Environ Earth Sci (2009) 59:765–774
DOI 10.1007/s12665-009-0072-y

ORIGINAL ARTICLE

Long-term changes of *Tamarix*-vegetation in the oasis-desert ecotone and its driving factors: implication for dryland management

Quanlin Ma · Jihe Wang · Xinrong Li · Shujuan Zhu · Hujun Liu · Kejie Zhan

Received: 18 August 2008 / Accepted: 20 January 2009 / Published online: 14 February 2009
© Springer-Verlag 2009

Abstract The Oasis-desert ecotone plays an important role in ensuring oasis ecological security. This study was to determine the main factors on the changes of desert vegetation in the oasis-desert ecotone, and to understand the mechanisms of the long-term changes. During past 50 years, the dominant plant species of *Tamarix*-vegetation in the Minqin oasis-desert ecotone changed from mesophytes to xerophytes and finally to super-xerophytes. The vegetative distribution area (belt width of *Tamarix*-vegetation between desert and oasis) markedly decreased from 1,000 m past to 30 m current. The coverage of *Tamarix* bushes reduced from 25 to 7%. The importance value (*IV*) of the bushes fell from 0.957 to 0.752, and Simpson index decreased from 0.702 in 1959–0.589 in 1992, and then increased to 0.712 in 2002. These changes in vegetation were closely related with the rapid decrease of groundwater table and the reduction of soil moisture due to unsustainable use of water resources for expanded agriculture development. These findings suggested that the change of *Tamarix*-vegetation in the oasis-desert ecotone was a process of vegetation degradation and concurrent desertification. The maintaining of stable groundwater and *Tamarix*-vegetation is a vital prerequisite for dryland management, especially, conserving ecological health of oasis-desert systems.

Keywords Shiyang River · Degradation · Succession · Oasis-desert ecotone · Desertification

Electronic supplementary material The online version of this article (doi:10.1007/s12665-009-0072-y) contains supplementary material, which is available to authorized users.

Q. Ma · J. Wang · S. Zhu · H. Liu · K. Zhan
Key Laboratory of Combating Desertification of Gansu Province, Gansu Desert Control Research Institute, 733000 Wuwei, Gansu Province, China

Q. Ma (✉) · X. Li
Shapotou Desert Research and Experiment Station, Cold and Arid Regions Experimental and Engineer Research Institute, Chinese Academy of Sciences, No. 260, West Donggang Road, 730000 Lanzhou, Gansu Province, China
e-mail: mql925@126.com

Introduction

Land degradation is a process of reducing potential land productivity and biodiversity, which leads to serious geological disasters and prevent the ecological sustainability (Khresat et al. 1998; Feng et al. 2005). For its serious and widespread impact on the environment, land degradation has been one of the most serious environmental and ecological problems in the world (Al-Dousari et al. 2000; Wesselsa et al. 2007). Most significant forms of land degradation are soil erosion, deterioration of vegetation, soil compaction and sealing, water logging and salinization (Stocking 2004). Desertification is the most typical and serious type of land degradation in arid areas (Lin and Tang 2002; Chen and Duan 2008). Vegetation degradation is a major contributory factor to desertification particularly with regard to soil erosion and loss of soil organic matter (Ma et al. 2007; Hanafi and Jauffret 2008).

The oasis-desert ecotone, as an early indicator of ecological response to environmental changes, is an interactive area between desert and oasis ecosystems (Di-Castri et al. 1988; Attrill and Rundle 2002; Su et al. 2007; Wang et al. 2007). It plays an important role in ensuring oasis ecological security and maintaining oasis internal stabilization (Li et al. 2007a; Su et al. 2007). However, the oasis-desert ecotone is more sensitive for disturbance than its adjacent ecosystems (Wang and Zhao 2001; Su et al. 2007). When it is disturbed during exploration or utilization, the ecotone has a potential trend to evolve into the desertified land or shifting sand dunes (Di-Castri et al. 1988; Ding and Zhang 2006). Undoubtedly, desert vegetation in the oasis-desert ecotone plays an important role in preventing desertification and maintaining oases stabilization (Zhao et al. 2008). However, little researches have been done on the mechanisms for the vegetation changes of oasis-desert ecotone. It is considered that long-term study on the oasis-desert ecotone is an essential approach to understand the changes of desert vegetation, and to provide the base for policy-making on dryland management.

The Minqin Oasis, located between Badain Jaran Desert and Tengger Desert, plays indispensable role in preventing the two deserts approaching each other. The oasis-desert ecotone around Minqin Oasis serves as an ecological protection belt to control shifting sand dunes and protect the Minqin Oasis from damage by moving sands. As a typical oasis-desert ecotone in northwest of China, with limited water resources, the ecotone has become a seriously degraded ecological region. *Tamarix*-vegetation, with area of 6857.3 ha in 2000, was major natural vegetation in Minqin (Liu et al. 2006). In recent decades, about two-thirds of *Tamarix*-vegetation in the oasis-desert ecotone seriously degraded (Yang 1999; Gao et al. 2006), which led Minqin region to become one of the areas with the most serious blown sands and one of the sources of sand-dust storms in China (Peng et al. 2004; Zhang et al. 2004). Therefore, the conservation and restoration of *Tamarix*-vegetation in the Minqin Oasis-desert ecotone is crucial to the ecological security and desertification prevention of Minqin Oasis. The objectives of this study are: (1) to examine the mechanisms of changes of *Tamarix*-vegetation in the oasis-desert ecotone in the lower reaches of Shiyang River during past 50 years, (2) to analyze driving factors on the changes of *Tamarix*-vegetation, and (3) to provide theoretical basis for the protection and rehabilitation of *Tamarix*-vegetation in arid areas and management of dryland.

