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ORIGINAL ARTICLE

Effects of ecological water conveyance on the ring increments of *Populus euphratica* in the lower reaches of Tarim River

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Abstract Because of long-term drying of the lower reaches of the Tarim River, oasis ecosystems are facing serious threats and have started to degenerate. An ecological water conveyance project has been started in the lower reaches of the Tarim River to save the degenerated ecosystem. The effects of ecological water conveyance on the ring width increments of *Populus euphratica* were studied by use of the trend analysis method, the moving *t* test technique, and a regression equation based on ring increment data from the past 40 years in the lower reaches of the Tarim River. Results showed that the ring increments of *Populus euphratica* in four monitoring transects along the river can be divided into two parts, 1970–2001 and 2002–2008. This division implies that ecological water conveyance had a positive effect on the increase of ring increments. The ring increments of *Populus euphratica* in Yinsu, Kardayii, Alagan, and Yiganbjma increased by 79.37, 174.5, 75.61, and 71.81% after ecological water conveyance. The years 2002, 2001, 2001, and 2002 were the transition years in the Yinsu, Alagan, Kardayi, and Yiganbjma transects, respectively. The ring width increments in Yinsu, Kardayi, Alagan, and Yiganbjma as a result of ecological water conveyance were 1.41, 0.987, 0.265, and 0.671 mm, respectively. The main cause of the changes in ring width increments was the rise of groundwater level. The results from this study should contribute to improved management of the ecosystems in the lower reaches of the Tarim River, and can also provide a scientific basis for implementing similar projects in other arid and semiarid areas.

Keywords Changing trend · Ecological water conveyance · Lower reaches of the Tarim River · Moving *t* test technique · Ring width increment

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Introduction

Water is an important ecological aspect of the composition, productivity, and stability of oasis ecosystems in arid and semi-arid areas (Poiani and Johnson 1993; Gullison and Bourque 2001). It also determines the conflicting processes of environment change, for example succession of plant communities, oasis metamorphosis, and desertification (Huete 1988; Li et al. 1998; Chen et al. 2003). Such ecosystems are small in scale and low in stability in arid and semi-arid regions (Chen et al. 2004a). Groundwater is an important source of water for the growth of natural vegetation in some arid and semi-arid areas. There has been much interest in the relationships between change of groundwater depth and vegetation succession in arid regions (Munoz-Reinoso 2001; Chen et al. 2004a; Naumburg et al. 2005; Xu et al. 2011). These studies indicate that the natural vegetation can be vulnerable, and can be severely affected, when the groundwater level declines.

Located in a remote part of the Taklimakan Desert, the Tarim River is a continental river in a region where the ecological environment is vulnerable. Intensive development of artificial oases and unbridled exploitation and utilization of water resources, especially in the lower reaches of the Tarim River, had led to noticeable changes in the environment in the past 50 years (Zu et al. 2003; Feng et al. 2005). As a result, the groundwater level has dropped and natural vegetation has decreased, which affects the stability of the ecosystem in the study area and curbs local sustainable economic development. A series of steps have been taken to save the ecosystems of the Lower Tarim River. The Chinese government has invested 107×10^8 yuan (RMB) since 2000 to synthetically harness the Tarim River and implement ecological water conveyance. Many studies have focused on the natural vegetation responses to groundwater change (Chen et al. 2004a; Xu et al. 2007; Wu and Tang 2010) as a result of artificial watering in arid areas.

Populus euphratica, the dominant species in the Tarim River Basin, is sensitive to water changes in arid regions (Cleverly et al. 1997; Devitt et al. 1997; Brignolas et al. 2000). It is important to understand the ecological restoration in the study area by investigating and analyzing the response of *Populus euphratica* ring increment to ecological water conveyance. Many scholars have studied the change of geographic distribution and physiology of *Populus euphratica* (Chen et al. 2003, 2004b; Fu et al. 2008; Raddi et al. 2009; Deng et al. 2010). Many studies using other species have compared changes of ring width increment with environment changes (Watmough et al. 1998; Touchan et al. 1999, 2005; Battipaglia et al. 2009; Yadav et al. 2009; Suresh et al. 2010). As a regional environment proxy, ring width increment data have the advantages of high temporal resolution, widespread distribution, long time series, and precise dating (Niinemets ülo 2010; Sano et al. 2010; Sun et al. 2010).

