http://glovis.usgs.gov/ and were used to classify the vegetation and calculate the LAI values in the study area. The three chosen images with WRS-2 Path/Row of 142/32 (imaging date July 20, 2013), 141/32 (imaging date June 11, 2013) and 141/33 (imaging date June 11, 2013), respectively, covered the entire study area and were little
impacted by clouds.

Pre-processings of the remote-sensing data, mainly including geometric and atmospheric corrections, were conducted prior to analysis. For the geometric correction, 17 control points recorded by a hand-held GPS were used to correct the positions of ground objects. The total calibration error was 0.44 pixels. The dark target method was used in the atmospheric correction (Lyapustin et al. 2004). In this method, the atmospheric path radiation data, which were calculated from a dark object identified on the images, were subtracted by the data for each pixel. The analysis and processing of remote-sensing data were performed with ENVI 4.6 software.

2.3 Vegetation discernment by remote sensing

According to the terrain features and main vegetation types in the study area, the land covers were classified into six categories for satellite remote sensing discernment: *Populus* woodland, *Tamarix* shrubland, *Phragmites* reedbank, farmland, sandy land and water body. A simple supervised classification method in support of data from a large number of vegetation field investigations was used to identify the six land covers by remotely sensed data. A total of 1024 training samples chosen from the plots used in field surveys across the lower basin of the Tarim River were used in the supervised classification method. The 1024 training samples included 388 samples of *Populus* woodlands, 317 of *Tamarix* shrublands, 75 of *Phragmites* reedbanks, 164 of sandy lands, 14 of farmlands and 66 of water bodies.

A simple random sampling survey and error matrix methods were used to evaluate the accuracy of the remote sensing classification results. The random sampling method evaluates accuracy by comparing the known vegetation types at randomly chosen locations.
with the vegetation types classified using the remote sensing images in the corresponding positions. We selected 53 plots of Populus woodlands and Tamarix shrublands, input the coordinates of each site into the resulting classification figure and calculated the classification accuracy of the Populus woodlands and Tamarix shrublands according to the correctness of the matches. The error matrix is a standard format for evaluating the accuracy of the classification; the total classification accuracy and single-category accuracy (including the accuracies of the producer’s and user’s) can be obtained from calculations and statistical tests (Congalton 1991). In this study, we used the 1024 training samples to evaluate the classification accuracy. Kappa analysis, which can determine the match between the training samples and the image classification results (Stehman 1996), was also used to evaluate the classification accuracy of all six land cover categories.

2.4 Vegetation LAI inversions from remotely sensed data

We built two empirical LAI-VI (vegetation index) models for the LAI inversions of the two most wide spread vegetation types in the study area, the Populus woodlands and Tamarix shrublands. Sixty observational plots, including 30 each of the Tamarix shrublands and Populus woodlands, were chosen along the lower reaches of the Tarim River to measure the LAI using an LAI-2250 canopy analyzer (LI-COR, Lincoln, USA), and the corresponding different VI values in the Landsat 8 OLI images were retrieved. The detailed field measurements and analyses were described in our previous paper (Zhu et al. 2014). Curve fittings were used to obtain the empirical LAI inversion model.

For the Tamarix shrublands, the NDVI (normalized difference vegetation index) was best for the fitting effects. The empirical relationship \( R^2 = 0.69 \) between the LAI of the Tamarix
shrublands (LAI$_T$) and the NDVI was

$$\text{LAI}_T = -0.216(\text{NDVI})^2 + 5.744\text{NDVI} - 0.356$$

(1)

For the Populus woodlands, the ARVI (atmospherically resistant vegetation index) was best for the fitting effects. The empirical relationship ($R^2 = 0.82$) between the LAI of the Populus woodlands (LAI$_P$) and the ARVI was

$$\text{LAI}_P = 8.119(\text{ARVI})^2 + 2.036\text{ARVI} + 0.095$$

(2)

Given that the Phragmites reedbanks in the river wetlands or near the reservoir and the terminal lake do not constitute typical xeric desert vegetation and that they compose little of the total area along the river, the LAI values of the Phragmites reedbanks were not calculated and analyzed in this study.