Materials and methods

Study area

The study was conducted in the northern transitional zones of the Minqin Oasis, located at the southeast periphery of the Badain Jaran Desert and in the lower reaches of the Shiyang River (from 38°20′ to 39°10′N and from 102°45′ to 103°55′E) with an average elevation of 1,367 m. The Minqin Oasis, with an area of approximate 2,381 km^2, occupies 7% of total area of Minqin County. The Oasis is divided into Baqu (in the upper reaches), Quanshanqu (in the middle reaches) and Huqu (in the lower reaches) based on their geographic position, water resources and agricultural practices (Sun et al. 2005; Gao et al. 2006) (Fig. 1). According to local meteorological records for period between 1954 and 2006 (ESM Figure 1), the mean annual precipitation is 115.8 mm, the mean potential annual evaporation is 2,644 mm, and 24 times of the precipitation. The precipitation in 1959, 1992 and 2002 were 38.6, 116.0 and 174.4 mm respectively at site I in the Minqin Oasis-desert ecotone. The mean annual temperature of the Oasis is 7.4°C with maximum of 40°C and minimum of −28.8°C. The prevailing wind comes from northwest with an annual mean velocity of 2.5 m/s (Han and wang 2002). The mean number of days with gales is 26.3, with dust and sandstorm is 25, with blowing sands is 37.5 and that with floating dust is 29.7. The main soil types are chestnut soil, brown soil and aeolian sandy soil (Feng et al. 1989). Natural vegetation type is desert vegetation. In the oasis-desert ecotone, there are natural and artificial vegetation. The shrub *Nitraria tangutorum*, *Tamarix ramosissima*, *Calligonum mongolicum* are the dominant plant species of natural vegetation, whereas *Haloxylon ammodendron* dominate the artificial vegetation. In desert area, there was

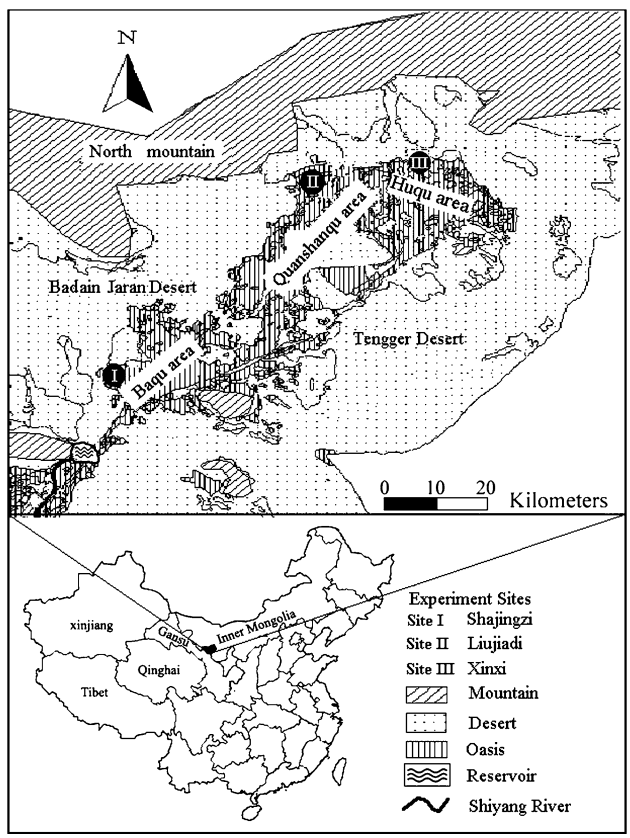

Fig. 1 Location of Minqin County with oasis, desert and experimental sites

Table 1 Experimental sites and their natural conditions

Experimental sites		Region	Location	Landform	Groundwater table (m, 2002)
Site I	Shajingzi	Baqu in the upper reaches	N102°58′26″ E38°35′24″	Fixed sand dunes	18.65
Site II	Liujiadi	Quanshanqu in the middle reaches	N103°20′47″ E38°56′24″	Fixed sand dunes	19.36
Site III	Xinxi	Huqu in the lower reaches	N103°34′45″ E39°01′30″	Semi-fixed sand dunes	11.32

only natural vegetation dominated by *N. tangutorum*, *Ephedra przewalskii*, *Caragana Korshinskii* and *Agriophyllum squarrosum*. The Oasis, with the *Populus* farmland shelterbelt, is an important area for grain and fruit production.

Vegetation survey

Long-term observation for *Tamarix*-vegetation was carried out at Minqin Integrated Experimental Station of Desertification Control, which was established in 1959 at Site I. Sampling quadrates of *Tamarix*-vegetation were selected. Species composition, number of plant species, plant height, canopy ranges and coverage of vegetation were annually observed and recorded. Three years (1959, 1992 and 2002), representing the developmental stages, were selected to analyze temporal changes in both species composition and biomass of *Tamarix*-vegetation.

A line-transect method was used to survey *Tamarix*-vegetation at three sites [Shajingzi in Baqu (site I), Liujiadi in Quanshanqu (site II) and Xinxi in Huqu (site III)] (Fig. 1; Table 1). In each sampling site, two perpendicular lines at length of 200 m were randomly selected (Ringvall et al. 2000). For each line-transect, species number, abundance, height, canopy range, and shrub coverage, grass coverage and overall coverage were recorded.

Importance value of species (*IV*) were calculated with the equation (*IV* = relative height + relative coverage); the *Simpson index* [$S = 1 - \sum P_i^2$, where P_i is the relative importance value (*IV*) of species *i*] was used to measure plant species diversity (Li et al. 2005).

At site I, at the peripheral zone of farmland, two sampling strips that were 20 and 35 m in length respectively were selected. The strips were perpendicular to the farmland. Along the 20 m-long sampling strip, 15 quadrates with sizes of 1 × 1 m at 0, 5, 10, 15 and 20 m away from the farmland were selected to measure the coverage, fresh and dry biomass of *Tamarix* bushes. Along the 35 m-long sampling line, 12 quadrates with sizes of 0.5 × 0.5 m at 8, 12, 16 and 35 m away from the farmland were selected to measure the height, base diameter, bushes coverage and biomass of 1-year-old *Tamarix* shoots following a clear-cut treatment. A trench was dug at base of the accumulated sand mounds at 35 m away from the farmland. The width and depth of the trench were 50 cm and 50 cm, respectively. The *Tamarix* bush mounds were irrigated twice a year, and the trench was buried with dry sands after irrigation to prevent evaporation.

Soil moisture measurement

Soil samples with three replications were taken manually using a core sampler at the windward slope of *Tamarix* sand mound at depth of 20, 40, 60, 80 and 100 cm. The soil moisture contents were tested using oven-dry method in the laboratory at 105°C for 24 h. Measurements of the soil sample weight before and after drying gave soil moisture contents in gravimetrical terms (Li et al. 2007b).

Starting from May 2003, three sets of neutron moisture gauge were set along a line perpendicular to the farmland at site I. Each set consists of four tubes, 5 m apart from one another. The tubes were buried to a depth of 1 m in the farmland and 2 m in *Tamarix*-vegetation. The tubes were set in the soil every other 20 cm a layer. The soil moisture contents were measured using a neutron moisture probe. The probe was calibrated with a regression equation obtained from a regression between soil moisture contents measured by oven-dry method against data from the neutron moisture probe. Thus, the soil moisture contents measured by the neutron moisture probe were in gravimetrical terms.

