Chinese Science Bulletin
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Springer

Evaluation of soil fertility of the shelter-forest land along the Tarim Desert Highway

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To study the changes of soil fertility of the shelter-forest land along the Tarim Desert Highway, soils from the forest land were collected at the layers of 0—10 cm, 10—20 cm, 20—30 cm. Different soil fertility parameters were measured, and quantitative evaluation of soil fertility was performed by the soil integrated fertility index (IFI). The main results show that the construction of the shelter forest along the Tarim Desert Highway improved the soil physical structure, increased soil porosity and enhanced water-holding capacity. With the increase of plantation time of the shelter forest, soil microbial biomass C, N, P and the activities of six types of enzyme were enhanced, which promoted the accumulation and transformation of soil nutrients of the forest land. Consequently, the soil nutrients in 12-year-old forest land were much higher than in the newer ones and drifting sand. However, soil salt content of the older forest land was higher owing to the drip-irrigation with salt water. Through the comprehensive evaluation, we found that soil fertility index in the forest land was enhanced with the forest age, and it had close correlations with the growth indices of the forest trees. In summary, construction of the shelter-forest along the Tarim Desert Highway accelerated the improvement of aeolian soil in the forest land, and the soil fertility improved year by year. We conclude that the forest trees grow normally under the stress of the present drip-irrigation with salt water.

Tarim Desert Highway, shelterforest land, soil fertility quality, comprehensive evaluation

Fertility of forest soil is viewed as the ability of soil to provide nutrients for forest trees, and it is of great importance to evaluate the fertility of forest soil[1−3]. At present, no standard method is available to evaluate soil quality, and among many methods, comprehensive evaluation method of soil fertility index is frequently used in the quantitative evaluation of soil quality, which evaluates soil fertility by comprehensively analyzing the physical, chemical and biological properties of soil[4−6]. The Tarim Desert Highway crosses over the Taklimakan Desert from north to south, and it is the lifeline for oil and gas exploitation, traffic and economy in Southern Xinjiang[7]. However, harshness of the weather, especially the moving sand along the Tarim Desert Highway causes severe damage to this highway[8]. To ensure smooth operation of the Tarim Desert Highway, The Tarim Desert Highway shelter-forest ecological project was initiated in 2003. The construction was started in August of the same year and finished in 2005. As a result, a 436-km-long and 72—78-m-wide belt with an area of 3128 hm^2 was planted, which stopped the sand drift and affected the fertility of interior soil[9]. To our knowledge, the changes in the soil fertility of the shelterforest along the Tarim Desert Highway have not been

Received September 2, 2007; accepted June 2, 2008
doi: 10.1007/s11434-008-6015-2
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Supported by Major Orientation Foundation of the CAS Innovation Program (Grant No. KZCX3-SW-342), CAS Action-Plan for West Development (Grant No. KZCX2-XB2-13), Major Scientific and Technological Special of Xinjiang Uygur Autonomous Region (Grant No. 200733144-3), the research projects of the Tarim Branch of PetroChina Company Limited (Grant Nos. 971008090016 and 971008090017), and CAS Xinjiang Institute of Ecology and Geography "Dr. Talent" Project of Oasis Scholars Training Plan

investigated and the available data cannot reflect the soil fertility accurately[10].

Therefore, there is a need to evaluate the soil fertility of the shelter-forest land along the Tarim Desert Highway comprehensively. We collected soils and drifting sand from different sites in the shelterforest, and measured many soil fertility parameters. In the meantime, we applied the method of comprehensive fertility index to revealing variations in soil fertility of different sites in the shelter forest. The objective of this study was to understand the improvement mechanism of aeolian soil in arid areas and provide a theoretical foundation for stable construction of shelter forest along the Tarim Desert Highway.

1 Study area description

1.1 Natural environment characteristics

Sampling sites were around the Tazhong Oil Field in the southeast of the Taklimakan Desert in China (Figure 1, Table 1). Natural environmental conditions along the desert highway were characterized by extreme arid climate, scarce surface water resources, high saline groundwater, intense wind and sand activity and infertile soil. According to the monitoring data, along the desert highway, precipitation is less than 50 mm/a, potential evaporation reaches 3800 mm/a, the highest temperature is 43.2℃, the lowest temperature is −19.3℃, the highest wind speed is 24 m/s, and the duration of total annual sand-moving wind with a speed higher than 6.0 m/s is from 550 to 800 h. Furthermore, dune morphology is complex and diverse; there are not only longitudinal composite dunes higher than 50 m, but also barchanic dunes lower than 1 m high. Coverage rate of secondary dune is over 60%, and annual moving distance of small dunes among big composite dunes is more than 15 m. Soil is mainly made up of aeolian soil with weak stability along the desert highway. The natural vegetation is

