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ORIGINAL ARTICLE

Restoration of the lower reaches of the Tarim River in China

Xiuqing Zhang · Yaning Chen · Weihong Li ·
Yi Yu · Zhihong Sun

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Abstract The middle and lower reaches of the Tarim River are areas of rich biodiversity and natural resources in the inland arid region of China. However, the Tarim River and its associated wetlands have been severely damaged and fragmented during the past several decades. To restore the deteriorated ecosystem and preserve the endangered riverine vegetation along the Tarim River, a project for releasing water from upper dams to the lower reaches of the Tarim River was initiated by China's government in 2000. Between 2000 and 2005, we monitored the responses of groundwater levels and vegetation to this mitigation along nine transects spaced at mean intervals of 45 km along the river from Daxihaizi Reservoir, the source of water conveyance, to the Lake Taitema, the mouth of the Tarim River. We found that average groundwater levels rose significantly from 8 to 4 m below ground surface. Species diversity did not change during the 5-year period, but the total vegetation coverage and canopy size of some species significantly increased. The endangered tree species, *Populus euphratica*, started to regenerate. Our results indicated that species diversity might recover very slowly, even if the trial water release program became a permanent river management practice. Management decisions about allocating limited water supplies among competing uses in arid regions will ultimately determine whether degraded river ecosystems, such as the Tarim River, can be restored.

Keywords Dams · Arid regions · Degraded ecosystem · Fragmentation · Inland rivers · *Populus euphratica* · Water recharge

Introduction

Among the factors causing habitat fragmentation across landscapes, damming has been generally recognized as foremost in river ecosystems (Sih et al. 2000; Wu et al. 2003). Regulation of water flow and fragmentation by dams are perhaps the most widespread of human impacts on the world's rivers. Globally, there are over 45,000 large dams in more than 150 countries, and over 300 of them are giant dams with heights >150 m, structural volumes >15 million m^3, or reservoir storage capacities >25 km^3 (Schrope 2000; Nilsson et al. 2005a). Currently, more than 1,500 dams are under construction worldwide, mostly in developing countries, such as China and India, which have large dam construction programs. Studies on the effects of large dams on biodiversity and on how the dams regulate river-margin species in these countries can be very valuable for biodiversity conservation. It is generally well known that dams impact species biodiversity in both upper and lower reaches by changing inundation patterns, regulating flows, and fragmenting landscapes (Nilsson and Berggren 2000; Jansson et al. 2000; Kingsford et al. 2004; Nilsson et al. 2005a). However, studies on processes and mechanisms of dynamic responses of species to dam-based river flow changes at a landscape scale are rare, and more knowledge is needed to provide a basis for better

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X. Zhang · Z. Sun (✉)
Inner Mongolia Agricultural University, Hohhot 010019, China
e-mail: tdftjf@126.com

Y. Chen · W. Li
Xinjiang Institute of Ecology and Geography,
Chinese Academy of Sciences, Urumqi 830011, China

Y. Yu
International Centre for Bamboo and Rattan,
Beijing 100102, China

management of the river systems and restoration of biodiversity (Robinson et al. 1992; Haila 2000; Renofalt et al. 2005).

Free-flowing rivers are essential to natural and human environments because they fulfill a multitude of ecological, economic, spiritual, cultural, and aesthetic needs and wants. Therefore, during the last few decades local communities, scientists, governments, and agencies have increasingly focused on restoring river ecosystems (Power et al. 1995; Ward et al. 2001; Wohl et al. 2005). The restoration of rivers faces challenges because most rivers in the world have been impacted by humans for a long time, and it is often the case that we do not know in what ways, and to what degree, a particular river or reach of a river system has been affected (Nilsson et al. 2005b). Historical knowledge of river water utilization and changes is therefore very important for river restoration. But even if we knew the historical impacts of human activities on the rivers, some rivers might be beyond recovery because of irreversible changes to channels and/or watersheds.

Damming changes water flow and hydrology, which inevitably leads to changes in the riverine vegetation. One approach to mitigating these impacts is to increase water discharge from dams to lower reaches. However, because of our limited knowledge of the processes and mechanisms underlying the effects of dam fragmentation, and the complexity of rivers with respect to hydrological, geochemical, and biological variables, it is very difficult to predict the specific responses of riverine communities to this practice (Nilsson et al. 2003).

