Postprint: Root Sucker Propagation Characteristics of Populus euphratica under Root Cutting Treatment in Different Irrigation Regimes

Authors: Wang Zikang

Date: 2022-09-26T00:00:00+00:00

Abstract

To consolidate the effectiveness of water conveyance in the lower reaches of the Tarim River, appropriate irrigation methods combined with root-cutting and sprouting techniques are required to promote the regeneration and rejuvenation of Populus euphratica forests and ecological restoration in downstream areas. Previous studies have rarely integrated different irrigation regimes with the ecological restoration effects of root-cutting and sprouting. Therefore, based on topographic characteristics, the study area was divided into three zones (A1, A2, and A3). Following trenching and root cutting in the study area, four irrigation regimes were established according to varying irrigation intervals, durations, and water volumes: a control group (natural conditions without irrigation, F1); an irrigation interval of 11 d, water volume of 6 m3 per 10 m of root-cutting trench, and irrigation duration of 2 d (F2); an irrigation interval of 23 d, water volume of 7 m3 per 10 m of root-cutting trench, and irrigation duration of 3 d (F3); and an irrigation interval of 33 d, water volume of 8 m3 per 10 m of root-cutting trench, and irrigation duration of 4 d (F4). The sprouting regeneration of Populus euphratica under different irrigation treatments was investigated. The results demonstrated: (1) The sprouting capacity of distal roots was superior to that of proximal roots, with sprouting rates of distal roots in zones A1, A2, and A3 being 70.7%, 77.1%, and 64.1%, respectively. The distance from sprouting points to the root cut surface was concentrated in the range of 1-16 cm; the distance between sprouting points and the mother tree was concentrated in the range of 5.5-7 m; the distribution depth of sprouting roots was concentrated in the range of 30-50 cm; and the diameter of sprouting roots was concentrated in the range of 0.4-0.7 cm. (2) Based on the number of Populus euphratica root suckers, the suitable soil temperature and water content ranges for root sprouting were determined to be 26.5-28.1 ℃ and 10.6%-13.1%, respectively. The optimal irrigation regime for Populus euphratica root sprouting was an irrigation interval of 23 d, water volume of 7 m3 per 10 m of root-cutting trench, and irrigation duration of 3 d (F3). These research results can provide a reference for the regeneration and rejuvenation of Populus euphratica forests in the Tarim River basin.

Full Text

Abstract

To consolidate the ecological water transfer effects in the lower reaches of the Tarim River, appropriate irrigation methods combined with root-cutting and sprouting techniques are necessary to promote the regeneration and rejuvenation of Populus euphratica forests and ecological restoration downstream. Previous studies have rarely integrated different irrigation patterns with the ecological restoration effects of root-cutting and sprouting. Therefore, based on terrain characteristics, the study area was divided into three zones (A1, A2, A3). After trenching and root cutting, four irrigation modes were established according to different irrigation intervals, durations, and water quantities: a control group (F1) with no irrigation; F2 with an 11-day interval, 6 m^3 water per 10 m of trench, and 2-day duration; F3 with a 23-day interval, 7 m^3 water per 10 m of trench, and 3-day duration; and F4 with a 33-day interval, 8 m^3 water per 10 m of trench, and 4-day duration. The sprouting regeneration of P. euphratica was investigated under these different irrigation treatments.

Results showed that: (1) The germination capacity of distal roots was superior to proximal roots, with distal root sprouting rates of 70.7%, 77.1%, and 64.1% in zones A1, A2, and A3 respectively. (2) The distance between sprouting points and root-cut surfaces concentrated in the 1–16 cm range. The distance between root suckers and parent trees concentrated at 5.5–7 m, accounting for 70.7% of observations. (3) Sprouting root distribution depth concentrated at 30–50 cm, representing 77.1% of cases. Root diameter concentrated at 0.4–0.7 cm, accounting for 64.1% of measurements. Based on sprouting quantities, the optimal soil temperature and moisture content ranges for P. euphratica root sprouting were determined to be 26.5–28.1°C and 10.6%–13.1%, respectively. (4) According to root sucker characteristics, the most suitable irrigation mode was the 23-day interval with 7 m^3 water per 10 m trench and 3-day duration (F3). These findings provide reference for the regeneration and rejuvenation of P. euphratica forests in the Tarim River basin.

