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RESEARCH ARTICLE

On the vulnerability of oasis forest to changing environmental conditions: perspectives from tree rings

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Abstract In water-limited regions, oases are important localities for maintaining ecological biodiversity and supporting social and economic development. For oases situated by the side of rivers, variability of streamflow is often considered as a dominant factor influencing the vulnerability of oases forest, whereas other factors receive much less attention. Here we argue that ecological and hydrological processes creating spatial habitat heterogeneity and particularly the change of habitat structure through time are critical aspects when assessing vulnerability of oasis forest. This is demonstrated by dendroecological studies of a dynamic landscape in Ejina Oasis in the lower reach of Heihe River, the second largest inland river in China. Our results show that radial growth of euphrates poplar trees in Ejina Oasis did not follow the variation of streamflow coming from the middle reach, and the poplar tree-ring growth did not change in the same way from one site to the other. An index of multi-directional change (*MDCi*) is defined from tree-ring data to describe the change in spatial habitats through time. We propose that the decreasing trend of *MDCi* indices since the 1950s is related to persistently increasing human activities, whereas high-frequency variability in *MDCi* indices is related to frequent and strong local disturbances such as windstorms as well as human activities that directly cause changes in streamflow. The results obtained from this study have potentially broad implications for identifying dryland ecosystems that are at risk or susceptible to change, and for making spatially explicit decisions for rational utilization of water resources.

Keywords Dendrochronology · Ecohydrology · Habitat heterogeneity · Heihe River · Multi-directional change · Spatial habitat · Streamflow

Introduction

Oasis is a unique geographic entity that appears as a well-vegetated "island" surrounded by large areas of drylands or deserts. It is characterized by having persistent water supply, abundant vegetation, and being isolated within semiarid to hyperarid regions (Shen et al. 2001). Oases have been important cradles for human civilization in the history. For example, the chain of oases over vast areas of drylands in western

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China played a significant role in bridging the ancient Silk Road, and contributed to cultural and economic communications between China and European countries as early as the eighth century (Huang 1995). Today, some of these ancient oases have disappeared due to either natural climate change or abuse of water and forest resources; others have changed their spatial scale and structure, and are still important localities for maintaining ecological biodiversity and supporting social and economic development in water-limited regions. Given that current global climate change coupled with increasing human activities could pose ecological risks to existing oases, characterizing the vulnerability of oases to changing environmental conditions has been one of the most important and challenging tasks in oases studies.

Forest is usually one of the key components in oases. Understanding the patterns and dynamics of forest growth and their relationships with the changing environment is critical for effectively evaluating the vulnerability of oases. For oases that are situated in different sections along a river, the growth of forest is usually constrained by fluctuation in streamflow (Seabloom et al. 2001) which is related to water supply from precipitation and/or melt of mountain glaciers in upstream areas (Shen et al. 2001). Previous studies of riparian forest in semiarid regions have addressed the ecological aspects of water availability in regulating forest growth (van Coller et al. 2000; Horton et al. 2001), and also the hydrological aspects of water distribution in relation to characteristics of precipitation, streamflow, and underground water (Mensforth et al. 1994). These ecological and hydrological processes, however, do not operate in isolation but interact in a complex way that is still poorly understood. Added to this complexity is the human alteration on land cover in the course of economic development (Miller et al. 2002). These interactions have received increasing interest in recent years and have emerged as an important research frontier at the interface of ecology, hydrology and economy (Wilcox et al. 2003; Cleverly et al. 2006; Wilcox and Thurow 2006; Ekness and Randhir 2007).

Besides the above complex interactions among different processes, an additional challenge for evaluating the vulnerability of oases is the scarcity of long-term and spatially dense data on the variability in forest growth. Most studies on oases forests mainly focused on observations of modern processes and on experimentations under controlled conditions. These observed records are often too short to encompass the full range of variability in forest growth. The experimentation is often limited in simple systems, and is difficult to detect impacts of spatially heterogeneous habitats on forest growth. To date, clarification of the complex ecohydrological processes and the spatiotemporal variability in forest growth that determine the vulnerability of an oasis still remains a vexing problem.

In this study we tackle the problem of oasis vulnerability by investigating tree-ring growth of oasis forest in response to changes in streamflow and human activities in Heihe Watershed of northwestern China. The tree rings represent an integrated result from interactions of various ecohydrological processes, and the longevity and distribution of trees allow for examination of spatiotemporal characteristics of forest growth. The areas under study are two typical oases situated in the middle and lower reaches of the Heihe River, which is approximately 880 km in length and is the second largest inland river in China. The oasis in the middle reach, Zhangye Oasis, is a fast-developing agricultural and urbanized centre, whereas the oasis in the lower reach, Ejina Oasis, is a small-scale but important area for ecological preservation. Conflicts on water supply and demand between Zhangye and Ejina oases have long existed but difficult to resolve due to limited amount of water resources in the watershed and increasing human activities in the middle reach (Liu and Zhao 2003; Liu et al. 2010). Two major terminal lakes in Ejina Oasis were dried out in 1961 and 1992, respectively, and the oasis was under threats of further habitat destruction.