During the last a few decades, remarkable progress has been made in the field of river restoration, with an integration of different disciplines such as economics, geomorphology, hydrology, and ecology (Cooper et al. 1998; Benda et al. 2002; Nilsson et al. 2003; Rood 2003; Rosgen 2006; Nilsson and Renöfält 2008). However, applicable methodologies and techniques for river restoration are still in early developmental stages (e.g., Jungwirth et al. 2002). Understanding the changes to river ecosystems brought about by past and present human developmental activity will be essential to the development of effective restoration tools and strategies.

In this study, we examined the responses of downstream river-margin communities to 5 years of increased water releases from the Daxihaizi Reservoir on the Tarim River in northwest China's Xinjiang Uyghur Autonomous Region. Tarim Basin is located between the Tangri and Kunlun Mountains. Occupying 207,000 square miles, it is the largest inland basin in the world. The middle portion of the Tarim Basin is the Taklamakan desert, the second world's largest sand desert (131,640 square miles) next to the Sahara. Under the extremely arid natural conditions and the pressure of the population, the ecosystems of the Tarim Basin have significantly deteriorated since China's government initiated an agricultural development plan in Xinjiang Uyghur Autonomous Region in the early 1960s. The establishment of many dams at the upper reaches of the Tarim River caused considerable environmental damage, such as arable land degradation, vegetation coverage decline, sandstorms, and desertification. Dams, together with associated activities such as irrigated agriculture, have been a major cause of the decline of freshwater biodiversity observed in recent decades. Tarim Basin is the major distribution area of *Populus euphratica* forest in the world. This forest decreased from 53,000 ha in the 1960s to 1,333 ha in 2000 in the Tarim Basin. Construction of the Daxihaizi Reservoir in 1972 resulted in a significant reduction of the mainstream water flow of the lower reaches of the Tarim River. During the last three decades, the ground water level in the lower reaches of the river dropped from 3–5 to 8–12 m (Chen et al. 2006a, b). In 2000, China's government started a huge restoration project, by transferring dam water to the lower reaches of the Tarim River to improve the ecological environment of the basin, including ecological restoration, water-saving irrigation, river course treatment, and flood control. The project has a total investment of 1.29 billion US dollars, and the projected area covers two-thirds of the Uyghur Autonomous Region. In this study, we examined the riverine vegetation responses to water recharge to the lower reaches of the river from 2000 to 2005.

Methods

Study area

This study was conducted in the Tarim Basin, lying between several mountain ranges in the Xinjiang Uyghur Autonomous Region in China's far west. The Tarim Basin is one of the largest endorheic drainage basins in the world with a total area of 1.02×10^6 km^2 and supports a population of 8.26×10^6. The Tarim river, the longest continental river in China, originates from glaciers, snowmelt, and rainfall of the surrounding mountains and runs eastward with a length of 1,300 km of the main channel. More than 80 % of the land in the basin was degraded.

The mean annual surface runoff of the river is 3.98×10^{10} m^3. Based on data from 77 meteorological stations located in the Tarim Basin, the mean annual precipitation of the area (1955–2000) is less than 50 mm, with 50–80 mm at the edge and 17–25 mm at the center of the basin. The potential annual evaporation ranges from 2,500 to 3,000 mm. Total annual solar radiation of the basin is between 5,690 and 6,360 MJ m^{-2}, and the annual cumulative $\geq$10 °C temperature ranges from 4,040 to 4,300 °C.

Monthly mean air temperature is 25 °C in July and −15 °C in January.

Much of the Tarim Basin is dominated by the Taklamakan desert. Except for sand dunes in the study area, which had an average height of 3.5 m, the topography was flat. The study area ranged from 860 to 790 min elevation. The area is sparsely settled by Uyghurs and other central Asian peoples, as well as Han Chinese, many of whom immigrated to this area during the last 50 years. Three plant communities were distributed in this region, and they were dominated by *P. euphratica*, *Tamarix ramosissima,* and *Apocynum venetum*, respectively. The *P. euphratica* community was mainly distributed closer to the riverbanks; the other communities were distributed randomly. The main associated species included *Tamarix hispida*, *Lycium ruthenicum*, *Phragmites communis*, *Alhagi sparsifolia*, and *Karelini acaspica*.

Water recharge project

Construction of the Daxihaizi Reservoir, which was filled from Lake Bosten (41°56′–42°14′N and 86°40′–87°26′E) located in the middle reaches of the Tarim River, was completed in 1972. Water discharged into the reaches of the Tarim River below Daxihaizi Reservoir was greatly reduced. The depths of the riverbed originally ranged from 2 to 5 m below the surface of the surrounding land. The total length of the river from the Daxihaizi Reservoir (41°35′19″N, 87°33′32″E) to Lake Taitema (39°16′30″N, 88°12′18″E), the previous mouth of the river, was approximately 320 km. By the late 1990s, damage to riparian plant communities was evident along this entire length. The cause of the degradation was tentatively identified as altered riparian hydrology due to reduced base flow downstream of the reservoir.