Keywords: Lower Tarim River; Populus euphratica forest; trench root cutting; root sucker; regeneration and rejuvenation

1 Introduction

The Tarim River, located in Xinjiang, is China’ s longest inland river. Populus euphratica, the typical species in the Tarim River basin, is the only tree species capable of forming independent forests in the arid desert regions of northwest China. The green corridor formed by P. euphratica forests blocks the convergence of the Kumtag and Taklamakan deserts. Since the 1970s, particularly after the construction of the Daxihaizi Reservoir in 1972, the 350 km river channel in the lower Tarim River dried up, causing a sharp reduction in P. euphratica forest area and forest degradation. To improve this critical ecological situation, ecological water transfer to the downstream channel of Daxihaizi Reservoir began in 2000, resulting in preliminary ecological improvement.

P. euphratica initially relies mainly on seed reproduction for population renewal. However, due to water resource scarcity and human activity impacts, sexual reproduction is limited, and most populations in China regenerate through clonal reproduction—root suckering. P. euphratica has strong root sprouting capacity, producing numerous root suckers under suitable environmental conditions. Studies show that flood irrigation and trench root cutting can promote root sprouting and create conditions for population renewal. The root system is the main carrier for P. euphratica root sprouting, with well-developed lateral roots that are mostly fine roots. Roots with sprouting capacity are typically fine roots without hard woodiness. When root diameter exceeds 1 cm, almost no sprouting occurs.

The proximal roots (connecting parent trees to suckers) and distal roots (far from parent trees) show significant morphological distribution differences. During early growth, root suckers have simple structures and cannot obtain nutrients independently, requiring proximal roots for nutrient uptake while expanding distal root distribution to acquire more resources. The distribution depth of sprouting roots varies by location, with P. euphratica root suckers concentrating on horizontal lateral roots within 40 cm of the soil surface. Current research on P. euphratica clonal reproduction focuses on sprouting, quantity, and relationships between traits and environmental factors, but lacks studies on root-cutting and sprouting effects under different irrigation methods.

This study employed different gradient irrigation methods after trench root cutting in the study area, investigating the quantity, growth status, and underground root characteristics of P. euphratica root suckers to understand basic characteristics of root sprouting reproduction after root cutting. The research identifies suitable soil temperature and moisture conditions, irrigation methods, and trench root cutting specifications for P. euphratica sprouting, which is significant for protection and restoration of P. euphratica forests in the lower Tarim River.

2 Study Area

The Tarim River basin (71°39 -93°45 E, 34°20 -43°39 N) is located in southern Xinjiang, adjacent to the Taklamakan Desert. As a typical arid inland river, it has a continental arid climate with average temperatures of 10.6–11.5°C. Annual precipitation is 10–50 mm in the source area and 80–200 mm in the main stream area. Desert riparian vegetation is dominated by P. euphratica and Tamarix ramosissima, with herbaceous plants including Phragmites australis, Alhagi sparsifolia, and Glycyrrhiza inflata.

The lower Tarim River is located in Ruoqiang and Yuli counties, Xinjiang, covering the 320 km section from Daxihaizi Reservoir to Lake Taitema, the most ecologically vulnerable area in the basin. After the river dried up, desert vegetation withered extensively and the ecosystem severely degraded. Since the 2000 ecological water transfer project, groundwater levels have risen and riparian vegetation and ecological environment have been restored. Due to river cutoff and ecological water transfer, the Tarim River has become both the most severely ecologically degraded area due to human disturbance and the most typical area for ecological restoration through human intervention.

The study selected a river section controlled by the Kunasite ecological gate in the lower Tarim River as the experimental area, located between the Qiwenkuoer River and the old Tarim River channel. This area has a water network composed of ecological gates, dams, and numerous channels, with concentrated P. euphratica distribution and strong spatial heterogeneity, making it ideal for experiments. Based on representative and consistent habitat conditions, three sample plots (A1, A2, A3) were selected according to terrain characteristics and adult tree distribution, with similar growth conditions of adult P. euphratica.

3 Methods

3.1 Trench Root Cutting

According to P. euphratica phenological characteristics, in early April before parent trees budded, suitable locations with good soil water retention and parent tree growth conditions were selected on sunny slopes. At 5-10 m from parent trees, 70-90 cm deep trenches were dug manually to cut horizontal roots with diameters of 1-3 cm. Roots larger than 3 cm were preserved. A total of 15-20 m long trenches were dug in each zone, with 5 trenches per zone, totaling 15 trenches. Manual cutting of horizontal roots effectively promotes root sucker sprouting.