A set of studies on the ecology, hydrology, and economy of the Heihe Watershed have been conducted over the past decade. Although some advances in the management of water resources have been achieved as a result of these researches and governmental administration, a solid scientific ground is still lacking for assessing the vulnerability of oasis forests and for developing plans for rational utilization of water resources (Li et al. 2005). The purpose of this study is to characterize spatiotemporal patterns and changes in forest growth to gain insights into oasis vulnerability with respect to environmental changes. The specific objectives of our study were (1) to provide tree-ring data for use as a reference baseline of past environmental variability; (2) to examine the growth response in oasis forest to changes in hydrological conditions; and (3) to evaluate the changes in spatial habitats of oasis forest and its vulnerability to changes in hydrological conditions.

Study area

The Heihe River starts from Qilian Mountain at the northern fringe of the Qinghai-Tibetan Plateau. It flows through Hexi Corridor on the Silk Road, and ends in terminal lakes in Ejina county of Inner Mongolia (Fig. 1). The Heihe Watershed covers an area approximately 130,000 km^2, and includes humid, semiarid, arid, and hyperarid zones from upper, middle to lower reaches. The area between Yingluoxia and Zhengyixia hydrological stations constitutes the middle reach, and that above Yingluoxia station is the upper reach and below Zhengyixia station is the lower reach (Fig. 1).

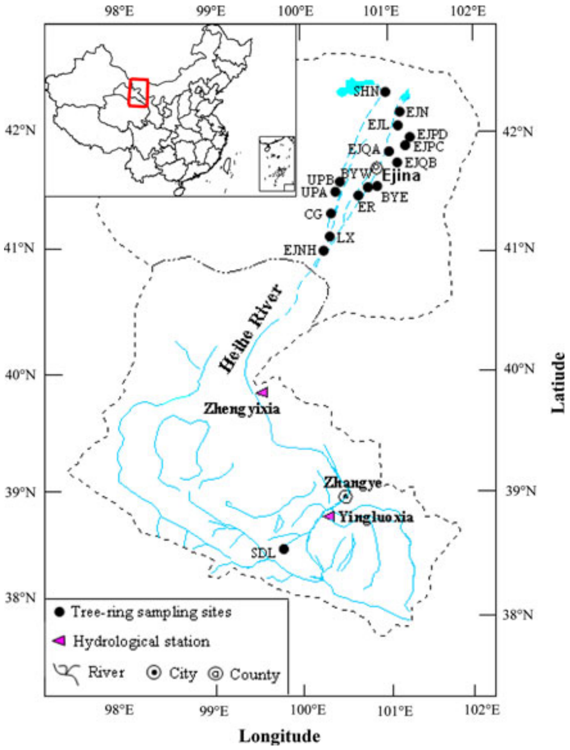

Fig. 1 Location of the tree-ring sampling sites and the hydrological stations in Heihe Watershed of the northwestern China

The Qilian Mountain in the upper reach has an elevation ranging from about 2,000 to 5,500 m above sea level. Mean annual total precipitation is about 250 mm in the low mountain zone, and could be as high as 800 mm in the high mountain zone. Glaciers in the high mountains are an important water resource for all the inland rivers in the region (Liu et al. 2003). Forests in the mountainous area of the upper reach mainly include *Sabina przewalskii* Kom. and *Picea crassifolia* Kom. Few human activities occur in this area.

The elevation of the middle reach of the Heihe Watershed is between about 1,000–2,000 m. Mean annual air temperature is about 8°C, and mean annual total precipitation is about 180 mm. Zhangye Oasis is dominated by irrigated farmland and is the most urbanized area in the watershed. It has a population about one million and has experienced a rapid socio-economic development (Liu and Zhao 2003).

The Ejina Oasis in the lower reach has an elevation about 900–1,100 m, and an area about 11,400 km^2 (Liu and Zhao 2003). The human population in the oasis is about 16,500, and people live mainly on farming and livestock husbandry. Mean annual air temperature is 6–8.5°C with warmest month in July being 22–26.4°C and coldest month in January being −9 to −14°C. Mean annual total precipitation is 37 mm. Mean number of heavy windy days (greater than 8th degree in the Beaufort wind scale) is 40–50 days. The Heihe River that flows within Ejina county is about 158 km and this section of the river is called Ejina River. The Ejina River is divided into two dominant tributaries, i.e., the east and the west tributaries, and they further diverge into 19 channels. These stream channels converge mainly to east and west terminal lakes and a few smaller lakes. The Ejina area is a natural oasis dominated by a single tree species, *Populus euphratica* Oliv. (Euphrates poplar). These poplar trees usually grow along river banks and distribute in patches depending on local habitats which vary in accordance to dynamics of the streamflow and disturbances (Fig. 2). Main shrub species in the oasis include *Tamarix ramosissima* Ledeb and *Sophara alopecuroides* L. The main soil type is forest-shrub meadow soil which alternates with fixed and semi-fixed wind-sand soil (Liu and Zhao 2003).