2.5 Statistical analysis and quantitative method description

Statistical analysis of the LAI results was used to obtain the quantitative relationships of vegetation cover at the transverse and longitudinal scales. To reveal the general spatial pattern of the riparian vegetation, twenty transects that were transverse to the river channel in the LAI image were chosen to retrieve the LAI values and the corresponding distances from the river channel (Fig. 1). The placement of the twenty transects was determined by the position approximately equidistant from the Daxihaizi Reservoir and the terminal Taitmar Lake. The approximate distance between two adjacent transects was 8 to 10 km. All twenty transects were located on the right side of the river, and the length of each transect was 5.5 km.

At the transverse scale, we analyzed the variation in the vegetation LAI based on the distance from the river channel. The quantitative relationships between the vegetation LAI
and the distance from the river channel were obtained by averaging the LAI values of all twenty transects at the same distance from the river channel.

At the longitudinal scale, we analyzed the variation in the cover width and the LAI of the riparian vegetation along the river channel. To reveal the spatial trend of riparian vegetation structure at the longitudinal scale, the 200-km-long river channel was equally divided into five sections with a length of 40 km from the Daxihaizi Reservoir to Taitmar Lake, and each section could thus include four chosen transects. The data from the four chosen transects in one section were averaged to represent the relevant vegetation structure of the section. Here, the average one-side cover width in each section was obtained by averaging the widths of the vegetation in the four transects. The average LAI value in each section was obtained by averaging the LAI values of the four transects within 0 – 1.5 km from the river. The variation and trend in the spatial structure of the vegetation at the longitudinal scale was exhibited by comparing the differences in the vegetation cover widths and LAI values among the five sections.

3. Results

3.1 Accuracy evaluation of remote sensing classification

Using the simple random sampling evaluation method, the classification accuracy of the Populus woodlands and the Tamarix shrublands was 73.6%. Using the error matrix evaluation method, the total classification accuracy of the six land covers was 89%, and the Kappa coefficient was 0.86 (Table 1).

The user and mapping accuracies of the sandy lands, farmlands and water bodies were more than 90%; the user accuracy of the Phragmites reedbanks was also more than 90%. However,
the mapping accuracy of the reedbanks was relatively low (Table 1), most likely because the herbs growing on dry land were very sparse and may have been incorrectly classified as *Tamarix* shrublands or *Populus* woodlands. The user and mapping accuracies of the *Populus* woodlands and *Tamarix* shrublands were relatively low (Table 1). The two vegetation types were sparse and had similar spectral characteristics to bare soil; thus, they were prone to inaccurate and omitted classifications. However, the lowest mapping accuracy was higher than 67%, which was sufficient to meet the needs of this study.

Some research found that the satellite imagery did not do a good job of identifying the structural characteristics of riparian vegetation (Glenn et al. 2008, Congalton et al. 2002). However, our results showed there were high classification accuracies of the different vegetation types through the Landsat remote sensing datasets in our study area. This was mainly due to the simple structure and single plant community of desert ecosystems in hyper-arid regions, which provide simple discernible terrain features for the remotely sensed supervised classification method. Our classification accuracy results indicated that the simple supervised classification method in support of a large amount of field vegetation survey data was an appropriate remote sensing method for discerning the vegetation types in hyper-arid regions.

3.2 Vegetation spatial distribution

The spatial distribution differed among the three vegetation types in the study area (Fig. 2). The *Phragmites* reedbanks were mainly concentrated around the Daxihaizi Reservoir and Taitmar Lake, and little *Phragmites* cover could be found along the river channel. *Populus* woodlands and *Tamarix* shrublands covered most of the study area. Although the difference
between the total area of the *Populus* woodlands and the *Tamarix* shrublands was not large (405.3 km² and 336.4 km², respectively), the cover widths of the two vegetation types were obviously different. The area covered by *Populus* woodlands was narrower nearer the river channel, but the area covered by *Tamarix* shrublands was wider. The *Tamarix* shrublands could also be found far away from the river channel where the *Populus* woodlands seldom occurred.

