Plant Ecol (2010) 209:279–290
DOI 10.1007/s11258-010-9723-z

Responses of saltcedar (*Tamarix chinensis*) to water table depth and soil salinity in the Yellow River Delta, China

Baoshan Cui · Qichun Yang · Kejiang Zhang · Xinsheng Zhao · Zheyuan You

Received: 7 August 2009 / Accepted: 13 January 2010 / Published online: 29 January 2010

Abstract Significant studies about *Tamarix chinensis* as an introduced invasive plant species have been implemented in North America. However, the response of native *T. chinensis* to its environment is not well known in China. *T. chinensis* is a useful species in preventing sea water intrusion in coastal areas of northern China. It is necessary to fully understand the relationships between environmental conditions and ecological characteristics of this species to better preserve its habitats. The Yellow River Delta Natural Reserve, one of the major distribution regions of *T. chinensis*, was then selected as a case study area to investigate the response of this species to water table depth and soil salinity (Na^+, Cl^-, Mg^{2+}). It was found that sites with shallow water table depths (less than 1.5 m) and low soil salinity (less than 30 psu), provided the best habitat conditions for *T. chinensis*. The results also showed that plant height, stem diameter, and crown width were all positively correlated to plant age, while they had negative correlations with water table depth. Negative correlations between plant height and soil salinity, plant stem diameter and soil salinity were also concluded. However, no obvious relationship between the crown breadth of *T. chinensis* and soil salinity was observed. Four types of *T. chinensis* habitats were obtained based on the ecological characteristics of *T. chinensis* individuals associated with soil salinity and water table depth, i.e., (1) Low water table with high soil salinity; (2) Deep water table with high soil salinity; (3) Deep water table with low soil salinity; (4) Inundation with low salinity. These results provide a sound basis for wetland management in the Yellow River Delta.

Keywords Saltcedar (*Tamarix chinensis*) · Distribution · Soil salinity · Ecological characteristics · Water table depth · Yellow River Delta

B. Cui (✉) · Q. Yang · X. Zhao · Z. You
School of Environment, State Key Joint Laboratory of Environmental Simulation and Pollution Control, Beijing Normal University, Beijing 100875, China
e-mail: cuibs@bnu.edu.cn; cuibs67@yahoo.com

K. Zhang
Department of Civil Engineering, The Centre of Environmental Engineering Research and Education (CEERE), University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4, Canada

Introduction

Research on relationships between plants and their environmental conditions has become a hotspot in present ecology studies (Vandekerckhove et al. 2000; Muradian 2001; Bestelmeyer et al. 2003; Toms and Lesperance 2003). This research is helpful in understanding plant distribution, plant succession, and risk of plant invasion. However, further knowledge about the effects of changing environmental conditions on plants and their responses to these perturbations is still required by ecological restoration practices (Radford and Bennett 2004; Kliebenstein 2004; Elmore et al. 2003).

Tamarix is an old world genus occurring in ancient Mediterranean region (Qaiser 1981; Zhang et al. 2003). Fifty-four species of this genus are identified all over the world (Baum 1967; Gaskin and Schaal 2002). As a native species, it is widely distributed in eastern and southern Asia, southern Europe, the Mediterranean countries, the Middle East, and North Africa (Baum 1967; Zhang et al. 2001; Zhang et al. 2003). *Tamarix* can tolerate a variety of environmental conditions and exist in habitats varying from drought areas like desert to humid areas such as riparian, lake, and reservoir edges (Dick-Peddie 1993; Gaskin and Schaal 2002; Horton et al. 2001a, b; Xu et al. 2007).

In 1800s, some species of the *Tamarix* genus were introduced to America (Baum 1967; Di Tomaso 1998). After that, they spread quickly and now they can be found in more than 1.5 million acres in western United States with huge economic costs as a result of exacerbating flooding and reducing wildlife biodiversity (Johnson 1986; Stenquist 2000; Zaveleta 2000). *Tamarix chinensis* receives more attention amongst different *Tamarix* species. In order to better understand this plant, researchers have been trying to identify the factors that affect the spread of *T. chinensis*. They found that this species tends to live in areas where ground water is reachable, and that flow modification plays an important role in the process of *T. chinensis* invasion and extension (Tomar and Gupta 1985; Elmore et al. 2003; Gries et al. 2003). Other researchers pointed out that soil salinity and fire may also influence distribution of this species (Lalir and Pouakoff-Mayber 1976; Nurit and Alexandra 1977; Busch and Smith 1995; Wiesenborn 1996; Lesica and Thomas 2004).

As native plants, nineteen species of the *Tamarix* genus are identified in 14 provinces of China (Yin 2002; Huang and Liang 2007). They are widely distributed from northwest arid and semi-arid areas to sub-humid regions in northern China. *T. chinensis* and other species of the *Tamarix* genus are considered as beneficial plants in China as they are widely used as windbreaks for preventing desertification and erosion in arid areas of northwestern China (Yang et al. 2006; Zhang et al. 2003; Li et al. 2004). Moreover, *T. chinensis* is also a kind of traditional Chinese medicine (Huang and Liang 2007).

In order to identify the relationships between plants of the *Tamarix* genus and their environmental conditions, researchers in China tried to investigate the effects of environment on these species. For example, some research in arid areas, i.e., Xinjiang and Gansu, focused on physiological response of *Tamarix* to water deficit. Species of the *Tamarix* genus in these areas mainly exist along the Tarim River and oases on the edge of the desert (Zeng et al. 2002). Sufficient water supply is required to maintain their physiological integrity (Devitt et al. 1997a, b). Variation of water table and hydrologic conditions greatly influences the growth of *Tamarix*. According to these studies, insufficient water supply leads to accumulation of Abscisic Acid (ABA), soluble sugar, K^+, CAT enzyme, and SOD enzyme and further drought causes lethal damage (Wang et al. 1999; Li et al. 2004; Fu et al. 2008).

The Yellow River Delta is the most concentrated distribution area of *T. chinensis* in China (Gu 1991; Gaskin and Schaal 2002). This area is being threatened by hydrological changes. Since 1990, the decreased flow rate of the Yellow River combined with road construction and oil exploitation has significantly changed the original hydrological conditions in this area. A restoration project was implemented in the area to improve wetland functions and protect the natural habitats for rare birds and vegetation in July 2002. However, due to a lack of investigation of effects of salinity and water regime on *T. chinensis*, over supplement of freshwater from the river channel resulted in the decrease of *T. chinensis* in most areas. Further understanding the responses of *T. chinensis* to the changing hydrological conditions of freshwater wetlands is required to better protect the natural habitats of *T. chinensis* in this area.

Previous studies demonstrated the vertical and horizontal spatial patterns of soil physiochemical properties, and groundwater conditions within *T. chinensis* invaded sites (Stromberg 1998; Horton and Clark 2001; Ladenburger et al. 2006). However, the influences of water table depth and soil salinity on the distribution and ecological characteristic of *T. chinensis* in its native sites still need further study. The objectives of this article are to: (1) investigate the effects of water table depth and soil salinity on *T. chinensis*; (2) identify the optimum environmental conditions for *T. chinensis*; and then (3) put forward management suggestions for *T. chinensis* in the context of restoration of freshwater wetlands.