In this work we studied:

1 changes in the trend of ring width increments of *Populus euphratica* before and after watering;
2 identification of the transition points of ring width increments in four transects; and
3 the effects of ecological water conveyance on the ring width increments of *Populus euphratica*

to determine the effects of an ecological water conveyance project.

Materials and methods

Study area

The Tarim River Basin is located near the Taklimakan Desert, the largest desert in China, with a total area of 1.02×10^6 km^2. It is composed of 9 water systems including the Aksu, Yarkat, Hotan, Qarqan, Kaxgar, Keriya, Kaidu-konqi, Weigan, and Dina rivers. The average annual surface runoff at the confluence of three headstreams (Aksu, Yarkat, and Hotan Rivers) is 45×10^8 m^3. Runoff is mainly composed of ice–snow melt water from high mountainous areas and precipitation in mountain areas. The climate belongs to the temperate continental arid climate. It is windy and dusty, the annual average surface air temperature is 10.8°C, and the annual average precipitation and potential average evaporation are 50 mm and 2,800 mm, respectively. After the Daxihaizi Reservoir was built in 1972, the stream flow of the river transect 321 km downstream was completely dried up. To save the increasingly degenerated natural vegetation and restore the seriously degenerated ecosystems a project of ecological water conveyance in the lower reaches of the Tarim River was started from May 2000.

Our study area is located between the Yinsu and Yiganbjma transects in the lower reaches of the Tarim River (Fig. 1). Vegetation is sparse in this area and largely follows the rivers to form a green belt. In the study area the dominant species is *Populus euphratica*; shrubs mainly include *Tamarix* spp, *Lycium ruthenicum*, *Halimodendron halodendron*, *Nitraria sibirica*; and herbs mainly include *Phragmites communis*, *Poacynum hendersonii*, *Alhagi sparsifolia*, *Karelinia caspica*, and *Glyzyrrhiza inflate*. Because the rainfall cannot meet the requirement of the natural vegetation, survival of the natural vegetation depends mainly on the groundwater.

Sampling and measurement of tree rings

To determine the possible effects of ecological water conveyance on the ring increments of *Populus euphratica*, we established four monitoring transects along the lower reaches of the Tarim River in 2007, where water conveyance occurred. The transects included Yinsu (C), Kardayi (E), Alagan(G), and Yiganbjmaa (H) (Fig. 1). The interval between two neighboring transects was approximately 40–50 km. In August 2009 we selected 30–40 healthy trees near the watercourse along each transect to collect ring width increment samples. Sampling and cross-dating were completed according to the standards of Stokes and Smiley (1968). A total of 157 trees were selected. Two cores were taken from each tree by use of an increment borer. The cores were numbered and transported to the laboratory.

We prepared the samples in the laboratory following the dendrochronological laboratory procedure of drying,

