# Stand structure and dynamics of riparian *Populus euphratica* forest located in Ejina Oasis, Inner Mongolia, China

September, 2014

Xiaogang LI

Graduate School of Environmental Science

(Doctor's Course)

**OKAYAMA UNIVERSITY** 

# 1 Introduction

#### 1.1 Riparian forest in dryland

Dryland ecosystems include many kinds of vegetation such as forests, shrublands, farms, grasslands and deserts, and many of them support only a small volume of biomass due to a lack of water. As low amount of precipitation, spring and stream flown out from groundwater and river water come from the outer area of arid region are usually the main water source in arid region. These water sources are unevenly distributed in a very limited area (oasis). These riverine areas are unique habitats that can provide very suitable place for plant growth in dryland. Therefore, most of vegetation in dryland usually distribute along river and form riparian ecosystem. Although riparian vegetation in arid and semi-arid region is poor in its species richness in comparison with other more humid area (Jean et al. 1996) and is restricted its distribution within narrow strip along river, it can support a high level of biomass in both quality (high biodiversity) and quantity (high productivity) (Han and Meng 1999). It has also an extreme value of ecological and economic aspects for local people.

Dawson and Ehleringer (1991) found that matured trees in semi-arid riparian forest in western United States could use groundwater by their deep root system, and in contrast, small trees were supported by streamwater and/or recent rain water stored in upper soil layer. Such difference in the main source of soil water was attributable to vertical elongation of root system caused by tree growth. As water flowing into oasis is usually originated in the exterior area, the amount of water flow is highly affected by irregular fluctuations of rainfall in water source region. As a result, unpredictable decrease and disappear of river flow causes severe damage on shallow rooted small plants and changes the structure of dryland riparian vegetation. Even for matured phreatophytes with deep root system, changes in groundwater level caused by the cessation of recharge from upstream has a great effect on their survival.

Dryland riparian forest plays important roles for many ecological situations in arid region. It can protect the ground condition against high solar radiation and meliorates the microclimate. As a result, soil formation is promoted beneath the forest canopy and capacity of soil water storage is improved by accumulation of alluminium. Mild and fertile environment can serve good habitat for wildlife and have important ecological and economic value for agricultural production for local people. Moreover, high and dense structure of riparian forest can prevent soil water erosion, strong wind and encroachment of sand dunes. Then it can provide effective natural barriers against the sand and dust storms (DSS) in open, flat and dry region where is the main source area of yellow sand raged to Japan in every spring. Breshears et al. (2003) reported the effective prevention of wind-driven sand flux by forest vegetation in semi-arid western USA, namely sand flux decreased to  $1.7 \times 10^{-1}$  gm<sup>-2</sup>d<sup>-1</sup> in forest from 1.5 and 15 gm<sup>-2</sup>d<sup>-1</sup> in grassland and shrubland respectively. Therefore restoration and protection of riparian forest in the source area of DSS is one of the best countermeasures to decrease DSS disaster.

Since the water flown from upper stream is the main water source of riparian forests in dryland, anthropogenic activities such as reclamation with intensive irrigation, construction of reservoir for industrial production and domestic use and water pollution especially in salinity have severe effects on water condition in riverine ecosystem. Then a large number of dryland riparian forests in Amudarya delta (Rüger 2003), Tarim River Basin (Liu et al. 2005) and Heihe River Basin (Wang and Cheng 1999; Zhao et al. 2004; Ji et al. 2006; Qi and Luo 2007) in northeast Asia and Vaal River Basin in south Africa (Seymour and Simmons 2008) and so on showed severe deterioration in their structure and functions. As a result, frequency and scale of DSS strengthened year by year. For example, in 1998, satellite monitoring detected long rage transport of DSS originated in northeast Asia to north American across the Pacific Ocean (Zhao et al. 2008).

#### 1.2 Populus euphratica forest

*Populus euphratica* Olive (Photo 1) is the representative tree species of dryland riparian forests (Tugay forest) (Rüger 2003; Thevs 2005) in arid and semi-arid regions extending from northeast and western Asia to North Africa and southern Europe (Fig. 1). It is a well-known member of the Salicaceae. The largest tree in Ejina Oasis is 27m in height and 207 cm in DBH with over 800 years old. Most of *P. euphratica* forests in Ejina Oasis are supported by inflow of Heihe River because of small amount of rainfall, e.g. only 34 mm in 2004. Moreover, annual inflow of Heihe River has shown wide fluctuation over past 50 year (Akiyama 2007). In such an unreliable environmental condition, a large proportion of *P. euphratica* forests in Ejina Oasis suffered severe damage and degraded.

*P. euphratica* forests in Ejina Oasis were classified into three categories by the size of dominant trees, namely juvenile stage with small dominants lower than 2 m in height, matured stage with and without suppressed trees lower than 4 m in height and



Photo 1 Populus euphratica Olive



Fig. 1 World distribution of P. euphratica forest

overmatured stage with trees bigger than 30 cm in DBH (Monda et al. 2008). Irrespective of the tree size, very high proportion of *P. euphratica* suffered severe damage on the apical stem (dieback). Dieback phenomenon can control leaf biomass to adjust water loss by transpiration to the amount of water supply under drought. Moreover, Monda et al. (2008) suggested that the loss of apical part of crown could promote regeneration on forest floor with almost the same amount of leaf biomass but low rate of leaf specific transpiration, which mean depression of water loss with high rate of photosynthesis. The most unique character of *P. euphratica* is its diversiform of leaves from lanceolate to dentate broad-ovate (Photo 2). Li and Zheng (2005) found that as leaf shape changed from lanceolate to dentate broad-ovate, the leaf structure become more xeromorphic, namely increase in palisade tissue but decrease in spongy tissue, increase in cuticular thickness and deepen stomata. As a result, matured tree has broad-ovate leaves at the top part of crown and lanceolate leaves at the lower and shaded part of crown. Saplings and sprouts growing on the forest floor have only lanceolate leaves. Zhang et al. (2003) found that the photosynthetic rate of broad-ovate



Photo 2 Diversiform of leaves

leaves was higher than that of lanceolate leaves under high radiation and showed remarkable midday depression to avoid excessive loss of water.

*P. euphratica* adopts sexual and asexual reproduction. A great amount of small seeds are shed over a long period of the year (July–September) and germinate on fresh deposition carried by flooding in summer season (Thevs et al. 2008). Most of them construct arrays of seedlings on a shore of flooding, in where salt is easy to accumulate. Then saplings from seed must undergo an extreme environmental condition with drought, low and high temperature and high salinity. On the other hand, sprout from lateral roots in less than 20 cm below the ground surface can invade new habitat of low water availability because of a long extension of lateral root more than 20 m away from parent tree (Wiehle et al. 2009).

Although living in arid and semi-arid area and most of the regions show high concentration of salinity in both water and soil, many researchers found that *P. euphratica* has poor ability in both drought and salt tolerance than other species (Fu et al. 2012). By the experimental analysis, Li et al. (2012) found that rate of root elongation of *P. euphratica* was slower than that of *Tamarix ramosissima*, a subdominant shrub species in *P. euphratica* forest, under continuous decrease of groundwater level, and Hukin et al. (2005) found that *P. euphratica* was more vulnerability to cavitation than *P. alba* and *P. trichocarpa*  $\times$  *koreana*.

