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Comprehensive eco-environmental effects of the shelter-forest ecological engineering along the Tarim Desert Highway

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In this work, we report a comprehensive study about the eco-environmental effects of the shelter forest along the Tarim Desert Highway, including the effects on aeolian environment, soil, micro-climate, biodiversity, and groundwater. The results show that: (1) The movement of windblown sand near the ground surface was affected by the shelter forest. The wind speed and sediment transport rate in the shelter forest decreased by 64%—80% and 87.45%—99.02%, respectively. In addition, there were also significant changes in the sand flux structure, the sand grain size, and the deflation and deposition on the ground surface. (2) Compared to the natural mobile sand, the soil bulk density in the forest area decreased while the total salt content, the total porosity, and the water content increased. In addition, the soil fertility was significantly improved in the forest area, and showed the "first rapid, then slow" variation pattern. (3) The shelter forest showed positive effects on the micro-climate. Within the 6 m height above the ground, the air temperature in the shelter forest at different heights was lower than that in the mobile sand, while the air humidity was higher, while, the soil temperature was also lower in the shelter forest than mobile sand. (4) The number of soil microbial species increased significantly with the improvement of habitat in the shelterbelt. However, the population of different species was not distributed evenly across the surveyed area. (5) Currently, no significant effects of groundwater-pumping and forest-irrigation water have been found on the groundwater level and its salinity. The variation amplitude of both groundwater level and salinity was at the level of centimeters and 1g/L, respectively. No obvious variation trend has been observed.

desert, shelter-forest engineering, environmental effect, aeolian environment, biodiversity

It has been well recognized that artificial engineering projects can exert extensive, intensive and rapid effects on the environment. Particularly, most of mining, industrial processing, hydraulic engineering, and traffic engineering projects have already shown some obvious negative effects on the ecological environment, while ecological restoration and reconstruction as well as disaster protection projects usually have positive effects. Few works on the environmental effects of shelter-forests in desert have been published at home and abroad[1], although there have been studies on the beneficial environmental effects of the protection forest system of the Shapotou Railway in Zhongwei, Ningxia of China[2−9].

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So far, a comprehensive analysis about the beneficial effects of sand protection systems on the environment has been reported little.

The Tarim Desert Highway shelter forest (466 km long and 72—78 m wide) runs through the Taklimakan Desert. Most areas it runs through are extremely drought with intensive sand-carrying wind activities. Although the shelter forest has successfully prevented the Tarim Desert Highway from sand damage, it also changed the ecological environment of the areas it runs through. It has been reported that such environmental effects were comprehensive. It can affect windblown sand movement, soil properties, local climate, ground water environment, etc.[10−13]. However, most previous studies concentrated on the effects brought about by single factors thereafter neglected the comprehensive effects. In this work, we conducted a comprehensive analysis about the effects of the shelter forest along the Tarim Desert Highway on various environmental factors, including atmosphere, plants and animals, soil, and groundwater. It can provide insights on the environmental assessment as well as the development of ecological restoration and reconstruction technologies in drought areas.

1 Study area

1.1 Natural conditions

The desert part of the Tarim Desert Highway is located in an area with latitude from 37° to 42°N and longitude from 82° to 85°E. It runs across the Taklimakan Desert from north to south along the longitude 84°E. The Taklimakan Desert is the second largest desert in the world, whose area is about 33.78×10^4 km^2. The local climate is extremely arid and rainless. It is probably the most arid area through out the Eurasia. More than 82% of its area is covered by drifting sand dunes. The Taklimakan Desert is known as “the Sand Dune Museum of the world” for its great variety of dune morphologies. It is also called “the Dead Sea” because almost none animals and plants live there. The desert area around the Tarim Desert Highway has little precipitation, strong winds, various types of sand dune, abundant sand source, and infertile soil. It is also short of plants as well as surface runoff. All of these seriously threaten the traffic security of the Tarim Desert Highway.

According to observational data of the weather stations along the Tarim Desert Highway[14], in the hinterland of desert, the annual precipitation and evaporation amount was 10.7 mm and 3806.4 mm, respectively, the annual average temperature was 12.7℃ with the maximum and minimum temperature being 43.2℃ and −19.3℃, respectively, the annual sunshine hours were 2854.2 h, the maximum depth of frozen soil was 88 cm, the number of strong windy day was 6 d/a, the number of flying dust day and flying sand day was 74 d/a and 45 d/a, respectively. The period from March to September is the wind season while the period during the October and the next February is the calm wind season. Along the highway, the wind power conditions changed with the location. Specifically, in Xiaotang, the north end of the Tarim Desert Highway, the dominant wind directions were N, NNE, NE, ENE, and E, and the resultant wind direction was NNE. While in Tazhong, the middle section of the highway, the dominant wind directions were ENE, NE, E and NNE. However, the south end of the highway was influenced by winds of variable wind directions, including NE, NW and SW, at the same time, annual average frequency of sand driving wind here was significantly lower than that of Xiaotang and Tazhong.

Along the Tarim Desert Highway, the groundwater storage was large, although the surface runoff was almost negligible. It has been estimated[14] that the basic reserve of groundwater was 16.29×10^8 m^3 and the dynamic annual recharge was about $9671.0-9931.0\times10^4$ m^3. The depth of groundwater level changed greatly with the ground landform. For example, it was below 5 m in interdune, whereas it can be above 20 m on the top of sand ridges. Moreover, the groundwater quality varied along the desert highway. The salinity of most groundwater salinity was about 3—5 g/L, and the maximum salinity was 30 g/L. The dominant hydrochemical type was $Cl\cdot SO_4-Na$.