The cover width of the riparian vegetation generally became narrower downstream from the Daxihaizi Reservoir toward Taitmar Lake (Fig. 2). The statistical analysis showed that the average cover width of the riparian vegetation decreased by a negative power function ($R^2 = 0.91$, $P < 0.05$) with an increase in the distance from the Daxihaizi Reservoir along the river (Fig. 3).

3.3 LAI spatial pattern

The LAI in the study area was generally low. The mean and maximum LAI values were 0.252 and 1.849 for the *Populus* woodlands and 0.253 and 1.653 for the *Tamarix* shrublands, respectively (Fig. 4, Table 2). Our statistical results showed that the area with an LAI of less than 0.5 accounted for 90.1% and 92.4% of the total area of the *Populus* woodlands and *Tamarix* shrublands, respectively. The low LAI indicated that the vegetation in this area is very sparse.

The LAI values generally decreased with increasing distance from the river channel at the transverse scale (Fig. 4). This phenomenon was consistent for the *Populus* woodlands (Fig. 4b) and the *Tamarix* shrublands (Fig. 4c). To quantify the spatial pattern of the vegetation LAI, we analyzed the relationship between the vegetation LAI and the distance from the river...
channel. The average LAI values of the overall riparian vegetation had a significant negative exponential relationship \( R^2 = 0.95, P < 0.0001 \) with the distance from the river channel (Fig. 5a). Within approximately 1 km from the river channel, the mean LAI clearly decreased with the distance from the river channel and was generally less than 0.1 when the distance exceeded 1 km. This indicated that the vegetation was very sparse in places farther from the river channel than 1 km.

The two different vegetation types showed different spatial structure at the transverse scale (Fig. 5b, c). The average LAI values of the *Populus* woodlands also had a negative exponential relationship \( R^2 = 0.95, P < 0.0001 \) to the distances from the river channel (Fig. 5b). However, the quantitative relationship \( R^2 = 0.79, P < 0.05 \) between the vegetation LAI and the distance from the river channel was of the Gaussian function type for the *Tamarix* shrublands (Fig. 5c). The peak value of the vegetation LAI was not close to the river channel but more than 0.5 km far away from the river (Fig. 5c). The vegetation LAI values of the *Tamarix* shrublands values in the riparian zone showed a declining trend toward the river channel in the riparian zone within 0.5 km.

The average vegetation LAI in the riparian zone within 1.5 km decreased linearly along the river at the longitudinal scale, except in the terminal areas of the river (Fig. 6). The average riparian vegetation LAI values near the terminal Taitmar Lake were higher than those in some upper areas along the river (Fig. 6). The relatively higher vegetation LAI in the terminal areas resulted from the intermittent accumulation of water in and around Taitmar Lake rather than the impacts of river flow. Hence, the results of the vegetation LAI in the terminal areas were not considered in the analysis of the variation in the vegetation LAI at the
4. Discussion