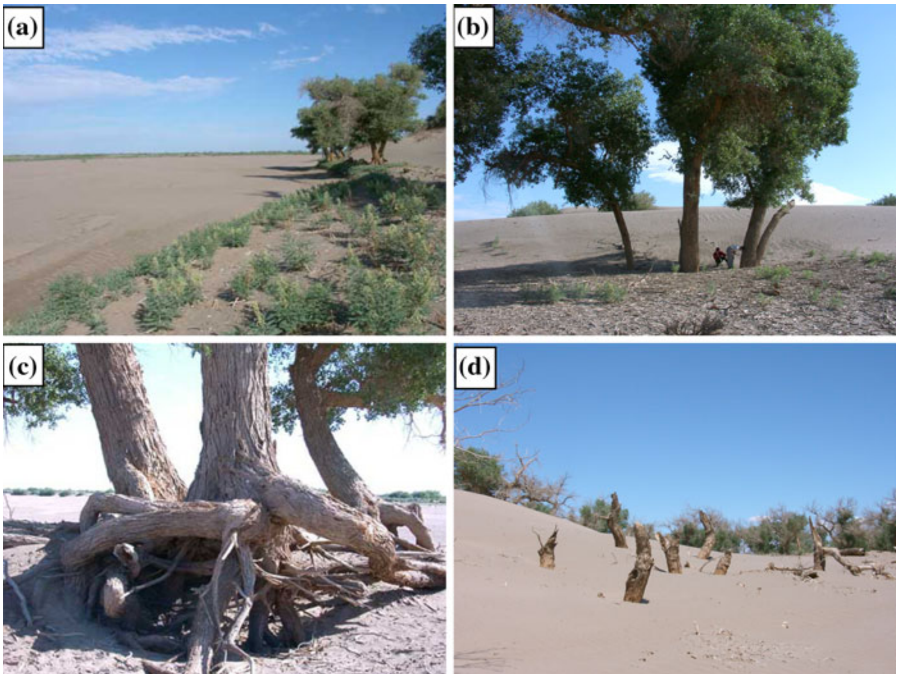

Fig. 2 Euphrates poplar trees growing in different site habitats in Ejina Oasis. **a** On the bank of stream channel; **b** At the edge of sand dune; **c** Surface soil removed and upper part of root exposed; **d** Sand accumulated and tree stems broken

Methods

Field sampling

Field sampling was conducted in the summers of 2002, 2003 and 2004. Tree-ring samples were collected from *Sabina* trees at Sidalong site in the end of the upper reach, and from poplar trees at 15 sites in Ejina Oasis of the lower reach of Heihe Watershed (Fig. 1). The Sidalong site was chosen to represent climatic and hydrologic conditions at the transitional point between the upper and middle reach of the Heihe Watershed. *Sabina* trees had higher longevity than other tree species in the region and were sensitive to regional environmental change (Zhang et al. 2003). The 15 sampling sites for poplar trees were selected to represent the spectrum of habitats that support mature forest and large patches of tree distribution in Ejina Oasis.

At each site, increment core samples (one core per tree) were extracted at breast height from trees that have large diameter and presumably old age. Selection of *Sabina* trees for sampling was based on characteristics that reflect large-scale climatic and hydrologic signals while reducing noise from local disturbances and competition among trees. The *Sabina* trees were growing in mountainous areas and the increment cores were extracted in a direction parallel to the slope contour. The sampled poplar trees were selected subjectively with consideration of obtaining signals that represent edaphic and hydrologic conditions in local habitat, such as river banks, flat ground, and sand dunes. The selection of poplar trees also considered the distance among trees so that competition among sampled trees was minimal. In total, increment core samples from 40 *Sabina* trees and 279 poplar trees were collected in the Heihe Watershed.

Tree-ring chronology development

In the laboratory, the increment core samples were mounted into grooved wooden boards and polished by hand with sandpapers of progressively finer grit (up to 600) so as to bring the rings clearly visible. Ring widths of the samples were measured to the nearest 0.01 mm using a Lintab tree-ring measuring system. The measured tree-ring sequences at each sampling site were crossdated by a variety of means including comparison of any morphological characteristics that are clearly visible in tree rings under microscope, matching the plots of ring-width sequences and marker years among samples, and quality-checking with the software COFECHA (Holmes 1983; Grissino-Mayer 2001).

