Ground-water level affects plant species diversity along the lower reaches of the Tarim river, Western China

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Abstract

We examined the relationship between plant species diversity and ground-water level in the lower reaches of the Tarim River, western China, by analysing the field data from 40 monitoring wells across nine study sites and 18 vegetation survey plots during the period from 2000 to 2002. We found that several of the species diversity indices were closely related to ground-water level, suggesting that the ground-water level played a dominant role in determining plant species diversity in the lower reaches of the Tarim River. The ground-water level was low in the lower reaches of the Tarim River, and displayed a descending gradient from the upper to the lower reaches. The low ground-water level was apparently one of the major attributes to the low plant species diversity; the Shannon–Weiner index was found to vary in a range from 0.53 to 1.93, and the Simpson index from 0.35 to 0.82. Plant species became less diverse, the structure of plant communities became simpler, and the diversity and abundance indices of the plant species decreased moving from the upper to the lower reaches of the Tarim River, corresponding to declining ground-water level. Our results indicated severe impacts of water stress on ecosystems of this arid region due to low ground-water level and scarce rainfall.

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Keywords: Community structure; Ground-water; Species diversity; Tarim River; Water stress

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1. Introduction

Species diversity, which is defined by the biodiversity of species and their aggregations, is closely related to the ecosystems stability (Pimm, 1984; Tilman and Downing, 1994; McNaughton, 1997; Tilman, 2000). Studies on species diversity have mostly been focused on the changes in species quantity and the degree of biodiversity, including pattern, formation, and regulations of the small- and large-scale temporal and spatial changes in species richness, abundance, and distributions (Zhou et al., 2000). Information on species diversity is of great importance to understand the composition, changes, and development of plant communities, as well as to understand the structural and functional stability of ecosystems. Many studies have found changes of species diversity with elevation (e.g. Whittaker and Niering, 1975; Alatalo, 1981; Baruch, 1984; Daubenmire and Daubenmire, 1968; Currie and Paquin, 1987; Wilson et al., 1990; Itow, 1991; Xie and Chen, 1994; He and Chen, 1997) and water availability (e.g. Monk, 1967; Auclair and Goff, 1971; Thalen, 1971; Gentry and Dodson, 1987). However, information is still lacking on the relationship between ground-water and species diversity, especially for the arid regions in western China.

The ecosystems in western China are extremely vulnerable to disturbances and habitat degradation due to severe lack of water resources. The intensified confrontation between environmental protection and economic development of the region has been inevitable as a result of exploitation and utilization of the limited water resources for the local economic activities on one hand, and great concerns for the deteriorating regional environment on another. Sustainable development of the regional socio-economy, therefore, has been seriously constrained. One particular area for such concern is the Tarim River in the south of the Uyghyr Autonomous Region of Xinjiang, western China. The Tarim River is the longest arid and intra-continental river in the world (Fig. 1). It runs eastward across the northern rim of the Taklamakan Desert, with the mainstream measuring 1321 km in length. Human activities related to the exploitation of water resources during the past five decades have led to significant changes to the natural ecological processes along the Tarim River, especially the lower reaches from the Daxihaizi Reservoir to the Lake Taitema between the Taklamakan and the Kuruk deserts (Chen, 1999; Ma et al., 2000; Liu and Chen, 2002).