In an attempt to halt and perhaps reverse severe degradation of riverine vegetation, China's government initiated a water recharge project in 2000. This project was to last at least 15 years. The plan called for releasing water from the Daxihaizi dam every 1–3 months and at a rate that kept each release within the river banks. By the end of 2005, eleven releases had occurred (Chen et al. 2006a, b; Zhao et al. 2009).

Field and lab measurements

Nine transects perpendicular to the river were established in the lower reaches of the Tarim River (Fig. 1). The first transect was located 22 km below the Daxihaizi Reservoir; others followed at intervals of 20–45 km. The nine transects were named Akdun (A), Yahepu (B), Yinsu (C), Abudali (D), Kardayi (E), Tugmailai (F), Alagan (G), Yiganbjima (H), and Kaogan (I). Each transect was 50 m wide and 1,000 m long. Three to six groundwater wells at depth between 8 and 17 m were dug along the center line of each transect at intervals of 100 m or 200 m depending on the topography and environmental heterogeneity. A total of 44 groundwater monitoring wells were established in 2000. We measured groundwater levels at 5- or 10-day intervals during each period of water discharge from Daxihaizi Reservoir and at 15- or 30-day intervals after each discharge event ended. The measurements began in May 2000 and ended in December 2005.

Adjacent to each well, a 50 × 50 m permanent plot was established for measuring plant species composition and abundance, plant height, leaf area, tree diameter, and vegetation coverage. We measured the plants once during the plant growth seasons from June to September in each year from 2000 to 2005. Soil samples were taken down to a depth of 50 cm in 4 soil pits using a spade, and the 4 soil pits were mixed into one soil sample. Three soil samples were randomly taken in each plant measuring plot. Soil pH was measured by using a paste of 1:1 ratio of fresh soil and deionized water. Soil moisture contents were determined by oven-drying 10 g of fresh soil samples at 105 °C for 48 h (Sollins et al. 1984). Groundwater alkalinity and salinity were measured using standard procedures.

Data analysis

The relationship between species abundance and environmental variables was studied using detrended canonical correspondence analysis (DCCA). We followed the calculation procedures suggested by TerBraak and Prentice (1988). DCCA is a direct gradient analysis technique in which the axes of vegetation ordination are restricted to linear groupings of environmental variables (Palmer 1993). We used this technique because DCCA has some advantages over other ordinations in that it makes the interpretation of the axes easier and has no marked horseshoe effect (TerBraak 1986). We analyzed seven environmental variables—groundwater depth, water salinity, water alkalinity, soil pH, soil electricity conductance, elevation, and soil moisture—as the environmental factor matrix of DCCA. CANOCO version 4.5 was used for the DCCA analysis.

The species importance value, P_i, which is a synthetic index for denoting the status and functions of a species in a plant community, was calculated as

$$P_i = \mathrm{Cr} + \mathrm{Dr} + \mathrm{Hr},$$

where Cr is the relative coverage (projected crown area divided by sampling plot area) of the species, Dr is the relative density of the species, and Hr is the relative height of the species.