To establish the technology of forest protection, Jin et al. (2010) tried to estimate the minimum amount of water demand for the total area of *P. euphratica* forests in Ejina Oasis as  $4 \times 10^8$  m<sup>3</sup>/year.

To improve the restoration technology of *P. euphratica* forest. Cao et al. (2012) found that water shortage and river channeling induced the failure of seed germination and extensive grazing reduced successive regeneration by sprout. The same result found by Säumel et al. (2011) suggested the prohibition of forest grazing was the most effective way to guarantee the success of regeneration.

#### 1.3 Objectives

In Ejina Oasis, most of riparian area along the east and west tributaries of Heihe River are occupied by large *P. euphratica* forests. These forests have important ecological and economic values for local people, such as suitable mild climate for both human residents and wildlife inhabitants, fertile soil for agricultural production and livestock husbandry and etc. The complicate structure of both underground and aboveground parts endues them to prevent soil erosion by stream and wind in the extreme weather condition. These huge and wide forests established in Badain Jaran Desert can effectively prevent DSS in Northeast Asia. However, most of them have been deteriorated by reclamation and over exploitation of forest material and desertification induced the predominance of harsh weather and the loss of ecological services from the forests. Therefore protection and restoration of *P. euphratica* forests become a very important issue for natural conservation and sustainable development of human society.

In Ejina Oasis, riparian forests along the, west tributary of Heihe River are relatively remained their original and natural situation, namely big size of canopy tree and huge number of regenerating small trees, because of long distance from the residential area. The permanent experimental plot was established in a natural *P euphratica* forest at the middle basin of the west tributary to clarify the forest dynamics and the key process ensuring the sustainability under unreliable weather condition for the development of management and restoration technology in dryland. Structure and growth of canopy trees were measured to reveal the mechanisms of forest sustainability. Numerical change of both canopy trees and understory population were investigated by demographic analysis to know the resilience of regeneration strategy. Effects of environmental factors on establishment, regeneration and growth of *P. euphratica* forest were examined by the spatial association of trees with site conditions.

# 2 Study Area

The study area of this research is the *P. euphratic* forest (39°52'-42°47' N, 97°10'-103°7' E) established in the riparian area of Heihe River in Ejina Oasis as shown in Fig. 2.



Fig. 2 Study area in Northwestern China

# (1) Heihe River

Heihe River originates from Qilian Mountains in Qinghai Province and Gansu Province and it flows into Sogo Nur and Gashun Nur located at the north end of Badain Jaran Desert, Inner Mongolia Autonomous Region. The upper reaches of Heihe River are mountainous region and many old oases are developed in the middle reaches extending along the silk road. After intensive water utilization for agricultural production in the middle reaches, Heihe River flows into Badan Jaran Desert which is one of the most arid area in China and the main origin of DSS (dust and sand storm).

(2) Ejina Oasis

At the middle part of the lower reaches of Heihe River, Ejina Oasis is developed at the center of flooding plain. Ejina basin is an extremely arid area. From 1957 to 2001, mean precipitation and mean evaporation at Ejina are 38.5 mm and 3599.5 mm respectively, and mean annual temperature is 8.1 °C, with a maximum of 43.1 °C in summer and a minimum of -38.5 °C in winter (Feng et al. 2009). Elevation ranges from 820 to 1400 m (Khasbagan and Soyolt 2008). Groundwater level is  $1 \sim 3$  m at the riparian zone (Zhang et al. 2005a). Prevailing wind is from northwest in winter and spring, and from southeast in summer and fall. Annual mean wind velocity ranges from 2.9 to 5.0 m s<sup>-1</sup> (Hou et al. 2013), with a maximum of 20 m s<sup>-1</sup> (Wang et al. 2004). There is no vegetation in Badan Jaran Desert and the sand is moving from northwest to southeast. Shifting sand dunes affect the amount of water flow in Heihe River. (3) Shift of river course

As an annual average of precipitation in Ejina, the lower reaches of Heihe River, is only about 40 mm and also very low precipitation in middle reaches (50 ~ 150 mm/yr) (Wu et al. 2010), the main source of water in Heihe River is rain and melted snow and glacier in Qilian Mountains, the upper most reaches of Heihe River. Moreover, annual variation of these rain and snow falls in mountainous region shows very high fluctuation (200-700 mm) (Wu et al. 2003) affecting the amount of river water flowing into Ejina Oasis. For example, the total amount of river water flown into Eijna Oasis varied from 1.3 billion to 0.4 billion m<sup>3</sup>/year in 1950s and 1980s, respectively. Course of Heihe River is gradually shifting from east to west within several hundred years by sand dunes encroaching into the lower reaches. Namely, about 2300 years ago, Heihe River flew into Old Juyanhai which located in the southeast of Ejina Oasis (Fig. 3). But about 800 years ago, river course changed from Old Juyanhai to Sogo Nur which was located in north east from Old Juyanhai, because of interception of river flow by encroachment of sand dunes. About 600 years ago, Heihe River could reach at Gashun Nur which was the north end of Badain Jaran Desert. Moreover, several hundred years ago Heihe River branched off at the upper part of the lower reaches into two courses as shown in Fig. 2 and the mainstream shifted from the east to the west tributary at present (Fig. 3).



Fig. 3 Evolution of alluvial fan/ delta/ lake system in Ejina

Although both the amount of river flow and the location of river course are unstable because of large fluctuation of rainfall and perpetual movement of sand dunes, large riparian forests mainly dominated by *Populus euphratica* have been maintained for long period in Ejina Oasis. However, location of these forests have been always shifted by the changes of river course, as mentioned before. When Heihe River flew into Old Juyanhai in about 2300 years ago (Fig. 3), main popular forest was established in the south of Ejina Oasis, but it extended into northeast flooding area according to the changes in river flow from Old Juyanhai to Sogo Nur in 600 years ago. Moreover, after the river reached to Gashun Nur, most of popular forests in the south of Ejina Oasis were extinguished and the main part of popular forest was shifted to the north of Ejina Oasis. After the branching of Heihe River into two tributaries, riparian area along the west tributary became the main forest site.

#### (4) Riparin forest

One of the main routes of dust and sand storm (DSS) runs on Badan Jaran Desert and Ejina Oasis. Then big riparian forests in Ejina Oasis are an important windbreaks against DSS (Zhao et al. 2004).

In addition, the riverine alluvial flatland along two tributaries of Heihe River is the most fertile land for agricultural production of both crop production and livestock husbandry. Therefore, in Xi Xia Era about 1000 years ago, arable land reached  $3.1 \times 10^4$  hm<sup>2</sup> which was larger than the extant popular forest in Ejina Oasis ( $2 \times 10^4$  hm<sup>2</sup>) (Sun et al. 2000). As present cultivated land is 48.98 km<sup>2</sup> (Wang et al. 2013) and population in Ejina Oasis are increasing, local people apt to open up farmland by cutting trees of riparian forest and to deteriorate forest ecosystem by introducing livestock into forest floor. As a result, most of popular forests along two tributaries of Heihe River are degraded irrespective of distance from residential area of Ejina Oasis.