Groundwater table monitoring

Well point method was used to monitor groundwater table (Alva and Paramasivam 1998). In each of the site I, site II and site III, 3–5 irrigation wells were sampled in 1961, 1995 and 1980, respectively. An electronic indicator meter was installed in each well to monitor the groundwater table monthly.

Statistical analysis

Windows-based SPSS 11th edition software (SPSS, Chicago, USA) was used for the analysis of variance (ANOVA). Descriptive statistics were used to calculate averages and standard deviations of the data from each set of reduplicates. Duncan's test at $P < 0.05$ was used for significant tests.

Results

The changes of *Tamarix*-vegetation in the Minqin Oasis-desert ecotone during past 50 years

During past 50 years, the general variations of *Tamarix*-vegetation at site I were changes in species composition, decrease of height, biomass, coverage and *IV* of the *Tamarix* bushes (Table 2). However, Simpson index of *Tamarix*-vegetation decreased at beginning, and then increased. Especially during recent 10 years, the changes of the *Tamarix*-vegetation became more intensive, with 10.3% reduction of *Tamarix* coverage and 11.9% of the overall coverage. The vegetative distribution area (belt width of *Tamarix*-vegetation between desert and oasis) at site I markedly reduced to about 30 m in 2002 from 1,000 m in 1990s. The number of species of annual plants significantly increased in the *Tamarix*-vegetation (Table 2).

In 1959, the dominant plant species of *Tamarix*-vegetation in the Minqin Oasis-desert ecotone were *T. ramosissima*, *Karelinia caspia*, *Elaeagnus angustifolia* and *Populus euphratica*, which were replaced by *T. ramosissim* and *Reaumuria songarica* in 1970s, and then replaced by *T. ramosissim*, *N. tangutorum* and *H. ammodentron* (artificial) in 1980s, and finally replaced by *N. tangutorum* and *H. ammodentron* (artificial) gradually since the end of 1990s. In conclusion, dominant species in the composition of *Tamarix*-vegetation changed from mesophytes to xerophytes and finally to super-xerophytes, which was a vegetation degradation process with expansion of desertification.

Spatial distribution of *Tamarix*-vegetation in the Minqin Oasis-desert ecotone

Tamarix-vegetation of site I had the lowest height, canopy range, coverage of *Tamarix* bushes, the overall coverage of the vegetation and number of species, and the highest death rate. Mesophytes such as *Karelinia caspia* and *Kalidium foliatum* disappeared (Table 3). *Tamarix*-vegetation was in its final stage of the succession in the Minqin Oasis-desert ecotone. For site III, *Tamarix*-vegetation belt remained little disturbed and therefore the belt had the largest width. There was no sign that the vegetation belt degraded so far. The *Tamarix* bushes had the highest height, and individual and overall coverage. The number of species of *Tamarix*-vegetation was the highest. The belt, therefore, had the best function of desertification combating. At site II, all of the observed data of *Tamarix* bushes and vegetation fall in between the above-mentioned two types, with a large area of dead *Tamarix* bushes. The changes of *Tamarix*-vegetation in the Minqin Oasis-desert ecotone had a gradient along the river from southwest to northwest (from the upper reaches to the lower reaches of the river). Although

Table 2 Structural changes of *Tamarix*-vegetation at site I in the Minqin Oasis-desert ecotone during past 50 years

Species	Mean height (cm, mean ± SD)			Species coverage (%, mean ± SD)		
	1959	1992	2002	1959	1992	2002
Tamarix ramosissima	200 ± 13.0a	168 ± 11.3b	152.5 ± 16.8b	25 ± 4.03a	17.3 ± 2.59b	7 ± 1.47c
Nitraria tangutorum	30 ± 1.8a	18 ± 1.7a	22 ± 2.1a	0.5 ± 0.22c	3 ± 0.72b	7.9 ± 1.58a
Kalidium foliatum	30 ± 3.4	–	–	20 ± 3.91	–	–
Glycyrrhiza uralensis	30 ± 2.1	–	–	10 ± 1.52	–	–
Karelinia caspia	30 ± 4.6	–	–	2 ± 0.43	–	–
Phragmites australis	20 ± 3.6	–	–	0.3 ± 0.08	–	–
Sonchus oleraceus	10 ± 1.2	–	–	0.1 ± 0.02	–	–
Limonium aureum	30 ± 3.3a	–	20 ± 3.4a	0.1 ± 0.01a	–	0.1 ± 0.02a
Reaumria songorica	–	21 ± 2.5	–	–	0.5 ± 0.11	–
Agriophyllum squarrosum	–		12 ± 1.3	–	–	0.3 ± 0.04
Bassia dasyphylla	–		8 ± 2.1	–	–	0.4 ± 0.06
Halogeton arachnoideus	–	2 ± 0.7b	8 ± 1.9a	–	0.1 ± 0.02a	0.3 ± 0.03a
Haloxylon ammodendron	–	265 ± 75.9a	175 ± 53.2b	–	11 ± 1.6a	3 ± 1.1b
Overall coverage (%, mean ± SD)				58 ± 10.27a	31.9 ± 7.13b	19.0 ± 3.42c
IV of *Tamarix* (mean ± SD)	0.957 ± 0.13a	0.897 ± 0.11a	0.752 ± 0.18b			
Simpson index (mean ± SD)	0.702 ± 0.16a	0.589 ± 0.13b	0.712 ± 0.21a			

Values with different letters are significantly different among the selected years at $P < 0.05$ level

Table 3 Structures of *Tamarix*-vegetation at three sites in the Minqin Oasis-desert ecotone