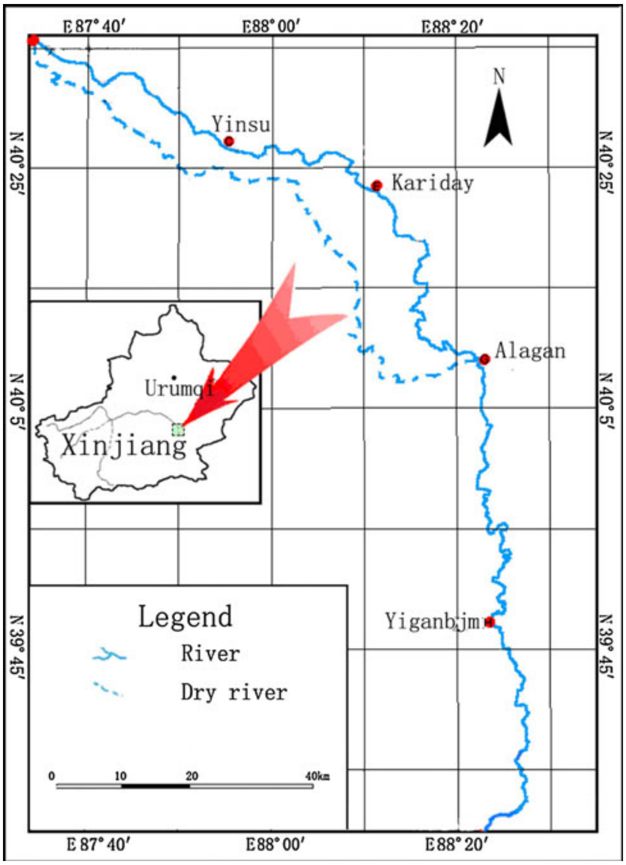

Fig. 1 Sketch map of the lower reaches of the Tarim River

mounting, sanding, and primary cross-dating (Fritts 1976). The ring increments of *Populus euphratica* were measured using the LINTAB™6 system (precision 0.001 mm; Rinntech, Heidelberg, Germany) on tree-ring cores. Cross-dating of the ring width increment series data was confirmed by use of COFECHA software (Holmes 1983), in which segments with weak correlation with the master series were discarded.

The growth trend of the ring increment of *Populus euphratica* was fitted using the negative exponential formula of ARSTAN software (http://www.ldeo.columbia.edu/res/fac/trl) to establish standard and residual chronologies (Cook 1985). Using a high pass filter, the residual chronology could preserve more high-frequency variations, eliminate lower frequency variations on the end of the time series, and seem to have better correlation with environmental factors. This chronology was used as the analysis target in this study.

Trend analysis

The ring increment trend of *Populus euphratica* in response to ecological water conveyance was analyzed by the cumulative sum method, which is one of the general methods to analyze the time series change (Page 1954; Hao et al. 2008; Liu et al. 2010). The trend analysis method, CUSUM, is defined as:

$$\mathrm{CUSUM} = \sum_{i=1}^{n} (x_i - \bar{x}) \tag{1}$$

In which, CUSUM represents the value of cumulative curve, x_i represents the ring increment of i, $\bar{x}$. represents the average ring increment in one transect, i represents the amount of time, and n represents the length of the time series. A downward gradient of the cumulative curve represents a decrease in the ring increment, an upward gradient indicates an increasing ring increment, and a horizontal gradient indicates that the ring increment is approaching the average annual value.

Transition point analysis

The transition point of the ring increment in the four transects was detected by the moving t test technique, a method used to investigate time series change. A time series, x, of n years of ring width increments can be divided into two sample groups, x_1 and x_2. μ_i, S_i^2, and n_i represent the average ring increment of x_i, variance of x_i, and the length of x_i. Assuming that $\mu_1 - \mu_2 = 0$ and the trend analysis method, T, is defined as

$$T = (\overline{x_1} - \overline{x_2}) \Big/ S_P^2 \left(\frac{1}{n_1} + \frac{1}{n_2} \right) \tag{2}$$

where, S_P^2 represents the variance of all ring increments, and S_P^2 is

$$S_P^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2} \tag{3}$$

At a specified level of significance of α ($\alpha = 0.05$), the standard t_α value can be obtained from the t table for the standard normal distribution, with t_α being the critical value. If $|T| > t_\alpha$, the change point is statistically significant.

Evaluation of the effects of ecological water conveyance on the ring increments of *Populus euphratica*

A regression equation relating accumulated total ring width increments in the four transects to the time series was established before the transition point. The ring width increment of *Populus euphratica* after the transition point could be obtained by use of the regression equation. The difference between the calculated and the observed values was considered to be the effect of ecological water conveyance.