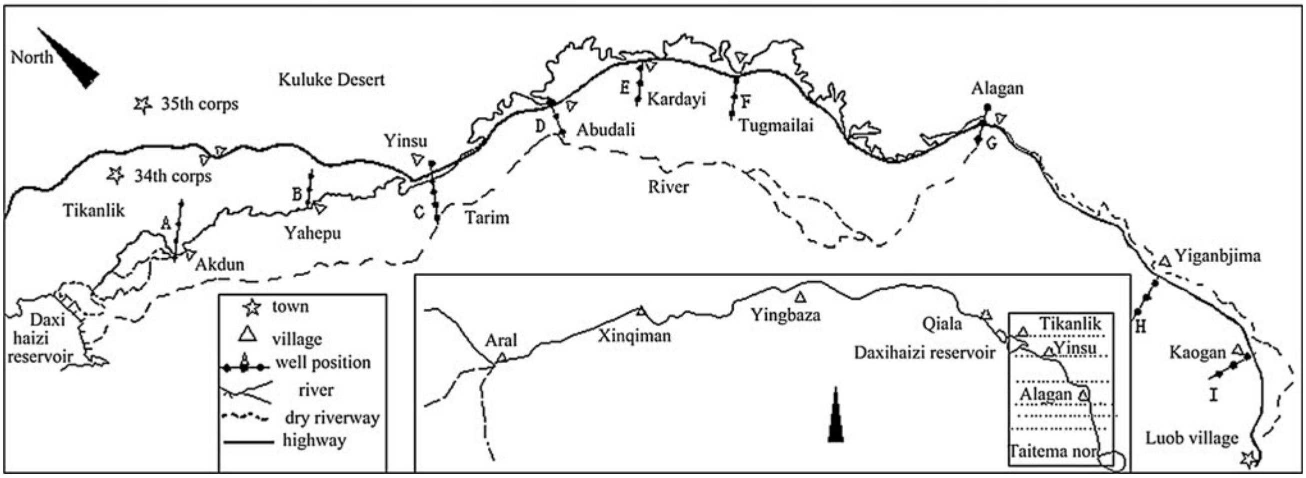

Fig. 1 Nine sample transects were established in the lower reaches of the TarimRiver: Akdun (*A*), Yahepu (*B*), Yinsu (*C*), Abudali (*D*), Kardayi (*E*), Tugmailai (*F*), Alagan (*G*), Yiganbjima (*H*), and Kaogan (*I*). Transect *A* to *I* was in the order from upper to lower reaches of the river

We calculated species diversity index and species richness index using the following formulas, respectively (Simpson 1949; Margalef 1958):

$$\text{Simpson index}: \text{Ds} = 1 - \Sigma \text{P}_i^2,$$

$$\text{Margalef index}: \text{Dm} = (S - 1)/\text{Ln}\ N,$$

where P_i is the relative importance value of the species i, N is the sum of the importance values of all species in a plot where species i was found, and S is the total number of species.

We used student t test or paired t test in statistical significance tests, whichever were applicable to the comparisons of the changes of variables before and after water recharges. Linear regression was used to analyze the relationship among the groundwater levels and amount and duration of water recharges. Stepwise regression was used to analyze the relationship between vegetation coverage and environmental variables. We used SPSS 11.0 (SPSS Inc., Chicago, Illinois, USA) for most statistical analyses.

Results

Groundwater levels

Water released from the Daxihaizi Reservoir into the lower reaches of the Tarim River significantly decreased depth to the water table for all the nine transects ($P < 0.01$) (Fig. 2). The effect along each 1,000 m transect declined with increasing transverse distance away from the main channel. Groundwater levels rose an average of 4.2 m within 200 m of the river bank, while they rose only an average of 2 and 0.5 m at distances of 600- and 900 m away from the river bank, respectively. Longitudinally, the increase of the groundwater levels was significantly larger at the upper sites (closer to Daxihaizi Reservoir) than the lower sites during the first 2 years of the project. After that, longitudinal differences were not significant except for the two most distant sites (transects H and I), which experienced less rise in groundwater levels than other sites.

The first water discharge event in 2000, which released approximately $100 \times 10^6\ \text{m}^{-3}$, only reached the Kardayi site (E), and the second water discharge reached the Alagan site (G). The third event in 2001 and all subsequent releases reached the mouth of the Tarim River. We found that the increases of the groundwater levels were positively correlated with both the duration of water release ($R^2 = 0.787$, $P < 0.01$) and the water volumes conveyed ($R^2 = 0.823$, $P < 0.01$).

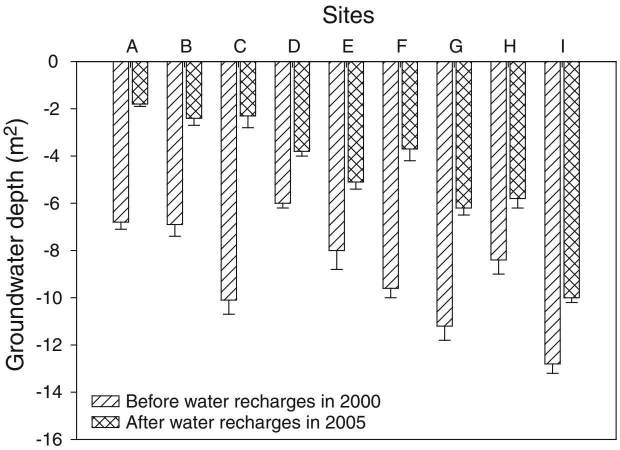

Fig. 2 Average groundwater levels for each transect before (2000) and after (2005) the initial 5-year period of water discharges into the lower reaches of the Tarim River. *Error bars* denote standard error of the means

Species diversity

Five years after the water discharge program began, we found that the vegetation cover had increased (data not shown). This change was mainly due to increased crown diameters of *P. euphratica* (details below), which was the dominant tree species along the Tarim River. We did not find any indication of increased species diversity at any sample site along the river, which was counter to our expectation. Changes in both the Margalef species richness index and the Simpson species diversity index between 2000 and 2005 were insignificant (Fig. 3).