Species	Mean height (cm, mean ± SD)			Species coverage (%, mean ± SD)		
	Shajingzi	Liujiadi	Xinxi	Shajingzi	Liujiadi	Xinxi
Tamarix ramosissima	152.5 ± 16.8b	138 ± 7.7c	182.5 ± 11.3a	7 ± 1.47c	9.95 ± 0.80b	19.4 ± 2.30a
Nitraria tangutorum	22 ± 2.1b	26.5 ± 3.3b	62.7 ± 7.4a	7.9 ± 1.58a	0.75 ± 0.12b	7.98 ± 1.14a
Bassia dasyphylla	8 ± 2.1b	25 ± 2.9a	30 ± 4.1a	0.4 ± 0.04b	3.59 ± 0.87a	0.76 ± 0.16b
Halogeton arachnoideus	8 ± 1.9b	20.5 ± 3.8a	30 ± 3.1a	0.3 ± 0.03b	6.01 ± 1.5a	0.74 ± 0.09b
Limonium aureum	20 ± 3.4a	–	16.5 ± 3.6a	0.1 ± 0.02a	–	0.56 ± 0.12b
Agriophyllum squarrosum	12 ± 1.3b	–	30.5 ± 5.1a	0.3 ± 0.04b	–	4.13 ± 1.53a
Haloxylon ammodendron	175 ± 53.2a	–	220 ± 43.4a	3.0 ± 1.1a	–	1.5 ± 0.23b
Karelina caspia	–	–	46 ± 6.2	–	–	2.35 ± 0.39
Calligonum mongolicum	–	40 ± 4.7	–	–	0.25 ± 0.07	–
Reaumuria songoria	–	28.5 ± 2.2	–	–	11.38 ± 1.89	–
Phragmites communis	–	–	26 ± 1.9	–	–	0.07 ± 0.01
Sophora alopecuroides	–	–	18.3 ± 2.6	–	–	0.7 ± 0.01
Salsola ruthenica	–	–	22 ± 3.6	–	–	0.67 ± 0.13
Artemisia spp.	–	29 ± 5.4	–	–	0.14 ± 0.02	–
Overall coverage (%, mean ± SD)				19.0 ± 3.42c	32.1 ± 3.65b	39.7 ± 3.11a
IV of *Tamarix* spp. (mean ± SD)	0.957 ± 0.13a	0.759 ± 0.16b	0.766 ± 0.10b			
Simpson index (mean ± SD)	0.702 ± 0.16a	0.770 ± 0.19a	0.785 ± 0.12a			

Values with different letters are significantly different among the selected sites at $P < 0.05$ level

there were no significant differences in Simpson index, the structure of *Tamarix*-vegetation changed from complex to simple and the degradation from serious to slight from the upper reaches to the lower reaches of the river. The ANOVA results showed that there were significant differences in the height, death rate, coverage and *IV* among the three sites except canopy range of *Tamari*x bushes (Table 3).

Spatial distribution of *Tamarix*-vegetation around famland

At site I where the surface of sand dunes was completely stabilized, the minimum width of *Tamarix*-vegetation belt was only 30 m, whereas the maximum width of *Tamarix*-vegetation belt was 75 m in the area where surface of sand dunes was semi-stabilized. There was a distribution gradient of *Tamarix*-vegetation along the distance away from the farmland: the longer the distance from the farmland, the lower the *Tamarix* bushes, the smaller the fresh shoot growth, the higher the death rate, and the lower the biomass of dry branches and leaves as well as the overall biomass were. ANOVA results showed that, in the transitional area, there were significant differences in the bush height, twig growth, branch death rate, bush coverage and biomass among the sites with different distances away from farmland (Fig. 2).

Results of a clear-cut treatment conducted at 8, 12 and 16 m away from farmland showed the length of fresh shoots, base diameter, bush coverage and fresh biomass decreased with the increase of the distance to the farmland in the following year. Results showed that there were significant differences in the height, base diameter, bush coverage and fresh biomass of *Tamarix* bushes among different distances away from farmland (Fig. 3). However, at the site 35 m away from the farmland with irrigation twice a year, the mean length of the fresh shoots and the base diameter were bigger than that of 8-m site away from the farmland. However, the bush coverage and biomass were lower than that of 8-m site, but higher than that of 16-m site. There were significant differences between 35-m site and 8, 12 and 16-m sites (Fig. 3). In the oasis-desert ecotone, the treatment of clear-cut and irrigation had significantly increased the shoot length, coverage and biomass.

Driving factors for changes of *Tamarix*-vegetation in the Minqin Oasis–desert ecotone

Precipitation

According to the meteorological data for the period from 1954 to 2006, observed at a local station, precipitation fluctuated with time, and the annual mean precipitation is only 115.8 mm. The rainfall mainly concentrated in the period from June to September. The number of days in which daily precipitation was more than or equal to 0.1 mm was 36. The length of successive rainy period

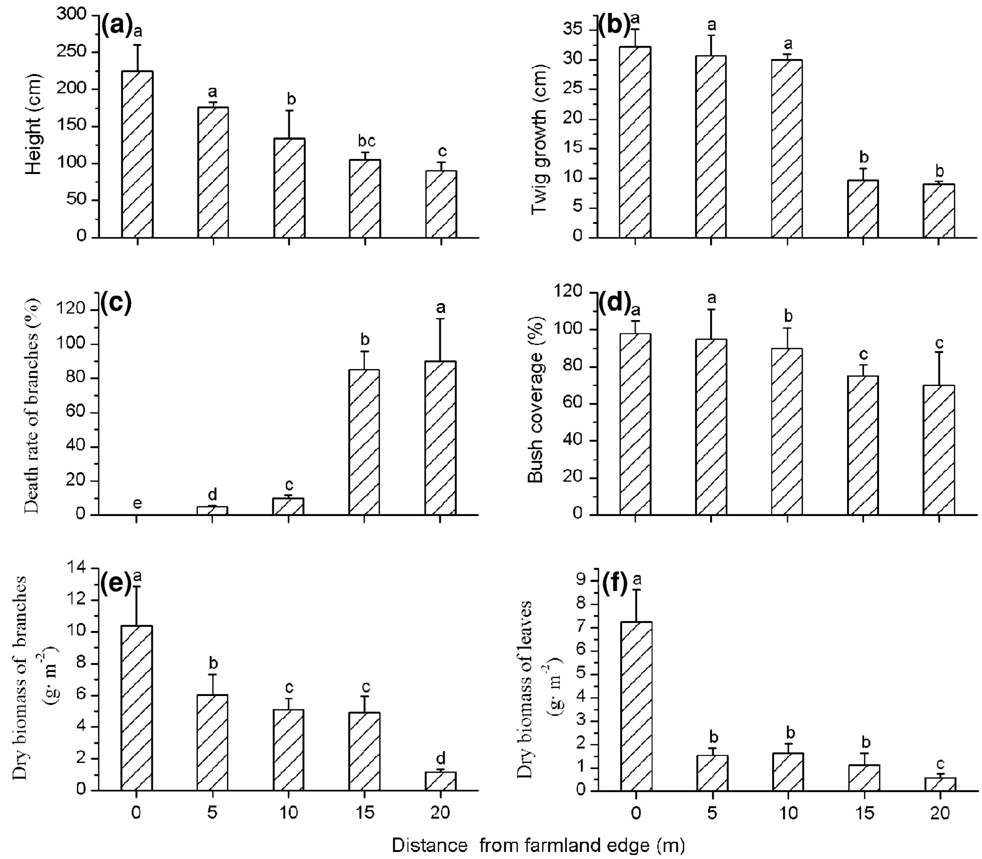

Fig. 2 Spatial distribution of *Tamarix* bushes along the distance away from farmland at site I. **a** Height, **b** twig growth, **c** death rate of branches, **d** bush coverage, **e** dry biomass of branches, **f** dry biomass of leaves (mean ± SD values with different letters are significantly different among the selected places away from farmland at $P < 0.05$ level)