3.2 Sprouting Investigation

The experimental period was April-October 2021. After irrigation, root sucker sprouting was investigated every 15 days. Five trenches were selected in each zone, totaling 15 trenches. Each trench was approximately 15-20 m long, with three 5 m monitoring belts established per trench. For each belt, 30 root suckers were selected to monitor sprouting quantity, plant height, sprouting root diameter, distribution depth, distance from parent tree, and distance from sprouting point to root-cut surface.

Plant height: Measured with a steel tape (precision 0.1 cm) using the highest main branch of each root sucker, with three repeated measurements averaged.

Sprouting root diameter: Measured with a 0.01 cm precision vernier caliper on sprouting roots near each sucker. Since diameters differed on both sides of suckers, both ends were measured and averaged, with three repetitions per end.

Distance from root sucker to parent tree: Measured with a tape measure from each sucker' s center to the parent tree' s straight-line distance (precision 0.01 cm), with three repetitions averaged.

Sprouting root distribution depth: Measured with a steel tape (precision 0.1 cm) as the vertical distance from sprouting roots to ground surface, with three repetitions averaged.

Distance from sprouting point to root-cut surface: Measured with a steel tape (precision 0.1 cm) as the straight-line distance from the sprouting point on the root to the cut surface, with three repetitions averaged.

3.3 Irrigation Treatments and Soil Monitoring

Soil moisture content (volumetric water content) and temperature were monitored at five depths (30 cm, 50 cm, 75 cm, 100 cm, 150 cm) using HOBO Ware U21-USB instruments. When soil moisture content is 6.0%–30.0%, it is suitable for P. euphratica root growth. Based on suitable moisture ranges and terrain/hydrological characteristics, four irrigation modes were established: F1 (control, no irrigation), F2 (11-day interval, 6 m^3/10 m, 2-day duration), F3 (23-day interval, 7 m^3/10 m, 3-day duration), and F4 (33-day interval, 8 m^3/10 m, 4-day duration). After irrigation, soil moisture was monitored using HOBO Ware. Sprouting was investigated post-irrigation to determine optimal soil temperature and moisture ranges based on sprouting quantities and soil conditions in different monitoring areas.

3.4 Data Processing and Analysis

Survey data were entered into Excel to calculate mean values for each parameter, which were used for comparative graphing. SPSS 20 software was used for one-way ANOVA and principal component analysis, with the LSD method for significance testing. ArcGIS 10.5 and Origin 2018 were used for mapping.

4 Results and Analysis

4.1 Root Sucker Quantity and Growth Status

Under different irrigation modes, root sucker plant height mainly distributed in the 0–5 cm range for F1 and F2, while F3 and F4 showed distribution in 5–10 cm and 15–30 cm ranges. Sprouting rates were 27.1% for F1, 27.6% for F2, 39.9% for F3, and 27.1% for F4. The F3 irrigation mode showed significantly higher sprouting rates than other modes. Root sucker height showed notable differences among irrigation modes, with F3 having the highest sprouting rate and plant height.

Both sides of root-cutting trenches showed significant differences in sprouting. Distal root sides had higher sprouting rates than proximal sides. In A1, A2, and A3, distal root sprouting rates were 70.7%, 77.1%, and 64.1% respectively, significantly higher than proximal sides. Distal root sucker height concentrated in 20-25 cm (37.6%, 20.1%, and 27.2% respectively), while proximal root height concentrated in 0-5 cm and 10-15 cm ranges.

4.2 Root Sucker Trait Characteristics

Overall, P. euphratica sprouting root diameter ranged 0.4-0.7 cm, with 64.1% of roots in this range. The 0.4-0.7 cm range showed the highest frequency across all zones, with 33.0% in A1, 46.2% in A2, and 47.6% in A3. Significance analysis showed no significant differences in sprouting root diameter among zones.

The distance between root suckers and parent trees concentrated at 5.5-7 m, accounting for 70.7% of observations. Among different zones, A1 and A2 showed distances concentrated at 5.5-7 m (35.9% and 44.8% respectively), while A3 concentrated at 8.5-10 m (42.9%). Sprouting root distribution depth concentrated at 30-50 cm, representing 77.1% of cases. In A1, A2, and A3, distribution depths concentrated at 30-50 cm (62.6%, 63.6%, and 53.3% respectively), with no significant differences among zones.