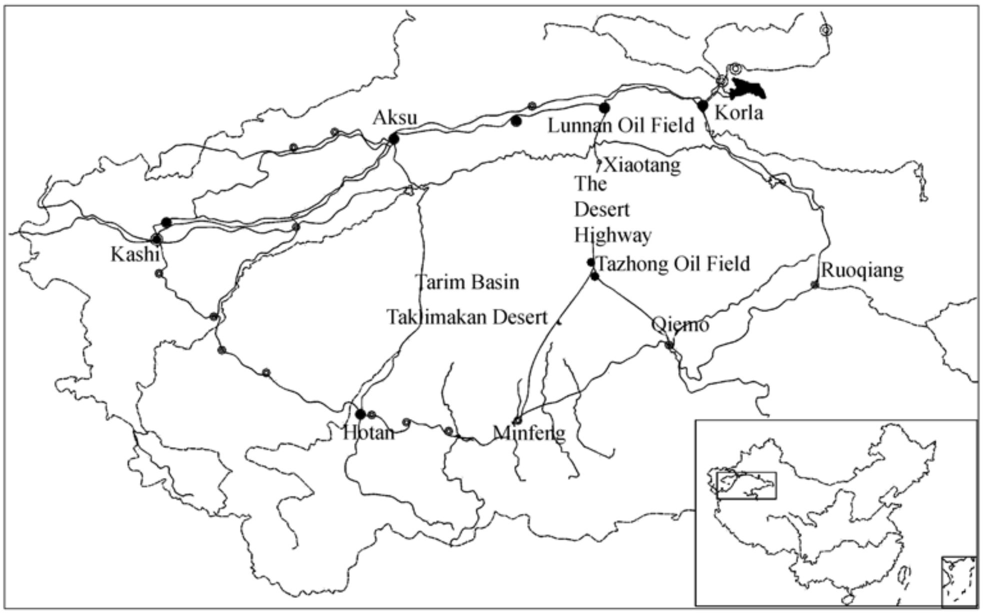

Figure 1 Geographical location of the study area.

Table 1 Locations of different shelter-forest lands

Forest land	Drifting sand as control treatment	Forest land planted in 2006	Forest land planted in 2005	Forest land planted in 2004
Sample site	Drifting sand around T-shaped road junction in Tazhong	Forest land around planting base of secondary phase *Cistanchc salsa*	Forest land irrigated with No. 69 water well	Forest land around planting base of first phase *Cistanchc salsa*
Geographic coordinate	39°08′N 83°42′E	39°08′N 83°44′E	38°53′N 83°13′E	39°08′N 83°43′E
Forest Land	Forest land planted in 2003	Forest land planted in 2001	Forest land planted in 1999	Forest land planted in 1995
Sample site	Forest land around Tazhong Botanical Garden in Tazhong	Forest land at southern T-shaped road junction in Tazhong	Forest land 2 km away from T-shaped road junction in Tazhong	Forest land at Zhongsandian in Tazhong
Geographic coordinate	39°07′N 83°42′E	39°07′N 83°41′E	39°08′N 83°40′E	39°08′N 83°39′E

rare, and vegetation coverage is quite low[11,12].

1.2 Plantation pattern of the shelter forest

Three shrub species of *calligonium*, *Tamarix* and *Haloxylon* with high tolerance against drought and salinity were selected as the plantation tree species for the shelter forest along the Tarim Desert Highway. The plantation pattern is characterized by mixed inter rows with a 1 m×1 m planting space in the 72—78-m-wide shelter forest. The forest is drip-irrigated with underground saline water containing about 4.04 g/L salts and having a pH of 8.13. The drip irrigation emitter is placed 1.5 m apart, and the irrigation frequency is 10 d with 450 m^3/ha irrigation quota. The fertilization is mainly by pouring soluble fertilizers such as urea into the fertilization installation, where the fertilizers are dissolved in water and applied to the soil with water. The amount of fertilizer used is 10—15 g per plant; fertilization time is in June, July and August, once a month.

2 Methods

2.1 Sampling method

Based on similar conditions such as site condition, age of the forest, peripheral tree species, distance from dripper and individual plant space, seven forest sites with different ages and one site for drifting sand collection were selected in July, 2006 (Table 1). Five sampling sites with little disturbance from humans and herbaceous vegetation were also chosen in the middle of each forest site. Soils at the layers of 0—10 cm, 10—20 cm, 20—35 cm were collected with a steel soil drill and the plant residues were discarded. Those soil samples of the same layer were fully mixed, immediately put into new sample bags, numbered, and stored in a refrigerator at 4℃ for microbial population analysis and counting.

2.2 Experimental analysis methods

Soil microorganism number was determined by the dilution-plate method[13]. Specifically, bacteria, actinomycetes and fungi were cultured respectively in beef extract-peptone medium, Gause 1 medium and potato dextrose agar medium with Bengal red.

Contents of soil nutrient and salt were determined by the conventional methods[14]. The contents of organic matter were determined by the potassium dichromate titration method; total N and available N were measured by kjeldahl method digested with H_2SO_4+$HClO_4$ and distillation after alkaline hydrolysis respectively; total P and available P were determined by the Mo-Sb-Vc colorimetric method dissolved with acid and extracted with 0.5 mol/L $NaHCO_3$ respectively; total K and available K were analyzed respectively by flame photometry dissolved with acid and flame photometry extracted with NH_4OAc. The content of soluble salt was determined by the drying residue method, and pH was determined by potentiometry.

Soil moisture content, soil volume weight and soil bulk density were determined respectively by the drying method, cutting ring method and volumenometer method. Total porosity was calculated by the soil volume, weight and soil bulk density.

Activities of soil protease, cellulose, invertase, phosphatase and urease were determined by colorimetric methods, but catalase activity was determined by the titration method[15].

Combined with the fumigation extraction method, soil microbial biomasses C, N, and P were determined respectively by volumetric analysis, ninhydrin colorimetry and total phosphorus method[16].