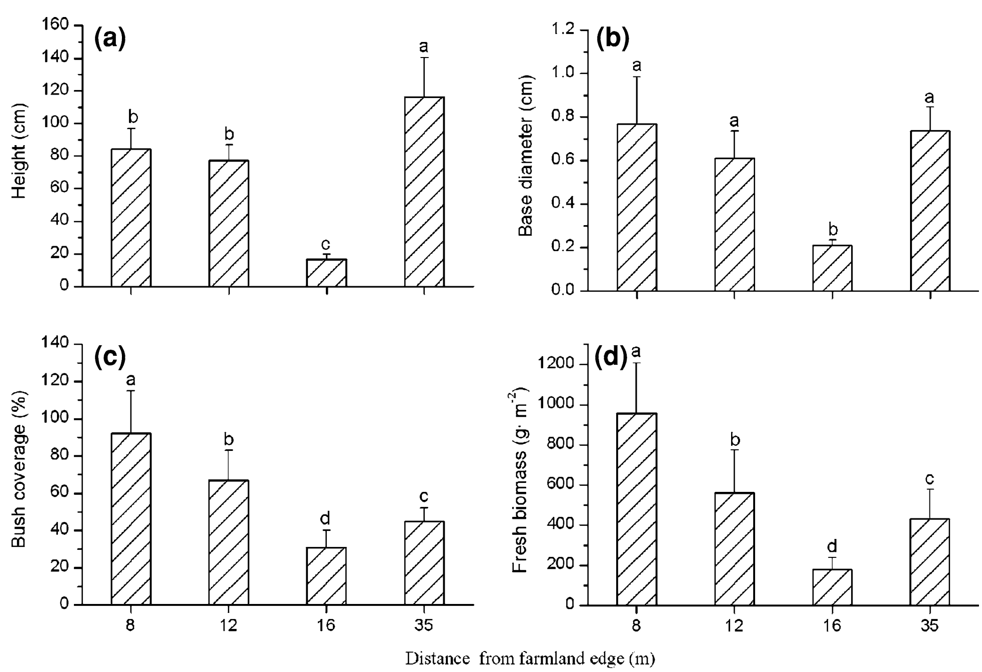

Fig. 3 Growth of *Tamarix* bushes along the distance away from farmland at site I after clear-cut in the previous year. **a** Height, **b** base diameter, **c** bush coverage, **d** fresh biomass (mean ± SD values with different letters are significantly different among the selected places away from farmland at $P < 0.05$ level)

was usually less than 2 days. The analog curve of precipitation showed that the spell of successive drought or wet was short, and the precipitation displayed an increasing trend (ESM Figure 2). The coverage of *Tamarix* bushes, appeared to be linearly correlated with the annual precipitation ($R^2 = 0.7303$, $P < 0.05$), decreased with the reduction of annual precipitation (Fig. 4). According to these results, it could deduce that the changes

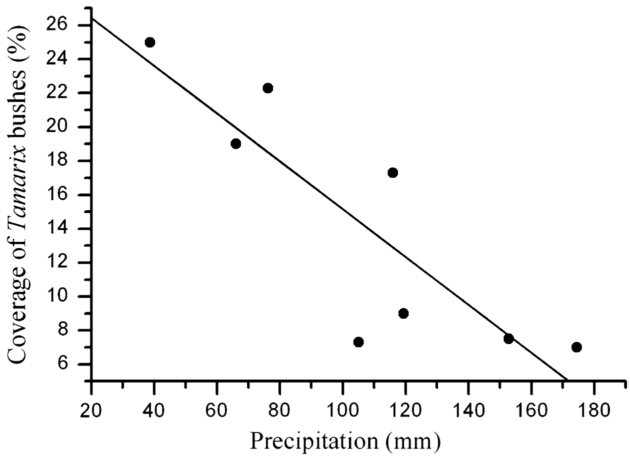

Fig. 4 Relationship between coverage of *Tamarix* bushes and the precipitation at site I

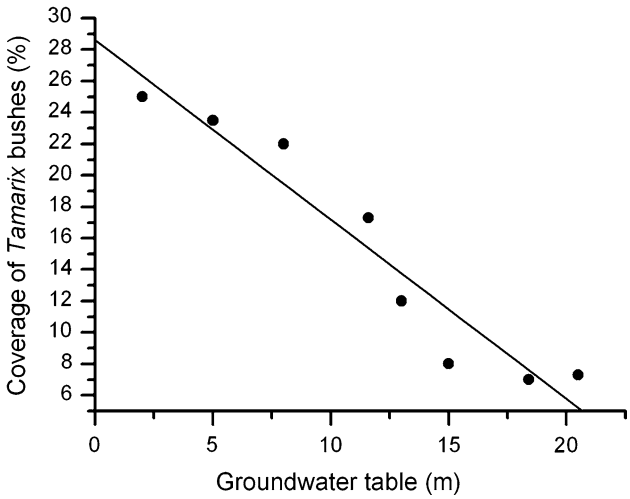

Fig. 5 Relationship between coverage of *Tamarix* bushes and the groundwater table at site I

of *Tamarix*-vegetation in the Minqin Oasis-desert ecotone was not drove by precipitation.