In the early 1960s, the Chinese government implemented an ambitious plan for agricultural development in Xinjiang, 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 migrants from outside of the region resulted in rapid development of agricultural projects and diversion of freshwater to newly reclaimed land for crop production. However, poor management practices soon led to severe environmental degradation at the early stages of the land reclamation in the Tarim River basin and its adjacent areas. Water flow in the mainstream of the Tarim River had been reduced substantially since the 1960s. For example, the water flow at the Qiala Station in the lower reaches of the Tarim River dropped by 80% in 40 years, decreasing from 1353 million cubic meters (MCM) in the 1960s to 267 MCM in the 1990s. Associated with the decreasing water flow was the declining vegetation coverage and intensified desertification: the forested areas decreased by 2000 km² and the grassland by 8500 km² since the 1950s, whereas the area affected by desertification increased from 1371 km² in 1959 to 1494 km² in 1996 (Deng et al., 2001). The problems were further exacerbated by deforestation and irrigation-induced salinity, resulting in considerable economic losses.
Construction of the Daxihaizi Reservoir in 1972 disrupted much of the stream-flow in the Tarim River, resulting in absence of surface water for a stretch of 321 km and dropping ground-water level in the lower reaches. Two lakes at the terminal of the Tarim River, the Lop Nur and the Lake Taitema, dried up in 1970 and 1972, respectively. The ground-water level dropped from between 3–5 m to 8–12 m below the ground surface over the past three decades (Chen, 1998; Tang and Zhang, 2001; Chen et al., 2003a, b, c). The dropping ground-water level resulted in marked changes in the community structures of plant and species composition. Some herbaceous plants such as *Phragmites communis*, *Poacynum hendersonii*, and *Alhagi sparsifolia* became extinct from the region, whereas distributions of *Tamarix* spp. and *Populus euphratica* experienced a large-scale decline (Liu and Chen, 2002). The severely reduced stream-flow in the lower reaches of the Tarim River led to intensified desertification and damages to the ecosystems along the riverbank, and greatly reduced the area of a so-called ‘Green Corridor’ between the Taklamakan and the Kuruk deserts. The National Highway No. 218 running through the ‘Green Corridor’ suffered from increased drifting sands. The lower reaches of the Tarim River became one of the regions with most severe problems caused by exploitation of water resources in western China.

The increasingly deteriorating environment, and ecosystem structure and function in the lower reaches of the Tarim River have caused great concerns locally and among the international communities. The central government of China committed a total of $10.7 \times 10^9$ yuan (RMB) for implementation of an emergency project conveying water to the Tarim River (artificial water-recharge, or so-called ecological watering) to raise the
ground-water to a level suitable for sustaining the growth of the local vegetation, therefore protecting the ‘Green Corridor’ and restoring the severely degraded ecosystems in the lower reaches of the Tarim River.

Previous studies on the Tarim River were mainly from the perspectives of changes in water resources (Ji, 1998; Li, 1998). Some researches have also been conducted to determine relationships between the regional economic development and ecological consequences concerning exploitation of water resources (Ma and Gao, 1997; Ma et al., 2000). However, the responses of vegetation to the changing water levels of the Tarim River have not been fully evaluated. Based on data from the field investigations between 2000 and 2002 (before and after the water conveyance to the Tarim River), we analysed the relationship between ground-water level and plant species diversity, and examined how the variation in ground-water level would affect the ecosystem structure and function. Our study was conducted in order to provide scientific information useful for restoring damaged ecosystems in the lower reaches of the Tarim River.

2. Materials and methods

2.1. Study area

The Tarim River basin, with an area of 1,020,000 km², covers the entire southern part of Xinjiang in western China. The main catchment is 1321 km long and covers an area of 17,600 km². The region is extremely arid with annual precipitation less than 50 mm, but potential evaporation more than 2000 mm per annum. The surface- and ground-water in the study area are far below the annual demand of 4.6 MCM for the regional agricultural and social activities. Hydrologically, the Tarim River basin represents a closed-loop catchment linked to several tributaries. The main catchment of the Tarim River basin is behind the confluence of the Hetian, Yarkand, and Akesu rivers. It is a unique freshwater ecosystem near one of the largest deserts in the world, the Taklamagan Desert.