The distance from sprouting point to root-cut surface concentrated at 1-8 cm, accounting for 75.2% of observations. In A1 and A2, distances concentrated at 1-8 cm (38.6% and 43.8% respectively), while A3 concentrated at 8-16 cm (40.0%). Based on these results, digging root-cutting trenches 5.5-7.0 m from parent trees is most conducive to sprouting, with sprouting root diameter less than 1 cm (fine roots) and distribution depth of 30-50 cm.

4.3 Soil Temperature and Moisture Effects on Sprouting

During the experimental period, soil moisture and temperature dynamics at 30 cm depth showed significant fluctuations post-irrigation, with moisture reaching saturation then declining. The 50 cm layer showed the greatest moisture variation, while moisture at 75 cm and 100 cm was significantly lower than at 30 cm. Soil temperature showed no major fluctuations, gradually increasing across all layers during the experiment.

Based on sprouting quantities, when sprouting root depth was 30-50 cm, sprouting was most favorable. When soil temperature was 26.5-28.1°C and moisture content was 10.6%-13.1%, sprouting numbers were highest. Therefore, the optimal soil moisture and temperature ranges for P. euphratica root sucker sprouting are 10.6%-13.1% and 26.5-28.1°C respectively.

5 Discussion

Trench root cutting is an effective measure for restoring P. euphratica forests. This study shows significant root sprouting effects after trenching (Figure 7).

Digging root-cutting trenches around parent trees facilitates seedling renewal, with optimal trench distance of about 5.5–7 m from parent trees. Studies indicate that sprouting-capable roots concentrate in shallow soil layers less than 1 cm diameter and within 40 cm of the surface. P. euphratica has shallow root characteristics, and as soil depth increases, aeration deteriorates, increasing resistance to natural sucker growth, making deep soil growth difficult.

This study found that sprouting root distribution concentrated at 30–50 cm depth in shallow soil, with optimal trench distance of 5.5–7 m from parent trees. Proximal and distal roots show significant differences in sprouting capacity, with proximal roots producing fewer suckers than distal roots. Large-diameter proximal roots have high lignification and low meristematic activity, resulting in weaker sprouting capacity compared to new distal roots. This study confirmed that distal roots have stronger sprouting capacity than proximal roots, with distal side sprouting rates of 70.7%, 77.1%, and 64.1% in the three zones—significantly higher than proximal sides—and distal root sucker height concentrated at 20–25 cm.

Root sprouting reproduction is affected by soil rhizosphere environment and root distribution. Soil water content shows significant positive correlation with sprouting quantity, growth height, and seedling production per node ($P < 0.05$). P. euphratica seedlings are more sensitive to environmental factors, easily affected by root distribution, water, and soil conditions. Principal component analysis of factors affecting sprouting showed the first three components cumulatively contributed 90.39%. The first component (strongly positively correlated with root distribution) is the key factor affecting sprouting, while the second and third components (strongly positively correlated with soil temperature and moisture) indicate these also significantly influence sprouting.

Ecological water transfer is crucial for river ecosystems and desert riparian forest ecosystems. After the "P. euphratica Forest Protection Action" began in2016, flood irrigation improved local ecological environments, producing large areas of P. euphratica seedlings. Irrigation is necessary for restoring forest vitality and promoting root sprouting. This study determined that the optimal irrigation mode is a 23-day interval with 7 m^3 water per 10 m trench and 3-day duration (F3). Under different irrigation modes, distal root sprouting rates were 64.1%, 77.1%, and 70.7%—significantly higher than proximal sides. These results provide important guidance for P. euphratica forest renewal and efficient water resource utilization in the Tarim River basin.

6 Conclusion

This study examined P. euphratica root sprouting regeneration patterns after trench root cutting in the lower Tarim River.

1) Trench root cutting benefits P. euphratica renewal. The F3 irrigation mode (23-day interval, 7 m^3/10 m, 3-day duration) produced the highest sprouting rate of 39.9%, with root sucker height concentrated at 15–30

cm. Distal root sprouting rates (64.1%, 77.1%, 70.7%) were higher than proximal sides, with distal root sucker height concentrated at 20–25 cm.