As same as the case of lower reaches, a great number of reservoirs was constructed in middle reaches to increase water utilization for agricultural and industrial productions because of the development of economic activity and the increase of population. It had great effects on water supply into Ejina Oasis. Such pressure increased year by year and consequently water flown into lower reaches was cut off completely since 1990s (Yang et al. 2012). As a result, all popular forests in Ejina Oasis suffered severe chronic drought stress for many years (Wang and Cheng 1999, Zhao et al. 2004, Ji et al. 2006, Qi and Luo 2007).

On the other hand, by the promotion activity of China Government for restoration of decayed ecosystem in Ejina Oasis, the Ecological Water Conveyance Project (EWCP) since 2000, vegetation in 80.4% of the oasis area and 91.5% of the desert regions showed remarkable improvement at middle and lower basin of the west tributary and lower basin of the east tributary (Yu and Wang 2012). Study site of this research located in lower basin of the west tributary (Fig. 2).

# 3 Materials and Methods

#### 3.1 Field investigation

In 2005, one permanent experimental plot of  $100 \times 100$  m (East corner: N 42° 7′ 25.1″, E 100° 49′ 45.4″; North corner: N 42° 7′ 28.2″, E 100° 49′ 44.4″; West corner: N 42° 7′ 27.5″, E 100° 49′ 40.3″; South corner: N 42° 7′ 24.4″, E 100° 49′ 41.2″) was established in the mature popular forest (Photo 2) growing on riparian flat land of the right bank of west tributary, Saihannuouer County, Western sector of Ejina Oasis (Fig. 3). The plot was located about 500m from the river and 400m from the forest edge.



Photo 2 Study plot

Undulation of ground surface and soil electrical conductivity (EC) were measured in 2010 at every 10 meters over the whole area of the plot by a mini-compass and EC meter (CONDUCTIVITY METEER ES-14, HORIBA), respectively.

In 2005, location, canopy width, height and diameter at breast height (DBH)

for trees higher than 2 meters of all living trees were measured. From 2009 to 2013, height of dead (except 2010) and living tops of all trees, DBH and crown projection area (CPA) of trees higher than 2 meters were measured once a year. In 2013, diameter at 10 cm height from the ground for trees lower than 2 meters were measured. Newly emerged individuals were numbered and their location and the same measurement items were recorded.



Fig. 4 Location of line plots

Table 1	Geographic	coordinates	of line	plots
	01			1

	River side	Forest edge
Line 1	N $42^\circ~7'~16.97''$ , E $100^\circ~49'~8.51''$	N $42^\circ~7'~8.09''$ , E $100^\circ~49'~22.93''$
Line 2	N $42^\circ~7'~13.07''$ , E $100^\circ~49'~4.09''$	N $42^\circ~7'~2.02''$ , E $100^\circ~49'~21.6''$
Line 3	N $42^\circ~7'~5.31''$ , E $100^\circ~48'~49.29''$	N $42^\circ~6'~51.52''$ , E $100^\circ~49'~7.35''$

Three line plots with 10 meters width were established from the river side to the forest edge in the next of the permanent plot in 2013 to analyze the changes of stand structure with the distance from the river as shown in Fig. 4. Latitude and longitude of each line plot are shown in Table 1. All trees in the plots were numbered and their coordinate locations were recorded. Height of dead and living tops of stem and bases of canopy, stem diameter (at breast height when H > 2 m or at 10 cm from the ground when H < 2 m) and dead and living CPA were recorded. Ground undulation was measured by Laser Rangefinder (TruPulse 360, laser Technology Inc.).

#### 3.2 Date analysis

Index of Aggregation (I<sub>a</sub>) was used to analyze the spatial distribution pattern of canopy trees (I<sub>a</sub> > 1, contagious; I<sub>a</sub> = 1, random; I<sub>a</sub> < 1, uniform distribution). A formal randomization test was done to calculate proportions of values in the frequency distribution. Using the usual two-tailed test with  $\alpha = 0.05$ , a data set was decided as (i) aggregated, (ii) random, and (iii) regular distribution pattern when P < 0.025,  $0.025 \le P \le 0.975$ , and P > 0.975, respectively (Maestre and Cortina 2002). The spatial associations of trees and environmental conditions were analyzed using an Index of Local Association (X) between two populations. This index (X) was calculated from the clustering indices and indicated positive and negative associations when X > 0 and X < 0, respectively. Formal randomization test was performed, in which the indices of clustering were randomly arranged by calculating the proportion of values in the frequency distribution that were as large as or larger than the observed value of X. Two-tailed test with  $\alpha = 0.05$  was used (Perry and Dixon 2002). Both indices (Ia, X)

were calculated with the Spatial Analysis by Distance IndicEs (SADIE) software package available at <u>http://home.cogeco.ca/~sadiespatial/index.html</u>.

The average values of EC and elevation in the four vertices of each subplot in the permanent plot were classified into 10 ranks (1, 0–3; 2, 3–6; 3, 6–9; 4, 9–12; 5, 12–15; 6, 15–18; 7, 18–21; 8, 21–24; 9, 24–27; 10, 27–30 mS cm<sup>-1</sup>) and 8 ranks (0, 0–4; 1, 4–8; 2, 8–12; 3, 12–16; 4, 16–20; 5, 20–24; 6, 24–28; 7, 28–32) respectively, for SADIE analyses.

# 4 Stand Structure

#### 4.1 Site condition in the plot

Figure 5 shows the contour lines of ground elevation in the plot. Although about 80 cm undulations in ground level were detected, over 90% of the plot was varied within 50 cm difference in elevation, because of a small but sharp depression at the west corner. A shallow riverbed ran from south to north in the western sector of the plot. The spatial change in soil salinity shown in Fig. 6 indicated that the eastern side of the plot was higher in salinity.

Both elevation and soil salinity were higher in the eastern side of the plot. In arid area, surface runoff is seemed to have a great effect on soil salinity, but soil salinity did not show any significant correlation with ground elevation (Fig. 7). It suggested that surface runoff in such flat area did not affect the distribution of soil salinity because of low frequency or unsteadiness of flow channel.

#### 4.2 Frequency distribution of tree sizes

Frequency distribution of tree height (Fig. 8) showed bimodal distribution in all census years with the threshold height at 2 m. About 30% of trees lower than 2 m were growing under the crown of other tree as shown in Fig. 8. Judging from low frequency around 2 m height and high proportion of understorys less than 2 m height, trees growing in the plot were classified into two groups, namely canopy trees higher than 2 m in height and saplings lower than 2m in height.



Fig. 6 Spatial distribution of soil salinity



Fig. 7 Relationship between elevation and soil salinity in the study plot



Fig. 8 Frequency distribution of tree height.■: saplings growing under canopy, □: saplings without any shading.

Frequency distribution of stem diameter (DBH for H > 2 m and  $D_{10}$  for  $H \le 2 \text{ m}$ ) are shown in Fig. 9. Fig. 9(a) to (e) showed unimodal distribution with the mode at 14 to 16 cm in DBH, which indicated the stable distribution of stem diameter of trees higher than 2 m. The mode of  $D_{10}$  of low trees in 2013 appeared at 0.8 cm. All tree diameter distribution of 2013 (Fig. 9(g)) showed bimodal distribution with the threshold diameter at 4 cm.