Ring-width chronology for each site was developed with the software ARSTAN (Cook and Holmes 1996). For *Sabina* trees that are sensitive to large-scale climatic variation, the age-related growth trend was removed using a negative exponential curve, a horizontal line through the mean, or a straight line with negative slope. For poplar trees that are under influence of ecohydrological disturbances, the growth trend related to tree's age and low-frequency stand dynamics were removed using a spline function with a 50% frequency response of 64 years (Cook and Peters 1981). The detrended ring-width sequences were then averaged together by year across different samples in a site. The resulting tree-ring chronology represents growth variations caused by common environmental forcing at a site. The length of chronologies used for analysis was chosen such that the interval had at least five sample replications. Chronological statistics, such as the mean sensitivity (a measure of the annual variability in tree-rings), mean inter-serial correlation (a measure of the amount of common signals among tree-ring sequences), expressed population signal (EPS which is a measure of the strength of environmental signals expressed by tree rings), subsample signal strength (SSS which is a measure of the strength of environmental signals contained in a subsample of tree rings relative to the whole number of samples), and the variance in first PC of tree-ring series (which is a measure of the amount of signals in tree rings that could be represented by the first principal component) were obtained to show basic characteristics of the tree-ring chronologies (Cook and Kairiukstis 1990).

Tree-ring growth in relation to hydrological conditions

Correlation analysis was conducted to examine the relationships between tree-ring chronologies and hydrological conditions in the Heihe Watershed. The hydrological data included monthly runoff from 1944 to 2001 at Yingluoxia hydrological station and from 1954 to 2001 at Zhengyixia hydrological station (Fig. 1). The runoff data at Yingluoxia station were used to evaluate the representativeness of *Sabina* tree-ring chronology for variation of runoff flowing from upper to middle reaches, and the streamflow data at Zhengyixia station were used to evaluate the influence of streamflow variability on poplar tree-ring growth in Ejian Oasis of the lower reach. Principal component analysis was used to examine its ability to capture common variance among site chronologies in Ejina Oasis.

Characterizing changes in the spatial habitat structure

For studying the changes in spatial habitat structure in Ejina oasis of the lower reach of Heihe watershed, we consider that poplar tree-ring indices from all the n sites in year $i-1$ compose a $(n \times 1)$ vector (H_{i-1}) representing the spatial habitat structure for year $i-1$, and those of the following year compose another $(n \times 1)$ vector (H_i). The change in spatial habitat from year $i-1$ to year i can then be evaluated by calculating an index of multi-directional change (MDC_i) in the following way.

$$MDC_i = \frac{2 \times Cov(H_{i-1}, H_i)}{V(H_{i-1}) + V(H_i)}$$

where the $Cov(H_{i-1}, H_i)$ refers the covariance of H_{i-1} and H_i, and the $V(H_{i-1})$ and $V(H_i)$ are variances of H_{i-1} and H_i, respectively. The MDC_i index measures the degree to which the habitat conditions at all sites change equally from year $i-1$ to year i. The greater the positive MDC_i value, the higher the similarity in habitat change across sites from one year to the next. The greater the absolute value of a negative MDC_i, the larger the departure in habitat change across sites. When the MDC_i, value approaches zero, the pace of habitat change turns erratic over space.

We detected the trends in the MDC_i series using Mann-Kendall (MK) test in which the MK test statistic Z follows the standard normal distribution and its statistical significance could be tested (Hirsch et al. 1982).

Results

Tree-ring chronologies

Crossdating of tree-ring samples was time-consuming, particularly for poplar trees. In the end, increment core samples from 32 *Sabina* trees and 226 poplar trees were successfully crossdated and were used for constructing tree-ring chronologies. Increment cores from eight *Sabina* trees and 74 poplar trees were not crossdatable due to poor sample quality such as too many fragmentation, rotten pieces, or dominant influence by local habitat. These samples were excluded from further analysis to guarantee precision of crossdating and to strengthen the common signals in tree rings.

The *Sabina* chronology was 781 years in length (spanning the period from AD 1222 to 2002), and the 15 poplar chronologies had various lengths ranging from 75 to 198 years (Table 1). Compared to *Sabina* trees, the poplar trees had relatively lower values in the mean inter-serial correlation (0.36–0.60), relatively greater values in the mean sensitivity (0.23–0.40), and similar values in EPS (0.73–0.93 mm) and the first PC (26.1–55.1%).