In this study, we retrieved and obtained quantitative data describing the variation in the riparian vegetation cover with the distance from the river channel. We argue that these quantitative relationships might represent some vegetation spatial patterns that are induced by rivers, because the distinct geomorphic, climatic and vegetative features in our study area provide desirable conditions to reveal riparian vegetation spatial structure that is controlled by river hydrology. First, the flat terrain of the lower basin of the Tarim River can prevent the constraints of topography on the formation and development of the spatial structure of riparian vegetation. Second, scarce precipitation ensures that the water source for vegetative growth is from river-controlled groundwater and flooding rather than rain water (Yuan et al. 2014, Yuan et al. 2015). Subsequently, the riparian vegetation dynamics should only be controlled by the river-induced hydrological processes, including the groundwater table dynamics, floodplain morphology and river flow regime. Third, three dominant species in the study area, *Populus euphratica*, *Tamarix* spp. and *Phragmites communis*, represent three typical vegetation types: tree, shrub and herb, respectively, which provided the ability to analyze the influence of river hydrology on different vegetation types. These distinct and desirable conditions in our study area could provide us a means to retrieve valuable and representative spatial structure information for vegetation that is only induced by the river. Based on the results from our investigation involving remote sensing data, the quantitative relationships between the riparian vegetation cover and the distance from the river can be summarized with the following expressions. At the transverse scale, an overall negative
exponential declining trend in the riparian vegetation coverage (LAI) was found, but the spatial distribution characteristics were different for different vegetation types. This negative exponential distribution was also suitable for trees, indicating that the vegetation with high water requirement was highly influenced by water source. A Gaussian-type distribution function was more suitable for fitting the spatial structure of shrubs. However, our data did not make it clear that the Gaussian type should be a normal or shew distribution for describing the transect distribution of vegetation LAI. Overall, the maximum vegetation coverage of the vegetation with the high drought tolerance would not be close to the river channel, and a declining trend toward the river channel between river channel and the place with the maximum vegetation coverage occurred for the shrubs. On the other hand, at the longitudinal scale, the cover width of the riparian vegetation declined according to a negative power function along the river, while the average vegetation LAI decreased linearly along the river except for near and around the terminal lake.

However, based on the error bars in Figs. 3 & 5, we find that great spatial variability in the riparian vegetation cover existed at the transverse and longitudinal scales in the context of the overall vegetation spatial patterns. This spatial variability in the vegetation was usually exhibited by patchiness, which has also been found in the results of some other field investigations (Bashforth et al. 2011). The spatial variability in the vegetation indicated that factors other than river hydrology mediate or disturb the spatial distribution of the desert riparian vegetation. Our field investigations and observations preliminarily showed that soil texture was most likely the critical influencing factor. In fact, soil texture is an important factor influencing the distribution and spatial patterns of vegetation in arid and semi-arid

We think that this factor should be emphasized in the analysis and modeling of riparian vegetation dynamics and distributions.

Our results can also help to improve the modeling of the formation of the spatial patterns in desert riparian vegetation. Two approaches have typically been used to simulate the formation and evolution of the spatial distribution of desert riparian vegetation. One approach is called minimalist models (Camporeale et al. 2013), which is usually used to study how the transverse distribution of riparian vegetation depends on the hydrological, morphological, and biological parameters involved in the model (Perucca et al. 2006b, Camporeale & Ridolfi 2006). In these models, the variation in the average vegetation biomass value along a river transect is usually the critical input process (Camporeale et al. 2013). For the first time, our results present multiple and reasonable vegetation spatial patterns from field investigations to support the parameters of the input processes in these models. Another approach is called connectivity models (Okin et al. 2015), which has been used to simulate the formation of desert vegetation patterns in drylands based on the concept of ecological connectivity (Okin et al. 2015). The novel concept of “connectivity” is currently being usefully applied to dryland ecology to characterize and explain the spatial interactions, dynamics and formation of vegetation patterns in dryland landscapes (Okin et al. 2015, Miller et al. 2012, Stewart et al. 2014). In connectivity models, the quantification of ecological connectivity is one of the key modeling parameters (Stewart et al. 2014). We believe that the quantification of ecological connectivity for particular desert riparian ecosystems needs to consider the specific spatial patterns of the riparian vegetation. It will
be valuable to improve the modeling of the formation and dynamics of desert riparian vegetation based on the results from our investigation.

5. Conclusions

Due to the simple structure and single plant community of desert riparian ecosystems in hyper-arid regions, the remotely sensed simple supervised classification method in support of a large amount of field vegetation survey data could reasonably discern the riparian vegetation types and retrieve the vegetation LAI in our study area. These remotely sensed LAI data provided abundant information on the vegetation spatial distribution, based on which we determined the quantitative relationships between riparian vegetation spatial structure and the distance to the river channel. These quantitative relationships are typical of river-induced vegetation spatial patterns because the distinct field conditions in our study area almost removed the influences of other factors on the formation and development of the riparian vegetation. To the best of our knowledge, this is the first time that a general riparian vegetation spatial pattern at the transverse and longitudinal scales has been obtained from field investigations. The quantitative relationships we obtained here would be valuable for the simulation of riparian vegetation dynamics and distributions in hyper-arid environments, particularly, for supporting the parameters of the input processes in relevant models.