Our study focused on the lower reaches of the Tarim River between the Taklamakan and the Kuruke deserts. The dry environmental conditions are responsible for the fragility and instability of the ecosystems in the area. The drainage basin is flat. Total annual solar radiation varies between 5692 and 6360 MJ m⁻², with cumulative daylight hours ranging from 2780 to 2980. Annual accumulative temperature ≥ 10 °C varies between 4040 and 4300 °C, with the average diurnal temperature ranging from 13 to 17 °C. Annual precipitation is averaged less than 50 mm, but potential annual evaporation is estimated in a range between 2500 and 3000 mm. Major plant species include *Populus euphratica*, *Tamarix ramosissima*, *T. hispida*, *Lycium ruthenicum*, *Phragmites communis*, *Alhagi sparsifolia*, *Apocynum venetum*, *Karelinia caspica*, and *Glycyrrhiza inflata*.

Nine study sites were established for monitoring ground-water level between the Daxihaizi Reservoir and the Lake Tetima, at an interval ca. 20–45 km (Figs. 1 and 2): Akdun, Yahepu, Yinsu, Abudali, Kardayi, Tugmailai, Alagan, Yiganbjima, and Kaokan. On each site, ground-water monitoring wells (varied between 8 and 17 m in depth) was installed along a transect perpendicular to the river. In this study, we used data from five sites based on the types of plant communities and species, and established 18 plots for studying plant species diversity. The measurement plots were along the same transects as the monitoring wells, with adjacent plots at between 100 and 200 m apart.
2.2. Biological measurements

We measured plant species composition and abundance, vegetation coverage, plant height, and diameter at breast height of trees, on plots of variable sizes based on types of plant community and life-forms: 5 × 5 m for herbage, 30 × 30 m for arbor/shrubs, and 50 × 50 m for mixed communities of arbor, shrubs, and herbage. Water and soil samples were collected and analysed using the standard procedures. Because the vegetation at the Akdun near the Daxihaizi Reservoir was saline meadow and affected largely by human activities, the site was omitted from our analysis. Table 1 lists the most abundant plant species on our study sites.

2.3. Assessment of plant species diversity

Plant species diversity can be assessed by measuring the abundance and uniformity of species in the plant communities or habitats. The species abundance refers to the quantity of species in a community or habitat, while the species uniformity refers to the distribution

Table 1
The common plant species in the lower reaches of the Tarim River, western China

<table>
<thead>
<tr>
<th>Code</th>
<th>Species</th>
<th>Code</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td><em>Populus euphratica</em></td>
<td>10</td>
<td><em>Karelinia caspica</em></td>
</tr>
<tr>
<td>02</td>
<td><em>Tamarix ramosissima</em></td>
<td>11</td>
<td><em>Salvia sp.</em></td>
</tr>
<tr>
<td>03</td>
<td><em>T. hispida</em></td>
<td>12</td>
<td><em>Halostachys caspica</em></td>
</tr>
<tr>
<td>04</td>
<td><em>Lycium ruthenicum</em></td>
<td>13</td>
<td><em>Salvia rutenica</em></td>
</tr>
<tr>
<td>05</td>
<td><em>Halimodendron halodendron</em></td>
<td>14</td>
<td><em>Hexinia polydichotoma</em></td>
</tr>
<tr>
<td>06</td>
<td><em>Phragmites communis</em></td>
<td>15</td>
<td><em>Scorzonera sp.</em></td>
</tr>
<tr>
<td>07</td>
<td><em>Alhagi sparsifolia</em></td>
<td>16</td>
<td><em>Taraxacum sp.</em></td>
</tr>
<tr>
<td>08</td>
<td><em>Glycyrrhiza inflata</em></td>
<td>17</td>
<td><em>Kochia prostrata</em></td>
</tr>
<tr>
<td>09</td>
<td><em>Apocynum venetum</em></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Locations of the nine study sites along the lower reaches of the Tarim River, western China, for monitoring ground-water level.
of individuals of all species in a community or habitat. The species diversity index is a composite index of the abundance and uniformity.