The species composition became simpler from the upper to the lower reaches of the river. At the Yahepu (B) andYinsu (C) sites, the tree species included *P. euphratica*, the shrub species included *T. ramosissiama*, *T. hispida*, *L. ruthenicum*, and the herb species included *Glycyrrhiza uralensis*, *Apocynum venetum*, *Athagi pseudathagi,* and *Phragmites communis*. At the Abudali (D) and Kardayi (E) sites of the middle reaches, the vegetation was dominated by *P. euphratica*, *T. chinensis*, *L. ruthenicum,* and *H. halodendron*. At the Alagan (G) and Yiganbjima (H) sites of the lower reaches, only a few species existed, such as *P. euphratica* and *T. chinensis*. There was a trend of decreasing species composition with increasing distance from the river channel at all the sites (Table 1).

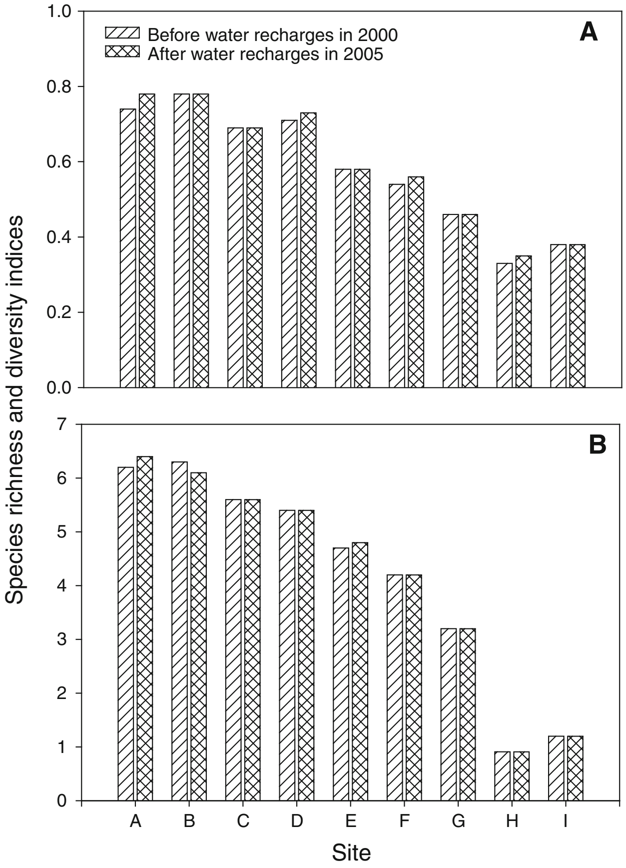

Fig. 3 Indices of (**a**) species diversity (Simpson Index) and (**b**) species richness of vegetation (Margalef Index) for the nine transects in the lower reaches of the Tarim River before (2000) and after (2005) the initial 5 year period of water discharges

The major plant species have different rooting depths (Table 2). The mean rooting depth of *P. euphratica* was 3 m under favorable growth conditions, but it can reach 6 m under unfavorable conditions. When the groundwater levels dropped below 7 m, the trees started to dieback. Another widely distributed species was *T. chinensis*. Its root depth can reach 10 m under favorable conditions.

Vegetation and environmental factors

The relationship between the vegetation distribution and environmental factors is shown in Fig. 4. Eigenvalues of axis 1 and axis 2 were 0.346 and 0.152, and they explained 42 and 16 % of the variance of the species–environment relationship, respectively. Axis 1 had a positive correlation with groundwater level (correlation coefficient $r = 0.662$) and had a negative correlation with soil moisture ($r = -0.631$, $P < 0.01$) and elevation ($r = -0.436$, $P = 0.2$). Axis 2 had a positive correlation with pH ($r = 0.603$, $P < 0.1$) and a negative correlation with soil organic carbon ($r = -0.552$, $P < 0.1$) and salinity ($r = -0.476$, $P = 0.3$). Using a stepwise Regression method, we found that axis 1 and axis 2 were significantly correlated with groundwater level (L, $P < 0.01$) and soil moisture (S, $P < 0.001$). The relationships were expressed as the following formulas:

$$X_1 = -9.5991L + 100.86;\ R^2 = 0.64$$

$$X_2 = 1.651S + 43.01;\ R^2 = 0.76$$

Table 1 Artificial water recharges implemented to the lower reaches of the Tarim River, Western China, from 2000 to 2005