Fig. 9 Frequency distribution of diameter of trees. (a)~(e) H > 2 m, (f) H  $\leq$  2 m, (g) all trees.  $\Box$ : diameter at 10 cm height,  $\blacksquare$ : DBH.

#### 4.3 Diameter-Height relationship

Fig. 10 shows the diameter-height relationships for all established trees in 2009, 2010, 2011, 2012 and 2013. D-H regression line was calculated for trees in optimum growth condition which located in the uppermost part of D-H distribution in Fig.10. The maximum tree height estimated by these D-H relationships was 14 to 15 meters, which indicated the upper limit of height growth in this area. Monda et al. (2008) estimated the maximum of 16.85 m in Ejina region. The difference in  $2 \sim 3$  m between these two estimates indicated that the site of the plot was not the optimum condition for tree growth.



Fig. 10 Relationship between tree height and diameter in five experimental period from 2009 to 2013.

Lengths of bars attached to the symbols represent the lengths of dieback stems.

Six big trees larger than 50 cm in DBH showed remarkable depression in their height from the trend lines of D-H growth in each year. All these trees had a long dead stem on their top part, indicated by vertical bar on the symbol in Fig.10. Therefore very high proportion of big trees in the forest suffered from dieback damage. However, the dieback phenomenon was not restricted for the big trees but for all trees with wide range of DBH. The smallest tree with dieback stem was 5.2 cm in diameter in 2009 and 1.6 m in height in 2013, respectively.

To clarify the effect of tree size on the degree of dieback, relationship between length of dieback stem and DBH and living tree height (HL) are shown in Fig. 11 and Fig. 12, respectively. Although an increasing trend of dieback stem length with DBH was slightly detected, there were no significant positive relations of dieback stem length with both DBH and HL, which indicated the lack of continuous changes of dieback degree with the present size of tree. Such independent relation might be explained by following two aspects. The length of dead stem on the apical part of crown measured in this research did not reflect the real dieback stem length, because of accidental but perpetual loss of dieback stem from the top in every time, or D-H relationship predicted mainly by small trees shown in Fig. 10 was not realized for wide range of tree size.

To clarify the validity of these two aspects, D-H relationship of dieback trees was shown in Fig. 13 with predicted regression line from Fig.10. Most of dead height (HD) shown as the top of vertical bar on the symbol in the figure indicated a good relation with the regression line for small trees less than 20 cm in DBH. Therefore, even though a part of dead stem top was lost continuously, HD of small trees, which includes dieback stem, can be considered as a tree height before dieback loss. On the other hand, HD of large trees bigger than 20 cm in DBH could not reach at the regression line and



Fig. 11 Relationship between dieback length and diameter



Fig. 12 Relationship between dieback length and HL

showed some constant maximum height at around 10 m which considered as the height limit for big trees in the plot. As a result, small trees can grow vigorously by following D-H regression line which can lead their height to 14 to 15 m in maximum before they grow bigger than 10 m in height and 20 cm in DBH. However, large trees bigger than 20 cm in DBH show a large fluctuation in their height growth by severe dieback damage on apical part of stem. Their growth shows oscillation between the maximum height at around 10 m and height of dieback damage at about 5m with continuous growth in DBH. As a result, trees bigger than 20 cm in DBH cannot exceed their height than that of smaller trees. Then the site conditions mainly suffered on height growth of bigger trees are the limiting factors of this forest site.



Fig. 13 Relationship between height and diameter of dieback trees

Average length of dieback stem of large trees (DBH > 50 cm) was longer than small trees as shown in Fig. 14, which suggested that the degree of stress causing dieback was greater on large trees than on small trees. Although degree of drought stress varied in each year, there were no significant difference in dieback length in each year, suggesting a cumulative result of dieback stem.



4.4 Spatial distribution

According to the classification shown in Fig. 8, spatial distributions of two classes, namely canopy trees and under growing saplings, are shown in Fig.15. In order to analyze the process of germination and settlement, under growing saplings were divided into newborn and old saplings. The former sapling recruited in the present year and the latter survived at least more than one year. Spatial distributions of these two sapling groups and canopy trees were shown in Fig. 15.



Fig. 15 Spatial distribution of all trees in (a) 2009, (b) 2010, (c) 2011, (d) 2012 and (e) 2013.

	Old saplings	Newborn saplings	EC	Topography
Canopy trees	0.2759*	0.2294*	0.1009	0.3678*
Old saplings		0.7517*	0.3067*	0.1602
Newborn saplings			0.4393*	0.3743*
EC				0.4663*

Table 2 Spatial associations in 2010

\*: Significant positive association, P < 0.05

Values in the cells are indices of association (X)

To analyze the spatial associations of trees in different growth stages and the effects of environmental factors such as soil salinity (EC) and ground level (topography) on the spatial distribution of trees, indices of local association (X) were calculated (Table 2). Significant positive associations were observed among all three growth stages. It suggested that young trees could germinate and survive under canopies of mature trees which could provide suitable shelter from strong solar radiation. Ground level positively affected on canopy tree locations, which suggested a possibility of tree trunk functioning to rise ground surface by preventing surface runoff. Germination of *P. euphratica* is greatly influenced by hydrological dynamics and suitable place for settlement is restricted to a certain limited site conditions along river bank (Thevs et al. 2008), at where salt is easy to accumulate. Positive associations of newborn saplings with both topography and soil salinity demonstrated that suitable place for seed germination was limited on hillocked bank with high salinity. Old sapling survived at least more than one year showed positive association with soil salinity but independent with ground level to

survive for more than one year. On the other hand, suitable place for both seed germinate and survival of sapling keeps moving in every time in relation with the changes in flooding level over forest floor. Then, under unreliable rainfall condition, saplings can be established on lower place when the amount of water flow is small and can invade into high ground level by heavy flooding. As a result, old saplings showed independent from ground level.

# 5 Dynamic of canopy trees

Forest dynamic was analyzed by two levels of tree size such as canopy trees and regenerating trees (Li et al. 2014). This chapter dealt with the dynamics of canopy trees. According to Monda et al. (2008), matured forest with frequent regeneration showed bimodal height distribution with the threshold height at 4 m. Therefore, trees higher than 4 m were considered as matured trees, and 2 m to 4 m height trees were considered as regenerating canopy trees.

#### 5.1 Numerical change

Average height and tree density of matured and regenerating trees were showed in Fig. 16. Matured trees showed a slight trend to increase their average height, such as a significant difference between 2009 and 2012 (Fig. 16a). On the other hand, average height of regenerating trees remained a constant level, irrespective of great changes in their density (Fig. 16b).

Some trees grew into upper tree class and some other trees were demoted into lower tree class by dieback of apical stem. As a result, number of matured trees increased in some year and regenerating trees increased in other year. Fig. 17 show the changes in number of admission and quitting trees of matured and regenerating tree classes over the last four years. From 2009 to 2011, a large number of trees could grow up into matured tree class from lower regenerating tree class, but from 2010 to 2012, the numbers of dead trees in matured tree class were greater than other years. On the other hand, almost a constant number of small saplings could grow into regenerating



Fig. 16 Changes in canopy tree height and density for 5 years. Height values are means  $\pm$  SD. Letters indicate significantly difference (P < 0.05).