Growth indices of forest trees, plant height and crown width were measured by tower chi, ground diameter was measured by vernier caliper, and above-ground biomass was weighted by an electric platform scale with 0.01 kg precision.

2.3 Comprehensive evaluation of soil fertility

2.3.1 Selection of evaluation index. Soil fertility reflects the combined physical, chemical and biological properties of the soil[17−19]. To reveal reliably the differences of single fertility index among different soil layers, the average values of soil parameters at 0—10 cm, 10—20 cm, 20—30 cm were analyzed with the principle component analysis (PCA) method to establish an evaluation system for soil fertility in the shelter forest along the Tarim Desert Highway[20−22].

In this evaluation system, soil physical property includes bulk density, total porosity and moisture content; soil chemical property includes soil nutrient factors consisting of contents of organic carbon, organic matter, total N, total P, total K, available N, available P, available K, and soil salt factors including pH value and total salt content; biological property includes the number of bacteria, actinomycetes and fungi, and soil enzyme activities of protease, cellulose, invertase, phosphatase, urease and catalase, and soil microbial biomass C, N, and P.

2.3.2 Calculation of soil integrated fertility index. Soil integrated fertility index (IFI) is a synthetic index of each soil parameter[23]. We selected the continuous function to evaluate each factor owing to the continuous nature of the soil fertility parameters. The ascending or descending property of this function was determined by the positive or negative property of factor loading of the principal component (Table 2), which agrees with the effects of these factors on vegetation[24]. For soil bulk density, soil pH value and total salt content, a function with descending property was chosen as follows[25]:

$$F(X_{ij}) = (X_{i\max} - X_{ij})/(X_{i\max} - X_{i\min}). \quad (1)$$

But for soil moisture content, porosity and all of the chemical and biological factors, a function with ascending property was introduced as follows [26]:

$$F(X_{ij}) = (X_{ij} - X_{i\min})/(X_{i\max} - X_{i\min}). \quad (2)$$

In the above equations, $F(X_{ij})$ shows the relative importance of each fertility factor (Table 3), X_{ij} is the value of each fertility factor, $X_{i\max}$ and $X_{i\min}$ express the maximum and minimum value of one factor.

Because the importance of each soil fertility parameter is different, weight coefficient was introduced, which was obtained by calculating the percentage of the communality of one factor and the numerical conversion was performed as follows[27, 28]:

$$W_i = Community_i / \varepsilon_{i=1}^{n} Community_i. \quad (3)$$

According to additive-multiplicative rule, the fertility index is synthesized multiplicatively by individual parameters. The integrated fertility index is therefore calculated by the following equation[20, 29]:

$$\mathrm{IFI} = \Sigma W_i \times F_i. \quad (4)$$

In this equation, W_i is the weight coefficient of each fertility factor (Table 2), and $F(X_{ij})$ expresses the relative importance of each fertility factor (Table 3).

2.4 Data processing and statistical analysis

Analysis of the difference of soil fertility factor: the averages of each soil fertility factor at 0—10 cm, 10—20 cm and 20—30 cm of the different forest sites were used, and multiple comparisons were performed by the method of least significant difference (DPS2000)[30]. The software Origin7.5 was used to draw the graphs[31].

Integrated evaluation of soil fertility: PCA of SPSS13.0 was used to evaluate the soil integrated fertility of the forest lands at different ages[32, 33].

The symbols of 0 a, 1 a, 2 a, 3 a, 4 a, 6 a, 8 a, and 12 a in the graphs represent respectively the drifting sand and soils from the forest lands planted in 2006, 2005, 2004, 2003, 2001, 1999, and 1995; different capital and lower letters represent the differences of one soil factor among different forest land soils at the $P<0.01$ and $P<0.05$ significance level, respectively.

3 Results

3.1 Variation of the physical property of soil in the forest land

As an important factor, soil physical property can influence the soil functions such as ability of aeration, water permeability, water retention and thermal conductive-ity[34,35]. As shown in Figure 2, soil bulk density decreased obviously with the increase of the forest age, but total porosity and moisture content increased remarkably ($F>F_{0.001}$). The differences among forest lands of different ages reached extreme significant levels, espe-

Table 2 Factor loading with principal component rotation, communalities and weight of the fertility indexes

Fertility index	Factor load	Community	Weight	Fertility index	Factor load	Community	Weight
Organic carbon	0.922	0.853	0.036	Bacteria	0.991	0.990	0.041
Organic matter	0.933	0.883	0.037	Actinomycetes	0.964	0.938	0.039
Total N	0.997	0.996	0.041	Fungi	0.975	0.969	0.040
Total P	0.995	0.992	0.041	Catalase	0.894	0.937	0.039
Total K	0.942	0.941	0.039	Phosphatase	0.944	0.974	0.041
Available N	0.953	0.982	0.041	Urease	0.912	0.973	0.041
Available P	0.968	0.989	0.041	Cellulase	0.805	0.849	0.035
Available K	0.988	0.992	0.041	Ivertase	0.993	0.987	0.041
pH value	–0.985	0.975	0.041	Protease	0.920	0.927	0.039
Total salt	–0.984	0.992	0.041	Microbial biomass C	0.968	0.942	0.039
Bulk weight	–0.993	0.987	0.041	Microbial biomass N	0.994	0.989	0.041
Total porosity	0.984	0.976	0.041	Microbial biomass P	0.969	0.985	0.041
Moisture content	0.980	0.981	0.041				
Eigenvalue		22.99		Contribution rate (%)		91.98	