Groundwater table

During past 50 years, the groundwater table widely and continually fell in the Minqin Oasis-desert transitional area. With the decrease of the groundwater table, the coverage of *Tamarix* bushes reduced continually ($R^2 = 0.9255$, $P < 0.001$), especially when the groundwater table reached 14 m from 10 m (Fig. 5). At site I, the *Tamarix* grew vigorously when the water table was 2.2 m in early 1960s. The vegetation had degraded since around 1979 and widely died since 1990. *Tamarix*-vegetation continued to degrade until the water table dropped to 18 m in 2002, which had no more effects on the growth of *Tam*arix (ESM Figure 3). The consumption of the groundwater resources at site II was not as intensive as site I. However, the overuse of groundwater resources in the upper reaches reduced the recharged amount to site II, which led to a similar drop of groundwater table as site I. Consequently, *Tamarix*-vegetation also underwent a similar degradation process, the only difference was that the wither bushes was protected and not taken away. The groundwater table at site III dropped to below 10 m by the year of 2000, *Tamarix*-vegetation also started to degrade, and would also showed similar tendency as site I after 18 years according to the dropping rate of the groundwater table which was 0.37 m per year in recent years. The dropping of the groundwater table is expected to be a leading factor causing changes of *Tamarix*-vegetation.

Soil moisture content

For each of the three sites, the mean soil moisture contents at depth of 0–100 cm were lower than that of the shifting sand dunes 2.49 ± 0.37%. The mean soil moisture contents at depth of 0–100 cm in the stabilized *Tamarix*-vegetation, at the location 30 m away from the farmland at site I and site II, were 0.89 ± 0.16% and 0.90 ± 0.15%, respectively. These soil moisture contents were lower than wilting coefficient of *Tamarix ramosissima* 1.003%. The soil moisture content at site III was 1.25 ± 0.34%, closing to but higher than the wilting coefficient, which is an essential reason why *Tamarix*-vegetation in this site grew relatively well (Fig. 6). Soil moisture content became a leading factor that affected the growth of *Tamarix* when the groundwater table dropped to the threshold value about 10 m.

At site I, the mean soil moisture contents at the depth of 20–180 cm at the locations 0, 5 and 15 m away from farmland, were 7.64 ± 1.13, 1.23 ± 0.20 and 1.17 ± 0.07%

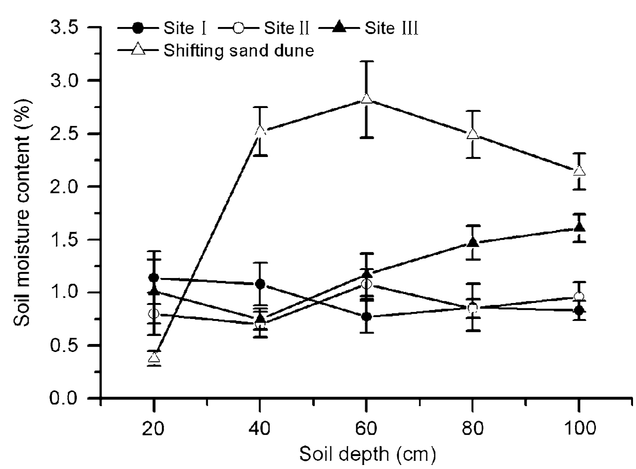

Fig. 6 Soil moisture contents of *Tamarix*-vegetation and shifting sand dune at three sites (mean ± SD)

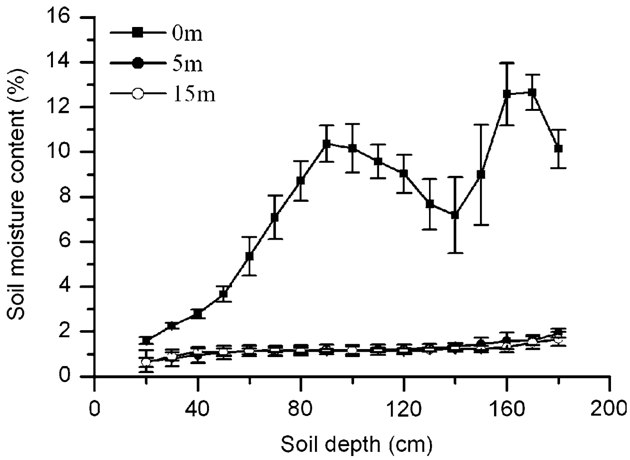

Fig. 7 Soil moisture contents along distance away from farmland (mean ± SD)

respectively. The results indicated that the soil moisture contents decreased with the increase of distance to the farmland. At depth about 140 cm at the location 0 m away from farmland, the soil moisture contents decreased because the soil turned from clay soil to sand-clay soil (Fig. 7). It implied that the seepage water from irrigation was important for the growth of the remaining *Tamarix* in the fringe zone of farmland.

Discussions

Species in *Tamarix* genus are distributed widely in the oasis-desert ecotone in arid area, and plays an important role in maintaining sandune stabilization and ensuring oasis ecological security (Liu 1987; Bikbulatova and Korulkina 2001). Due to their wide adaptation range and high value of ecological services, *Tamarix* spp. are also widely used for windbreaks and desertification control in arid and semi-arid areas, and also introduced to humid and semi-humid areas (Kleinkopf and Wallace 1974; Bikbulatova and Korulkina 2001; Huang and Gao 2004; Glenn and Nagler, 2005; Shafroth et al. 2005; Yang 2005; Whiteman 2006). The results of this study indicated that the dominant plant species of *Tamarix*-vegetation in the Minqin Oasis-desert ecotone changed from mesophytes to xerophytes and finally to super-xerophytes during past 50 years. The basic succession of *Tamarix*-vegetation revealed by this study corresponds to the observations made in other arid areas (Yin 1995). However, the dominant plant species of *Tamarix*-vegetation at the same research area exhibited a following process before 1950s: *Kalidium* spp.→*Kalidium* spp. and *Tamarix* spp.→*Tamarix* spp. and *Kalidium* spp.→*Tamarix* spp. and *Elaeagnus angustifolia* or *Populus euphratica*. This was a succession process from hygrophytes to mesophytes. Number of shrubs and trees as well as total biomass increased through the process (Li 1989; Yang 1999; Gao et al. 2006). In addition, since *Tamarix* spp. were introduced to the western US at the end of the 19th Century, they have become the dominant or sub-dominant species in over a dozen different riparian, wetland, xeric and halophytic plant associations in the western US and northwest Mexico. Millions of dollars was spent in controlling *Tamarix* spp. with chemical, physical, and biological measures per year (Baum 1967; Anderson 1998; Shafroth et al. 2005).