Materials and methods

Study area

The study area is located at entrance of the Yellow River to the Bohai Sea. It belongs to the Yellow River Delta natural reserve (Fig. 1). This area spans from 37°35′N–38°12′N to 118°33′E–119°20′E and is characterized as a temperate, continental monsoon climate with distinct seasons, and distribution of rain and heat. The annual average air temperature and rainfall are 12.1°C and 551.6 mm, respectively, with 196 frost free days.

The Yellow River Delta is a typical region with frequent land–ocean interactions. Significant amounts of sediment are carried everyday by the Yellow River and deposited at the river mouth, new lands are then formed. On the other hand, sea water intrusion continuously erodes the land. The average water table ranging from 0.2 m to 3.0 m was observed in the last two decades (Li et al. 2008). The Yellow River changed its channel from the old course to the present one in 1997. *T. chinensis* mainly distributes in the embankment of the old Yellow River channel and its neighbor sites. *T. chinensis* is the dominant shrub species in these areas. Native herb species include *Lepiironia articulata*, *Phragmites australis*, *Suaeda heteroptera*, and *Imperata cylindrica*. These plants have quite different ecological niches and live in various environmental conditions. This nature reserve is also habitat for bird species in the study area and many of them are protected species regulated by national government such as *Ciconia boycia* and *Grus japonens*. The Yellow River Delta is also an important over-wintering and breeding site for migrating birds from the Northeast Asian Inland and the Western Pacific Rim.

Sampling

This study began from September, 2006. Eight sampling sites with different community characteristics were selected (Figs. 1, 2 for D1 to D6 and F1 to F2). In each sampling site, a quadrat with an area of 10,000 m^2 (100 m × 100 m) was set to measure water table depths along with plant information. Eight soil samples and 40 plant individuals were randomly collected in each quadrat. The height, stem diameter, density, and crown breadth of each plant was also recorded. Soil samples were collected at varying depths from 0 to 20 cm using a stainless steel soil probe. These samples were then pooled and homogenized within polyethylene bags, and marked with site number and collection date. Finally, a total of 64 soil samples and 320 individuals were

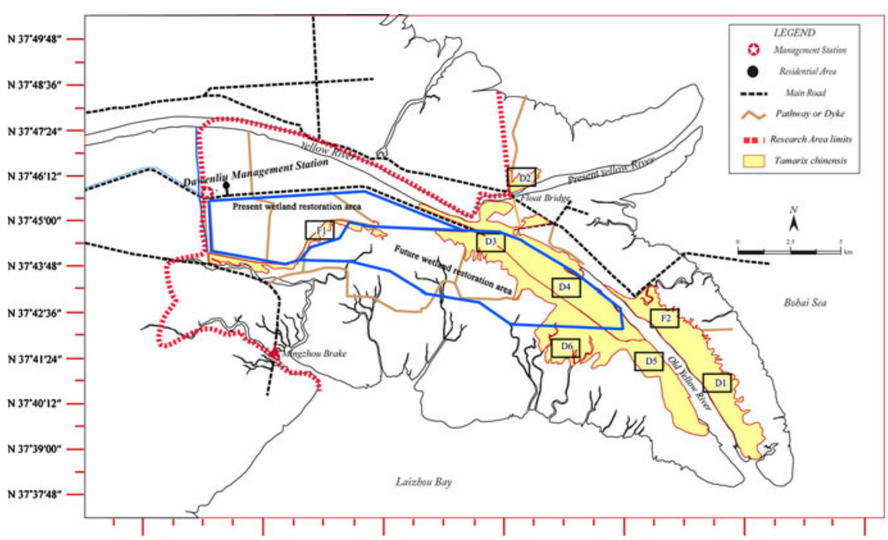
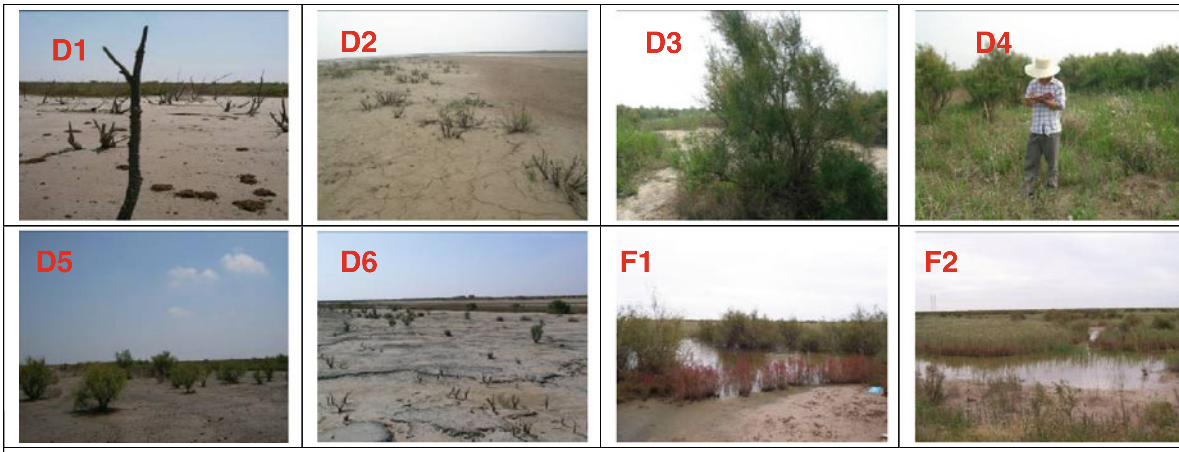


Fig. 1 Study area in the Yellow River Delta. Eight sampling sites denoted as D1 to D6 and F1 to F2 were selected to represent different environment conditions of *T. chinensis* community. In 1997, the Yellow River changed its channel from the old river way to the present one in the north. Banks of the old Yellow River channel and neighbor sites are the most concentrated distribution areas of *T. chinensis*



D1: It was 2.4km far away from sea and the north 0.5km from old Yellow River channel. There were a lot of death saltcedar (*Tamarix chinensis*) influenced by sea water and flooding of old Yellow River channel. **D2**: It was in the north 0.5km far from present Yellow River channel. Saltcedar (*Tamarix chinensis*) grew on highlands as individual. **D3**: It was in the south 1.5km far from old Yellow River channel. Saltcedar (*Tamarix chinensis*) developed naturally with rich biodiversity, and there no flood during one year. **D4**: It was in the south 1km far from old Yellow River channel. Saltcedar (*Tamarix chinensis*) developed naturally with rich biodiversity, and there no flood during one year.**D5**: It was in the south 1.0km far away from old Yellow River channel. Saltcedar (*Tamarix chinensis*) distributed in the bank side of a artifical channel with width of 3m, water in the channel came mainly from floods and rains. **D6**: It was in the south 5km from old Yellow River channel. There was 2.0mm salt covering on the surface. and intrinsic Saltcedar (*Tamarix chinensis*) began to die from 2003, surface became bareness. **F1**: It located in restoration region far from old and present Yellow River channel. Saltcedar (*Tamarix chinensis*) distributed around swamp wetlands.**F2**:It is in the north 1.0km far away from old Yellow River channel. Saltcedar (*Tamarix chinensis*) was flooded from July to September every year.