On the contrast, the soil type along the Tarim Desert Highway was simple, mainly the weakly formed aeolian sandy soil that was loose, coarse grained soil containing only a few clay particles. The aeolian sandy soil showed only weak biological activity, with little accumulation of organic matters whereas a high lime content. Particularly, the mobile aeolian sandy soil that predominated the desert highway area had a pH value of 9 and contained the organic matters, the salts, and the moisture less than 1%, 2%, and 0.5%, respectively. Most plants cannot survive over there. As a consequence, there were a few plant and animal species found in the desert area along the highway, including 5 animal species such as *Araneida*, *Lepus yarkandensis*, *Dipus sagitta*, *Meriones meridianus*, *Camelus bactrianus*, and 19 plant species that belonged to eight families such as *T. taklamakanensis* PYZhang.et MTLiu, *Phragmites communis*, *Bidens parviflora Willd*, *Calligonum mongolicum Turcz.*, *Heliotropium micranthum* (Pall.) Bge, etc.[14].

1.2 Species, structure, and irritation of the shelter forest

Because of the special environment in the area around the Tarim Desert Highway, the plants *Calligonum L*, *Tamarix L.*, and *Haloxylon Bge* that have high tolerance to salts, aridity, low and high temperatures, as well as wind erosion and sand bury were selected for the shelter forest. Particularly, *Calligonum L* and *Haloxylon Bge* were mainly planted in high dune areas, while *Tamarix L* was mostly planted in interdune. In the areas where the underground level is low, both *Tamarix hispida Willd* and *Tamarix elongata Ledeb* were selected for their high salinity tolerance[15].

Based on the comprehensive consideration of the protection benefit, the stability, and the landscape benefit of the shelter-forest ecological engineering, the mixed belt mode was selected for the sand-blocking belt in which the plant and row space was 1 m × 2 m and 1 m × 1 m, respectively. On the contrast, the mixed row mode was adopted in the sand-binding belt in which the plant and row space was 1 m× 2 m and the two rows along each side of the highway were made of *Tamarix L* with a plant and row space of 1 m × 1 m.

In addition, due to the complicated surface morphologies as well as the high evaporation rate and high salinity groundwater for irrigation along the Tarim Desert Highway, conventional irrigation methods such as the ridge, furrow, and sprinkler irrigation cannot be adopted. Therefore, the drip irrigation using high salinity groundwater was adopted here, which has the advantages of the high terrain adaptability, the low irrigation intensity, the small evaporation and leakage loss, the high irrigation efficiency, and water saving[14,16,17].

2 Methods

2.1 Effects on aeolian environment

The wind power was measured using DET Ⅰ mobile polygradient anemometer station (Changchun Meteorological Instrument Research Institute). The rate of sand transporting was measured by step-like array trap. The iron bars were inserted into sand surface to measure the wind erosion on the ground. The morphology of dunes and their migration was monitored by a total station (NTS-352). Atmospheric dustfall were collected by a dustfall jar using the dry method[18] in which the top of dustfall jar was 1.5 m above the ground. The grain size of sand collected above was measured by a laser particle size analyser (Marven 2000) using Folk-Ward grain size parameters[19].

2.2 Effects on soil properties

The soil salt content was measured by weighing the mass of dried-residue. The pH value was determined by potentiometry. The moisture content, the specific gravity, and the bulk density of soil were measured by the oven-drying method, the bottle method, and the cutting ring method, respectively. The total porosity was calculated from the bulk density and the specific gravity.

The factors related to soil fertility including the soluble salts content, the organic matter content, the total N, P, K content, and the available N, P, K content were measured. The organic matter content was determined by the potassium dichromate titration-external heating method, the total and available N content was measured by Kjeldahl method digested with H_2SO_4 and $HClO_4$, and the distillation method after alkaline hydrolysis, respectively. The total P was determined by the Mo-Sb colorimetry after being dissolved with acid, while the available P was measured by the Mo-Sb colorimetry after being extracted with 0.5 mol/L $NaHCO_3$. The total and available K was analyzed by flame photometry after being dissolved with acid and extracted NH_4OAc, respectively. The soil fertility was evaluated by using continuous membership functions and the comprehensive fertility index IFI was calculated by IFI=$\Sigma W_i \times F_{i,}$, in which W_i is the weight vector of soil fertility factor *i* and $F(X_{ij})$ represents the membership degree between the fertility factor *i* and *j*[20].

2.3 Effects on micro-climate

Both the local atmospheric temperature and humidity were monitored using temperature/humidity probes (HOBO Pro HR/Temp, Onset Inc, USA) that were placed at different height above the ground. The soil temperature was monitored using soil temperature probes (HOBO H8 Water/Soil Temp, Onset Inc, USA) that were buried in ground with different depths, and the data were collected by Outdoor/Industrial 4-Channel External Logger (Onset Inc, USA).

2.4 Effects on biodiversity

The soil microbial fatty acid was analyzed by the fatty acid methyl esters (FAME) method[21]. The soil bacterial diversity was determined by the polymerase chain reaction-denaturing gradient gel electrophoresis (PCR-DGGE). The diversity of bacterial fatty acids and DNA fragments was indicated by the diversity index (H), the abundance (S), and the evenness (E_H):

$$H = -\sum_{i=1}^{S} P_i \ln p_i = -\sum_{i=1}^{S} (N_i / N)\ln(N_i / N), \quad (1)$$

$$E_H = H / H_{\max} = H / \ln S, \quad (2)$$

in which P_i is the mass percentage of fatty acid i or the intensity ratio of specific band to the total bands, and S is the number of fatty acids or the DNA bands in a specific soil sample.

2.5 Effects on groundwater

The level of groundwater was measured by a tape ruler and a home-made simple device including an ammeter and a piece of long conducting wire. The groundwater salinity was measured by weighing the mass of dried-residue. The electrical conductivity was determined by a portable electric conductivity meter (DDB-303A). The pH value was obtained using a pH meter (PHS-3C). The carbonate and bicarbonate content was determined by the dual-indicator neutralization method, while the calcium, magnesium and sulfate ions content was determined by Ethylene diamine tetraacetic acid (EDTA) complexometric titration. The chloride content was measured by $AgNO_3$ titration. The potassium and sodium content was analyzed by a flame photometry and calculated with the subtraction method.