The importance value, \( V_i \), which is a synthetic index for denoting the status and function of a species in a community, was calculated as

\[
V_i = C_r + D_r + H_r,
\]

where \( C_r \) is the relative coverage, \( D_r \) the relative density, and \( H_r \) the relative height of plants.

We calculated the commonly used species diversity indices (i.e. Shannon–Weiner index and Simpson index), species richness indices (i.e. Margalef index and Menhinik index), and species distribution indices (i.e. JSW and JSI indices) using the following formula (Simpson, 1949; Margalef, 1958; Whittaker, 1972; Ludwig and Reynolds, 1988):

- Shannon–Weiner index: \( H = - \sum_{i=1}^{n} p_i \ln p_i \),

- Simpson index: \( D = 1 - \sum_{i=1}^{n} p_i^2 \),

- Margalef index: \( d_M = (S - 1)/\ln N \),

- Menhinick index: \( D = S/\sqrt{N} \),

- Pielou index 1: \( JSW = \left( - \sum_{i=1}^{n} p_i \ln p_i \right) / \ln S \),

- Pielou index 2: \( JSI = \left( 1 - \sum_{i=1}^{n} p_i^2 \right) / (1 - 1/S) \),

where \( p_i \) is the relative importance value of the species \( i \), \( N \) the sum of the importance values of all species on a plot where species \( i \) is found, and \( S \) the total number of species.

3. Results

3.1. Ground-water level

During the period from 2000 to 2002, four intermittent artificial water recharges to the lower reaches of the Tarim River were implemented (Table 2). By December 2002, a total

<table>
<thead>
<tr>
<th>Water delivery</th>
<th>First</th>
<th>Second</th>
<th>Third</th>
<th>Fourth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting (y/m/d)</td>
<td>2000/05/14</td>
<td>2000/11/03</td>
<td>2001/04/01</td>
<td>2001/09/12</td>
</tr>
<tr>
<td>Ending (y/m/d)</td>
<td>2000/07/13</td>
<td>2001/02/14</td>
<td>2001/07/06</td>
<td>2001/11/17</td>
</tr>
<tr>
<td>Volume (×10^6 m^3)</td>
<td>98.83</td>
<td>220.00</td>
<td>184.00</td>
<td>197.00</td>
</tr>
</tbody>
</table>
of 1000 MCM water were conveyed over a period of 439 days. The first water recharge, at about 100 MCM, reached the vicinity of the Kardayi section; the second water recharge, at about 220 MCM, traveled to 146 km downstream from the Alagan site. The third and fourth water recharges brought the water to the terminal of the Tarim River, the Lake Taitema. After the third water recharge in November 2001, the coverage of water in the Lake Taitema basin was 4.5 km$^2$, and increased to 16 km$^2$ following the fourth water recharge in November 2002 (data from Chen et al., 2003a, b, c).

The implementation of artificial water recharges increased ground-water levels along the river channel, but the effect became less further away from the water source (Fig. 3); the ground-water level rose the most, up 84%, at the Akdun site 20 km downstream from the Daxihaizi Reservoir, and the least, only 8%, at the Kaogan site. The water recharges also increased the transverse response of ground-water level on both sides of the river channel; the affected distance perpendicular to the river channel increased from 450 m after the first water recharge to 1050 m after the fourth (Fig. 4). Changes in the ground-water level during and after the water recharges were most apparent within 250 m along both sides of the river channel. Beyond 750 m, the ground-water level was only slightly affected.