Starting date	Ending date	Duration (day)	Amount (MCM)
5/14/2000	7/13/2000	61	98.8
11/3/2000	2/14/2001	104	220
4/1/2001	7/6/2001	97	184
9/12/2001	11/17/2001	67	197
7/20/2002	11/10/2002	110	293
3/3/2003	7/11/2003	131	250
9/12/2003	11/7/2003	56	90
4/22/2004	6/25/2004	62	120
8/27/2004	11/7/2004	70	230
5/7/2005	6/7/2005	30	52
8/30/2005	10/31/2005	61	228

Unit “MCM” used in the table means million cubic meter

Table 2 Rooting depths of major species in the lower reaches of the Tarim River basin

Species	Depth of main roots (m)	Favorable condition (m)	Unfavorable condition (m)
Populuseuphratica	<7.0	1.0–4.0	5.0–6.0
Tamarix spp.	<5.0	1.0–6.0	7.0–10.0
Phragmitescommunis	0.5–1.0	1.0–3.0	3.0–5.0
Glyzyrrhiza inflate	1.0–2.0	1.0–3.0	3.0–6.0
Alhagisparsifolia	>4.0	1.0–4.0	4.0–7.0
Halostachyscaspica	<1.6	1.0–2.5	3.0–5.0
Halimodendronhalodendron	1.0–3.0	2.0–4.0	4.0–6.0
Poacynumhendersonii	2.0–3.0	1.5–4.0	4.0–6.0
Kareliniacaspica	>3.0	1.0–3.0	4.0–7.0
Elaeagnusangustifolia	0.5–2.5	1.0–4.0	5.0–8.0
Halocnemumstrobiaceum	1.0–2.0	1.0–2.5	3.0–5.0

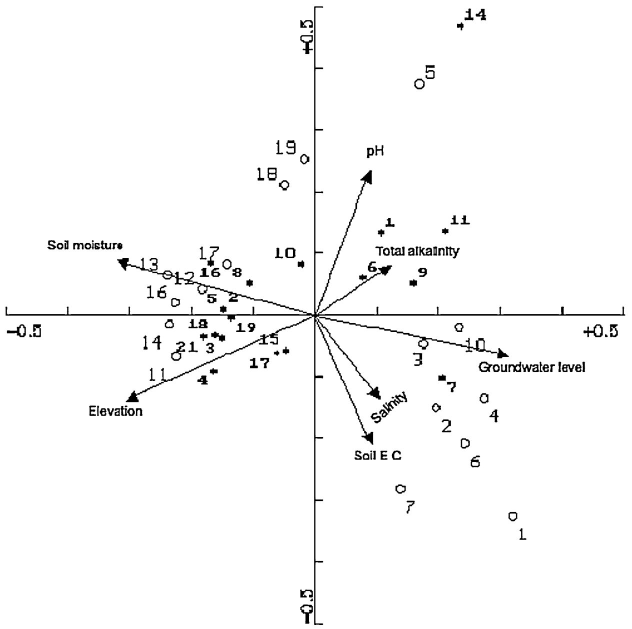

Fig. 4 DCCA ordination between vegetation distribution and environmental variables. The vectors represent environmental variables. The length of the vector is proportional to its importance, and the angle between two vectors reflects the degree of correlation between the two variables. The angle between a vector and each axis reflects the importance of the environmental variable to vegetation distribution. The numbers represent the vegetation samples. The abbreviations of "Soil E C" means soil electric conductance

We found that average vegetation cover was significantly correlated with average depth to the water table (2000–2005) (Fig. 5). Vegetation cover averaged approximately 15 % at groundwater depths between 3 and 5 m and 7 % at groundwater depths between 7 and 9 m.