Results and discussion

Changing trend of ring width increment of *Populus euphratica*

The effectiveness of ecological water conveyance has been demonstrated, and the method is important in the protection of the ecosystems (Hou et al. 2007). The curve in the four transects showed that there is an inflection point at 2001 or 2002 that suggests a change in the growth trend after that point (Fig. 2). The ring width increments of *Populus euphratica* changed slightly over the past several years in the first part, whereas they increased rapidly in the second part. Brignolas et al. (2000) demonstrated that the ring width increments of *Populus euphratica* have a strong relationship with groundwater level. With changes in groundwater level, there will be large fluctuations in the ring increments (Brignolas et al. 2000). However, the changing of groundwater level depends on the duration and volume of ecological water conveyance. The duration and volume of water conveyance in the lower reaches of the Tarim River from 2000 to 2007 is shown in Table 1. Because of drought, ecological water conveyance to the lower reaches of the Tarim River was not initiated in 2008. Ye et al. (2009) have found that the relationship between the watering volumes and the increment of groundwater level tends to remain steady when the watering volumes are sufficient. The groundwater level rose after ecological water conveyance (Xu et al. 2007). The composition, distribution, and growth status of the natural vegetation responded directly to the rise in groundwater level. It was noted that the ecological water conveyance had strong effects on the ring width increments of *Populus euphratica* (Fig. 2). The average ring width increments of *Populus euphratica* in the four transects of Yinsu, Kardayi, Alagan, and Yiganbjma increased by 79.37, 174.5, 75.61, and 71.81% after the ecological water conveyance. The coverage of *Populus euphratica* reached a peak value of 34.76% in 2005, increased rapidly from year 2002 to 2005 and dropped a little in 2006 (Ye et al. 2009). The curves reached the extreme values after 2 or 3 years of ecological water conveyance, which indicated that the sensitivity of *Populus euphratica* to groundwater change decreased after a long drought (Fig. 2).

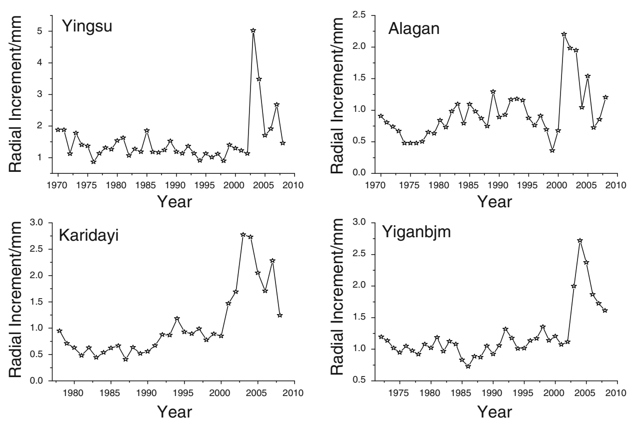

Fig. 2 The trend of ring increment in the lower reaches of the Tarim River

Table 2 shows the decadal variations of the ring width increments of *Populus euphratica* in the four transects in the lower reaches of the Tarim River. The results indicated that the ring increments in different transects had different changing trends. The ring increments had been slightly decreasing before 2000 in Yinsu, but they fluctuated in the other transects during the same period. The average ring increment was higher in the 1990s than in the 1970s in the other three transects. One possible cause of the increase in ring width increments may be climate change in the lower

Table 1 Statistical results of ecological water conveyance to the lower reaches of the Tarim River