Fig. 2 Eight sampling sites in study area (All of these pictures were taken in September 2007)

collected. In order to obtain the age of individuals, we made a cross-section from the points where all stems joined together. The number of annual rings was counted using a 10–20× microscope. Water table was measured from a well located in the center of each quadrat. Odyssey Capacitance water level probes were placed in these wells with 30 min interval for 24 h.

Testing

In the laboratory, soil samples were placed in a crucible and dried for 24 h at 105°C to remove soil water. They were then sieved (2 mm) for further testing. Soil salinity was measured with a ratio of 1:5 of suspension of soil sample to deionized water solution using conductivity meter JNC3100. For Cl^-, liquid was first obtained by filtering soil–water suspension, and then 1 ml mixture was tested using Ion Chromatograph (Small 1989). For measurement of Na^+ and Mg^{2+}, samples were tested by atomic absorption spectrophotometry at wavelengths of 330.2 and 285.2 nm separately (Welz 1999).

Data analysis

Linear regression analysis was employed to analyze the relationships between the individual height, stem diameter, crown breadth of *T. chinensis*, and its age, respectively. *F*-test was used to implement significance analysis for regression. One-Way analysis of variance (ANOVA) was used to test the effects of water table depth and soil salinity on the height, stem diameter, and crown breadth of *T. chinensis*. The results of analysis were evaluated at the significance level 0.05 by using the Statistical Package for the Social Sciences (SPSS) 16.0.

Results

Soil salinity and water table depth

Eight sample sites were identified based on their water table depths (Table 1). Sites at which water table depths were lower than ground surface were denoted as D1 to D6. The increasing number indicated a lower water table depth. Two sites with surface water were denoted as F1 and F2. The higher number, F2, indicated the deeper surface water table of the two sites. There were significant differences in soil salinity at depths varying from 0 to 20 cm and water table depth in these eight sample sites. The data showed that D6 had the highest soil salinity (Mean = 58 psu, SD = ±9) and the lowest water level depth (Mean = −2.55 m, SD = ±0.07), and F2 had the least soil salinity (Mean = 12 psu, SD = ±1) and the deepest surface water (Mean = −0.65 m, SD = ±0.04) (Table 1). The results also showed that water table depth was positively correlated to the concentration of Na^+, Cl^-, and Mg^{2+} ($R^2 = 0.83$, $P < 0.01$ for water table depth and Cl^-; $R^2 = 0.79$, $P < 0.01$ for water table depth and Na^+; and $R^2 = 0.72$, $P < 0.01$ for water table depth and Mg^{2+}) (Fig. 3).

Ecological characteristics and age

Analysis of the results of biological and ecological characteristics of *T. chinensis* showed that the average stem height of *T. chinensis* in D6 (0.47 m)

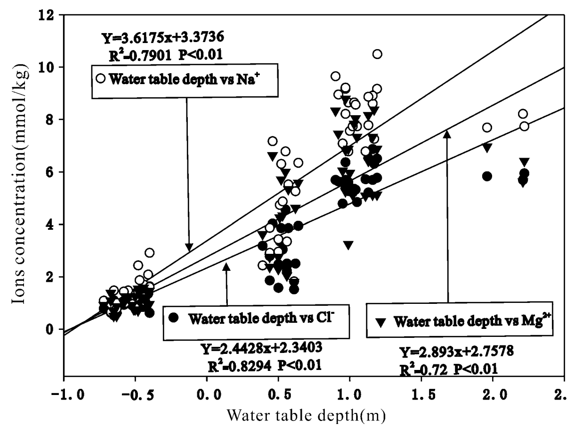


Fig. 3 Relationships of water table depth and concentration of Na^+, Cl^-, Mg^{2+} . In each sampling sites, 8 soil samples were collected and 64 samples were got in all for each iron. All of the three irons show positive relationships with water table depth

Table 1 Water table depth and soil salinity associated with Na^+, Cl^-, Mg^{2+} and pH (Mean ± SD) in different sample sites

Sample sites ID	Characteristics	Water table depth (m)	Salinity (psu)	Na+ (mmol/kg)	Cl^- (mmol/kg)	Mg2+ (mmol/kg)
D1	Low water table with high salinity	0.39 ± 0.02	42 ± 2	8.74 ± 0.12	5.41 ± 0.11	4.67 ± 0.22
D2	Lower water table with low salinity	0.90 ± 0.03	26 ± 4	9.91 ± 0.22	5.89 ± 0.23	7.33 ± 0.18
D3	Deep water table with low salinity	1.44 ± 0.04	18 ± 1	8.26 ± 0.38	5.01 ± 0.47	5.25 ± 0.24
D4	Deep water table with low salinity	1.50 ± 0.08	16 ± 1	7.13 ± 0.15	3.75 ± 0.26	4.21 ± 0.45
D5	Deeper water table with high salinity	1.85 ± 0.06	45 ± 5	15.96 ± 0.33	8.48 ± 0.28	8.79 ± 0.29
D6	Deepest water table with high salinity	2.55 ± 0.07	58 ± 9	17.91 ± 0.25	10.34 ± 0.33	10.58 ± 0.53
F1	Shallow inundation with low salinity	−0.08 ± 0.02	14 ± 1	6.70 ± 0.18	3.77 ± 0.07	4.75 ± 0.66
F2	Deepest inundation with low salinity	−0.65 ± 0.04	12 ± 1	5.70 ± 0.44	3.58 ± 0.19	4.21 ± 0.47

In each sampling site, 8 soil samples (0–20 cm) were collected randomly. All of them were tested in laboratory using standard testing method. In each sampling site, water table depth were tested with Odyssey Capacitance water level probe for 24 h with an interval of 30 min. For those water table depth is under ground surface, we name them with D1 to D6. From D1 to D6 water table become deeper and deeper. While for the sites with surface water, we use F1 to F2 to indicate its flood depth

Table 2 Ecological characteristics of *Tamarix chinensis* individuals in different sampling sites