3 Results and discussion

3.1 Effects on aeolian environment

(i) Changes in wind power and rate of sand transporting. As shown by the results observed on flat sand ground in interdunes, when the 5 min-average wind speed at a height 1 m above the ground on the mobile sand outside the shelter forest was 6.6 $m \cdot s^{-1}$ and the rate of sand transporting at a height 20 cm above the ground was 0.51 $g \cdot min^{-1} \cdot cm^{-1}$; while inside the shelter forest, the wind speed decreased to 1.5—3.3 $m \cdot s^{-1}$, only about 22.73%—50% of that outside the shelter forest, and the rate of sand transporting was as low as 0.005—0.064 $g \cdot min^{-1} \cdot cm^{-1}$, only about 0.98%·12.55% of that outside shelter forest. The rate of sand transporting reached its minimum in the middle part of the shelter forest where it was decreased by 99.02% compared to that outside the shelter forest. Although the wind speed recovered a little bit on the open space in the forest, it continued to decrease when entering the forest belt again with an amplitude as high as 64%·80% (Figure 1).

(ii) Variations of wind-sand flow structure. The wind-sand flow structure in interdunes was observed at multiple sites simultaneously both inside and outside the shelter forest. The results are shown in Figure 1. It can be seen that the wind-sand flow structure at all sites (S1—S5) followed a general law, i.e., the relative sand concentration decreases with the height. However, the wind-sand flow structure inside the shelter forest was significantly different from that outside (Figure 2). Specifically, the relative sand concentration at 2—4 cm height differed little at each site, while at 0—4 cm height, the relative sand concentration inside the shelter forest (S2—S5) was less than 65% but as high as 78% in the mobile sand (S1). At 6—20 cm height, the relative sand concentration in the mobile sand (S1) was only 17% while it was 32%—64% inside the shelter forest. It can be inferred that the decrease of sand particle concentration near the ground surface with the height was fast in the mobile sand but slow inside the shelter forest. Moreover, the sand particle distribution in the upper layer was more even inside the forest compared to that in the mobile sand. Therefore, it was clear that the relative sand concentration of the upper layer inside the shelter forest was relatively high due to the unloading of the sand in the lower layer. It has also been found by Liu[22] and Zhang et al.[23]. All of these results revealed that the sand particles carried by airflow entered the shelter forest mostly by the saltation and suspension and mostly were distributed over the upper layer as a result of the significant decrease in the wind speed near the ground surface in the shelter forest.

(iii) Variations of sand grain size. As shown by the analysis of sand samples in interdunes, due to small amounts of sediments on the ground in the middle of the sand-obstructing shelterbelt and sand-binding shelterbelt, as well as in the open space in the forest belt, the sand grain size was pretty close to that of the original sand

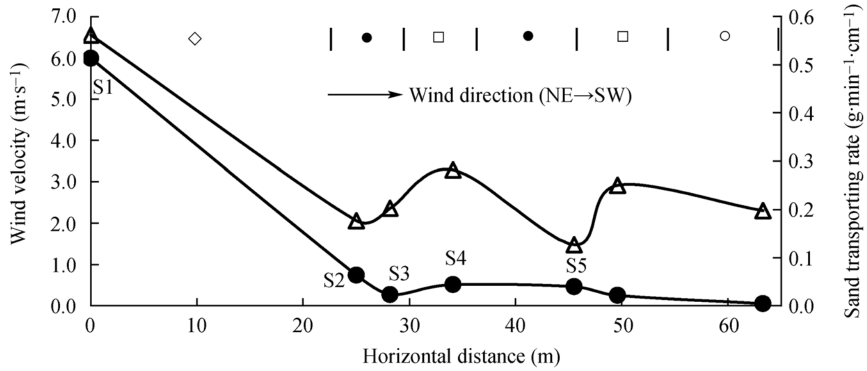

Figure 1 Variation of the wind speed at the height of 1 m and the sand transporting rate at 20 cm height above the ground inside and outside the shelter forest as measured in interdunes. ◇ Shifting sand; ● sand-obstructing forest; □ open space in forest; ○ sand-binding forest; –△– wind velocity; –●– sand transporting rate.

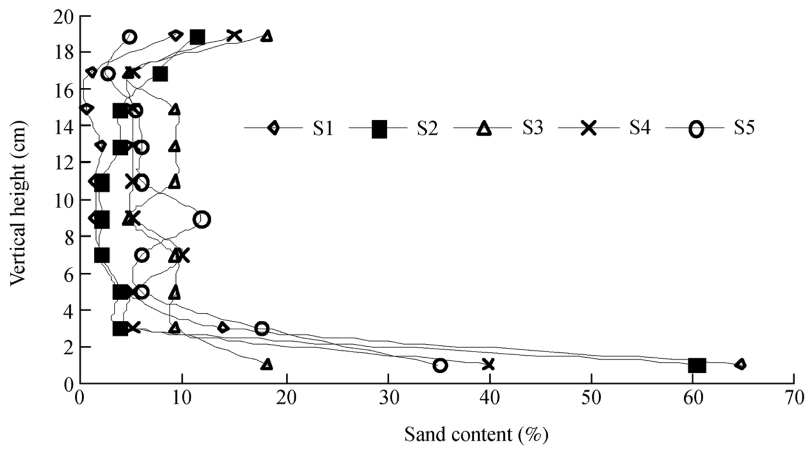

Figure 2 Variation of wind-sand flow structure inside and outside the shelter forest in interdunes (for the location of S1—S5 see Figure 1).