Many factors could affect vegetation and population changes, e.g. drought, soil erosion, habitat quality, seed availability and viability, as well as human-induced activities (Honnay et al. 1999; Rodriguez et al. 2005; Wang et al. 2005; Zhang et al. 2008). Vegetation change at all scales is governed by both dispersal limitation and the ability of species to establish and persist (Thompson et al. 2001). Most of species in *Tamarix* genus, e.g. *T. ramosissima*, are actually intermediate drought-tolerant species (Jiang and Gao 1992; Devitt et al. 1997; Xiao et al. 2005; Lite and Tromberg 2005). They are more suitable for habitats of banks of rivers and lakes or alluvial plains. This might be a key reason why *Tamarix*-vegetation and bushes are easily degraded under drought conditions.

Climate changes have influenced and altered a wide variety of semiarid and arid ecosystem functions (Lin and Tang 2002). Drought has been the major casual factors leading to the loss of dominant grass species, or replacement of a desirable grass species by undesirable shrubs or alien weeds (Zhang 1994). From soil and plant water relations, it is concluded that all perennial plants in the transition zone between oases and desert in arid area must have sufficient access to groundwater to ensure long-term survival (Thomas et al. 2006). Desert soils in an arid rain-fed environment have low and limited water contents, in which soil water availability is the prime factor limiting the number and size of perennial plant species and thus is the main constraint in permanently controlling desertification (Li et al. 2004). For *Tamarix*-vegetation in the Minqin Oasis-desert ecotone closed in a nature reserve since 1982, there was no direct intervention from human activities such as grazing, burning and deforestation (Tang et al. 2001). Changes of *Tamarix*-vegetation appeared to be closely related to biological and ecological characteristics of *Tamarix* spp., disappearance of surface water resources, the rapid decrease of groundwater table and the reduction of soil moisture content due to the intensive human-induced activities, especially agriculture activities. This result is consistent with previous research conclusions (Feng et al. 1989; Yang 1999; Chen et al. 2006). Under the current ecological conditions, it is hard to restore the degraded vegetation by conventional treatments alone. For instance, clear-cutting and revegetation without irrigation, thinning and destruction of soil crusts did not perform well. So restoration of groundwater such that it remains continuously accessible to the perennial plants is a prerequisite for the conservation of *Tamarix*-vegetation and ecological health of oasis-desert systems. This also provides an idea and approach by controlling water conditions not only to recover the degraded *Tamarix*-vegetation in arid and semi-arid areas, but also to control extension of *Tamarix* spp. in humid and semi-humid areas.

Conclusions

In the oasis-desert ecotone in arid area, as one of main vegetation types, *Tamarix*-vegetation is extremely important for sand dune stablization and protecting oasis from sand burial. However, during the past several decade years, dominant species in the composition of *Tamarix*-vegetation changed from mesophytes to xerophytes and finally to super-xerophytes, which strongly indicated vegetation degradation and land desertification in the oasis-desert ecotone. These replacements were closely related with the rapid decrease of groundwater table and the reduction of soil moisture due to unreasonable groundwater use for expanded agriculture development. The maintaining of stable groundwater and condign composition and structure of *Tamarix*-vegetation is a vital prerequisite for dryland management, especially, conserving ecological health of oasis-desert systems.

Acknowledgments We thank FengChun Zhang for his detailed edits on the manuscript. We also thank editors and two anonymous reviews whose comments greatly improved the manuscript. This study is supported by the project of "National Key Technologies R and D Program of China (2007BAD46B03; 2006BAD26B0802)", "West Light" Talent Cultivation Program and Gansu Innovation Team on Desert Control.

References

Al-Dousari AM, Misak R, Shahid S (2000) Soil compaction and sealing in Al-Salmi area, WesternKuwait. Land Degrad Dev 11:401–418

Alva AK, Paramasivam S (1998) Effects of monitor well purging technique on selected chemical properties of surficial groundwater. Bull Environ Contam Toxicol 60:525–530

Anderson B (1998) The case for saltcedar. Restor Manag Notes 16:130–134

Attrill MJ, Rundle SD (2002) Ecotone or eco-cline: ecological boundaries in estuaries. Estuar Coast Shelf Sci 55:929–936

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

Bikbulatova TN, Korulkina LM (2001) Composition of *Tamarix hokenakeri* and *T. ramosissima*. Chem Nat Compd 37(3):216–218

Chen XH, Duan ZH (2008) Changes in soil physical and chemical properties during reversal of desertification in Yanchi County of Ningxia Hui autonomous region, China. Environ Geol. doi: 10.1007/s00254-008-1382-1

Chen YN, Li WH, Chen YP, Zhao RF, Wan JH (2006) Ecological response and ecological regeneration of transfusing stream water along the dried-up watercourse in the lower reaches of the Tarim River, Xinjiang. Arid Zone Res 23(4):521–530

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

Di-Castri F, Hansen AJ, Holland MM (1988) A new look at ecotones: emerging international projects on landscape boundaries. Biology International, Special Issue 17:1–163, IUBS, Paris

Ding JL, Zhang Y (2006) Vegetation actualities and feasibility of restoration for the periphery of oasis in extreme arid region: taking Qira County of Xinjiang as an example. Ecol Econ 2:183–189

Feng ZC, Chang SP, Shi YF (1989) The correlation analyses between the natural vegetation and soil fertility in western sandland of Minqin. J Gansu Agr Univ 60(2):67–76

Feng JM, Wang T, Qi SZ, Xie CW (2005) Land degradation in the source region of the Yellow River, northeast Qinghai-Xizang Plateau: classification and evaluation. Environ Geol 47:459–466

Gao ZH, Li ZY, Wei HD, Ding F (2006) Quantitative monitoring of vegetation cover change by using remotely sensed data over Minqin Oasis, Gansu. Geogr Res 25(4):587–595

Glenn EP, Nagler PL (2005) Comparative ecophysiology of *Tamarix ramosissima* and native trees in western US riparian zones. J Arid Environ 61:419–446

Han FG, Wang J (2002) The ecological climate resources and its exploitation along the edge of Minqin Oasis. J Arid Land Resou Environ 16(3):51–56

Hanafi A, Jauffret S (2008) Are long-term vegetation dynamics useful in monitoring and assessing desertification processes in the arid steppe, southern Tunisia. J Arid Environ 72:557–572

Honnay O, Hermy M, Coppin P (1999) Impact of habitat quality on forest plant species colonization. Forest Ecol Manage 115:157–170

Huang PY, Gao RR (2004) Research on the extension of *Tamarix* shrubs resulted from development projects in arid area. J Forest Res 15(1):45–48

Jiang J, Gao HF (1992) A study on drought resistant ordination of *Tamarix* L. Arid Zone Res 9(4):41–45