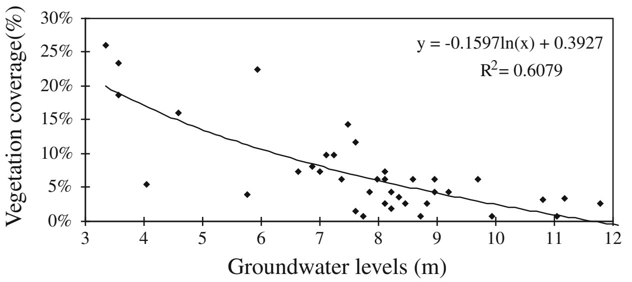

Fig. 5 Regression of vegetation coverage and groundwater level at the nine transects in the lower reaches of the Tarim River after (2005) the initial 5-year period of water discharges

Characteristics of tree physiology and soil properties

The crown size of *P. euphratica* trees significantly increased during the study period. The crown size of *P. euphratica* when averaged across all sites doubled by 2005 from an initial value of about 5 m^2. The change in the crown size of *P. euphratica* was greatest for trees located nearest to the river bank and became progressively less with increasing distance (Fig. 6). There was no significant difference in crown sizes between 2000 and 2005 for trees located more than 700 m away from the river.

We found new *P. euphratica* seedlings in some vegetation plots that were located close to the river channel after recharges (data not shown). They were found exclusively under the crowns of older *P. euphratica* trees, normally in densities of 1–5 seedlings per adult tree.

Discussion

The most important and difficult issue in conserving the biological value of inland rivers are the assurance of flow. However, the majority of the rivers in the world have been desiccated or progressively depleted (Nilsson et al. 2005a). Water flow in the lower reaches of the Tarim River, the longest inland river in the world, was virtually stopped decades ago to meet irrigation needs. In the early 1960s, China's government implemented an ambitious plan for agricultural development in the Tarim Basin; and vast reclamation projects were undertaken in conjunction with the construction of many dams in the upper reaches of the Tarim River. Settlement of large numbers of immigrants from outside of the region resulted in rapid agricultural development and diversion of freshwater to newly reclaimed crop lands. However, poor agricultural management soon led to severe environmental degradation in the whole Tarim Basin. Construction of Daxihaizi Reservoir in 1972 disrupted much of the stream flow in the river, resulting in the absence of surface water for a stretch of 300 km and the drying up of the two lakes, Lake Lop Nur

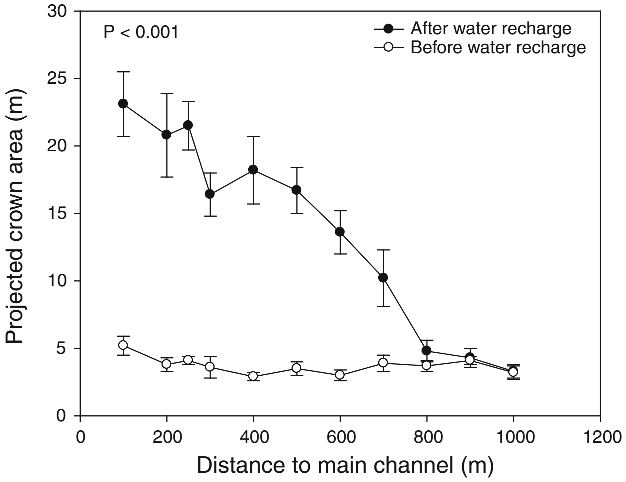

Fig. 6 Effect of distance from the river bank on the average projected crown area of *P. euphratica* before (2000) and 5 years after (2005) the start of the water release program along the lower reaches of the Tarim River. The *P* values represented a significant difference between before and after water recharges using a paired t-text. *Error bars* are ±1 standard error of the mean

and Lake Taitema, at the terminal of the Tarim River (Chen et al. 2003). Groundwater levels dropped from 3–5 m to 8–12 m below the ground surface (Tang and Zhang 2001). Some herbaceous plants such as *Phragmites communis*, *Poacynum hendersonii,* and *Alhagi sparsiforlia* became extinct in the region, and the distributions of *Tamarix* spp. and *P. euphratica* experienced a large-scale decline.

Our finding that species diversity did not increase significantly in the wake of the water discharge program indicated that the restoration of riparian ecosystems in arid regions might need more time than 6 years of continuous water supply to recover. One reason for the lack of response was probably the loss of the soil seed banks for herbaceous and shrub species that existed before the river dried up. Sheep grazing could be another reason that we did not find seedlings of other species. Although water discharged into the lower reaches of the Tarim River has facilitated recovery of *P. euphratica* and *Tamarix* spp. populations, it was insufficient to recover biodiversity of the larger degraded plant communities, especially herbaceous and shrub components.