surface covered by coarse particles. However, the sand inside the shelter forest did not contain the coarse particles while the average content of very fine sand and silts increased by 3.90% and 4.85%, respectively. Moreover, the fine sand and middle sand content decreased by 0.66% and 0.37%, respectively. The average particle size (3.493φ) decreased too. The three sites inside the forest showed a good sorting feature as well as the top of mobile dunes outside the shelterbelt, even though the former σ_τ was larger than the latter. However, the dunes in interdunes only showed the moderate sorting features. Therefore, it can be inferred that the sorting features inside the forest were poorer than the original small dunes while better than that flat sand ground in interdunes. Specifically, the grain size distribution of each site inside the shelter forest as well as the top of mobile dune outside the shelter forest was approximately symmetrical with a moderate kurtosis, while the curve of the flat sand ground in interdunes showed a negative skewness with a small kurtosis (Table 1). Therefore, it was clear that, as a result of the significant decrease in the wind speed near the ground surface, a large amount of fine particles deposited inside the shelter forest. Similarly, the analysis of atmospheric dust fall also revealed that, compared with the sand sample from the top of mobile dunes, the grain size distribution of atmospheric dust fall deviated from that of the salt crust layer inside the shelter forest with a fine tail as well a larger median and average particle size in φ value, which meant a narrower distribution. On the contrary, in interdunes, the grain size distribution of atmospheric dust fall was very similar to that of the salt crust layer, indicating that the sediments on the ground surface in interdunes were mainly made of airborne dusts. Generally, the highway traffic was not affected by the sand deposition on the road shoulders and road surface, the sand burial of the migratory dunes, except the slight sand deposition during strong sand storms.

(iv) Changes in landform Inside the shelter forest, aeolian deposition landforms are dominant, including nebkhas in a small scale, sheet-like sand deposition in a middle scale, and ridge-like sand deposition in a large scale. There are also some deflation landforms inside the shelter forest. They cannot develop into a large size in interdunes, but can develop into large scale on the windward slopes of secondary dunes in sand ridges. On the upwind side of the shelter forest, both the shape and orientation of small mobile dunes located in interdunes have been changed by the sand-obstructing belts and their surrounding ridge-like deposition. On the windward slope of ridge-like sand deposition around the sand-obstructing forest belts, the stable slope surface was finally formed, although it can be destroyed for a short time by the dunes moving forward. On the leeward slope of the shelter forest, a large-scale deflation can be developed. It led to the formation of deflation hollows in interdunes, and in particular, led to the decrease in relief amplitude in the topographic relief regions. Therefore, we can conclude that the shelter forest can efficiently block the windblown sands as well as winds. On the windward side of the shelter forest, the wind speed decreased significantly. However, with the recovery of the wind speed, the wind-sand flow gradually became unsaturated at the leeward side, leading to the formation of sand deflation[24].

3.2 Effects on soil properties

(i) Changes in soil moisture, salt content, and soil texture. Compared with the mobile sand (Table 2), inside the shelter forest, the soil bulk density decreased while the total salt content, the total porosity, and the water content increased. It indicates that, after the construction of the shelter forest, the soil permeability and texture became better and more porous, respectively, while the soil salt content became larger. Moreover, the experimental observations at multiple comparisons showed that they were significantly different at 0.05 levels in the soil bulk density of the forest soils with different forest ages, as well as in the total porosity, the total salt and water content.

The total salt content of the salt crust layer inside the forest was 17.6—58 times larger than that of 0—5 cm

Table 1 The grain composition (%) and grain size parameters of the sand samples collected on the ground surface inside and outside the shelter forest

Site		Grain composition (%)					Grain size parameters				
		Coarse sand (mm)	Medium sand (mm)	Fine sand (mm)	Very fine sand (mm)	Silty sand (mm)	Average particle size		Sorting	Skewness	Kurtosis
		>0.5	0.5—0.25	0.25—0.125	0.125—0.063	0.063—0.005	M_d (φ)	M_d (mm)	σ_τ	SK	KG
Outside the shelter forest	Dune's summit	0	4.61	46.37	45.43	3.59	2.968	0.128	0.587	–0.009	0.947
	Interdunes	7.72	0.44	21.07	54.38	16.38	3.331	0.099	0.943	–0.273	1.820
Inside the shelter forest	Sand-obstructing forest belt	0	0.04	19.25	58.34	22.36	3.517	0.087	0.603	0.033	0.975
	Open space in forest belts	0	0.11	22.68	58.32	18.89	3.444	0.092	0.599	0.029	0.971
	Sand-binding forest belt	0	0.06	19.31	58.18	22.44	3.517	0.087	0.607	0.035	0.979
	Salt crust inside the shelter forest	0	0.12	21.64	56.87	21.38	3.483	0.089	0.637	0.065	1.021
	Atmospheric dustfall inside the shelter forest	0	0	28.97	60.41	10.62	3.296	0.102	0.538	0.034	0.973

Table 2 The variation of main physical and chemical properties of shelter forest soils with different forest ages[a)]

Forest age (a)	Bulk density ($g\cdot cm^{-3}$)	Total porosity (%)	Water content (%)	Total salt ($g\cdot kg^{-1}$)
0	1.94 a	33.6 a	0.61 a	0.47 a
1	1.81 b	35.28 b	1.82 b	0.77 ab
2	1.73 c	37.89 c	2.12 c	0.94 b
3	1.67 d	39.69 d	2.55 d	1.17 b
4	1.63 e	40.39 d	3.05 de	1.62 c
6	1.57 f	42.30 e	4.72 ef	1.92 c
8	1.40 g	48.02 f	7.21 f	2.65 d
12	1.28 h	50.38 g	9.09 g	3.49 e

a) The values shown in the table are the average of the layers 0—10 cm, 10—20 cm, and 20—35 cm. The letter after the numbers indicates their results of multiple comparisons. The numbers followed by different letters indicate that they are significantly different at 0.05 levels, otherwise, they are not significantly different at 0.05 levels (the same below).

layer in the mobile sand. In addition, the salt content of 0—5 cm and 5—15 cm layers in the forest soil was larger than that of mobile sand, whereas the salt content of 15—30 cm layer was lower, indicating that the soil salt content at up to 15 cm depth was dominated by the soil salt on the surface while below 15 cm the salt content was significantly affected by leaching irrigation. Particularly, the salt content variation of the crust layer showed an obvious regularity with the forest age. Specifically, the salt content decreased with the forest age and finally reached a steady level. However, the salt content below the salt crust layer varied little.