Table 3 Value of membership degree of fertility factor in the forest land

Forest age (a)	0	1	2	3	4	6	8	12
Organic carbon	0.000	0.131	0.230	0.026	0.230	0.814	0.989	1.000
Organic matter	0.000	0.117	0.235	0.358	0.780	0.819	0.889	1.000
Total N	0.000	0.175	0.286	0.365	0.476	0.603	0.778	1.000
Total P	0.000	0.143	0.286	0.375	0.429	0.607	0.804	1.000
Total K	0.000	0.324	0.542	0.645	0.717	0.813	0.939	1.000
Available N	0.000	0.069	0.105	0.140	0.192	0.398	0.577	1.000
Available P	0.000	0.078	0.155	0.237	0.288	0.473	0.555	1.000
Available K	0.000	0.123	0.185	0.240	0.316	0.537	0.731	1.000
pH value	1.000	0.831	0.640	0.545	0.430	0.298	0.112	0.000
Total salt	1.000	0.900	0.845	0.769	0.620	0.519	0.280	0.000
Bulk weight	0.000	0.194	0.321	0.413	0.464	0.556	0.816	1.000
Total porosity	0.000	0.100	0.256	0.363	0.405	0.518	0.859	1.000
Moisture content	0.000	0.142	0.178	0.228	0.288	0.485	0.778	1.000
Bacteria	0.000	0.222	0.289	0.295	0.359	0.528	0.693	1.000
Actinomycetes	0.000	0.345	0.495	0.561	0.558	0.645	0.772	1.000
Fungi	0.000	0.196	0.302	0.335	0.445	0.430	0.651	1.000
Catalase	0.000	0.578	0.670	0.349	0.574	0.888	0.988	1.000
Phosphatase	0.000	0.395	0.493	0.570	0.712	0.921	0.985	1.000
Urease	0.000	0.014	0.103	0.223	0.181	0.331	0.409	1.000
Cellulase	0.000	0.545	0.806	0.154	0.608	1.015	0.990	1.000
Ivertase	0.000	0.327	0.355	0.383	0.476	0.605	0.778	1.000
Protease	0.000	0.457	0.577	0.681	0.734	0.826	0.904	1.000
Microbial biomass C	0.000	0.149	0.226	0.303	0.456	0.827	0.977	1.000
Microbial biomass N	0.000	0.178	0.351	0.257	0.427	0.595	0.775	1.000
Microbial biomass P	0.000	0.153	0.227	0.298	0.318	0.429	0.582	1.000

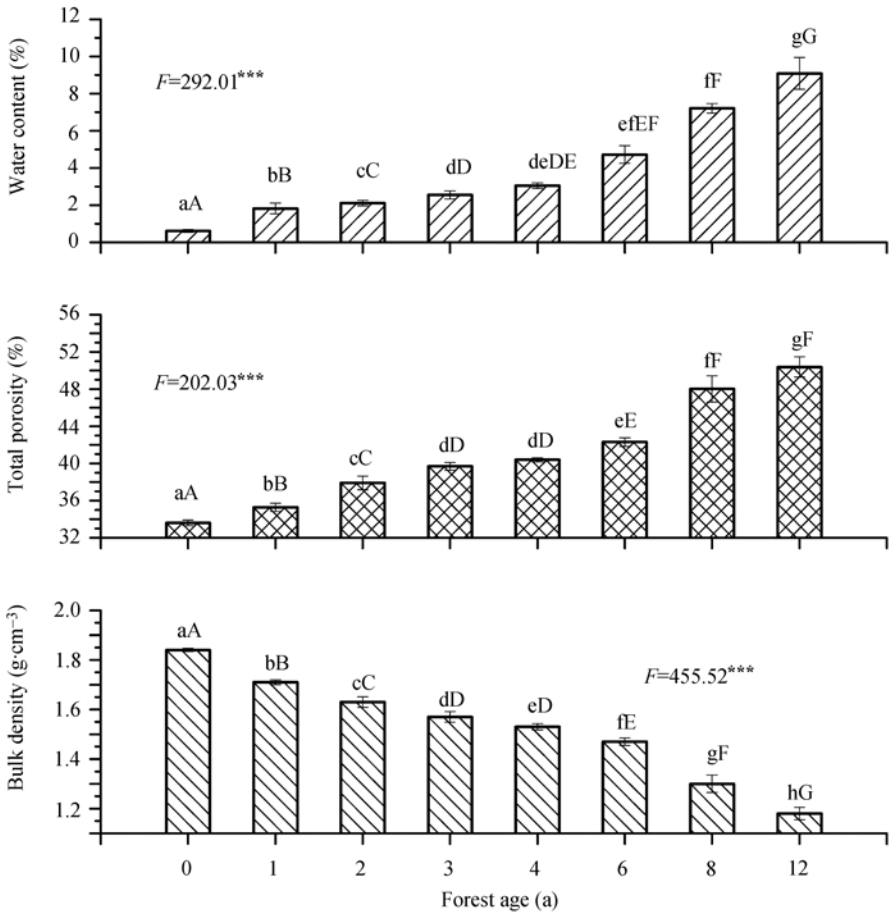

Figure 2 Soil physical properties of the forest land.