Phase	Start (year-month-day)	End (year-month-day)	Duration (days)	Volume (10^8 m^3)	Arriving transect
First	2000-5-14	2000-7-12	60	0.98	Kardayi
Second	2000-11-3	2001-2-5	95	2.25	Alagan
Third (1)	2001-4-1	2001-7-6	97	1.84	Alagan
Third (2)	2001-9-12	2001-11-18	68	1.98	Taitma Lake
Fourth	2002-7-20	2002-11-10	114	3.31	Taitma Lake
Fifth (1)	2003-3-1	2003-7-11	133	3.4	Taitma Lake
Fifth (2)	2003-8-4	2003-11-3	92	2.85	Taitma Lake
Sixth (1)	2004-4-1	2004-6-1	64	1.2	Taitma Lake
Sixth (2)	2004-8-1	2004-11-1	46	2.3	Taitma Lake
Seventh (1)	2005-5-7	2005-6-7	32	0.524	Taitma Lake
Seventh (2)	2005-8-30	2005-11-2	65	2.3	Taitma Lake
Eighth	2006-9-25	2006-11-30	66	2.33	Kaogan
Ninth	2007-9-15	2007-10-19		0.14	Kardayi

Table 2 The decadal variation of radial increment (mm) in the lower reaches of the Tarim River

Transects	1970–1980	1981–1990	1991–2000	2001–2008
Yinsu	1.411	1.33	1.139	2.326
Alagan	0.653	0.948	0.871	1.437
Kardayi	0.762	0.549	0.892	1.993
Yiganbjma	1.038	0.964	1.158	1.811

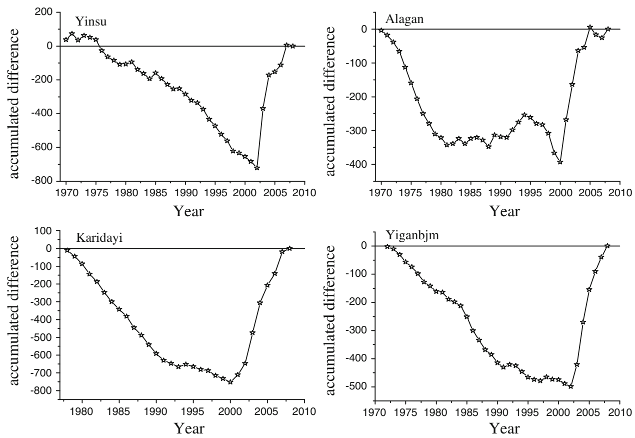

Fig. 3 The cumulative curve of ring increment of *Populus euphratica* in the four transects

reaches of the Tarim River. Hao et al. (2008) studied the changing trend of temperature and precipitation in the Tarim River Basin. Their results showed that precipitation in the lower reaches of the Tarim River was increasing.

Cumulative curves of ring width increments of *Populus euphratica*

The changing trend of the ring width increments of *Populus euphratica* in the four transects was further confirmed by the cumulative sum method (Fig. 3). The change of cumulative curves reflected the increase or decrease of ring width increments over time. Figure 3 shows there was a monotonic decrease in accumulated ring width increments from 1970 to 2001 and then a continuous increase from 2002 to 2008. The changing trend of the cumulative curve in Alagan was different from that in the other transects. The ring width increments reached a relatively stable state after 1980, the curve almost unchanged in the past 20 years. This means that *Populus euphratica* gradually adapted to the changing environment after a period of adjustment in Alagan.

The cumulative curves in the four transects reflected not only the long-term trend of average ring increments of *Populus euphratica,* but also the possible transition point. As a result of ecological water conveyance, the curve changed from rising to declining. The changed years were