In the mobile sand, all salts were chlorides, among which the NaCl content was highest, followed by $CaCl_2$, KCl, and $MgCl_2$. On the contrast, in the forest soil, besides the chlorides, there were also a significant amount of sulfates, even some carbonates. The dominant cation was sodium ion in most samples, while the calcium ion also was dominated in some samples.

(ii) Changes of soil fertility. In a soil profile of the forest soil, the content of organic matter, the total N, and the total P increased from the bottom to the top, particularly, increased the most significantly in the crust layer. On the contrary, the total K content changed little. In addition, the content of organic matter as well as the total N increased with the increase of forest age in each layer, while the content of the total P and K increased only in the layers above the 15 cm but decreased in the crust layer with the forest age. The total P content in the 15—30 cm layer increased with the forest age, whereas the total K content changed little.

The above results show that the soil fertility was improved significantly after constructing the shelter forest (Figure 3). Specifically, the integrated fertility index (IFI) of the mobile sand was only 0.082, while it increased to 0.917 in the 12-year forest age soil. In addition, the increase of soil fertility with the forest age showed a “first rapidly, then slowly” pattern[25].

3.3 Effects on micro-climate

(i) Changes in air temperature and humidity. The air temperature and relative humidity in both mobile sand and forest land were measured respectively at the 2, 6 and 8m height in late July, 2006. The data showed that the air temperature of the mobile sand was higher than that of the forest land at all heights, whereas the relative humidity of the mobile sand was lower (Table 3). The experimental data at multiple comparisons further revealed that the air temperature of the mobile sand was significantly different from that of the forest land at the 2 and 6m height but no obvious difference at 8 m. In the meantime, the relative humidity showed a trend similar to the temperature: there was significant difference in relative humidity at the 2 and 6 m height between the mobile sand and forest land while no obvious difference at 8 m. It can be inferred that the shelter forest had less influences on the air temperature and relative humidity with the increase of height[26].

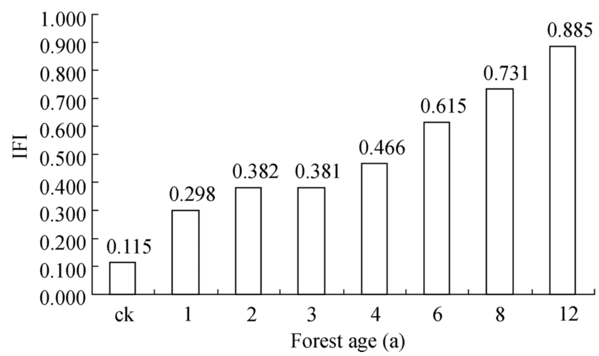

Figure 3 The variation of soil fertility with the shelter forest age.

(ii) Changes in soil temperature. The soil temperature in both mobile sand and forest land was measured respectively at the depths of 5, 10, 15, 20, 40, 60, 80 and 100 cm in late July, 2006. By comparing the data at multiple comparisons, we found that the soil temperature of the forest land was significantly lower than that of mobile sand at the same depth, and in particular, the difference at eight depths was significant (Table 4). In addition, the soil temperature of both mobile sand and forest land decreased with the depth. However, the amplitude of soil temperature variation in the mobile sand was obviously larger than the forest land in a depth range from 5 to 100 cm. All of these indicated that the shelter forest had significant regulation effects on the

Table 3 Variation of air temperature and relative humidity at different heights above the ground surface inside and outside the shelter forest

Site	Height (m)	Air temperature (℃)	Relative humidity (%)	Site	Height (m)	Air temperature (℃)	Relative humidity (%)
Mobile sand	2	30.88±4.66 a	15.38±6.70 d	Forest land	2	30.17±4.96 c	16.47±6.22 c
	6	30.87±4.51 a	16.90±6.37 c		6	30.62±4.69 b	17.85±6.73 b
	8	30.75±4.47 ab	16.75±6.24 c		8	30.70±4.57 ab	21.07±8.12 a

soil temperature. The reason why the shelter forest can lower the soil temperature may be as follows: First, because of the water supplemented by irrigation, the soil moisture can increase the specific heat capacity of soil, which led to a decreased amplitude of soil temperature variation; second, the radiation intensity on the ground could be lowered as a result of the absorption and reflection of the solar radiation by the forest canopy.

Table 4 Changes of soil temperature at different depths inside and outside the shelter forest

Depth (cm)	Mobile sand (℃)	Forest land (℃)
5	32.47±5.08 a	29.97±3.00 c
10	31.46±2.97 b	28.96±1.58 de
15	31.06±2.06 b	28.35±1.05 e
20	30.82±1.48 b	28.25±0.85 e
40	29.72±0.49 cd	27.31±0.42 f
60	28.37±0.28 e	26.27±0.24 g
80	26.90±0.19 fg	25.32±0.18 h
100	25.28±0.16 h	24.32±0.15 i

3.4 Effects on biodiversity

(i) Changes in diversity of plants and animals in forest land. The plant species in the range of physical sand-protection system along the Tarim Desert Highway increased after the construction of the shelter forest. A survey (20 m×20 m quadrat) was conducted in forest land in September, 2006. It was found that there were some herb plants such as *Bidens parviflora Willd*, *Phragmites communis*, *Salsola ruthenica Iljin, Apocymum venetum L*, etc. appearing in forest land, among which *Halogeton glomeratus (Bieb.) C. A. Mey* and *Phragmites communis* were the majority. Besides, there were also a few *Haloxylon Bge.* and *Calligonum mongolicum Turcz* seeding. Moreover, some ant nests, mouse holes, rabbit holes and lizard caves were found in the surveyed areas, indicating the activity of soil animals. The number of ant nest was the most in every surveying area, followed by mouse holes and lizard caves (Table 5). It is clear that the shelter forest can significantly improve the living environment of a variety of plants and animals. Most species found in the forest are indigenous plants, while a few species are brought by human activities.