Fig. 17 Changes in number of (a) matured and (b) regenerating trees over four years.  $\Box$ : regenerating canopy trees grown into matured tree class;  $\blacksquare$ : matured trees diebacked into regenerating canopy tree class;  $\blacksquare$ : saplings grow into regenerating canopy trees diebacked into sapling class;  $\blacksquare$ : dead.

tree class in every year and, from 2012 to 2013, relatively a large number of regenerating trees were quit into sapling class by dieback.

#### 5.2 Height growth

Canopy trees were classified into three categories, namely well growing, diebacked and dead trees, which continued growth for the census period, diebacked or dead in any census period, respectively. Changes in average height of these trees are shown in Fig. 18. Well growing matured trees showed gradual increase in average height but not significant, indicating higher trees did not have any advantage in their growth over lower trees (Fig. 18a). Tree height of three categories of regenerating trees showed no significant difference for all census period (Fig. 18b).

Changes in average net height growth (difference of height between successive years) are shown in Fig. 19. From 2009 to 2011, diebacked matured trees showed significantly higher vitality in height growth after dieback than well growing trees (Fig. 19a). But after 2011, trees in both categories showed almost the same height growth. Regenerating trees showed no significant trend of height growth in both two categories (Fig. 19b).

Figure 20 shows the changes in relationship between changes in stem length and tree height of canopy trees. Both well growing and damage from dieback occurred in all range of tree height, indicating no remarkable height class which was favorable to grow or easy to suffer from dieback. However most of dead trees indicated by  $\times$  mark on the abscissa axis were shorter than the average height of living trees, which resulted a gradual increase in average height of matured trees from 2009 to 2012 (Fig. 16a).



Fig. 18 Changes in average height of (a) matured trees and (b) regenerating trees.
●: well growing, ■: diebacked and ▲: dead trees.



Fig. 19 Changes in average net growth length of (a) matured trees and (b) regenerating trees.

 $<sup>\</sup>bigcirc$ : well growing,  $\bigcirc$ : diebacked trees.

Total length of grown and diebacked stems of four years are shown in Fig. 21. Growth length of matured trees was obviously longer than dieback length in 2009 - 2010 and it roughly showed a balance with the loss of stem length from 2010 to 2013 (Fig. 21a). On the other hand, these length of regenerating trees showed greatly fluctuation for four years and unbalanced in each year (Fig. 21b). It indicated that the total length of matured trees was more stable than that of regenerating trees.



Fig. 20 Relationship between change in stem length and tree height of canopy tree in four years.

 $\bigcirc$ : living trees,  $\times$ : tree height of dead tree, vertical line: the threshold height between regenerating and matured tree.



Fig. 21 Total length of grown and diebacked stem of canopy trees in the plot.
(a) Matured trees, (b) Regenerating trees. □: grown length, ■: dieback length.

Seasonal changes in precipitation and air temperature in Ejina Oasis were showed in Fig. 22, which showed great fluctuation in annual precipitation from 11.2 mm to 40.7 mm/12 months.



Fig. 22 Seasonal changes in precipitation and air temperature from 2008 to 2012 in Ejina Oasis.

 $\uparrow$  :census time.

The effect of annual precipitation on proportions of grown and diebacked trees were shown in Fig. 23. For both matured and regenerating trees, proportion of grown trees gradually decreased as amount of precipitation increased and diebacked trees showed vice versa. Meanwhile, more than 70% of both canopy trees could grow well when annual precipitation decreased around 10 mm. These results indicated that amount of precipitation was not a factor to promote the tree growth. Precipitation did not directly influence the growth of canopy trees. Growth of regenerating trees could be influenced by other environmental factors beyond precipitation and showed greatly



Fig. 23 Relationships between annual amount of precipitation and proportions of well grown  $(\bigcirc)$  and diebacked trees  $(\bigcirc)$  of (a) matured and (b) regenerating trees.

fluctuation, which induce the fluctuation in total stem length (Fig. 21). However, growth and dieback of matured trees were balanced indicating that they did not influenced by precipitation and maintained a stable relation.

CPA of matured trees showed some fluctuations around a constant level of 0.35 m<sup>2</sup>m<sup>-2</sup> over 5 years and did not show any trend to increase or decrease, although regenerating trees showed a slight trend to decrease in CPA (Fig. 24). Such stable CPA for long period suggested a fixed structure of forest canopy with an effective replacement of dieback loss by equivalent canopy growth to regulate the amount of leaves (Li et al. 2014). This indicated that this *P. euphratica* forest was a matured forest stage even though vegetation coverage could reach only 35% and could maintain potential forest productivity under variable environmental condition of dryland.



Fig. 24 Changes in canopy projection area (CPA) of matured ( $\bigcirc$ ) and regenerating ( $\bigcirc$ ) canopy trees.

#### 5.3 Spatial distribution of canopy trees

Spatial distribution of canopy trees in three categories are shown in Fig.25. Ia values shown in the upper part of each distribution map indicated contagious distribution of diebacked trees, while random distribution of well growing trees and dead trees. Ia value of all canopy canopy trees (2.072) indicated contagious distribution with some loose clumps. Therefore very high proportion of dieback damage on living trees at all parts of the plot and the contagious distribution of canopy trees resulted loose clumps of diebacked trees in the plot.

Significant positive associations were observed between diebacked tree and both well growing tree (0.2616) and dead tree (0.2857) as shown in Table 3. However, well growing tree and dead tree have not any spatial association, although both of them were apt to distribute in the northwest part of the plot as shown in Fig.26. It indicated that well growing trees and dead trees distributed independently with each other and the death in neighbor tree was not a profitable phenomenon for their intraspecific competition for soil water and their growth

All canopy trees and diebacked tree showed significant positive association with elevation and no association with soil salinity, while well growing tree and dead tree showed no association with both environmental conditions. It indicated that soil salinity did not have significant effect on tree growth and survival, but ground undulation affected on survival of canopy trees (Table 3). The higher the elevation, the greater the rate of survival became. The cause of positive association of diebacked trees with ground undulation was not seem to be a high risk of water deficit on convex ground but to be a high proportion of dieback damage on living trees which preferred to grow on convex ground.



Fig. 25 Distribution maps of (a) well growing, (b) diebacked and (c) dead canopy trees. Ia value shows significant (P<0.05) contagious distribution with \*.

	Well growing tree	Dieback tree	Dead tree	EC	Elevation
All canopy trees	0.2595*	0.8116*	0.3612*	0.1085	0.3381*
Well growing tree		0.2616*	-0.0179	0.1622	0.1366
Dieback tree			0.2857*	0.1875	0.3214*
Dead tree				0.0008	0.1845
EC					0.4663*

# Table 3 Values of local association (X) of canopy trees and environmental factors.

\*: Significant positive association, P<0.05

#### 6 Regeneration

#### 6.1 Regeneration strategies

As seed size of P euphratica is only 1-2 mm in length, it can retain germination ability for only 1 week (Zhang et al. 2005b), but such diminutive seed can readily disperse over long distances (Cao et al. 2009; Hao et al. 2012). Their wide dispersal allows access to a variety of locations where they establish as effective pioneer trees under variable environmental conditions. This capability is attributable to a large production of small seeds by individual trees over a long period of the year. Therefore, the establishment of new P euphratica forests is relatively easy at riverine sites where water availability is stable.