We found that changes in the ground-water level were related to both the duration of water recharges and the water volumes conveyed. At the Yinsu site, for example, the ground-water level rose progressively corresponding to the four water recharges from May 2000 to November 2002 (Fig. 5; measured at an observation well 150 m from the river channel); the ground-water level rose from $-9.87$ m (negative sign indicates depth relative to ground surface) before the initiation of water recharge to $-7.74$, $-3.79$, $-3.61$ and $-3.16$ m, respectively, following each water recharge.
3.2. Temporal and spatial sequences of the change in plant species diversity

Changes in plant species diversity were clearly related to the changes in ground-water level along the river. In the early 1950s, the *Populus euphratica* forests were densely...
distributed along the riverbanks of the Tarim, Nashen, and Qiwenkor rivers between south of Qiala and north of Alagan. The forests extended 7–10 km from the riverbanks. Many plant species such as *Populus euphratica*, *T. chinensis*, *Phragmites communis* were distributed in corridor-shaped patterns when the rivers were periodically recharged from flooding. The establishment of state farms since 1958 resulted in continuous expansion of reclaimed farmlands, causing increased water diversion from the rivers. This led to reduced water for maintaining the health of the regional vegetation, and contributed to overall degeneration of ecological environment. Construction of the Daxihaizi Reservoir in the 1970s disrupted the stream-flow downstream from the Tikanlik, causing the retreat of river tail. Under conditions without any surface water flow, the ground-water level dropped sharply, from a depth of 3–5 m in the period of the 1950s–1960s to 8–12 m in 2000 over much of the region (Fig. 6). The duration of stream-flow cut-off became longer and the ground-water level dropped lower towards the lower reaches (Table 3). Natural vegetation relying on ground-water was placed under great threat, especially in the area downstream from the Alagan.

The plant species composition and the spatial structure of the plant communities changed under conditions of gradually decreasing ground-water level from the upper to the lower reaches. On the Yahepumahan and Yinsu sites of the upper reaches, ground-water level was in a range between 6.35 and 8.34 m. *Populus euphratica* was a dominant tree species, and shrubs were composed of *T. ramosissiama*, *T. hispida*, *L. ruthenicum* and *Halimodendron halodendron*. Herbs consisted mainly of *Glycyrrhiza uralensis*, *Apocynum venetum*, *Athagi pseudathagi*, *Phragmites communis*. On the Abudali and Kardayi sites of the middle reaches, ground-water depth dropped to 8.41–9.16 m; vegetation was dominated by *Populus euphratica* and *T. chinensis*, with *L. ruthenicum* and *H. halodendron*

![Groundwater level changes](image_url)
being companion species. Because of the low ground-water level, herbs were sparse, with almost no other herbs except the occasionally occurring *Athagi pseudathagi* that has long and penetrating roots. Much of the vegetation was in a degenerate state, dominated by *T. chinensis* and degenerate forests of *Populus euphratica*. On the Alagan and Yiganbjima sites of the lower reaches, the ground-water level was lower than 10 m below the ground surface; the vegetation was in an extremely degenerate state; three types of the plant communities existed: *Populus euphratica*, *T. chinensis*, and mixture of *Populus euphratica* and *T. chinensis*. The *Populus euphratica* forests were in a severely degenerate state. With decreasing ground-water level from the upper to the lower reaches, the vegetation displayed a clear trend of decreasing types and quantities of the plant communities; the structure of the plant communities became simpler; the species diversity indices were considerably reduced. There was also a clear trend of decreasing species composition with increasing distance from the river channel (Table 4).

<table>
<thead>
<tr>
<th>Period</th>
<th>Qiala Station</th>
<th>Tikanlik</th>
<th>Alagan</th>
<th>Luobu village</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tarim</td>
<td>Kongque</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1951–1960</td>
<td>1353</td>
<td>0</td>
<td>1353</td>
<td>900–800</td>
</tr>
<tr>
<td>1961–1970</td>
<td>1138</td>
<td>0</td>
<td>1138</td>
<td>288</td>
</tr>
<tr>
<td>1971–1980</td>
<td>669</td>
<td>100</td>
<td>769</td>
<td>47</td>
</tr>
<tr>
<td>1981–1990</td>
<td>392</td>
<td>201</td>
<td>593</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 3
Water volume (×10⁶ m³) at four observational stations in the lower reaches of the Tarim River between 1950s and 1990s