(ii) Changes of microbial diversity in forest land. (1) Changes of microbial fatty acids diversity. The microorganisms inhabited in different soils have their own characteristic fatty acids. Therefore, the fatty acids diversity of soil microorganisms can be revealed the diversity of soil microorganism population. It has been found by F-tests that there was significant difference in the indices of Shannon diversity (H), Richness (S) and Evenness (E_H) to the soil microorganism fatty acids in the forest lands with different forest ages. The difference in H and E_H was particularly significant (Table 6). The experimental data at multiple comparisons further revealed that, after constructing the shelter forest, the Shannon diversity index gradually increased with the forest age, and reached the maximum after 8 years, and the Shannon diversity index of 12-year-old forest land was lower than that of 6 and 8-year-old forest land. Particularly, the difference in Shannon diversity indices between forest land and the mobile sand did not become significant until the shelter forest had been constructed for 3 years. With the increase of forest age, the fatty acid richness increased greatly, while the evenness kept a constant or even decreased a little. It can be inferred from all of these data that the number of microbial species increased significantly after constructing the shelter forest. However, the population of each microbial species was not distributed evenly across the surveyed area.

(2) Changes of bacterial gene diversity. Previous results showed that the soil microorganisms in the shelter forest along the Tarim Desert Highway consisted of fungi, actinomycetes, and bacteria, among which the bacteria were dominant[27]. Particularly, the DNA diversity index of the soil bacteria in forest lands was found to increase significantly with forest ages. The change

Table 5 Biodiversity in the shelter forest (unit: Plant)

Sites	*Hexinia polydichotoma*	*Halogeton arachnoideus* Moq.	*Phragmites australis* Trin. et Steud.	*Salsola ruthenica* Iljin	*Apocynum venetum*	Seedling of *Haloxylon ammodendron*	Seedling of *Calligonum* L	Ant nest	Mouse holes	Rabbit holes	Lizard caves
K290.70	628	69	91	4	0	0	0	96	4	0	63
K269.35	0	93	2	14	139	1	0	1066	24	0	46
K218.70	106	392	287	24	0	78	7	426	5	2	16
K224.40	0	4	636	0	0	0	0	107	11	8	13
K248.80	21	0	0	0	0	12	2	58	2	0	12
K182.20	74	68	0	0	0	0	0	2874	0	0	0

was significant at 0.01 levels, as revealed by an F-test (Table 7). The data at multiple comparisons further indicated that, after the constructing shelter forest, the diversity index of DNA sequence showed an obvious increase during the first year, and became significant at 0.01 levels, indicating the construction of shelter forest can effectively facilitate the increase in DNA sequence diversity of soil bacteria. In addition, the richness index *S*, which is the band number detected in DNA fragment analysis of soil bacteria, varied from 2.00 to 11.67 and showed a statistical significance for the forest lands with different forest ages, similar to the variation of the diversity index *H*. However, there was little difference in the evenness index E_H, suggesting that the content of bacteria DNA sequences with different length in forest land did not vary obviously.

Table 6 The fatty acid diversity of microorganisms in the shelter forests with different forest ages[a)]

Forest age (a)	Diversity (*H*)	Richness (*S*)	Evenness (E_H)
0	1.92±0.05 a	13.33±0.58 abc	0.81±0.06 abc
1	2.27±0.23 ab	19.33±1.08 ab	0.84±0.03 ab
2	2.34±0.24 abc	27.67±1.43 a	0.85±0.06 a
3	2.38±0.21 bcd	27.67±1.22 abcd	0.78±0.05 abc
4	2.58±0.44 cde	29.00±1.86 bcd	0.77±0.03 bc
6	3.07±0.37 de	36.33±3.04 bcd	0.77±0.03 bc
8	3.12±0.23 e	45.67±3.33 cd	0.74±0.03 c
12	2.84±0.42 cde	47.00±5.39 d	0.67±0.02 d
B value	5.98**	3.74*	5.83**

a) * and ** indicate the significant difference at 0.05 and 0.01 levels, respectively (the same below).

The capital letters after the numbers indicate the multiple comparisons results. The results with the same letter mean that the difference among them is statistically insignificant at 0.01 level, and *vice versa*, the difference is significant.

It can be concluded that the number of soil microorganism species increased greatly after the construction of the shelter forest, as shown clearly by the increase of microbial diversity index with the forest age.

Table 7 The bacterial gene diversity in forest soils with different forest ages

Forest age (a)	Diversity (*H*)	Richness (*S*)	Evenness (E_H)
0	2.26±0.07 aA	11.67±0.58 aA	0.92±0.04 aA
1	2.28±0.11 aA	11.00±1.00 abA	0.95±0.02 aA
2	2.24±0.16 aA	10.67±0.58 bA	0.93±0.03 aA
3	1.56±0.24 bB	5.67±1.53 cB	0.92±0.03 aA
4	1.30±0.05 cBC	4.33±0.58 dC	0.90±0.10 aA
6	1.17±0.15 cCD	3.67±0.58 dCD	0.91±0.12 aA
8	0.90±0.27 dDE	2.67±0.58 eDE	0.92±0.07 aA
12	0.65±0.03 eE	2.00±0.00 eE	0.94±0.05 aA
F value	74.36**	197.83**	0.19