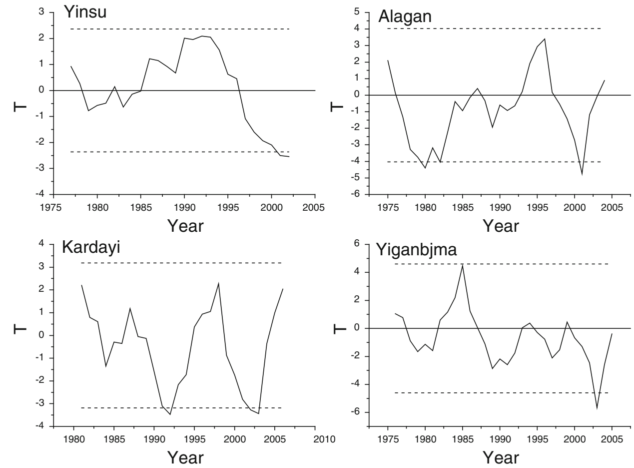

Fig. 4 The moving *t* test technique of ring increment of *Populus euphratica* in the four transects

the possible transition points of ring increments in the four transects (Fig. 3).

Ring increment transition point of *Populus euphratica*

Trends for the change of ring increments in the four transects revealed the possible transition points. To identify the exact change point of the ring increments in the four transects, the annual ring increment data from 1970 to 2008 in the four transects were tested by the moving *t* test technique. The results of the moving *t* test technique are represented in Fig. 4. The ring increments in Alagan had three distinct transition points, the years 1980, 1982, and 2001; the ring increments in Kardayi had two distinct transition points, the years 1992 and 2001. On basis of the changing trend analysis combined with the moving *t* test technique, a more significant changing trend was apparent in Yinsu, Alagan, Kardayi, and Yiganbjma in 2002, 2001, 2001, and 2002, respectively; the statistical significance levels of the four transects were 5, 5, 1, and 1%, respectively. Therefore, the transition points in Yinsu, Alagan, Kardayi and Yiganbjma were the years 2002, 2001, 2001, and 2002, respectively.

Regression equations and estimated ring increments of *Populus euphratica*

The above results showed that the transition points of the ring increments in Yinsu, Alagan, Kardayi, and Yiganbjma were 2002, 2001, 2001, and 2002, respectively. Regression equations between the accumulated total ring increments in the four transects (obtained by using the time series data before the transition years: 1970–2002 in Yinsu, 1970–2001 in Alagan, 1978–2001 in Kardayi, and 1972–2002 in Yiganbjma)

Table 3 Estimated radial increment (mm) of *Populus euphratica* in every year in the four transects

Transect	Year	Observed value	Estimated value	Effect of ecological water conveyance	Transect	Year	Observed value	Estimated value	Effect of ecological water conveyance
Yinsu	2002	1.125	1.105	0.020	Kardayi	2001	1.468	1.028	0.439
	2003	5.025	1.094	3.931		2002	1.691	1.056	0.635
	2004	3.485	1.084	2.401		2003	2.776	1.085	1.692
	2005	1.705	1.074	0.631		2004	2.730	1.113	1.617
	2006	1.910	1.064	0.846		2005	2.050	1.141	0.909
	2007	2.680	1.054	1.627		2006	1.705	1.169	0.536
	2008	1.460	1.043	0.417		2007	2.281	1.197	1.084
Alagan	2001	2.203	1.116	1.087		2008	1.243	1.226	0.017
	2002	1.983	1.132	0.851	Yiganbjma	2002	1.117	1.131	−0.014
	2003	1.948	1.148	0.800		2003	1.998	1.138	0.859
	2004	1.045	1.164	−0.119		2004	2.721	1.145	1.576
	2005	1.540	1.180	0.360		2005	2.373	1.152	1.222
	2006	0.725	1.197	−0.472		2006	1.865	1.158	0.707
	2007	0.853	1.213	−0.360		2007	1.724	1.165	0.559
	2008	1.203	1.229	−0.026		2008	1.613	1.172	0.440

and the time series were established, in which x represents the time series and y represents the accumulated total ring increment in the four transects. The regression equations were:

Yinsu transect $\quad y = -0.0051x^2 + 1.436x + 0.63$

Alagan transect $\quad y = 0.0081x^2 + 0.605x + 0.12$

Kardayi transect $\quad y = 0.014x^2 + 0.366 + 0.97$

Yiganbjma transect $\quad y = 0.0034x^2 + 0.924x + 0.615$

These equations and the data for the accumulated total ring increments in the four transects were used to estimate the values of ring increments in the lower reaches of the Tarim River. The effect of ecological water conveyance was considered to be responsible for the difference between the estimated and observed values. The results (Table 3) showed that starting from the transition years, implementation of the ecological water conveyance project resulted in an increasing ring increment trend along the watercourse from Yinsu transect to Alagan transect which is especially noteworthy after 2–3 years of ecological water conveyance.