cially for the soil bulk density and total porosity. Soil bulk density decreased from 1.9 g/cm^3 in the beginning to 1.3 g/cm^3 after 12 years, an decreased of 50%. Total porosity increased from 35% in the beginning to 51% after 12 years. It is considered that increases of soil bulk density and soil total porosity are beneficial to soil water retention in the shelter-forest[36,37]. In deed, we showed that the content of soil water in the forest land after 12 years is much higher than that in drifting sand. Guo et al. reported that there was little difference between the fixed sand and drifting sand in regard to soil moisture content and the water content in fixed sand was far lower than the maximum field water capacity[38]. It is likely that the construction of shelter-forest along Tarim Desert Highway allowed the drifting sand to be fixed gradually, which led to decreased soil bulk density, increased porosity and water content, and improved soil structure.

3.2 Variations of soil chemical properties in the forest land

As a vital component of soil fertility, soil chemical property reflects the potential ability of soil to provide nutrients for the plants[39,40]. Soil organic carbon content, which is mainly influenced by climate and vegetation, is the result of the equilibrium between the inputting organic matter and the departing organic matter mainly caused by soil microbial decomposition[41,42]. From Figure 3 we can find that after the forest tree has been planted in the drift land, the change of soil organic carbon content was initially negligible. But when the forest age is more than 6 years old, it increased rapidly and reached a stable value of about 12.5 g/kg, much more than that of the drifting sand ($F > F_{0.001}$). The increase of organic matter is likely due to the fact that the forest trees of older age provided the soil with more organic matter. Soil organic matter is one of the most important components of soil fertility[43]. Figure 3 shows that no depletion of soil organic matter was observed, instead an obvious increase in the forest land along the Tarim Desert Highway was found ($F > F_{0.001}$).

Elements of N, P and K are three types of mineral elements that are absorbed in a large amount by a plant from soil. Because of the low reactivity of N and the insolubility and immobility of P, N and P have been viewed as the two most important elements that limit plant growth in most forest lands[44,45]. As shown in Figures 4 and 5, all of the soil nutrient factors, including contents of total and available N, P, and K, increased

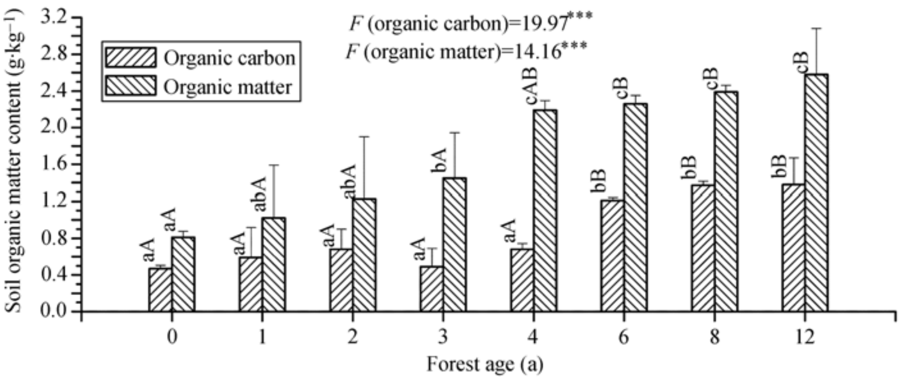

Figure 3 Soil organic matter of the forest land.

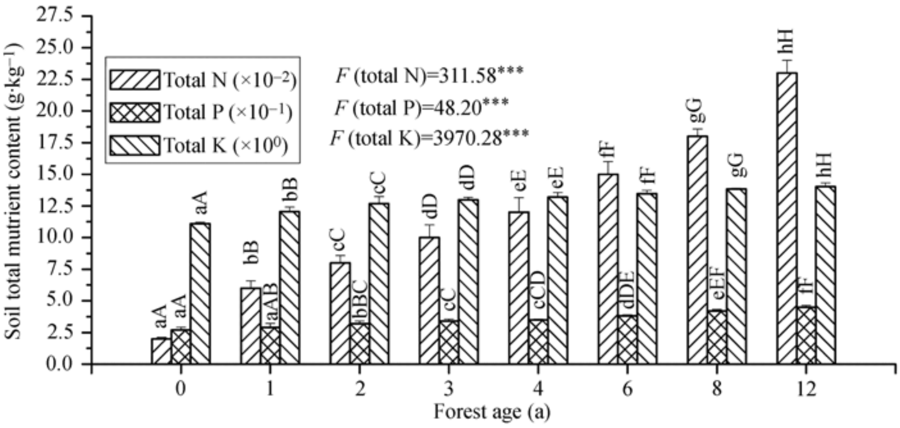

Figure 4 Soil nutrients of the forest land.