3.5 Effects on groundwater

(i) Groundwater depth variation during pumping. The depth of all water supply wells for irrigation is within 120 m. The unit discharge is all about 30 m^3/h. As shown by the variation of groundwater level of all observation wells around the water supply well in the 69th well areas (Figure 4), the time course of groundwater level variation including water level depression and water level rise can be divided into two stages, the acceleration and deceleration stage, respectively. The variation of drawdown as a function of pumping time *t*, which was calculated by subtracting the initial depth from the depth in time *t*, is shown in Figure 5. The drawdown in the 1st to the 24th observation well all showed a similar variation with the pumping time (Figure 4). The drawdown variation during pumping can be divided into several obvious stages. Specifically, the water table dropped rapidly at the beginning, and then was followed by a slow variation process in which the slope of the drawdown vs. time curve gradually decreased. The groundwater level finally approached a stable value at the end of pumping. Similarly, the groundwater level recovery, which was calculated by subtracting the groundwater level at recovery time *t* from its initial value, is shown in Figure 6 as a function of recovery time. The groundwater recovery in the 1st to the 24th observation well all exhibited a similar varia-

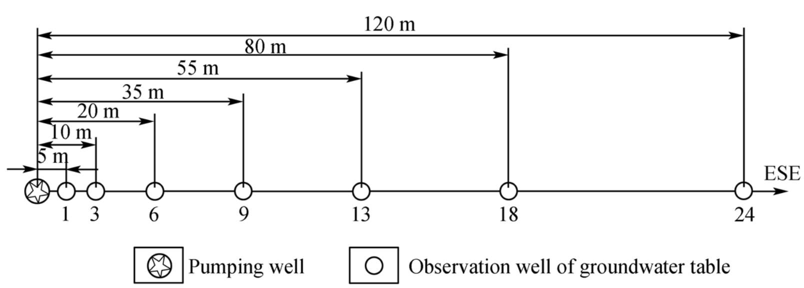

Figure 4 The pumping well and observation well location.

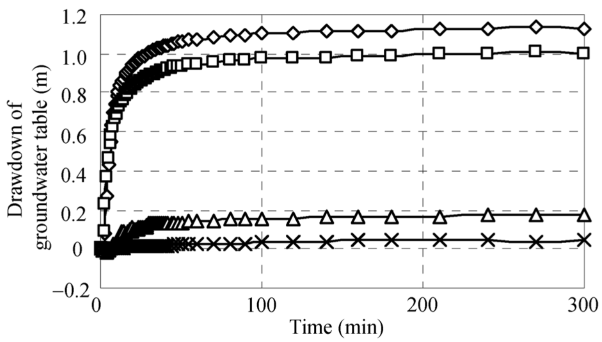

Figure 5 The variation of drawdown as a function of pumping time. —◇—, No. 1 observation well; —□—, No. 3 observation well; —△—, No. 9 observation well; —×—, No. 24 observation well.

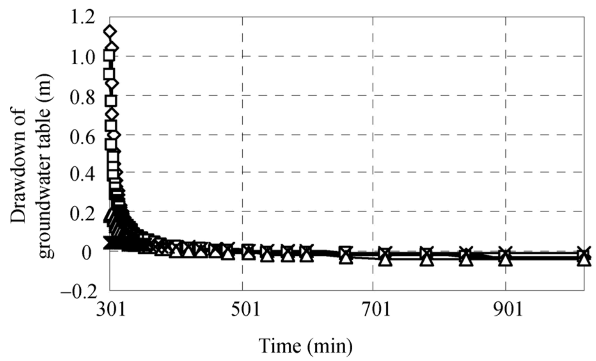

Figure 6 The time course of the groundwater level recovery. —◇—, No. 1 observation well; —□—, No. 3 observation well; —△—, No.9 observation well; —×—, No. 24 observation well.

tion, and in particular, the recovery curve of the 1st and the 3rd observation well was almost identical. In addition, the recovery rate of groundwater level was large at the beginning, then gradually decreased. The groundwater level could recover its initial value during a very short period.

(ii) Groundwater depth variation along the highway. Currently, the exploited groundwater along the Tarim Desert Highway is the phreatic water in Quaternary deposits. The groundwater depth varies greatly with different terrain types. Specifically, the depth of groundwater in interdunes is about 1.3—13.9 m, while it becomes larger on the top of ridges with a maximum depth of 63.2 m.

The groundwater depth is affected mainly by the surface evaporation, the river supplies, and other factors under natural conditions. It fluctuates among seasons. Particularly, it has been found that the groundwater in desert can be significantly affected by the surface evaporation when its depth was less than 5 m[14]. About 50% of the areas along the Tarim Desert Highway are located between the ridges, where the groundwater depth is small. Consequently, under natural conditions, the groundwater depth along the desert highway is significantly affected by surface evaporation, leading to substantial water loss. However, as shown by the data of groundwater depth obtained from the monitoring wells, the groundwater depth changed little along the Tarim Desert Highway after the construction of the shelter forest, and the variation amplitude was of centimeter-level (Table 8). Therefore, the current amount of groundwater pumping did not show any obvious effects on the groundwater depth along the desert highway[28].

(iii) Changes of groundwater salinity. The water samples in monitoring wells with different groundwater levels along the desert highway were analyzed. And the results showed that the salinity of most monitoring wells was relatively stable and the variation amplitude was within the range of ±1/L. However, at the monitoring well around K182.2 (the highway milepost), the groundwater salinity was found to increase by 2.13 g/L during a period from September 2006 to November 2007 (Figure 7). The salinity increase may be attributed to the intensive water evaporation and salts concentration caused by the significant vertical water circulation, ecause this site is located in the shallow groundwater area with a groundwater depth of only 1.75 m. In addition, the salinity may also increase as a result of the leaching of salts accumulated in soil by irrigation water. This may be the direct reason for the observed salinity increase.