However, our findings that the total vegetation coverage and the crown size of *P. euphratica* significantly increased after water again flowed in the river indicate that the physical environmental conditions, such as soil moisture and temperatures under tree canopies, might be again favorable for growth of shrubs and herbs. If that is true, then species diversity might eventually increase in the course of natural succession. Most plants in the region of the Tarim Basin rely heavily on their physical environments and the interdependencies among herbs, shrubs, and trees (Huang 1993; Liu and Chen 2002). Therefore, increases in vegetation cover should foreshadow the return of displaced herbaceous and shrub species and an attendant increase in species diversity. Although our study plots initially lacked tree seedlings, 5 years after the rehabilitation program began, seedlings were found as far as 50-m distance from the river (unpublished data). This regeneration was possible because the water table had risen to within 2–4 m of the ground surface (unpublished data).

In arid ecosystems, ecological processes such as soil development, plant growth and vegetation recovery, and biodiversity and organism abundance are mainly based on the dynamics of the ground water levels. Therefore, any marked lowering of ground water levels could significantly reduce the total area of wetlands such as rivers, lakes, ponds, and marshes and also change wetland spatial patterns. Groundwater levels played a dominant role in determining ecosystem structure and function in the lower reaches of the Tarim River (Chen et al. 2006a, b), and the groundwater level is the constraining factor for riparian ecosystem restoration (Hou et al. 2007). Our findings supported the above statements.

The results showed that ground water level and soil moisture have opposite effects in DCCA analysis. On the one hand, plants use a lot of water to maintain growth and reproduction and decreases in soil moisture should have negative impacts. On the other hand, because plant roots can reach the water table when it is high, plant growth and reproduction might be maintained independent of soil moisture levels found closer to the soil surface. For example, increased groundwater levels not only facilitated the rehabilitation of *P. euphratica* and *Tamarix* communities in this study, but also facilitated the recovery of wildlife habitats because of the increased wetlands after increasing groundwater levels (Zhao et al. 2009). Wetlands are of particular importance to arid ecosystems because of their unique ecological roles in biodiversity conservation and oasis development (Zhou et al. 2006). Plants and animals that are dependent upon temporary wetlands have adapted to live in such extreme environmental conditions. Water birds are able to use the patches of unpredictably filled wetlands, and invertebrates are capable of withstanding long dry periods. Therefore, assessing the dynamics of groundwater levels and using them properly in *P. hendersonii* agricultural practice and management are vital issues for developing effective restoration strategies in riparian systems in arid regions.

Our findings were consistent with those of Puckridge et al. (1998) and Kingsford et al. (2004): flow regime is the most important factor regulating wetland habitats along arid zone rivers. The variable and unpredictable water flow along the Tarim River affected the spatial distribution patterns of wetlands throughout its history. Jansson et al.

(2000) also reported that free-flowing rivers had higher plant species diversity than regulated rivers.

To maximize the effects of water recharge on species diversity, two methods of water recharge have been suggested recently (Chen et al. 2006a, b)—“double-river-channel” and “overflow” conveyances. By doing so, the surface water overflow supply benefits the germination and stabilization of plant seeds. Stream-water conveyance should be timed to coincide with seed maturation to enhance germination success and other ecological benefits of water recharge. However, these methods become less effective with increasing distance downstream, because the volume of water needed to equally recharge the entire length of the river exceeds the amount available for that purpose: the limited water supply must be allocated among various competing uses.

Even under the current trial regime of water recharge, there has been a debate about costs and benefits. Water released downstream is not available to convert hundreds of hectares of arid land to productive farmland. Some groups believe that the millions of tons of discharged water lost by evaporation and evapotranspiration during the water conveyance are a complete waste. The value of ecosystem services is not appreciated or understood. Consequently, restoration of arid riparian ecosystems faces an uphill battle not only in the Tarim Basin of western China, but also elsewhere where water resources are limited and competing demands are strong.

Implications for practice

- Groundwater levels of downstream riparian areas can increase rapidly after water discharges from upper dams, and plant species whose survival and growth heavily depend upon groundwater, such as *P. euphratica* respond positively.
- The water recharge program needs to be continued longer than 6 years if partial recovery of pre-dam riparian plant species diversity is desired. More time is needed to allow for natural succession to re-establish self-sustaining populations of the herb and shrub species lost when the riverway dried up.
- Water recharge increased the size of *P. euphratica* tree crowns, although we did not find a significant change in their basal area.
- Apportioning limited water supplies among competing uses continues to be a challenge in arid regions. Strategies for water distribution greatly depend upon the needs of local human populations, economics, agricultural practices, and specific natural conditions. To develop good water allocation strategies, well-founded knowledge of socio-economic and natural environments is required, and social and physical scientists can contribute to designing such a strategy. Lastly, water management needs to ensure implementation of water use plans and strict compliance with water laws.

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