Relationship between *Sabina* tree-ring chronology and runoff variation

Correlation analysis showed that the radial growth of *Sabina* trees was positively correlated to May–August runoff at Yingluoxia hydrological station for the period 1944–2001 ($r = 0.45$, $n = 58$, $p = 0.0004$). When the tree-ring chronology and the runoff data were smoothed by a 11-year running average, the two series showed a highly similar pattern ($r = 0.92$, $n = 48$) (Fig. 3). These observations indicated that the *Sabina* tree-ring chronology could reflect the low frequency variation in runoff flowing from the upper into the middle reach of the Heihe Watershed. Putting the observed record of stream runoff at the Yingluoxia hydrological station into the context of the 781-year-long *Sabina* tree-ring chronology, it is clearly visible that the variability of stream runoff in the observed period represents only a small subset of the full range

Table 1 Dendrochronological characteristics for the *Sabina przewalskii* ring-width chronology (site SDL) and the 15 site chronologies of *Populus euphratica* in Heihe Watershed of the northwestern China

Site code	Chronology period	Number of samples crossdated (collected)	Mean inter-serial correlation	Mean sensitivity	EPS (SSS)	PC1 (%)	Correlation with May–August runoff
SDL	1222–2002	32 (40)	0.59	0.24	0.91 (0.80)	38.0	0.45*
BYE	1891–2003	17 (20)	0.46	0.32	0.89 (0.79)	36.8	0.08
BYW	1876–2003	22 (25)	0.46	0.33	0.88 (0.74)	29.9	−0.11
CG	1888–2003	18 (20)	0.48	0.39	0.82 (0.68)	26.1	−0.07
EJNH	1916–2003	10 (20)	0.50	0.36	0.78 (0.85)	36.1	−0.21
ER	1880–2003	21 (24)	0.48	0.31	0.90 (0.76)	34.1	0.25
LX	1883–2003	17 (20)	0.55	0.40	0.89 (0.82)	38.3	0.47*
SHN	1913–2003	17 (20)	0.51	0.39	0.89 (0.79)	36.4	−0.16
UPA	1929–2003	10 (15)	0.36	0.30	0.77 (0.83)	35.2	0.02
UPB	1912–2003	25 (25)	0.60	0.34	0.93 (0.79)	38.2	−0.18
EJL	1845–2001	15 (20)	0.38	0.26	0.78 (0.72)	27.3	−0.21
EJN	1909–2001	18 (20)	0.54	0.40	0.92 (0.83)	43.3	−0.02
EJPC	1804–2001	18 (20)	0.60	0.23	0.92 (0.83)	43.1	0.02
EJPD	1885–2001	6 (10)	0.38	0.27	0.81 (0.96)	51.6	−0.10
EJQA	1842–2001	5 (7)	0.55	0.25	0.80 (1.00)	55.1	0.11
EJQB	1837–2001	6 (13)	0.46	0.30	0.73 (0.95)	44.0	−0.34

Location of the sampling sites is shown on Fig. 1. The chronology period is truncated to include at least five sample replications. Mean inter-serial correlation and mean sensitivity are obtained from the corresponding values calculated in a sliding window of 50 years on the time span of the tree-ring series. EPS corresponds to the maximum number of sample replications and SSS corresponds to five sample replications. PC1 corresponds to the common period of the samples. Correlation with runoff is calculated for the period 1944–2001 for SDL site chronology and for the period 1954–2001 for other site chronologies

* Denotes significance at the level $P < 0.01$

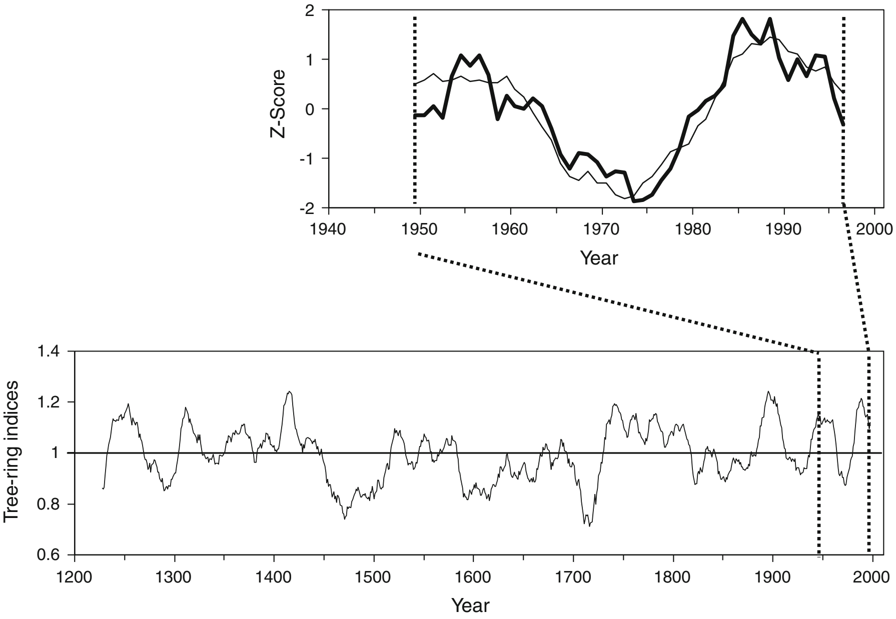

Fig. 3 Tree-ring width chronology of *Sabina przewalskii* from A.D. 1222–2002 (*bottom graph*) and its comparison with observed stream runoff at Yingluoxia hydrological station for the period A.D. 1944–2001 (*top graph* in which *light line* refers to tree-ring series and *dark line* refers to stream runoff). Both series are 11-year running averages with the points placed at the middle position

of natural runoff variability (Fig. 3). Notable features of the long *Sabina* chronology is the sustained below average growth in the mid-fifteenth century to the early sixteenth century and in the late sixteenth century to the mid-eighteenth century. The minimum of tree-ring indices during these two intervals were much lower than that of the observed period.