Table 4
Zonal species composition in study area

<table>
<thead>
<tr>
<th>Species</th>
<th>Distance from riverbed (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td><em>Populus euphratica</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Tamarix L.</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Lycium ruthenicum</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Alhagi sparsifolia</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Glycyrrhiza inflata</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Apocynum venetum</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Phragmites communis</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Cynanchum sibiricum</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Halostachys caspica</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Sophora alopecuroides</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Scorzonera sp.</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Salsola sp.</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Karelinia caspica</em></td>
<td>+</td>
</tr>
<tr>
<td><em>Halimodendron halodendron</em></td>
<td>+</td>
</tr>
</tbody>
</table>
3.3. Plant species diversity

Low levels of plant species diversity were found for the five study sites: the Shannon–Weiner index was in a range between 0.53 and 1.93; whilst the Simpson, abundance (Margelef index), and Menhinick indices ranged 0.35–0.81, 0.91–7.28 and 1.15–5.20, respectively. There were apparent trends of decreasing values in the above indices with the decreasing ground-water level from the upper to the lower reaches of the Tarim River (Fig. 7a and b).

For the uniformity indices across the five sites, the JSW index varied from 0.76 to 0.91, and the JSI index from 0.69 to 0.94. There was no apparent trend in the species uniformity.
indices across the study sites except the Yiganbjima. The species uniformity index for the Yiganbjima site was low compared to other sites (Fig. 7c) as only two species, i.e. *Populus euphratica* and *T. chinensis*, were found there.

Overall, the plant species diversity indices decreased from the upper to the lower reaches consistent with decreasing ground-water level (Table 5).

### 4. Discussion

Ecosystems in arid regions are structurally and functionally fragile, and are therefore more susceptible to changes in environmental conditions than those in mesic habitats. Because of severe water limitation, any change in ground-water level will likely affect plant growth, community structure, plant species diversity, and ecosystem succession in arid regions, which in turn would affect the environmental conditions (Wassen et al., 1989, 1990; Rey Benayas et al., 1990; Ross et al., 1994; Stromberg et al., 1996; Lammerts et al., 2001; Munoz-Reinoso, 2001).

The impact of physical environment on the survival and succession of plant communities in the lower reaches of the Tarim River is obviously stronger than that of the biological factors (Huang, 1993; Liu and Chen, 2002). Most plants in the region rely heavily on the physical environment for their survival; the interdependence among herbs, shrubs and arbors is weak. The abundance and uniformity of plants are low along the lower reaches of the Tarim River due to the long-term stream-flow cut-off and the consequent degeneration of the ecosystems. The levels of plant species diversity indices are much lower in the lower reaches of the Tarim River compared with many other regions of China, reflecting the vulnerable ecological environment in this extremely arid area (Table 6).

Our study draws attention to the following issues:

1. Natural vegetation in the lower reaches of the Tarim River has degenerated and even died in large areas due to the considerable drop of ground-water level caused by damming and exploitation of water resources for farmlands, which disrupt at times many ecological processes. For example, the productivity, decomposition, and stability of the local ecosystems were reduced; the structure of plant communities was simplified. Most of the plant communities are now composed of species with strong capability of salt- and drought-tolerance, such as *Populus euphratica*, *T. chinensis* and *Athagi pseudathagi*. Plant species diversity of the region has been greatly reduced.

2. The ground-water level played a dominant role in determining the plant species diversity in the lower reaches of the Tarim River. With increasing distance from the

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**Table 5**
The changes of groundwater level and plant species diversity in the lower reaches of the Tarim River