Before the ecological water conveyance, the average ring increments of *Populus euphratica* were 1.29, 0.757, 0.862, and 1.06 mm in Yinsu, Kardayi, Alagan, and Yiganbjma, respectively. The slope of the regression equation increased slightly over the last several decades before initiation of the ecological water conveyance project in the three transects, except for the Yinsu transect. Several studies have detected an increasing trend in precipitation since the 1980s (Xu et al. 2006, 2007, 2010). The increasing precipitation may partly weaken the negative effect of the drought and resulted in an increase of the ring increments of *Populus euphratica* in the study area.

Water conveyance changed the ring increments of *Populus euphratica* in the four transects (Table 3). The new order of the ring increments was: Yinsu > Kardayi > Yiganbjma > Alagan. The ring width increments in these four transects increased during 2000–2004 and reached a maximum for the past 40 years in 2003 or 2004. The maximum values of ring increments in Yinsu, Alagan, Kardayi, and Yiganbjma were 5.03, 1.98, 2.78, and 2.72 mm, respectively. The ring width increments gradually became flat during 2005–2008. These findings showed that water conveyance was conducive to the growth of the natural vegetation and restoration of the degenerated ecosystems.

The trend of the effects of ecological water conveyance was consistent with the trend of observed values. In general, the effect of ecological water conveyance also can be divided into two parts (2001–2004 and 2005–2008). The effect increased in the first part and decreased slightly in the second part (Table 3). The average effects of ecological water conveyance in Yinsu, Kardayi, Alagan, and Yiganbjma were 1.41, 0.987, 0.265, and 0.671 mm, respectively. Results from this study can provide the scientific basis for evaluating the effects of water conveyance and provide scientific support for implementing the same projects in other arid and semi-arid areas in the world.

Conclusions

Determining the effects of ecological water conveyance on vegetation, especially *Populus euphratica,* has been a puzzling problem for a long time. Using ring increment data collected from the four transects along the lower reaches of the Tarim River from 1970 to 2008, this study qualitatively and quantitatively analyzed the effect of ecological water conveyance on the ring increments increase of *Populus euphratica*. Results showed that the ring increments of *Populus euphratica* in the four transects can be divided into two parts. In the first part, the ring increment of *Populus euphratica* was almost unchanged over several years, whereas it increased rapidly in the second part. The cumulative curves in the four transects followed the same trend.

The results of the moving *t* test technique with statistical significance indicated that the transition years of the changing trend of ring increments at the Yinsu, Alagan, Kardayi, and Yiganbjma transects were 2002, 2001, 2001, and 2002, respectively. Following the transitional year, there was a significant difference between the estimated values and the observed values at the same transect in 2001–2008. The estimated values were obtained from the regression equations between the accumulated total ring increments and the time series. These differences implied that ecological water conveyance had a positive effect on the increase of ring increments in the downstream part of the Tarim River. The effects of ecological water conveyance on the ring increments in Yinsu, Kardayi, Alagan, and Yiganbjma were 1.41, 0.987, 0.265, and 0.671 mm, respectively.

Because of the arid and fragile environment, the ecosystems in the Tarim River Basin faced serious threats. The relevant departments should take economic and technical measures to protect the degenerated ecosystems and promote regional sustainable development. This study should contribute to improving the management of degenerated ecosystems. The methods used to evaluate the effect of ecological water conveyance in this study can be adapted in other arid and semi-arid areas in the world.

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