Euphrates poplar tree-ring growth in relation to streamflow variation

The low annual total precipitation (37 mm averaged in period 1957–2002) in the hyperarid region of the lower reach of Heihe Watershed is not sufficient for the demand of water in oasis forest growth. Underground water recharged from streamflow is considered an important source of water for maintaining oasis forest. Our correlation analysis for the period 1954–2001 showed, however, that the streamflow coming from the Zhengyixia hydrological station did not have a consistent correlation with the poplar tree-ring chronologies (Table 1). The highest correlation coefficients occurred between May–August streamflow and tree-ring chronologies at sites LX ($r = 0.47$, $n = 48$, $P = 0.0007$) and EJQB ($r = -0.34$, $n = 48$, $P = 0.0179$). Further examination of the correlations among the 15 site poplar chronologies for the common period 1929–2001 also showed poor correlations among these sites (mean correlation coefficient $r = 0.16$, $n = 73$).

Principal Component (PC) analysis of the 15 site-chronologies for the common period 1929–2001 showed that the amount of variance represented by the first PC in a moving 31-year interval was low (between 23 and 38%) and relatively greater in years before the 1950s than after (Fig. 4), indicating that the spatial pattern of growth was complex and not stable through time. Consequently it is inappropriate to use the PCs to represent the whole region and the whole period for analysis of past environmental variability.

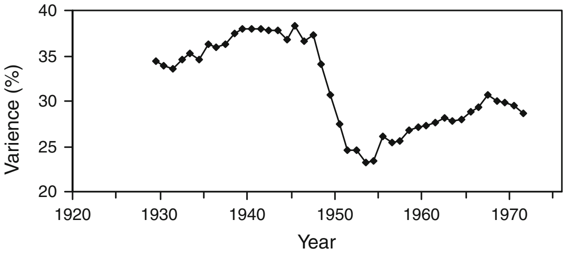

Fig. 4 Variance represented by the first principal component of the 15 euphrates poplar tree-ring chronologies in a moving 31-year interval (the point is placed on the first year) over the common period A.D. 1929–2001

Changes in the spatial habitat structure

The indices of MDC_i were calculated for the period 1891–2001 during which there were 15 site chronologies in the interval 1929–2001 and at least 10 site chronologies in other intervals (Fig. 5a). The MDC_i indices showed both low- and high-frequency changes. In the period before 1950s, the MDC_i indices were relatively high except for intervals at 1900s and 1930s. The MDC_i indices since 1950 was characterized by a general decreasing trend and a higher frequency in occurrence of negative MDC_i, values. The decreasing trend was significant at the level $P < 0.05$ as tested by Mann-Kendall statistic Z ($Z = -2.25$).