Regeneration under forest canopy depends on the establishment of recruits under newly opened canopy gaps before the immigration of other plant species. However, seeds of *P. euphratica* can germinate only at the margins of river course or in shallow puddles (Thevs et al. 2008), which may not always be located under canopy gaps. Moreover, short-lived seed cannot establish seed bank in the forest floor. Therefore, sprout from lateral root system seems an effective strategy to occupy gap being far from suitable site for germination (Wiehle et al 2009).

The maintenance of saplings under a stable canopy is an effective regeneration mechanism for species of a large number of small short-lived seeds. To secure sustainable regeneration of *P. euphratica* forest, the persistence of a large number of young plants being able to survive for a certain years as a "sapling bank" is important to be maintained in where they can await the occurrence of canopy gap. 6.2 Numerical changes in sapling banks

Figure 25 shows the frequency distributions of tree heights for five different cohorts, i.e., saplings older than 2009 and those recruited in 2010, 2011, 2012 and 2013. The changes in the frequency distributions of particular cohorts are presented in columns of Fig. 25. In 2010, 28% of saplings were new recruits. Such a high rate of new entry in 1 year indicates vital and continuous regeneration activity, but the magnitude of new entry fluctuated widely from 6% to 28%.



Tree height (cm)

Fig. 25 Changes in the frequency distribution of sapling height in five different cohorts within the experimental plot.

Blue, red, black and orange indicate the saplings in 2009, 2010, 2011, 2012 and 2013.

A large number of saplings were persisted on the forest floor in each year. However, through the experimental period, very few saplings (<1%) could grow into canopy class through the transition height (2 m). High rate of mortality with vital recruitment and few saplings progressed into canopy class were the numerical situation of the sapling bank of *P. euphratica*.

#### 6.3 Height growth

The relationships between growth in stem length and initial stem height are shown in Fig. 26 for four periods. Across all census periods, the smaller the initial height of saplings were, the longer the annual growth of stem length became as



Fig. 26 relationship between sapling growth in stem length and initial sapling stem length in four different time periods.

 $\bigcirc$ : positive net growth and dieback,  $\times$ : dead.

indicated by dashed lines in Fig. 26. On the other hand, the higher the saplings became, the longer the stem length of dieback became, but they could survive. Moreover, relatively a large proportion of saplings (23-32%) died in each year. As indicating by  $\times$ marks on the abscissa axis, survival rate decreased as the height of saplings became small, because newly recruited saplings were vulnerable to environmental stress.

Thus, smaller saplings could not show high survival rate but maintained high positive height growth to grow into large saplings. On the other hand, larger saplings could not grow well but could survive by the control of water loss with stem dieback. High rate of sapling loss from sapling bank was balanced by vital new recruitment in each year. The combination of such demographic mechanisms indicated that the relationship between sapling mortality and growth is a key process of regeneration.

#### 6.4 Period of persistence

Most saplings persisted for long period in the understory. From the census data, the turnover time in the sapling bank was calculated (Table 4) by the following procedure in Masaki et al. (2006). The total number of saplings in 2009 (the first year) was 520, and the total number of survivor saplings in 2013 (the last year) was 246. Therefore, the mortality rate over 4 years was

 $D = \ln(520/249)/4 \times 100 = 18.41\%.$ 

The total number of saplings in 2012 was 447 (249+77+67+21+33), which exceeded the number of survivors from the cohort in 2009 (249). Thus, the recruitment rate was  $N = \ln(447/249)/3 \times 100 = 14.63\%$ .

The turnover time was, therefore,

 $T = (1/D + 1/N)/2 \times 100 = 6.1$  years.

The turnover time represents the period during which the saplings persisted in the understory vegetation beneath the forest canopy.

On average, saplings could persist on the forest floor for about 6 years (Table 3), thereby allowing the formation of effective sapling bank on forest floor.

	1 0	
Mortality rate	Recruitment rate	Turnover time
28.41%	14.63%	6.1 years

Table 4 Turnover time in the saplingbank

# 6.5 Volume of sapling bank

Fig. 27 shows the changes of summed total length and density of saplings for five years. Summed total length increased from below 300 m in 2009 to almost 400 m in 2010, and it became stable between 400 m and 450 m from 2010 to 2013. The density of saplings was almost constant over 5 years. Although few saplings (<1%) in the bank grew into the canopy tree class (>2 m tall) (Fig. 25), the stable density and constant volume of stem length of young individuals in the sapling bank (Fig. 27) suggested a long-term persistence of stable sapling bank with high proportion of newcomer and long longevity of established saplings.

To persist for many years on the forest floor, saplings must be highly drought-tolerant. Mechanisms of drought-tolerance include diverse physiological, ecological, and morphological traits, such as an enhanced ability for water absorption with low leaf water potential and a deep, wide root system (Larcher 2003). *P. euphratica*  saplings can control their leaf areas by partial defoliation of their distal parts (dieback) to escape lethal damage from drought (Monda et al. 2008). Therefore, the combination of demographic stability and physiological response to environmental stress was the key process for the persistence of sapling bank.



Fig. 27 Changes in summed total length and density of saplings over 5 years.

#### 7 General Discussion

# 7.1 Background

#### (1) Riparian forest in dryland

As low amount of precipitation, springs and streams flown out from groundwater and river water come from outer area are usually the main water source in arid region. Therefore, most of vegetation in dryland usually distribute along rivers and form riparian ecosystems. High and dense structure of dryland riparian forest can break the strong wind and prevent encroachment of sand dunes, which is an effective natural barrier against the dust and sand storm (DSS). However a large number of dryland riparian forests in the world are confronted with severe deterioration in their structure and functions, because of water shortage by anthropogenic activities in the upper stream.

#### (2) *Populus euphratica* forest

*Populus euphratica* is one of the representative tree species of dryland riparian forests. For more than several 1000 years, the riverine alluvial flatland along Heihe River in Ejina Oasis was used for crop production and livestock husbandry, but most of the area are deteriorated by over exploitation of forest materials. Moreover, Ejina Oasis is one of the main routes of DSS. Therefore protection and restoration of remained *P. euphratica* forests become a very important issue for prevention of DSS, conservation of natural ecosystem and sustainable development of human society.

#### (3) Objectives

A permanent experimental plot was established in a natural P. euphratica forest

at the middle basin of the west tributary of Heihe River to clarify the forest dynamics and the key process ensuring the sustainability under unreliable weather condition for the development of management and restoration technology in dryland.

#### 7.2 Stand structure

#### (1) Dieback

Frequency distribution of tree sizes showed bimodal with the threshold at 2 m in height and high proportion of small trees grew under forest canopy. Very high proportion of big trees suffered from dieback damage. However, it was not restricted for the big trees but for all trees with wide range of DBH.