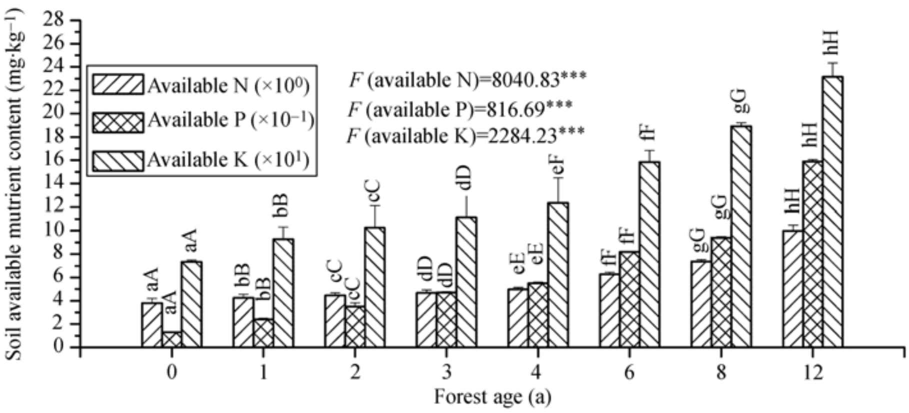

Figure 5 Soil available nutrients of the forest land.

with the increase of the forest age ($F > F_{0.001}$), and the available nutrients changed more obviously.

Total soil salt and pH are used as common indexes to reflect the status of soil salt, which affects soil fertility greatly[46,47]. Because the trees in the shelter forest along the Tarim Desert Highway were drip-irrigated with groundwater saline since it had been constructed, soil pH and total salt increased quite obviously with the increase of the forest age ($F > F_{0.001}$), indicating that the drip irrigation with saline water caused the increase of salt content[48]. Moreover, there is a close correlation between the total soil salt and the pH because both of them can reflect soil salt content. Compared with the drifting sand, the soil total salt of the forest land of 12 years old increased by about 10-fold, and the pH increased from 8.3 to 9.1 (Figure 6).

3.3 Variations of soil biological properties in the forest land

Soil biological property plays an important role in the transformation and providing of soil nutrients[49,50]. The increase of the number of soil microbial organisms can enhance soil fertility[51]. As a pool of active nutrients, soil microbial biomass is a vital source of available nutrients for plant growth[52,53]. Soil enzymes show sensitive responses to the change of environmental conditions and are sensitive indicators of soil biological activities[54,55]. After the shelter forest along Tarim Desert Highway was constructed, the number of soil microbial organisms increased obviously and significant differences among the forest lands of different ages were shown ($F > F_{0.001}$). The maximum number of soil microbial organisms appeared in the forest land of 12 years old (Figure 7). Similarly, soil microbial biomass C, N, and P also increased remarkably, and biomass C and P have an increase pattern characterized by "slow-rapid-slow", but biomass N increased slowly (Figure 8). Moreover, with the increase of the shelter-forest age, the soil enzyme activities increased as a whole ($F > F_{0.001}$); activities of protease and invertase enhanced linearly, and the activities of the other enzymes decreased (Figure 9).

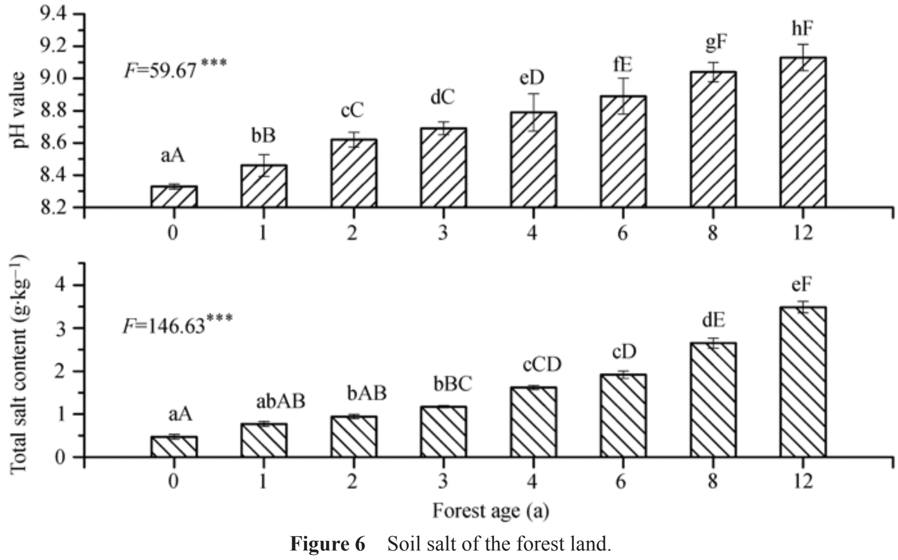

Figure 6 Soil salt of the forest land.

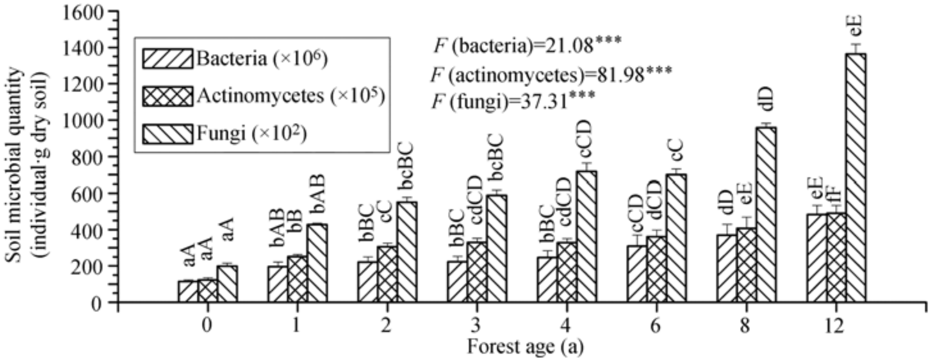

Figure 7 The number of soil microbial organisms in the forest land.