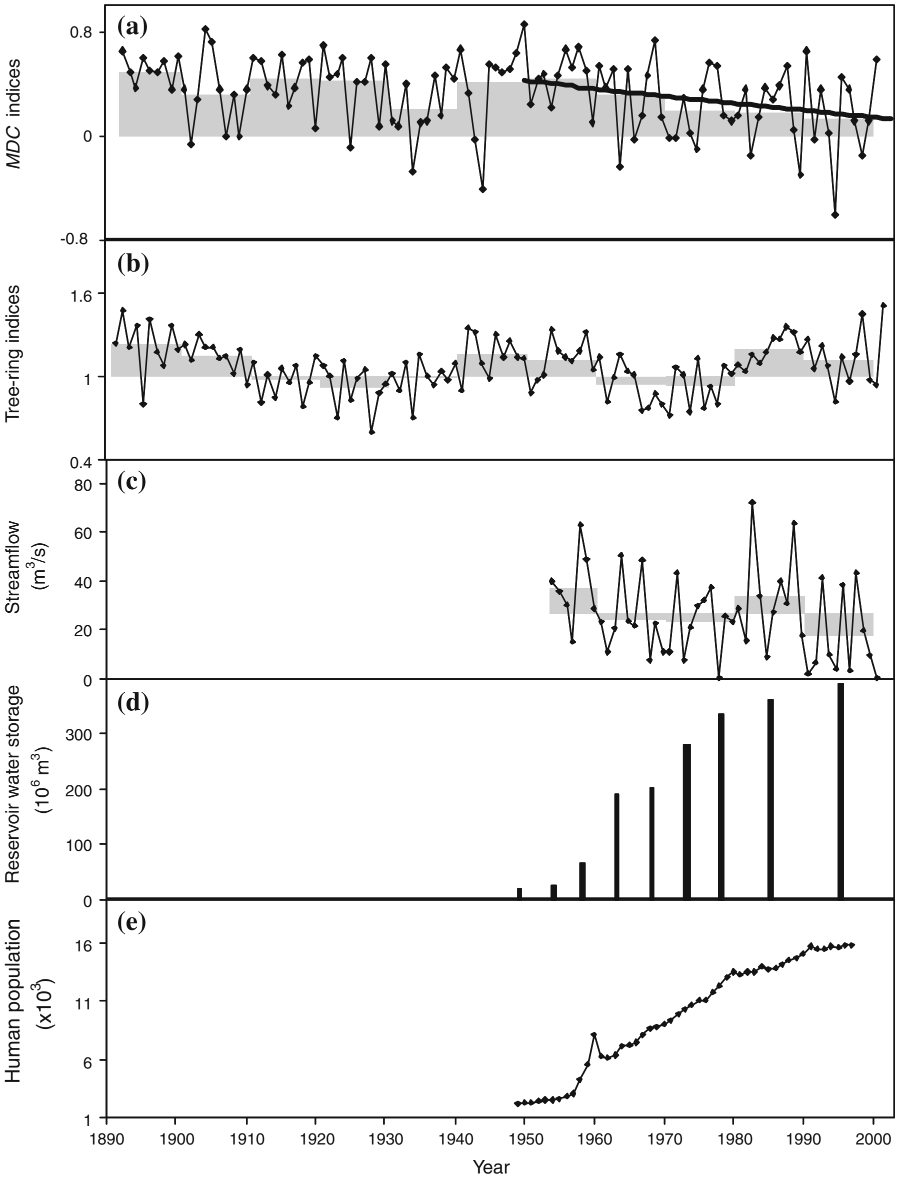

Fig. 5 Comparison of the MDC_i series for Ejina Oasis with ecohydrological and human activity records in Heihe Watershed of northwestern China. **a** MDC_i series for Ejina Oasis superimposed by the trend line since 1950; **b** *Sabina* tree-ring chronology representing the variability of stream runoff flowing from the upper to middle reach of the Heihe watershed; **c** Observed streamflow at Zhengyixia hydrological station; **d** Water storage capacity of reservoirs constructed in the middle reach; **e** Human population in Ejina county. The histogram shows non-overlapping decadal average of the time series

Discussion

In dendroecological studies, large-scale environmental change affects the annual growth rings of the same tree species in a similar way, making it possible for crossdating tree-ring samples and for extracting signals of regional environmental change from tree rings (Fritts and Swetnam 1989). Moisture-sensitive tree rings in watershed regions have been successfully used to reconstruct past streamflow variability (Woodhouse 2004; Lara et al. 2008). Our dendroecological studies showed that (1) the radial growth of poplar trees in Ejina Oasis did not follow the variation of streamflow coming from the middle reach, (2) the poplar tree-ring growth did not change in the same way from one site to the other, and (3) the spatial pattern in poplar tree-ring growth were different before and after the 1950s. These observations suggested that the amount of streamflow that reached the poplar sites were different from one site to the other and the structure of spatially heterogeneous habitats was not stable but changing in different directions through time. Although time-varying divergences in streamflow reconstructions due to differential influence of climatic features have been reported (Woodhouse and Lukas 2006), the spatial and temporal inconsistent patterns among the 15 site poplar tree-ring chronologies in this study are unlikely due to climate because the Ejina oasis has a flat landform and is under influence of the same climate. We consider that habitat conditions specific to a local site played a major role in shaping the tree-ring growth.

Characterizing spatial habitat structure and clarifying its impact on population dynamics are among the central issues being discussed in landscape ecology. Previous studies in the lower reach of the Heihe Watershed mainly focused on landscape structure of the oasis at a certain time or a few discrete points of time (Li et al. 2001; He et al. 2007). Changes in the spatial habitat structure through time, however, received less attention due to lack of observed record for past habitat change. Given that the Ejina River diverges into 19 channels in a relatively flat landscape which often lead to changes in the position of channels, our multiple site tree-ring chronologies in Ejina Oasis provided a unique opportunity to investigate the multi-directional change (MDC_i) in spatial habitat structure and to explore its implications for assessing vulnerability of oasis forest.