# (2) Diameter-Height relationship

The maximum tree height estimated by D-H relationship was 14 to 15 m, which indicated that the site of the plot was not the optimum condition for tree growth. Small trees grew vigorously by following D-H regression line which could lead their height to 14 to 15 m in maximum before they grew bigger than 10 m in height and 20 cm in DBH. However, large trees bigger than 20 cm in DBH showed a large fluctuation in their height growth by severe dieback damage on apical part of stem. As a result, bigger trees couldnot exceed their height than that of smaller trees. Then the site conditions mainly suffered on height growth of bigger trees are the limiting factors of this forest site.

# (3) Spatial association

Spatial associations among different tree size groups suggested that seed germination and survival of saplings mainly occurred under canopy of matured tree. Positive associations in spatial distribution of newborn saplings with both topography and soil salinity demonstrated that suitable place for seed germination was limited on hillocked bank with high salinity. Suitable place for both seed germinate and survival of sapling keeps moving in every time in relation with the changes in flooding level over forest floor. Then, saplings could be established on lower place when the amount of water flow was small and could invade into high ground level by heavy flooding. As a result, old saplings showed positive association with soil salinity but independent from ground level.

#### 7.3 Canopy tree

# (1) Height growth

Well growing matured trees showed gradual but not significant increase in average height, which indicated higher trees did not have any advantage in their growth over lower trees. From the analysis of the relation between tree height and changes in stem length, there was no specific height class which was favorable to grow or easy to suffer from dieback. However most of dead trees were shorter than the average height of living trees, resulting a gradual increase in average height of matured trees (Li et al. 2014). More than 70% of both well grown and dieback canopy trees could grow well even when annual precipitation decreased around 10 mm, which indicated that precipitation did not directly influence the growth of canopy trees.

#### (2) Balance of loss with growth

Total growth length of matured trees was roughly balanced with the total loss of stem length by dieback, which suggested stable amount of leaf biomass in forest canopy irrespective of annual fluctuation in weather condition (Li et al. 2014). CPA of matured trees was maintained around a constant level of  $0.35 \text{ m}^2\text{m}^{-2}$  for over 5 years, which suggested a fixed structure of forest canopy with an effective replacement of dieback loss by equivalent canopy growth to regulate the amount of leaves (Li et al. 2014). Then this *P. euphratica* forest was a matured forest stage even though vegetation coverage reached at only 35% and it could maintain potential forest productivity under variable environmental condition of dryland.

# (3) Spatial association

Since well grown trees did not have any significant spatial association with dead trees, the death in neighbor tree was not a profitable phenomenon for their intraspecific competition for soil water and their growth. Spatial association of trees with environmental factors indicated that soil salinity did not have significant effect on tree growth and survival, but ground undulation affected on survival of canopy trees.

#### 7.4 Sapling bank

# (1) Regeneration strategies

As a large number of small seeds is produced over long period of the year, the establishment of new forest is relatively easy at riverine sites where water availability is stable. However short-lived seed cannot establish seed bank in the forest floor. Therefore, sprout from lateral root system seems an effective strategy to occupy gap being far from suitable site for germination. To secure sustainable regeneration of P euphratica, the persistence of a large number of young plants being able to survive for a certain years as a "sapling bank" is important to be maintained in where they can

await the occurrence of canopy gap.

#### (2) Numerical changes

Within the sapling bank, high rate of mortality was compensated by vital recruitment and few saplings could progress into upper canopy class, which suggested a stable situation in numerical aspect.

(3) Size and growth

Smaller saplings could not show high survival rate but maintained high positive height growth to grow into large saplings. On the other hand, larger saplings could not grow well but could survive by the control of water loss with stem dieback.

(4) Turnover time

The turnover time estimated by census data was 6.1 years which guaranteed the persistence of effective sapling bank on forest floor. Long period of turnover time seemed to be supported by prompt physiological response to environmental stress, such as dieback for the control of leaf biomass to avoid wilting death.

# 8 Conclusions

- (1) Populus euphratica is one of the representative tree species of dryland riparian forests, but most of the area are deteriorated by over exploitation. Therefore protection and restoration of remained *P. euphratica* forests become a very important issue for prevention of DSS, conservation of natural ecosystem and sustainable development of human society.
- (2) High proportion of trees irrespective of tree size in DBH suffered from dieback damage.
- (3) Small trees grew vigorously by following D-H regression line which could lead their height to 14 to 15 m in maximum before they grew bigger than 10 m in height and 20 cm in DBH. However, large trees bigger than 20 cm in DBH showed a large fluctuation in their height growth by severe dieback damage and could not exceed their height than that of smaller trees.
- (4) Positive associations in spatial distribution of newborn saplings with both topography and soil salinity demonstrated that suitable place for seed germination was limited on hillocked bank with high salinity and saplings could be established on lower place when the amount of water flow was small and could invade into high ground level by heavy flooding.
- (5) From the analysis of the relation between tree height and changes in stem length, there was no specific height class which was favorable to grow or easy to suffer from dieback.
- (6) Total growth length of matured trees was roughly balanced with the total loss of stem length by dieback, which suggested stable amount of leaf biomass in forest

canopy irrespective of annual fluctuation in weather condition. The experimental *P. euphratica* forest was a matured forest stage even though vegetation coverage reached at only 35%.

- (7) Soil salinity did not have significant effect on tree growth and survival, but ground undulation affected on survival of canopy trees.
- (8) Within the sapling bank, high rate of mortality was compensated by vital recruitment and few saplings could progress into upper canopy class.
- (9) Smaller saplings could not show high survival rate but maintained high positive height growth to grow into large saplings. On the other hand, larger saplings could not grow well but could survive by the control of water loss with stem dieback.
- (10) The turnover time estimated by census data was 6.1 years which guaranteed the persistence of effective sapling bank on forest floor.

# 9 References

- Akiyama T (2007) A study on groundwater recharge system and water use in the Heihe River basin in an arid region of China. Ph.D.thesis. Nagoya Univ, Japan
- Breshears DD, Whicker JJ, Johansen MP, Pinder JE (2003) Wind and water erosion and transport in semi-arid shrubland, grassland and forest ecosystem: quantifying dominance of horizontal wind-driven transport. Earth Surf. Process. Landforms Earth 28:1189-1209
- Cao D, Li J, Chen W, Li J (2009) Temporal heterogeneity of *Populus euphratica* seed rain in Ejina Oasis, China. Eurasian J For Res 12:1–8
- Cao D, Li J, Huang Z, Baskin CC, Baskin JM, Hao P, Zhou W, Li J (2012) Reproductive characteristics of a *Populus euphratica* population and prospects for its restoration in China. PLoS ONE 7(7):e39121
- Dason TE and Ehleringer JR (1991) Streemside trees that do not use stream water. Nature 350(6316):335-337
- Feng Q, Xi HY, Liu W, Si JH, Chang ZQ, Su YH (2009) The research of three-dimensional numerical simulation of groundwater-flow: taking the Ejina Basin, Northwest China as example. Sciences in Cold and Arid Regions 1(3):238-248