2) P. euphratica underground sprouting roots mainly appeared in the 30–50 cm soil layer, with diameters of 0.4–0.7 cm. The distance from sprouting point to parent tree concentrated at 5.5–7 m, and distance to root-cut surface concentrated at 1–16 cm.
3) Sprouting root diameter, distribution depth, distance to parent tree, and distance to cut surface are key factors affecting sprouting, followed by soil temperature and moisture content.
4) The optimal soil temperature and moisture ranges for P. euphratica root sprouting are 26.5–28.1°C and 10.6%–13.1%, respectively. The most suitable irrigation mode is 23-day interval, 7 m^3 water per 10 m trench, with 3-day duration.

References

[1] Wang Genxu, Cheng Guodong. The spatial pattern and influence caused by water resources in arid desert oases[J]. Acta Ecologica Sinica, 2000, 20(3): 363-368.

[2] Kong Zijie, Deng Mingjiang, Ling Hongbo, et al. Ecological security assessment and ecological restoration countermeasures in the dried-up area of the lower Tarim River[J]. Arid Zone Research, 2021, 38(4): 1128-1139.

[3] Huang Yue, Bao Anming, Wang Shifei, et al. Eco-environmental change in the lower Tarim River under the influence of intermittent water transport[J]. Acta Geographica Sinica, 2013, 68(9): 1251-1262.

[4] Chen Y, Li W, Xu C, et al. Desert riparian vegetation and groundwater in the lower reaches of the Tarim River basin[J]. Environmental Earth Sciences, 2015, 73(2): 547-558.

[5] Zhao Wanyu, Chen Yaning, Zhou Honghua, et al. Reproductive ability and relative environment factors of degraded Populus euphratica forest in ecological water delivery project at lower reaches of Tarim River[J]. Journal of Desert Research, 2009, 29(1): 108-113.

[6] Li Mengyi, Deng Mingjiang, Ling Hongbo, et al. Evaluation of ecological water security and analysis of driving factors in the lower Tarim River, China[J]. Arid Zone Research, 2021, 38(1): 39-47.

[7] Deng Mingjiang, Yang Pengnian, Zhou Haiying, et al. Water conversion and strategy of ecological water conveyance in the lower reaches of the Tarim River[J]. Arid Zone Research, 2017, 34(4): 717-726.

[8] Gutierrez J R, Arancio G, Jaksic F M. Variation in vegetation and seed bank in a Chilean semi-arid community affected by ENSO 1997[J]. Journal of Vegetation Science, 2000, 11(5): 641-648.

[9] Zhao Wenzhi, Chang Xueli, Li Qiuyan. Artificial water diversion effects of Heihe River on Populus euphratica Oliv. desert riparian forests in Ejina[J]. Acta Ecologica Sinica, 2005, 25(8): 1987-1993.

[10] Ye Ziqi, Deng Rujun, Wang Yuchen, et al. Branching patterns of clonal root of Populus euphratica and its associations with soil factors[J]. Journal of Beijing Forestry University, 2018, 40(2): 31-39.

[11] Huang Jingjing, Jing Jialin, Cao Dechang, et al. Cloning root system distribution and architecture of Populus euphratica in the dry up area of the lower Tarim River[J]. Arid Zone Research, 2021, 38(4): 1128-1139.

[12] Li Lijun, Zhang Xiaoqing, Chen Changqing, et al. Ecological effects of water conveyance on the lower reaches of Tarim River in recent twenty years[J]. Arid Land Geography, 2018, 41(2): 238-247.

[13] Zheng Yaqiong, Zhang Xiao, Liang Jiye, et al. Clonal growth characteristics of the endangered species Populus euphratica Oliv. and Populus pruinosa schrenk[J]. Acta Ecologica Sinica, 2016, 36(5): 1331-1341.

[14] Zhang Hao, Li Junqing, Li Jingwen, et al. The reproductive phenological rhythm characteristics of Populus euphratica Oliv. population in the Ejina oasis of Inner Mongolia[J]. Journal of Inner Mongolia Agricultural University (Natural Science Edition), 2007, 28(2): 60-66.

[15] Wang Yuchen, Wang Wenjuan, Zhong Yueming, et al. Study on the foraging behavior of clonal roots and its influencing factors in Populus euphratica Oliv.[J]. Plant Science Journal, 2020, 38(3): 410-417.

[16] Klimesova J, Pokorna A, Klimes L. Establishment growth and bud availability, plant injury, and environmental heterogeneity[J]. Botanique, 2009, 87(2): 195-201.

[17] Bartuskova A, Klimesova J. Reiteration in the short-lived root sprouting herb Rorippa palustris: Does the origin of buds matter?[J]. Botany, 2010, 88(7): 630-638.