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References


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Table 1: Error matrix of incorrectly classified pixels of the six land cover types by the remote sensing method

<table>
<thead>
<tr>
<th>Land cover types</th>
<th>Classified pixels</th>
<th>Mapping accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tamarix shrublands</td>
<td></td>
</tr>
<tr>
<td>Tamarix shrublands</td>
<td>9982</td>
<td>67.5</td>
</tr>
<tr>
<td>Populus woodlands</td>
<td>3121</td>
<td></td>
</tr>
<tr>
<td>Populus woodlands</td>
<td>6403</td>
<td>76.1</td>
</tr>
<tr>
<td>Sandy lands</td>
<td>1424</td>
<td>95.8</td>
</tr>
<tr>
<td>Farmlands</td>
<td>8</td>
<td>99.4</td>
</tr>
<tr>
<td>Water bodies</td>
<td>0</td>
<td>99.9</td>
</tr>
<tr>
<td>Phragmites grasslands</td>
<td>14369</td>
<td>75.4</td>
</tr>
<tr>
<td>Total</td>
<td>18386</td>
<td></td>
</tr>
<tr>
<td>Reference samples</td>
<td></td>
<td>Total accuracy = 89.0%</td>
</tr>
<tr>
<td>User accuracy</td>
<td>54.3</td>
<td>Kappa coefficient = 0.86</td>
</tr>
<tr>
<td></td>
<td>82.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95.6</td>
<td></td>
</tr>
</tbody>
</table>

Note: The numbers listed in a row are the pixel numbers of the land cover type classified into the six land cover types. The numbers listed in a column are the pixel numbers of the six land cover types classified into the land cover type in the column.
Table 2: Statistical characteristics of the leaf area index (LAI) of the *Tamarix* shrublands and the *Populus* woodlands in the study area

<table>
<thead>
<tr>
<th></th>
<th>Number of pixels</th>
<th>Minimum LAI</th>
<th>Maximum LAI</th>
<th>Mode LAI</th>
<th>Average LAI</th>
<th>Standard deviation</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Tamarix</em> shrublands</td>
<td>450293</td>
<td>0.005</td>
<td>1.653</td>
<td>0.182</td>
<td>0.253</td>
<td>0.158</td>
<td>62.3</td>
</tr>
<tr>
<td><em>Populus</em> woodlands</td>
<td>373813</td>
<td>0.007</td>
<td>1.849</td>
<td>0.102</td>
<td>0.252</td>
<td>0.178</td>
<td>70.5</td>
</tr>
</tbody>
</table>
Fig. 1: Location of the lower basin of the Tarim River, China. Twenty transects we chose to conduct the statistical analysis were illustrated in the figure.
Fig. 2: Spatial distribution of the six categories of land covers obtained by the Landsat 8 OLI datasets in the lower Tarim River basin.
Fig. 3: Variation in the average vegetation cover width along the river. The cover width is the width on one side of the river. The $y$ error bars represent the maximum and minimum average widths in one section.
Fig. 4: Spatial distribution of the leaf area indices (LAI$s$) of (a) both the *Populus* woodlands and the *Tamarix* shrublands, (b) the *Populus* woodlands, and (c) the *Tamarix* shrublands in the lower Tarim River basin.
Fig. 5: Variation in the average vegetation leaf area index (LAI) along the riparian transects transverse to the river channel with increasing distance from the river channel (a) for the overall average LAI, (b) for the average LAI of the *Populus* woodlands, and (c) for the average LAI of the *Tamarix* shrublands. The gray error bars represented the maximum and minimum LAI values.
Fig. 6: Variation in the average leaf area index (LAI) within 1.5 km along the river. The error bars indicate the standard deviations.