- Fu A, Li W, Chen Y (2012) The threshold of soil moisture and salinity influencing the growth of *Populus euphratica* and *Tamarix ramosissima* in the extremely arid region. Environ Earth Sci 66:2519-2529
- Hao P, Li J, Zhou W, Liu Q, Zhang Y (2012) Spatial pattern and utility of *Populus euphratica* seed rain: a simulation study combined with field investigations. For Stud China 12:169–179
- Han D, Meng X (1999) Recent progress of research on oasis in China. Chinese Geogr Sci 9:199–205
- Hou L, Zou S, Xiao H, Yang Y (2013) Sensitivity of the reference evapotranspiration to key climatic variables during the growing season in the Ejina oasis northwest China. SpringerPlus 2(Suppl 1):S4
- Hukin D, Cochard H, Dreyer E, Thiec DL, Triboulot MBB (2005) Cavitation vulnerability in roots and shoots: does *Populus euphratica* Oliv., a poplar from arid areas of Central Asia, differ from other poplar species? Journal of Experimental Botany 56(418):2003-2010
- Ji X, Kang E, Chen R, Zhao W, Zhang Z, Jin B (2006) The impact of development of water resources on environment in arid land inland river basins of Hexi region, northwestern China. Environ Geol 50:793–801

- Jin X, Schaepman M, Clevers J, Su Z, Hu G (2010) Correlation Between Annual Runoff in the Heihe River to the Vegetation Cover in the Ejina Oasis (China). Arid Land Reasearch and Management 24:31-41
- Khasbagan and Soyolt (2008) Indigenous knowledge for plant species diversity: a case study of wild plants' folk names used by the Mongolians in Ejina desert area, Inner Mongolia, P. R. China. Journal of Ethnobiology and Ethnomedicine 4(2) doi: 10.1186/1746-4269-4-2
- Larcher W (2003) Physiological plant ecology, 4th edn. Springer, Berlin, Heidelberg, New York.
- Li J, Yu B, Zhao C, Nowak RS, Zhao Z, Sheng Y, Li J (2012) Physiological and morphological responses of *Tamarix ramosissima* and *Populus euphratica* to altered groundwater availability. Tree Physiology 33:57-68
- Li X, Li Y, Zhang G, Wang L, Yoshikawa K (2014) Dynamics of canopy tree of riparian forest, *Populus euphratica*, and their relationship with environmental conditions in Ejina Oasis, Inner Mongolia, China. J. Arid Land Stud 24(1):17-20
- Li Z, Zheng C (2005) Structural Characteristics and Eco-adaptability of Heteromorphic Leaves of *Populus euphratica*. For Stud China 7(1):11-15
- Liu J, Chen Ya, Chen Yo, Zhang N, Li W (2005) Degradation of Populus euphratica

community in the lower reaches of the Tarim River, Xinjiang, China, J. Environ Sci 17(5):740-747

- Maestre MT, Cortina J (2002) Spatial patterns of surface soil properties and vegetation in a Mediterranean semi-arid steppe. Plant Soil 241:279–291
- Masaki T, Tanaka H, Shibata M (2006) Forest ecology, with long-term perspectives. 1st edn. Bun-ichi Sogo Shuppan Co., Tokyo, Japan (in Japanese)
- Monda Y, Miki N, Yoshikawa K (2008) Stand structure and regeneration of *Populus euphratica* forest in the lower reaches of the Heihe River, NW China. Landsc Ecol Eng 4:115–124
- Perry JN, Dixon P (2002) A new method to measure spatial association for ecological count data. EcoScience 9:133–141
- Qi S, Luo F (2007) Environmental degradation problems in Heihe River Basin, northwest China. Water Environ J 21:142–148
- Rüger N (2003) Habitat suitability for *Populus euphratica* in the Northern Amudarya delta-a fuzzy approach
- Seymour CL, Simmons RE (2008) Can severely fragmented patches of riparian vegetation still be important for arid-land bird diversity? J. of Arid Environ

- Säumel I, Ziche D, Yu R, Kowarik I, Overdieck D (2011) Grazing as a driver for *Populus* euphratica woodland degradation in the semi-arid Aibi Hu region, northwestern China. J. Arid Environ 75:265-269
- Sun H, Wang L, Tian Y (2000) Renovation and succession of ecosystem of Ejina Oasis. J. Arid Land Resources and Environment 14(5):15-18
- Stutz JC and Morton JB (1996) Successive pot cultures reveal high species richness of arbuscular endomycorrhizal fungi in arid ecosystems. Can. J. Bot. 74:1883-1889
- Thevs N (2005) Tugay vegetation in the middle reaches of the Tarim River-Vegetation tupes and their ecology. Arch Nat Conserv Landsc Res 63-84
- Thevs N, Zerbe S, Schnittler M, Abdusalih N, Succow M (2008) Structure, reproduction and flood-induce dynamics of riparian Tugai forests at the Tarim River in Xinjiang, NW China. Forestry 81:45–57
- Wang G, Cheng G (1999) Water resource development and its influence on the environment in arid areas of China—the case of the Hei River basin. J Arid Environ 43:121–131
- Wang X, Guo H, Chang Y, Zha L (2004) On paleodrainage evolution in mid-late

Epipleistocene based on radar remote sensing in northeastern Ejin Banner, Inner Mongolia. J Geograph Sci 14:235-241

- Wang Y, Feng Q, Liu G, Si J (2013) The prediction of LUCC in Ejina Oasis based on Markov model. International Conference on Remote Sending, Environment and Transportation Engineering (RSETE 2013):780-783
- Wiehle M, Eusemann P, Thevs N, Schnittler M (2009) Root suckering patterns in Populus euphratica (Euphrates poplar, Salicaceae). Trees 23:991-1001
- Wu J, Ding Y, Ye Y, Yang Q, Zhang X, Wang J (2010) Spatio-temporal variation of stable isotopes in precipitation in the Heihe River Basin, Northwestern China. Environ Earth Sci 61:1123-1134
- Wu Y, Wen Y, Zhang Y (2004) Analysis of the exchange of groundwater and river water by using Radon-222 in the middle Heihe Basin of northwestern China. Environmental Geology 45:647-653
- Yang L, Huang Q, Wang Y, Zhang Y, Meng J (2012) Analysis of Ecological water demand and measures of ecological comprehensive management in the downstream of Heihe River. Advanced Materials Research 518-523:6967-4971
- Yu J, Wang P (2012) Relationship between water and vegetation in the Ejina Delta. Bulletin of the Chinese Academy of Sciences 26(1):68-75

- Zhang L, Guo J, Li W, Zhang F, He W, Feng J, Bi Y (2003) Diurnal changes in photosynthetic characteristics of two differently shaped leaves in the desert plant *Populus euphratica*. Israel Journal of Plant Sciences 5:251-259
- Zhang Y, Wu Y, Su J, Wen X, Liu F (2005a) Groundwater replenishment analysis by using natural isotopes in Ejina Basin, Northwestern China. Environ Geol 48:6-14
- Zhang Y, Li J, Zhang H, Zhou D, Wu F, Cheng C, Li J, Li S (2005b) Spatiotemporal patterns of seed dispersal in *Populus euphratica*. Acta Ecol Sinica 25:1994–2000 (in Chinese)
- Zhao TL, Gong SL, Zhang XY, Jaffe DA (2008) Asian dust storm influence on North American ambient PM levels: observational evidence and controlling factors. Atmos Chem Phys 8:2717-2728
- Zhao W, Chang X, He Z (2004) Responses of distribution pattern of desert riparian forests to hydrologic process in Ejina oasis. Sci China Ser D Earth Sci 47:21–31