[18] Wu Fengping, Li Junqing, Li Jingwen, et al. The characteristics of root suckers of Populus euphratica Oliv. in three habitats of Ejina Oasis[J]. Acta Ecologica Sinica, 2008, 28(10): 4703-4709.

[19] Li Zhijun, Liu Jianping, Yu Jun, et al. Investigation on the characteristics of biology and ecology of Populus euphratica and Populus pruinosa[J]. Acta Botanica Boreali Occidentalia Sinica, 2003, 23(7): 236-240.

[20] Cao Dechang, Li Jingwen, Chen Weiqiang, et al. Development and growth of root suckers of Populus euphratica in different forest gaps in Ejina Oasis[J]. Acta Ecologica Sinica, 2009, 29(4): 1954-1961.

[21] Sun Hongxiang, Yao Yunfeng. Study on technology of diversiform-leaved poplar forest regeneration and restoration of Ejina Oasis[J]. Journal of Arid Land Resources and Environment, 2000, 14(Suppl. 1): 69-73.

[22] Feng Qi, Si Jianhua, Li Jianlin, et al. Feature of root distribution of Populus euphratica and its water uptake model in extreme arid region[J]. Advances in Earth Science, 2008, 23(7): 765-772.

[23] Zhu Yajuan, Dong Ming, Huang Zhenying. Adaptation strategies of seed germination and seedling growth to sand dune environment[J]. Chinese Journal of Applied Ecology, 2006, 17(1): 137-142.

[24] Li Peng, Zhao Zhong, Li Zhanbin, et al. Advances on the interactional mechanism between root system and eco-environment[J]. Journal of Northwest Forestry University, 2002, 17(2): 26-32.

[25] Li Xinrong, Ma Fengyun, Long Liqun, et al. Soil water dynamics under sand-fixing vegetation in Shapotou area[J]. Journal of Desert Research, 2001, 21(3): 3-8.

[26] Gao Shengfeng, Ye Mao. Effect of flood on growth of Populus euphratica in extreme arid region in the upper and middle reaches of Tarim River[J]. Ecological Science, 2020, 39(2): 50-57.

[27] Tian Yongzhen, Si Jianhua, Cheng Yesen, et al. Experimental study on rejuvenation and regeneration of residual Populus euphratica forest in desert valley[J]. Journal of Arid Land Resources and Environment, 2009, 23(9): 155-159.

[28] Han Jianhua, Zhou Fang, Zhang Lixia, et al. Construct the ecological security barrier in the north: Discussion on natural reproduction and artificial regeneration of Populus euphratica forest in Siziwang Banner[J]. Forestry Science and Technology Information, 2021, 53(2): 19-22.

[29] Pei Hongwei, Zhang Hongjuan, Li Yali, et al. Characteristics and drivers of turf evapotranspiration in northern China: A case study of turf (Poa pratensis) in Zhangjiakou City, Hebei Province[J]. Water Saving Irrigation, 2021(11): 1-14.

[30] Feng Qi, Si Jianhua, Chang Zongqiang, et al. Response of root distribution of Populus euphratica Oliv. to soil moisture content in extreme arid region[J]. Journal of Arid Land Resources and Environment, 2009, 23(11): 186-190.

[31] Ling H B, Guo B, Zhang G P, et al. Evaluation of the ecological protective effect of the large basin comprehensive management system in the Tarim River basin, China[J]. Science of the Total Environment, 2019, 650: 1696-1706.

[32] Zhang Wenxia, Liu Puxing, Feng Qingrong, et al. Spatial and temporal response and its causes of the growing season of Populus euphratica to global warming in China' s oases during 1960-2015[J]. Acta Geographica Sinica, 2017, 72(7): 1151-1162.

[33] Ling H B, Zhang P, Xu H L, et al. Determining the ecological water allocation in a hyper-arid catchment with increasing competition for water resources[J]. Global and Planetary Change, 2016, 145: 143-152.

[34] Zhu Yuwei, Sang Baye, Chen Qimin, et al. Rejuvenation techniques of Populus euphratica forest in Hetian River Basin[J]. Journal of Southern Agriculture, 2012, 43(10): 1544-1548.

[35] Gutierrez J R, Arancio G, Jaksic F M. Variation in vegetation and seed bank in a Chilean semi-arid community affected by ENSO 1997[J]. Journal of Vegetation Science, 2000, 11(5): 641-648.

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