Khresat SA, Rawajfish Z, Mohammad M (1998) Land degradation in the northwestern Jordan: causes and processes. J Arid Land Resour Environ 39:623–629

Kleinkopf GE, Wallace A (1974) Physiological basis for salt tolerance in *Tamarix ramosissima*. Plant Sci Lett 3(3):157–163

Li BC (1989) During Ming and Qing dynasties the damage desert vegetation and process in desertification in the lower reaches oasis of Shiyang River. Arid Zone Res 6(3):25–31

Li XR, Ma FY, Xiao HL, Wang XP, Kim KC (2004) Long-term effects of revegetation on soil water content of sand dunes in arid region of Northern China. J Arid Environ 57:1–16

Li XR, Jia XH, Dong GR (2005) Influence of desertification on vegetation pattern variations in the cold semi-arid grasslands of Qinghai-Tibet Plateau, North-west China. J Arid Environ 64:505–522

Li J, Zhao C, Zhu H, Li Y, Wang F (2007a) Effect of plant species on shrub fertile island at an oasis–desert ecotone in the South Junggar Basin, China. J Arid Environ 71:350–361

Li XR, He MZ, Duan ZH, Xiao HL, Jia XH (2007b) Recovery of topsoil physicochemical properties in revegetated sites in the sand-burial ecosystems of the Tengger Desert, Northern China. Geomorphology 88:254–265

Lin NF, Tang J (2002) Geological environment and causes for desertification in arid-semiarid regions in China. Environ Geol 41:806–815

Lite SJ, Tromberg JC (2005) Surface water and ground-water thresholds for maintaining *Populus–Salix* forests, San Pedro River, Arizona. Biol Conserv 125:153–167

Liu YX (1987) Desert flora of China (No. II). Science Press, Beijing, pp 367–381

Liu HJ, Wang JH, Chang ZF, Ma QL, Zhang KJ (2006) Characteristics of desert flora and vegetation in lower reach of Shiyang River Basin. Chin J Ecol 25(2):113–118

Ma YH, Fan SY, Zhou LH, Dong ZY, Zhang KC, Feng JM (2007) The temporal change of driving factors during the course of land desertification in arid region of North China: the case of Minqin County. Environ Geo l51:999–1008

Peng HJ, Fu BJ, Chen L, Yang ZH (2004) Study on features of vegetation succession and its driving force in Gansu desert areas—a case study at Minqin County. J Desert Res 24(5):628–633

Ringvall A, Patil GP, Taillie C (2000) A field test of surveyors' influence on estimates in line transect sampling. Forest Ecol Manage 137:103–111

Rodriguez AR, Mora JL, Arbelo C, Bordon J (2005) Plant succession and soil degradation in desertified areas (Fuerteventura, Canary Islands, Spain). Catena 59:117–131

Shafroth PB, Cleverly JR, Dudley TL, Taylor JP, Van Riper III C, Weeks EP, Stuart JN (2005) Control of *Tamarix* in the western United States: implications for water salvage, wildlife use, and riparian restoration. Environ Manag 35(3):231–246

Stocking MA (2004) Soil erosion and soil fertility. In: Forsyth T (ed) Encyclopedia of international development. Routledge, London, New York, pp 647–648

Su YZ, Zhao WZ, Su PX, Zhang ZH, Wang T, Ram R (2007) Ecological effects of desertification control and desertified land reclamation in an oasis–desert ecotone in an arid region: a case study in Hexi Corridor, northwest China. Ecol Eng 29:117–124

Sun DF, Dawson Richard, Li H, Li BG (2005) Modeling desertification change in Minqin County, China. Environ Monit Assess 108:169–188

Tang XP, He CR, Song ZS (2001) Scientific survey of Minqin Liangucheng National Nature Reserve of Gansu. China Forestry Publishing House, Beijing, pp 1–49

Thomas FM, Foetzki A, Arndt SK, Bruelheide H, Gries D, Li XY, Zeng FJ, Zhang XM, Runge M (2006) Water use by perennial plants in the transition zone between river oasis and desert in NW China. Basic Appl Ecol 7:253–267

Thompson K, Hodgson JG, Grime JP, Burke MJW (2001) Plant traits and temporal scale: evidence from a 5-year invasion experiment using native species. J Ecol 89:1054–1060

Wang YC, Zhao CY (2001) Study in desert-oasis ecological fragile zone. Arid Land Geogr 24(2):182–188

Wang ZY, Wang GQ, Li CZ, Wang FX (2005) A preliminary study on vegetation-erosion dynamics and its applications. Sci China Ser D5:689–700

Wang YG, Xiao DN, Li Y (2007) Temporal–spatial change in soil degradation and its relationship with landscape types in a desert–oasis ecotone: a case study in the Fubei region of Xinjiang Province, China. Environ Geol 51:1019–1028

Wesselsa KJ, Princea SD, Malherbeb J, Smallc J, Frostd PE, VanZylb D (2007) Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa. J Arid Environ 68:271–297

Whiteman KE (2006) Distribution of salt cedar (*Tamarix* spp. L) along an unregulated river in South-western New Mexico, USA. J Arid Environ 64:364–368

Xiao SC, Xiao HL, Si JH, Liu FM (2005) Growth characteristics of *Tamarix ramosissima* in arid regions of China. Acta Bot Boreal Occident Sin 25(5):1012–1016

Yang ZH (1999) Research on desert vegetation changes for 40 years at Shajingzi area in Minqin. J Desert Res 19(4):394–398

Yang LW (2005) Evaluation on ecological value of *Tamarix* spp forest in Hotan Drainage Basin. J Desert Res 25(2):268–274

Yin LK (1995) *Tamarix* spp.—the keystone species of desert ecosystem. Arid Zone Res 12(3):43–47

Zhang XS (1994) Principles and optimal models for development of Maowusu sandy grassland. Acta Phytoecologica Sin 18(1):1–16

Zhang KC, Qu JJ, Ma ZH (2004) Environmental characteristics of sandstorm in Minqin County in recent 50 years. J Desert Res 24(3):257–260

Zhang XY, Wang XM, Yan P (2008) Re-evaluating the impacts of human activity and environmental change on desertification in the Minqin Oasis, China. Environ Geol 55:705–715

Zhao WZ, Hu GL, Zhang ZH, He ZB (2008) Shielding effect of oasis-protection systems composed of various forms of wind break on sand fixation in an arid region: a case study in the Hexi Corridor, northwest China. Ecol Eng 33:119–125