Sample sites ID	Characteristics	Parameters (Mean ± SD)					
		Height (m)	Stem diameter (m)	Crown breadth (m)	Density (individuals/100 m^2)	Age composition	Coverage (%)
D1	Low water table with high salinity	1.89 ± 0.02	0.015 ± 0.004	0.49 ± 0.02	64 ± 7	1, 2, 3, 4, 5	20 ± 3
D2	Lower water table with low salinity	2.82 ± 0.27	0.024 ± 0.007	0.33 ± 0.06	22 ± 6	1, 2, 3, 4, 5	5 ± 1
D3	Deep water table with low salinity	2.08 ± 0.05	0.062 ± 0.006	1.82 ± 0.13	83 ± 7	1, 2, 3, 4, 5	68 ± 5
D4	Deep water table with low salinity	1.66 ± 0.07	0.050 ± 0.006	2.02 ± 0.04	86 ± 6	1, 2, 3, 4, 5	45 ± 5
D5	Deeper water table with high salinity	1.20 ± 0.04	0.029 ± 0.008	0.63 ± 0.04	48 ± 3	1, 2, 3, 4, 5	25 ± 1
D6	Deepest water table with high salinity	0.47 ± 0.05	0.012 ± 0.007	0.40 ± 0.04	46 ± 3	1, 2, 3, 4, 5	5 ± 2
F1	Shallow inundation with low salinity	5.51 ± 1.00	0.095 ± 0.005	2.33 ± 0.10	11 ± 3	5	5 ± 1
F2	Deepest inundation with low salinity	3.15 ± 0.02	0.021 ± 0.007	0.58 ± 0.04	39 ± 3	4, 5	13 ± 1

Age composition was obtained by laboratory analysis while other data were obtained by field researches. In each site, 40 plant samples were collected. Average value of different variables are calculated and shown with deviation

was the least in all measured samples (Table 2). Site D6 had the smallest coverage (5%) in all these eight sites. The highest average stem height and coverage (68%) were found in D2 and D3, respectively. Sites D4 and F1 had the highest and lowest density, respectively. The largest and the smallest average crown breadth were found in F1 and D2, respectively. The height of 320 *T. chinensis* individuals varied from 0.4 to 5.51 m with an average of 1.02 m. The mean stem diameter was 0.05 m varying from 0.01 to 0.1 m. The average and range of crown breadth of *T. chinensis* individuals were 0.95 m and 0.36, 2.34 m, respectively. Furthermore, significant negative relationships between the height ($P < 0.01$), stem diameter ($P < 0.01$), and crown breadth ($P < 0.05$) of *T. chinensis* and water table depth were identified and illustrated in Fig. 4. Negative relationships between the height ($P < 0.001$) and stem diameter ($P < 0.005$) of *T. chinensis*, and soil salinity were also shown in Fig 5, while no obvious relationship between the crown breadth ($P > 0.05$) of *T. chinensis* and soil salinity was observed (Fig. 5).

The age of sampled *T. chinensis* plants varied from 1 to 16 growth rings. All the 320 plant samples were categorized into 5 classes based on their ages. Those with 1, 2 to 4, 5 to 6, 7 to 10, and 11 growth ring (s) were denoted as Class 1, 2, 3, 4, and 5, respectively. As a result, only Class 4 and Class 5 were observed at site F2. Only Class 5 was obtained at site F1, while the remaining sampling sites had all 5 age classes. Logarithmic fit regression analysis was used to model the growth of *T. chinensis* individuals to investigate the relationships between ecological characteristics and age. All plant samples from eight sites were grouped based on their age classes and were analyzed separately. Significant positive relationships between the height ($P < 0.01$), stem diameter ($P < 0.01$), and crown breadth ($P < 0.01$) of *T. chinensis* and their age classes were observed (Fig. 6). In this study, Class 5 was selected to implement regression analysis between the heights, stem diameter, crown breadth of *T. chinensis*, and water table and soil salinity.

Discussion

Ecological characteristics of *T. chinensis* individuals

Tamarix chinensis is a facultative phreatophyte and grows quickly in favorable conditions (Lesica and Miles 2004). James et al. (1997) reported that

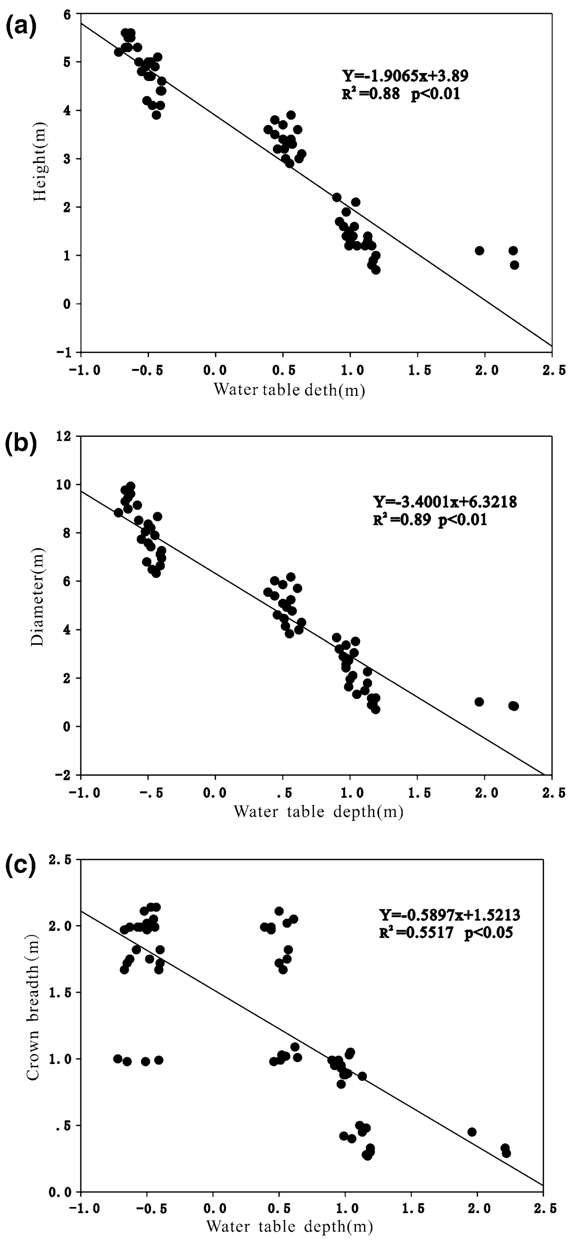


Fig. 4 Relationships between water table depth and ecological characteristics of *Tamarix chinensis* individuals using linear regression analysis (**a** is for water table depth and height, **b** is for diameter and **c** is for crown breadth). In each site, 8 plant samples belonging to age class 5 was chosen for analysis. Totally, 64 samples were obtained