<table>
<thead>
<tr>
<th>Section</th>
<th>Groundwater depth (m)</th>
<th>Shannon–Weiner index</th>
<th>Simpson index</th>
<th>Margalef index</th>
<th>Menhinick index</th>
<th>JSW index</th>
<th>JSI index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yinsu</td>
<td>4.98</td>
<td>1.93</td>
<td>0.82</td>
<td>7.28</td>
<td>5.2</td>
<td>0.88</td>
<td>0.93</td>
</tr>
<tr>
<td>Abudali</td>
<td>5.10</td>
<td>1.86</td>
<td>0.82</td>
<td>6.37</td>
<td>4.62</td>
<td>0.89</td>
<td>0.94</td>
</tr>
<tr>
<td>Kardayi</td>
<td>6.19</td>
<td>1.78</td>
<td>0.81</td>
<td>6.37</td>
<td>4.62</td>
<td>0.86</td>
<td>0.93</td>
</tr>
<tr>
<td>Alagan</td>
<td>8.72</td>
<td>1.26</td>
<td>0.7</td>
<td>2.73</td>
<td>2.31</td>
<td>0.91</td>
<td>0.93</td>
</tr>
<tr>
<td>Yiganbjima</td>
<td>9.29</td>
<td>0.53</td>
<td>0.35</td>
<td>0.91</td>
<td>1.15</td>
<td>0.76</td>
<td>0.69</td>
</tr>
</tbody>
</table>
water source and from the river channel, the ground-water level decreased, plant species number was reduced, and the structure of plant communities was simplified. The degeneration of ecosystems became more severe towards the lower reaches from the Yinsu to the Yiganbjima.

(3) In the reverse succession of plant communities, the environment and the plant communities are in a dynamical exchange between selecting and selected state. The continued declining of ground-water level resulted in the degeneration of the plant communities in the order of herbs → shrubs → trees due to the long-term stream-flow cut-off. However, some plants can adapt ecologically to the environmental changes. For example, *Populus euphratica* has two strategies for reproduction: (a) sexual reproduction through seeds, and (b) vegetative reproduction through roots. Currently, there is almost no possibility of seed reproduction under the prevailing conditions of extremely low soil water. For *Phragmites communis*, it has three ecological types, i.e. the tall growth-form, the short growth-form, and the creeping growth-form depending on the habitats. The growth of *Athagi pseudathagi* relies on its long roots; the roots grow up to about 10 m in length, and have a strong regenerating capability. *T. chinensis* too has strong ecological adaptability: with dropping ground-water level, it evolves towards a super-xeric desert type, whereas it develops towards a halophilous desert type if the ground-water level rises and salinity becomes more severe.

(4) The artificial water recharges to the lower reaches of the Tarim River facilitated the rehabilitation of *Populus euphratica* community and *Tamarix* community by raising the ground-water level. However, the four artificial water recharges from 2000 to 2002 were far from sufficient for rehabilitating the degraded plant communities, as exhibited by decreasing plant species diversity downstream and further away from the river channel.

(5) The artificial water recharge to the lower reaches of the Tarim River was implemented for the purpose of improving ecological conditions of the region. However, the current regime is only effective to the natural vegetation within the relatively short distance from the river channel, which is difficult to rehabilitate and maintain ecosystem stability at a larger spatial scale. Most of the *Populus euphratica* forests are now in their
mature stage. The sandy lands between the forests are in active motion, therefore difficult for regeneration of herbs in large areas by stream-water conveyances in a linear way along the natural river channel.

For effective rehabilitation of ecosystem stability at a larger scale in the lower reaches of the Tarim River, we suggest that the future artificial water recharge be implemented by a ‘double-river-channel’ conveyance concept and the surface water supply by an overflow concept. By doing so the surface water overflow supply would benefit the fixation and germination of plant seeds. Coincidence between the timing of the seed maturity and the timing of the stream-water conveyances should be considered to ascertain germination success of plant seeds, therefore enhancing the ecological benefits of the stream-water conveyances.

In summary, our study demonstrated the significance of ground-water level to plant species diversity and ecosystem stability in arid environment and the effectiveness of the artificial water recharges to raise ground-water level as means to restore the severely degenerate vegetation in the lower reaches of the Tarim River in western China.

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