The MDC_i indices showed that the spatial habitat structure is not stable through time and there is a decreasing trend since the 1950s (Fig. 5a). Such temporal change in habitat mosaic has been considered one of the fundamental attributes of many heterogeneous landscapes such as natural floodplain ecosystems (Magyar et al. 2007; Whited et al. 2007). Putting together the information about upstream runoff variation as indicated by the *Sabina* tree-ring chronology (Fig. 5b), the streamflow at Zhengyixia hydrological station (Fig. 5c), number of reservoirs constructed in the middle reach (Fig. 5d), and human population in Ejina County (Fig. 5e), we found that, before 1950s, intervals of rich upstream runoff such as those in the 1890s–1900s and 1940s–1950s corresponded to relatively high MDC_i values, but interval of low upstream runoff in the 1910s–1930s did not correspond to low MDC_i, values (though relatively low in the 1930s). The decreasing trend in the MDC_i indices since the 1950s was accompanied by a generally decreasing trend in the streamflow at Zhengyixia station (Fig. 5c), increasing trend in the capacity of reservoirs' storage of water in the middle reach (the number of reservoirs increased from 2 in year 1949 to 98 in year 2004) (Fig. 5d), and increasing trend in human population in the lower reach (Fig. 5e). These observations suggested that when human activity in the watershed was in small scale and low intensity such as before the 1950s, the change in spatial habitats was in a generally same direction across sites, whereas persistently increasing human activities in the middle and lower reaches since the 1950s could alter the stream regime and result in multi-directional change in spatial habitats.

The high-frequency change in spatial habitats, not receiving much attention in the past, is an important feature revealed from the MDC_i indices. Here we argue that this high-frequency change is related to frequent and strong local disturbances such as windstorms as well as human activities that directly cause change in stream channels. In Ejina region, there are about 40–50 days having strong wind blow (greater than 8th degree in the Beaufort wind scale) and about 10 days having sand storm (visibility less than 1 km) in average in a year (Ejina Chorography 1998). These strong windstorms occur most frequently in spring. Surface soil condition could be altered by strong wind blow leaving part of trees' root exposed to the air, and other trees' trunk partly buried (Fig. 2c, d). Such frequent and strong wind could consequently affect tree growth to an extent that varies from site to site depending on the types of local soil structure and topography. Observed records showed that extremely strong wind/sand storms occurred in years 1973, 1979, 1980, 1981, 1991, 1992 and 1993 (Ejina Chorography 1998). Our MDC_i indices were low either in these years (e.g., 1979–1981, 1992) or the following years (e.g., 1974–1975, and 1995), suggesting that the spatial habitats in these years tend to change in different directions. With regard to human activities that directly alter stream channels, the artificial block of the Ejina east tributary in 1941 and the removal of block in 1952 provide a chance to examine their effects on the change in spatial habitats. The MDC_i indices decreased sharply from 1941 to 1944, and were relatively low in 1952–1955 (Fig. 5a). Examination of the year-to-year changes in site chronologies, however, did not show an obvious spatial pattern in growth increase or decrease from the west tributary sites to east tributary sites. For earlier periods that lack documentations, the low values of MDC_i indices were likely associated with such disturbances, particularly, strong wind/sand storms because the extent of human activities were relatively low.

The characteristics of low- and high-frequency change in spatial habitats imply that Ejina Oasis is vulnerable to persistently increasing human activities and ecological disturbances influencing local site conditions. In fact, the area of poplar forest in Ejina Oasis has reduced from 50,000 ha from the early 1970s to 29,400 ha in the early 2000s, and the forest shows a tendency of increasing the number of patches (Zhao et al. 2003). Shrinkage and fragmentation of oasis forest could affect the structure of oasis-dessert atmosphere boundary layer and weaken the oasis breeze circulation which could pose further risk to oasis forest by allowing dry and hot air to flow from the desert into the oasis (Lu et al. 2004). Improved understanding of the historical change in spatial habitat is particularly useful for vulnerability assessment in areas where habitat fragmentation and destruction are frequent and severe.

Conclusions

Oasis forest is sensitive to environmental changes due to its unique geographic location surrounded by desert. Scarcity of long-term and spatially explicit record of habitat conditions often limits our ability to evaluate the vulnerability of oasis forest to changing environment. Our dendroecological study in Heihe Watershed of northwestern China showed that although the lower reach Ejina Oasis has a quite flat landform, the underground hydrological properties over space are not as the same flat as the above ground. The heterogeneous habitat structure is not a static one but rather it varies through time and the influence of such temporal change on oasis forest was underestimated before. Besides the supply of stream water which is widely considered as a dominant factor constraining the growth of oasis forest, our study demonstrated that persistently increasing human activity could cause spatial habitats to change gradually in different directions. Frequent and strong disturbances like windstorm could be an important factor influencing the high-frequency change in spatial habitat structure. The tree-ring chronologies derived from this study will contribute to ecohydrological proxy database for historical reference of environmental variability and for comparisons with other studies in and beyond the Heihe Watershed.

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