Table 8 The groundwater depth changes in monitoring wells before (2003) and after constructing the shelter forest (Unit: m)

Year	Site									
	K145		K184		K248		K353		K451	
	Depth	Variation	Depth	Variation	Depth	Variation	Depth	Variation	Depth	Variation
2003	7.100	0	2.107	0	7.320	0	2.433	0	9.613	0
2004	7.150	–0.050	2.500	–0.393	7.370	–0.050	2.620	–0.187	9.538	0.07
2005	7.121	–0.021	2.185	–0.077	7.420	–0.100	2.499	–0.066	9.614	
2006	7.121	–0.021	2.258	–0.151	7.430	–0.110	2.557	–0.124	9.612	0.00
2007	7.140	-0.039	2.297	0.190	7.445	0.125	2.549	0.116	9.602	0.01

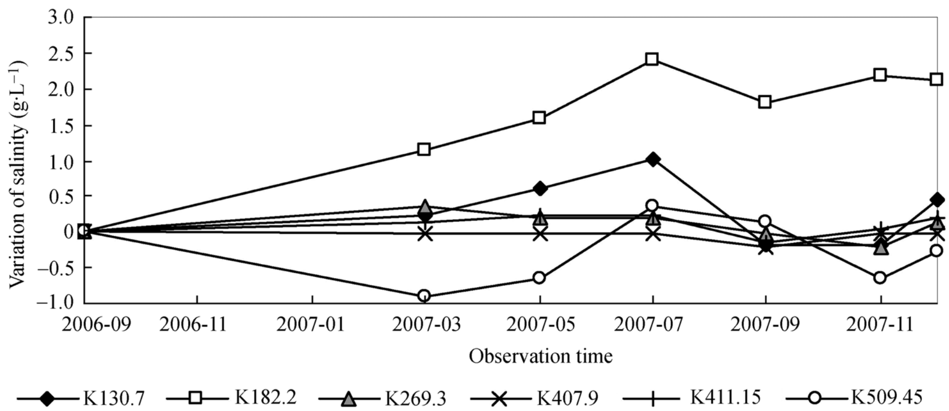

Figure 7 The variation of groundwater salinity at different sites along the desert highway (the symbols such as K130.7 represent the highway milepost).

4 Conclusions

(1) The effects of the shelter forest on aeolian environment were significant. The windblown sand movements near the ground surface were changed significantly by the forest. Specifically, compared with the mobile sand, inside the shelter forest, the wind speed and the rate of sand transporting were decreased by 64%—80% and 87.45%—99.02%, respectively. In addition, the sand particle concentration near the ground surface decreased rapidly with the height in the mobile sand, but slowly inside the forest areas. Moreover, the sorting characteristics of windblown sand inside the forest were poorer than that on the top of mobile dunes outside the forest, but better than the flat sand ground in interdunes. Furthermore, the shelter forest also changed the landforms significantly. It was found that the aeolian deposition landforms were dominated inside the shelter forest, including the small scale nebkhas around shrub, the middle scale sheet-like sand deposition, and the large-scale ridge-like sand deposition. Particularly, on the upwind side of the shelter forest, both the shape and orientation of small mobile dunes in interdunes have been changed as a result of the sand-obstructing belts as well as their surrounding ridge-like sand deposition, while on the leeward side of the shelter forest, a large-scale deflation landform developed because the wind-sand flow gradually became unsaturated with the recovery of the wind speed. Therefore, we can conclude that the shelter forest can efficiently block the windblown sands as well as winds.

(2) The effects of shelter forest on soil properties were significant. Compared with the mobile sand, inside the shelter forest, the soil bulk density decreased while the total salt content, the total porosity, and the water content increased. Moreover, the experimental observations at multiple comparisons showed that there was a significant difference at 0.05 level in the soil bulk density of the forest lands with different forest ages, as well as in the total porosity, the total salt and water content. In addition, the soil fertility was improved significantly after constructing the shelter forest, and the increase of soil fertility with the forest age exhibited the “first rapidly, then slowly” pattern. The soil integrated fertility index (IFI) of the mobile sand was only 0.082, while it increased to 0.917 in the soil of 12-year-old forest land.

(3) The shelter forest showed significant effects on micro-climate. The air temperature of the mobile sand was higher than that of the forest land at all measured heights, whereas the relative humidity of the mobile sand was lower. The shelter forest had less influences on the air temperature and relative humidity with the increase of height. Moreover, within the range of 100 cm depth, the soil temperature in the forest land was significantly lower than that in mobile sand at the same depth. However, the variation amplitude of soil temperature in the mobile sand was obviously larger than in the forest land. All of these indicated that the shelter forest had significant regulation effects on soil temperature.

(4) The effects of the shelter forest on the biodiversity were significant. The plant and animal species, and the soil microorganisms in particular, increased after the construction of the shelter forest. Specifically, there was significant difference in Shannon diversity index (H), Richness (S) and Evenness (E_H) among the fatty acids of

soil microorganism in the forest lands with different forest ages, among which the Shannon diversity index increased gradually with the forest ages and reached its maximum after 8 years, the richness also increased greatly, while the evenness only exhibited a slight decrease. In addition, the DNA diversity index of the soil microbial inside the forest was found to increase significantly with the forest ages at 0.01 level. However, the richness index *S*, which is the band number detected in the DNA fragment analysis of the soil microorganism, varied greatly among the soils with different forest ages. In contrast, there was little difference in the evenness index. Therefore, it can be concluded that the shelter forest can significantly improve the living environment of creature.

(5) The groundwater pumping and irrigation did not show any obvious effects on the groundwater environment. The drawdown and recovery of the groundwater level in a single well can be divided into two stages. The groundwater depth can be recovered to its initial level within a very short period. In addition, the groundwater depth did not show significant changes before and after constructing the shelter forest, and the change amplitude was of centimeter-level. In addition, the groundwater salinity was affected little by the groundwater pumping. Its variation amplitude was within ± 1 g/L. However, the groundwater salinity increased obviously in the shallow groundwater areas, which may be the result of the leaching of salts accumulated in soil by irrigation water.

In short, the shelter forest along the Tarim Desert Highway has shown significant positive effects on the local ecological environment, and can contribute significantly to the sustainable development of the ecosystem in the areas along the desert highway.

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