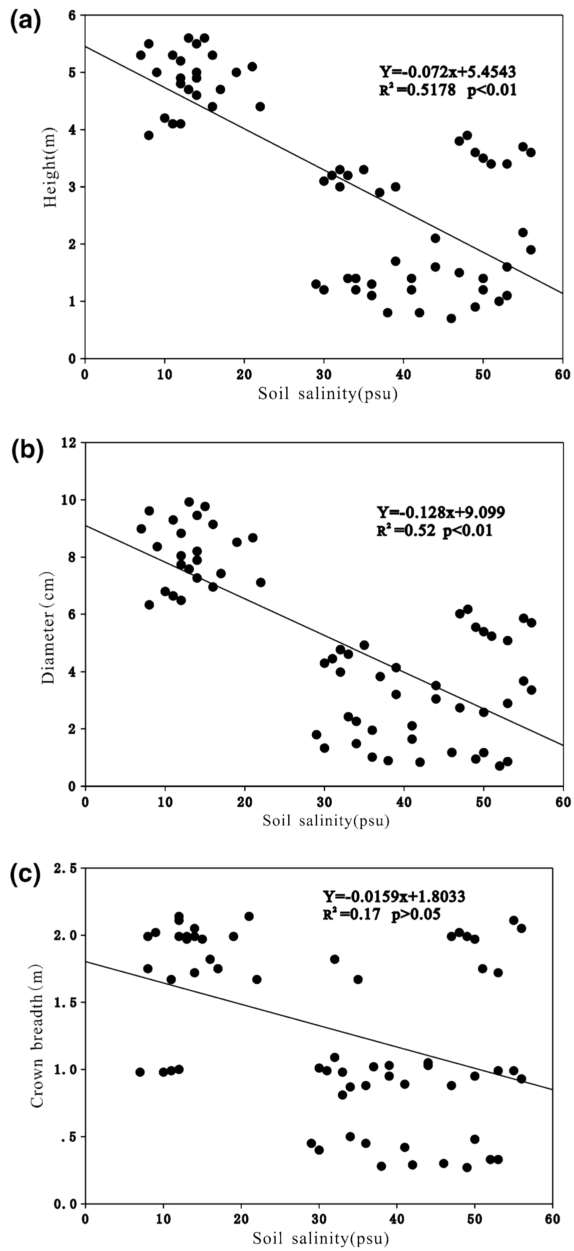


Fig. 5 Relationships between soil salinity and ecological characteristics of *Tamarix chinensis* individuals using linear regression analysis (**a** is for water table depth and height, **b** is for diameter and **c** is for crown breadth). In each site, 8 plant samples belonging to age class 5 was chosen for analysis. Totally 64 samples were used

T. chinensis could form dense communities and replace local species in a short time when invading a new place. In this study, height, stem diameter, and crown breadth were selected to represent ecological characteristics of *T. chinensis* in different age classes. Study results showed that these three indicators and

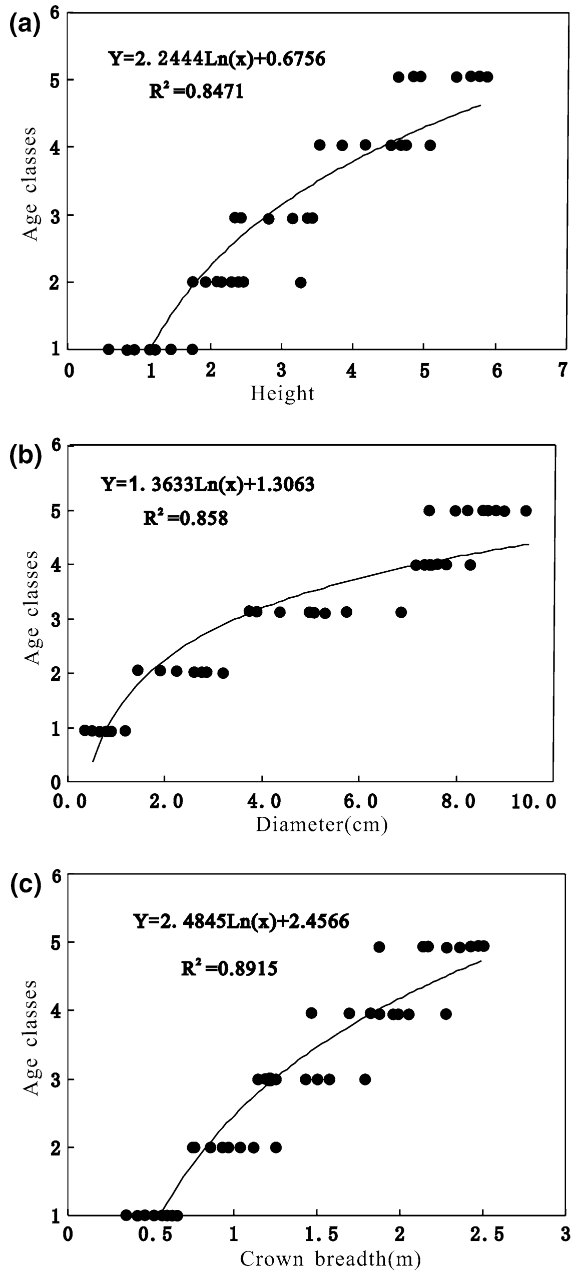


Fig. 6 Relationships between ecological characteristics of *T. chinensis* individuals and their age class using logarithmic fit linear regression analysis. They are **a** age class and height **b** age class and diameter, **c** age class and crown breadth. All plant samples were categorized into 5 age class considering amount of their growth rings. Those with 1 growth ring was labeled grouped as class 1, with 2–4 growth rings as class 2, with 5–6 growth rings as class 3, with 7–10 growth rings as class 4, and those with more than 11 growth rings as class 5. In each sampling site, average value of each age class was calculated separately. As a result, 8 average values from all sampling sites were obtained. The result shows that linear regression using logarithmic fit better simulate the relationships

age classes better fit the logarithmic model. As shown in Fig. 6, all of these three indicators exhibit a similar increasing trend. Different growth rates of *T. chinensis* are observed in five age classes. In Classes 1 and 2, *T. chinensis* individuals grow much faster than that in Classes 3, 4, and 5. The growth of mature individuals is stable and slower than that of the younger ones. Mature plants are less vulnerable to inundated conditions than the younger ones. Brotherson and Field (1987) presented that young individuals could not survive more than 30 days in an area with surface water, while mature individuals were able to survive approximately 70 days in a flooded site. This result was also obtained at sites F1 and F2. In these two inundated sites, young individuals disappear and only those belonging to Class 4 or Class 5 can survive.

A variety of characteristics of *T. chinensis* individuals was observed in different environmental conditions. In this study, the average height of individuals in Class 5 is more than 4.5 m, while the average height of *Tamarix* individuals (18 years old and belonging to age class 5) was only 3 m in the Tarim River Basin of Northwest China where water is limited (Anniwaer and Yin 1997). This result is consistent with the previous studies in the U.S. Lesica and Miles (2001) reported that in Montana (United States), the height of 30 to 40 years old *Tamarix* plants was only 4 m or less, while other researchers presented that if water supply and temperature were favorable, the maximum height of *T. chinensis* individuals could be more than 6 m (Ladenburger et al. 2006; Walker et al. 2006; Evangilista et al. 2007). Stromberg (1998) presented that in a favorable site, such as the State of Arizona, the average number of growth rings per centimeter was 2.36. This result is similar to those obtained in the current study (Fig. 6b). In sites located in Utah, however, the growth rate of *Tamarix* plants was much slower and an average 7.68 growth rings per centimeter was found (Walker et al. 2006). The crown breadths of individuals fit the ranges of those found in the flood plain of Bighorn Basin, Wyoming, USA (Ladenburger et al. 2006). The highest crown breadths observed in our study, are much smaller than those (up to 10 m) found in the Arkansas River Basin of southeastern Colorado (Evangilista et al. 2007).