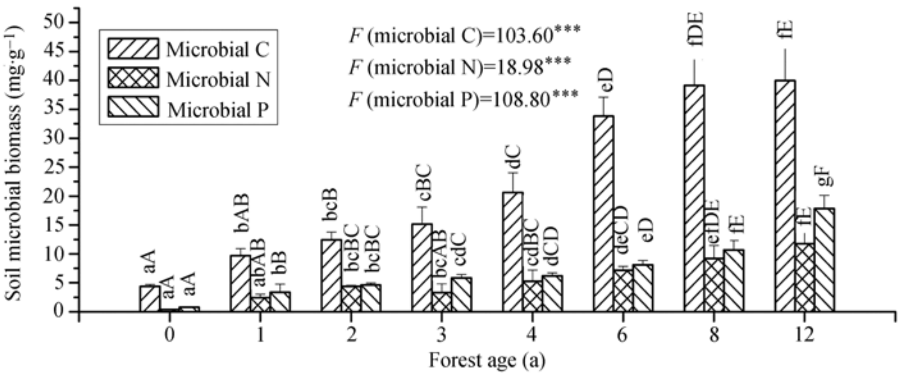

Figure 8 Soil microbial biomass of the forest land.

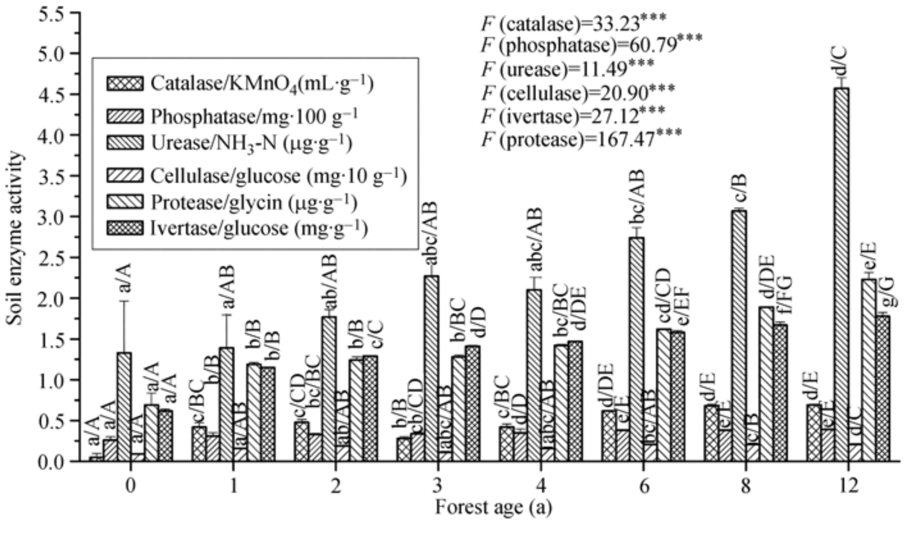

Figure 9 Soil enzyme activities of the forest land.

3.4 Change of soil fertility in different forest lands

As shown in Figure 10, the soil fertility improved after the construction of the shelter forest, which may be explained by the artificial vegetation planted in the drifting sand, combined with the effect of human activities that promoted the biological cycling and bioaccumulation in the soil. As the result, soil physicochemical properties improved, biological activity enhanced and finally soil fertility increased[56]. Soil integrated fertility index increased from 0.082 in the drifting sand to 0.917 in the forest land of 12 years. The magnitudes of change of soil fertility among the different forest lands relate to the interval of the forest age. For example, the age of forest land planted in 1995 is 4 years older than that of forest land planted in 1999, and the corresponding fertility index is increased by 0.178; but the fertility index of the forest land planted in 2005 is increased only by 0.089 compared with that of the forest land planted in 2006. As a result, the variation of soil fertility had a pattern of "first rapidly, then slowly" after the shelter-forest land had been constructed in drifting sand.

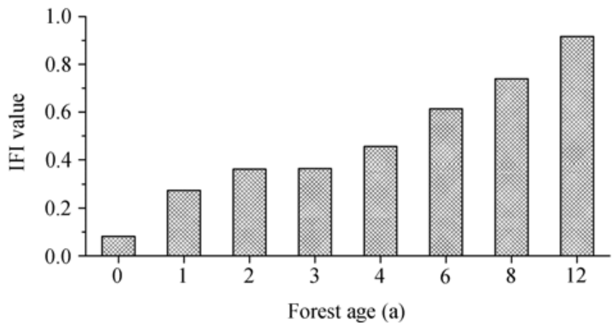

Figure 10 Soil fertility of the forest land.

From the contribution rates and the accumulative contribution rates of the principal components for all the fertility factors (Table 2), we can see that the contribution rate of the first principal component is 91.98% (>85%), which can fully represent the effects of original variables[41,57]. According to factor load capacity, those soil factors with greater effects on soil fertility are: total N, total P, available K, pH value, total salt, microbial biomass P, microbial biomass C, microbial biomass N, bulk density, porosity, actinomycetes, and invertase. Therefore, microbial biomass and physical property are main contributive factors to soil fertility.

3.5 Verification of the evaluation results of soil fertility in the forest lands

Forest trees at the forest sites with higher fertility grow better[58,59]. Plant height, crown width, ground diameter and aboveground biomass are common indexes used to describe the growth status of forest trees[60]. To determine the reliability of the integrated evaluation results of soil fertility, the shelter forest species *Calligonium* was selected as the study object and the correlation between the IFI value for soil integrated fertility evaluation and the growth indices of *Calligonium* was analyzed (Table 4). The results showed that the correlations between crown width, ground diameter, branch number, above ground biomass and IFI value are obvious (P<0.01), and the correlation between plant height and IFI value is also significant (P<0.05). Indeed, we found that the trees of *Calligonium* in higher IFI soil grow better, and the IFI value for the integrated evaluation of soil fertility can accurately characterize the soil fertility level of the forest land.

4 Discussions

We measured the physical, chemical and biological properties of the soil and evaluated the soil fertility of the shelter-forest land along the Tarim Desert Highway in this paper. Also we found that with the increase of plantation time of the shelter forest, the soil bulk density was decreased, soil porosity was increased, contents of N, P, K were enhanced, microbial organism numbers and biomasses were increased, and the soil enzyme activities were enhanced. All of these changes improved the soil fertility. Our results are consistent with the report by Gu et al.[10], who found that in the extremely arid Taklimakan Desert, artificial vegetation drip-irrigated with saline water promoted the formation process of aeolian soil and improved the physical and chemical properties of soil, which was mainly reflected in the improvement of soil fertility. They also found that the longer the vegetation was constructed, the greater improvement of soil property occurred. Wang et al. studied the soil physicochemical properties of the land growing

Table 4 Correlations of IFI values of forest soil and the growth indexes of the forest trees[a)]

Year	Plant height (cm)	Crown width (cm)	Ground diameter (cm)	Basal branch (individual)	Aboveground biomass (kg)	IFI value
1995	234.2	229.5×255.6	5.6	6.0	9.4	0.917
1999	227.0	187.7×207.2	5.2	5.1	7.0	0.739
2001	216.4	195.6×179.1	4.8	4.6	5.3	0.613
2003	217.2	151.6×146.9	3.3	3.4	3.5	0.456
2004	177.4	154.2×152.4	2.4	3.2	3.1	0.366
2005	152.3	126.1×104.6	2.0	1.8	2.5	0.363
2006	141.6	100.8×112.3	2.1	2.0	2.2	0.274
Correlation coefficient	0.868*	0.968**	0.961**	0.960**	0.992**	

a) Use Pearson correlation, two tails test, ** expressed significance at α=0.01 level, and * showed significance at α=0.05 level. Values of plant height, crown width, ground diameter, branch and aboveground biomass are average of 10 *Calligonium*.

for 4 years in the south of Mu Us Desert and found that the soil nutrient of the Ephedra land was much higher than that of the semi-shift sand[61]. Cao et al. also found that the soil physicochemical properties were improved after *Caragana microphylla lam* vegetation had been planted on the mobile dune of Horqin sandy land and the soil enzyme activities were enhanced with the increase of the forest age[62]. Compared with no irrigation, restoration and reconstruction of artificial vegetation drip-irrigated with saline water is beneficial to the enhancement of soil nutrients and biological activities. The main reason probably is that the forests with older trees have more branches and leaves to prevent the mobile sand to land on the surface layer of forest soil and the older trees have well developed roots to provide more nutrients to accelerate the biological propagation.

Soil fertility reflects the combined physical, chemical and biological properties of the soil, and it is closely related to soil quality[63]. Evaluation of soil fertility of the shelter-forest along the Tarim Desert Highway showed that with the increase of the age of the shelter-forest, soil integrated fertility index IFI increased, and the soil integrated fertility level of the 12-year-old forest was improved greatly. There was notable positive correlation between IFI value and the growth indices of *Calligonium* trees. Li et al. evaluated the soil fertility quantitatively and analyzed the correlation between soil fertility and crop yield; they found that the soil fertility level can be precisely measured by IFI and IFI value had an extremely high correlation with rice yield[5]. Other researchers also reported that soil integrated fertility index (IFI) is an effective method to evaluate soil quality[6]. We therefore used the integrated fertility index to evaluate the soil fertility of the shelterforest land under extremely arid desert conditions.

The shelterforest along the Tarim Desert Highway is located in the hinterland of the Taklimakan Desert, which is viewed as the biggest drifting desert in the world with harsh natural conditions. Soil fertility of the forest land drip-irrigated with saline water was increased continuously and the forest trees grew well, which prevented the sand flow and made the desert highway uninterrupted. Compared with the sand-prevention system of artificial vegetation planted in Shapotou region with no irrigation, which is a successful example, the stable construction of the Tarim Desert Highway shelterforest has expanded the means for restoration and reconstruction of degraded ecosystems along main roads. However, with continued increase of forest age in the shelterforest drip-irrigated with saline water, soil salt accumulated. Under this condition, whether the similar soil fertility improvement will be sustained in the future deserves our careful attention. Therefore, similar evaluation of the shelterforest soil should be carried out in the future, which could validate the results of this study and provide stronger scientific supports for the restoration and reconstruction of ecological environment in arid areas.

The authors thank Xinjiang Institute of Ecology and Geography, CAS and Xinjiang Corps' Oasis Agriculuture Key Laboratory for providing technical support.

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