Tamarix chinensis can survive in different regions varying from arid to humid regions, and from high latitudes to low latitudes. Significant differences of ecological characteristics are caused due to a variety of environmental conditions. Possible factors may include climate, annual precipitation, ground water, and species competition (Brotherson et al. 1984).

Influence of water table and soil salinity on *T. chinensis*

Water table depth and soil salinity are two major factors that influence growth and distribution of *T. chinensis* (Tomar and Gupta 1985; Gries et al. 2003). Results of this study showed that the *T. chinensis* individuals were mainly distributed at modest water table depth and moderate soil salinity conditions. *T. chinensis* can better grow in locations where groundwater is reachable (Elmore et al. 2003; Sher and Marshall 2003). Excessive water supply can inhibit the growth of this species (Horton et al. 2003). Harris (1966) presented that *T. chinensis* seed was not able to germinate in an inundated area for a long period of time. Mature individuals cannot survive in a site where long term surface water exists as their roots may become putrefied (Glenn and Nagler 2005). These results were verified in our research. In sites with surface water (F1 and F2), only mature individuals were observed. Community density and cover were lower in these areas (Table 2). In arid and semi-arid areas, *T. chinensis* can form dense communities in oases and on the edge of deserts (Zeng et al. 2002). Water deficiency is a serious problem faced by *T. chinensis* in those areas (Devitt et al. 1997a). Although this species has superb mechanisms to absorb water from deep soil and to reduce transpiration, a deeper water table will threaten its survival. Zhuang et al. (2005) and Fu et al. (2008) reported that in the Tarim River Basin, when the water table reached 3.12 m, normal physiological processes of *Tamarix ramosissima* individuals would be disturbed and serious injuries would be caused when water table reached 6 m below the surface. Individuals even died when water table below the surface was greater than 8 m. Graf (1985) reported when the water table exceeded 3–10 m, *Tamarix* began to disappear. The range of water table depth in our study is much lower than these from aforementioned literature. We observed when water table depth increased to 1.5 m or more, the values of ecological indicators such as plant height and diameter decreased significantly.

Another major factor that influences the growth of *T. chinensis* is soil salinity. Soil salinity in study area is high, possibly caused by shallow groundwater (salinity varying from 3.5 to 70.5 psu) (Yao and Yang 2007) and strong evaportranspiration (Cleverly et al. 2002). The maximum soil salinity reached 60 psu. Soil salinity greatly influences germination and growth as well as plant community characteristics (Nurit and Alexandra 1977; Busch and Smith 1995). *T. chinensis* is a halophilic species and its seed requires a certain degree of salinity to germinate (Zhang et al. 2008). In our study, all individuals grow in locations where soil salinity is over 10 psu. *T. chinensis* can survive in salinized sites due to their ability to avoid excessive salt absorption and to excrete salt out of their bodies (Lesica and Thomas 2004). This ability will be weakened when soil salinity increases to a high level. *T. chinensis* may not survive under such conditions.

Our research indicated that some ecological characteristics of *T. chinensis* such as the height and diameter had negative relationships with soil salinity. As soil salinity increases, the biochemical processes of *T. chinensis* are inhibited or completely disrupted (Lalir and Pouakoff-Mayber 1976). Salinity tolerance varies among different classes of *T. chinensis* individuals. Younger individuals cannot survive when salinity increases to over 25 psu (Chen et al. 2008). The salinity threshold for mature individuals is higher. Mature individuals show greater survivability when soil salinity is less than 60 psu. As a result, the tolerance range of *T. chinensis* to soil salinity varies from 10 to 60 psu in the yellow River Delta. As shown in Fig 5, all plant samples can be divided into two groups based on soil salinity. In sites with soil salinity below 30 psu, individual height and diameter are much higher than that in sites where salinity over 30 psu. The soil salinity tolerance range for *T. chinensis* is much higher than the previous study in Tarim River (12 psu), where climate is very dry and ground water table is about 6 to 10 m (Zhuang et al. 2005). One possible explanation is that sufficient water supply can increase the ability of *T. chinensis* to survive in higher soil salinity conditions.

The results of our study showed that sites with less water table depth (less than 1.50 m) and lower soil salinity (less than 30 psu) were more suitable for the growth of *T. chinensis*. Areas meeting these two conditions are mainly located in highlands along the embankments of old Yellow River channel. These areas are seldom influenced by sea water. Plants in these areas can easily access fresh water from the Yellow River. The most concentrated and largest distribution of *T. chinensis* are also observed in these areas in the Yellow River Delta.

Suitable sites for *T. chinensis* in the Yellow River Delta

Significant differences of ecological characteristics among eight sampling sites were found by implementing One-Way analysis of variance (ANOVA) (Table 3). Individuals with similar ages exhibit different ecological characteristics. By comparing ecological characteristics of all sampling sites, the best habitat conditions are D3 and D4 considering the height, coverage, crown, stem diameter, and density of *T. chinensis* individuals (Table 2). Age composition reflects establishment time, and most of these eight sample sites include five age classes except sites F2 and F1. Few individuals are more than 16 years old, reflecting the history of the newly formed flooding areas and wetlands.

Based on the soil salinity and water table depth, *T. chinensis* habitats can be categorized into four types: (1) lower water table with higher salinity. Salt crystals with thickness up to 1.33 mm on the ground surface can be frequently observed in locations where soil is wet. In this kind of habitat, *T. chinensis* has a lower coverage. This type includes D1 and D2; (2) deeper water table with higher salinity. This type includes D5 and D6. There are some salt crystals accumulated on the surface of D5, where *T. chinensis* germinates mainly after the rain seasons. Many mature *T. chinensis* individuals can be observed in D6, while younger ones are less prevalent; (3) deeper water table with lower salinity. This type includes D3 and D4, which are the main distribution zones of *T. chinensis* in the Yellow River Delta. Plant communities in these sites has larger density (above 86 plants/100 m^2) compared to other sites; (4) inundation with lower salinity. This includes F1 and F2. These areas are flooding areas. Recently, *T. chinensis* in F1 has been seriously disturbed by the restoration project for wetlands. Distribution and characteristics of *T. chinensis* influenced by environmental conditions in the Yellow River Delta conform to the conclusion that relationships between the species and water tables as well as soil salinity, are the primary mechanisms by which *T. chinensis* dominates riparian zones (Busch and Smith 1995; Stromberg 1998; Glenn and Nagler 2005).

Table 3 One-way ANOVA analyses of the ecological characteristics between 8 sampling sites and tests results using *F*-test. Samples of age class 5 were used for this test. For each variable, 40 data were used

Variables	*df*-treatment	*df*-total	*F* value
Height	7	39	25.47
Diameter	7	39	24.18
Crown breadth	7	39	36.23

Management implications

Tamarix chinensis communities are destroyed in the Yellow River Delta due to flow modifications and anthropogenic activities (e.g., wetland restoration and road construction). Since the mid 1990s, the flow rate of the Yellow River has significantly decreased as a result of excessive water consumption upstream. Insufficient fresh water supply leads to sea water intrusion. A freshwater wetland restoration project has been implemented in the region around F1 since 2002 to restore some functions of the degraded wetland ecosystem (Fig.1). A large amount of freshwater was conducted to the project area to restore the hydrological links between the river and floodplain. Significant changes were observed in the project area after 7 years. Biodiversity greatly increased in this area as a result of soil desalinization. However, due to insufficient knowledge about *T. chinensis*, excessive fresh water was pumped to this area in the past several years and led to vast areas of surface water. As *T. chinensis* cannot survive with surface water for a long period of time, substantial populations of this species have disappeared or have been replaced by *P. australis*.

Recently, plants in sites D3 and D4 have suffered from sea water intrusion. The local management institution of the Yellow River Delta plans to start another project to restore degraded freshwater wetlands. For the purpose of riparian ecosystem management, as well as effective conservation and restoration of freshwater wetlands, a more comprehensive understanding of the relationships between species and changing environment conditions is required. Results from this research provide a sound basis for preservation of *T. chinensis* habitats. Based on this research, the natural resource managers and wetland restoration policy makers in the Yellow River Delta should (1) identify the interaction areas between *T. chinensis* habitats and freshwater wetlands to preserve native species and natural plant habitats; and (2) reveal the competition between *T. chinensis* and other plant species. To this end, proper amounts of water should be pumped to the study areas to keep water table depths at a reasonable level for plants, as well as to reduce soil salinity and increase biodiversity.

Acknowledgments The authors would like to acknowledge Juanzhang Lu and Yueliang Liu from the Yellow River Delta Management Bureau, and Feng Lu and Lidong Wang from the Dawenliu Management station for their help with field works. This research was financially supported by the State Key Basic Research Development Program of China (973 Program) (No. 2006CB403303), and the Natural Science Fund Project of China (No.U0833002; 40571149). The authors also acknowledge the contributions of the anonymous reviewers and editors for their time and efforts.

References

Anniwaer, Yin LK (1997) Study on biomass of the *Tamarix* genus. Environ Prot Xinjiang 1:46–50

Baum BR (1967) Introduced and naturalized Tamarisks in the United States and Canada. Baileya 15:19–25

Bestelmeyer BT, Brown JR, Havstad KM, Alexander R, Chavez G, Herrick (2003) Development and use of state-and-transition models for rangelands. J Range Manag 56:114–126. doi:10.1002/1096-9837

Brotherson JD, Field D (1987) *Tamarix*: impacts of a successful weed. Rangelands 9:110–112

Brotherson JD, Carmen JC, Szyska LA (1984) Stem-diameter age relationships of *Tamarix ramosissima* in central. Utah 37:362–364

Busch DE, Smith SD (1995) Mechanisms associated with decline of woody species in riparian ecosystems of the Southwestern U.S. Ecol Monogr 65:347–370

Chen JX, Qiao LQ, Gou SH, Wang YX, He HB (2008) Experiment of salinity tolerance of *Tamarix*. Shandong For Sci Tech 1:18–19

Cleverly JR, Dahm CN, Thibault JR, Gilroy DJ, Allred Coonrod JE (2002) Seasonal estimates of actual evapotranspiration from *Tamarix ramosissima* stands using three-dimensional eddy covariance. J Arid Environ 52: 181–197

Devitt DA, Piorkowski JM, Smith SD, Cleverly JR, Sala A (1997a) Plant water relations of *Tamarix ramosissima* in response to the imposition and alleviation of soil moisture stress. J Arid Environ 36:527–540. doi:10.1006/jare.1996.0216

Devitt DA, Sala A, Mace KA, Smith SD (1997b) The effect of applied water on the water use of saltcedar in a desert riparian environment. J Hydrol 192:233–246. doi:10.1016/S0022-1694(96)03105-8

Di Tomaso JM (1998) Impact, biology, and ecology of saltcedar (*Tamarix* spp.) in the southwestern United States. Weed Tech 12:326–336

Dick-Peddie WA (1993) New Mexico vegetation-past, present, and future. University of New Mexico Press, Albuquerque, NM, p 244

Elmore AJ, Mustard JF, Manning SJ (2003) Regional patterns of plant community response to changes in water: Owens Valley, California. Ecol Appl 13:443–460

Evangilista P, Kumar S, Stohlgren TJ, Crall AW, Newman GJ (2007) Modeling aboveground biomass of *Tamarix ramassissima* in the Arkansas River Basin of southeastern Colorado, USA. West N Am Nat 67:503–509

Fu AH, Chen YN, Chen YP (2008) Changes of stem water potential of *Tamarix ramosissima* under drought stress in lower reaches. Chin J Ecol 27:532–538

Gaskin JF, Schaal BA (2002) Hybrid Tamarix widespread in U.S. invasion and undetected in native Asian range. Proc Natl Acad Sci USA 99:11256–11259. doi:10.1073/pnas.132403299

Glenn EP, Nagler PL (2005) Comparative ecophysiology of *Tamarix ramosissima* and native trees in western U.S. riparian zones. J Arid Environ 61:419–446. doi:10.1016/j.jaridenv.2004.09.025

Graf WL (1985) Tamarisk and river-channel management. Environ Manag 6:283–296. doi:10.1007/BF01875060

Gries D, Zeng F, Foetzki A, Arndt SK, Bruelheide H, Thomas FM, Zhang X, Runge M (2003) Growth and water relations of *Tamarix amosissima* and *Populus euphratica* on Taklamakan desert dunes in relation to depth to a permanent water table. Plant Cell Environ 26:725–736

Gu FT (1991) Chinese Tamarisk and its exploration in the mouth area of the yellow River. Grassland Chin 3:33–36

Harris DR (1966) Recent plant invasions in the arid and semiarid southwest of the United States. Ann Assoc Am Geogr 56:408–422

Horton JL, Clark JL (2001) Water table decline alters growth and survival of *Salix gooddingii* and *Tamarix chinensis* seedlings. For Ecol Manag 140:239–247. doi:10.1016/S0378-1127(00)00314-5

Horton JL, Kolb TE, Hart SC (2001a) Responses of riparian trees to inter-annual variation in ground water table depth in a semiarid river basin. Plant Cell Environ 24:293–304

Horton JL, Kolb TE, Hart SC (2001b) Physiological response to groundwater depth varies among species and with river flow regulation. Ecol Appl 11:1046–1059

Horton JL, Hart SC, Kolb TE (2003) Physiological condition and water source use of Sonoran Desert riparian trees at the Bill Williams River, AZ, USA. Isotopes Environ Health Stud 39:69–82. doi:10.1080/1025601031000096772

Huang SW, Liang JY (2007) Progress of studies on *Tamarix* Linn. Strait Pharm J 19:5–9

James RC, Stanley D, Smith AS, Dale AD (1997) Invasive capacity of *Tamarix ramosissimain* a Mojave Desert floodplain: the role of drought. Oecologia 111:12–18. doi:10.1007/s004420050202

Johnson S (1986) Alien plants drain western waters. Nature Conservency News. September–October

Kliebenstein DJ (2004) Secondary metabolites and plant/environment interactions: a view through *Arabidopsis thalianatinged* glasses. Plant Cell Environ 27:675–684. doi:10.1111/j.1365-3040.2004.01180.x

Ladenburger CG, Hild AL, Kazmer DJ, Munn LC (2006) Soil salinity patterns in Tamarix invasions in the Bighorn Basin, Wyoming, USA. J Arid Environ 65:111–128. doi:10.1016/j.jaridenv.2005.07.004

Lalir A, Pouakoff-Mayber A (1976) Effect of salinity on respiratory pathways in root tips of *Tamarix tetragynal*. Plant Physiol 57:167–170

Lesica P, Miles S (2001) Tamarisk growth at the Northern margin of its naturalized range in Montana, USA. Wetlands 2:240–246. doi:10.1672/0277-5212

Lesica P, Miles S (2004) Ecological strategies for managing tamarisk on the C.M. Russell National Wildlife Refuge, Montana, USA. Biol Conserv 119:535–543. doi:10.1016/j.biocon.2004.01.015

Lesica P, Thomas HD (2004) Is Tamarisk allelopathic? Plant Soil 267:357–365

Li XY, Zhang XM, He XY, Zeng FJ, Thomas FM, Foetzke A (2004) Drought stress and irrigation effects on water relations of *Tamarisk ramosissima* in the Qira Oasis. Acta Phytoecologica Sinica 28:644–650

Li SN, Wang GX, Deng W, Lu YX (2008) Variations of groundwater depth in Yellow River Delta in recent two decades. Pro Geogr 5:49–56

Muradian R (2001) Ecological thresholds: a survey. Ecol Econ 38:7–24. doi:10.1016/S0921-8009(01)00146-X

Nurit BN, Alexandra PM (1977) Salinity stress and the content of proline in roots of *Pisum sativum* and *Tamarix tetragyna*. Ann Bot 41:173–179

Qaiser M (1981) The genus *Tamarix* (*Tamaricaceae*) in Pakistan. Pak J Bot 13:107–158

Radford JQ, Bennett AF (2004) Thresholds in landscape parameters: occurrence of the white-browed *treecreeper*, *Climacteris affinis* in Victoria, Australia. Biol Conserv 117:375–391. doi:10.1016/j.biocon.2003.08.002

Sher AA, Marshall DL (2003) Seedling Competition between native *Populus Deltoides* (*Salicaceae*) and exotic *Tamarix Ramosissima* (*Tamaricacea*) across water regimes and substrate types. Am J Bot 90:413–422

Small H (1989) Ion chromatography. Plenum Press, New York

Stenquist S (2000) Saltcedar integrated weed management and the Endangered Species Act. In: Spencer N (ed) Proceedings of the X International Symposium on Biological Control of Weeds 4–14 July 1999. Montana State University, Bozeman, Montana, USA, pp 487–504

Stromberg J (1998) Dynamics of Fremont cottonwood (*Populus fremontii*) and salt cedar (*Tamarix chinensis*) populations along the San Pedro River, Arizona. J Arid Environ 40:133–155. doi:10.1006/jare.1998.0438

Tomar OS, Gupta RK (1985) Performance of some forest tree species in saline soils under shallow and saline water-table conditions. Plant Soil 87:329–335. doi:10.1007/BF02181900

Toms JD, Lesperance ML (2003) Piecewise regression: a tool for identifying ecological thresholds. Ecology 84:2034–2041. doi:10.1890/02-0472

Vandekerckhove L, Poesen J, Wijdenes DO (2000) Thresholds for gully initiation and sedimentation in Mediterranean Europe. Earth Surf Process Landforms 25:1201–1220. doi:10.1002/1096-9837

Walker LR, Barnes PL, Powell EA (2006) *Tamarix aphylla*: a newly invasive tree in southern Nevada. Western North Am Nat 66:191–201. doi:10.3398/1527-0904

Wang X, Hou P, Yin LK, Feng DQ, Pan BR (1999) Effect of soluble substance of *Tamarix* under soil water stress slowly. Arid Zone Res 16:6–11

Welz B (1999) Atomic absorption spectrometry. Wiley, New York

Wiesenborn, WD (1996) Saltcedar impacts on salinity, water, fire frequency, and flooding. Saltcedar Management Workshop, Rancho Mirage, CA. California Exotic Pest Plant Council 9–12

Xu F, Guo WH, Wang W, Xu WH, Wang YF, Wang RQ (2007) A comparison of photosynthetic characteristics between *Tamarix chinensis* and *Phragmites australis* in the Yellow River Delta. Shandong For Sci 173:29–33

Yang LW, He BY, Huang PY, Nuer B (2006) Evaluation on ecological value of *Tamarix* spp forest in Hotan basin. J Desert Res 25:268–274

Yao RJ, Yang JS (2007) Quantitative analysis of spatial distribution pattern of soil salt accumulation in plough layer and shallow groundwater in the Yellow River Delta. Trans CSAE 8:45–51

Yin LK (2002) The ex-situ protection and the ecological adaptability of *Tamarix* L.in China. Arid Zone Res 19:12–16

Zaveleta E (2000) Valuing ecosystem services lost to *Tamarix* invasion in the United States. In: Mooney HA, Richard JH (eds) Invasive species in a changing world. Island Press, Washington DC, pp 261–302

Zeng FJ, Li XM, Zhan XM (2002) A review of the water physiological characteristics of *Tamarix* and its prospect. Chin J Appl Ecol 13:611–614

Zhang YM, Pan BR, Yin LK, Yang WM, Zhang DY (2001) The research history of the family *Tamaricaceae*. Acta Bot Boreal Occident Sin 21:796–804

Zhang DY, Pan BR, Yin LK (2003) The photo geographical studies of *Tamarix* (*Tamaricaceae*). Acta Botanica Yummnica 25:415–427

Zhang LB, Song YR, Wu X (2008) Salt tolerance capacity and the effects on the improvement of coastal saline soil. J Anhui Agric Sci 36:5424–5426

Zhuang L, Chen YN, Li WH, Zhao YH (2005) Relationship of the protective enzymes of desert vegetations with water table in the lower reaches of Tarim River. Acto Bot Boreal Occident Sin 25:1287–1294