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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

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ABSTRACT

Desertification around oases is the major obstacle for sustainable development of oases in arid regions of northwest China. An effective way of maintaining the stability of oases is to recover the relatively stable ecological zone between an oasis and desert from the destroyed ecological rift zone. This paper presents a typical case of successful efforts in ecological restoration and desertified land reclamation of oasis–desert ecotone. On the basis of stabilization of mobile dunes and agricultural use of reclaimed land, some successful techniques including established straw checkerboards and planting drought-tolerant indigenous shrubs, leveling sand dunes and drawing water for irrigation, closing dunes for grass reservation were carried out in 1975. In the restoration area, a stable artificial protective forest system had been developed. Pedological analyses indicate that the fine particle fraction (silt and clay content) in 0–10 cm soil surface layer has been increased from 2.6% on the untreated mobile sandy land to 9.3–37.3% in the restoration areas, and correspondingly, soil organic C has been increased from 0.63 to 1.88–9.70 $g\,kg^{-1}$ during the 28 years of restoration period. In these 28 years, a 10 cm depth of minero-organic topsoil in the irrigated *Picea sylvestris* forest-land has been developed. It is also observed that sand transportation rate during sandstorm events has been significantly reduced. The increase of vegetation cover indicates a remarkable environmental improvement. Overall, the ecological restoration approach in this study is of practical significance for the rebuilding of rift zone ecosystem and maintenance of the stability of oasis in the arid regions of northwest China.

1. Introduction

Such a wide desert, or Gobi, interspersed with many oases of different sizes and shapes is the main geomorphologic feature in the arid region of northwest China (Cheng et al., 1999). These oases formed naturally in river deltas or were established in alluvial–diluvial plains and edges of diluvial–alluvial fans by drawing the water for irrigation from the rivers in different

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historical periods (Zhang et al., 2003). In this region, oases represent only a very small portion (4%) of the land surface; they are important for agricultural and human activity, with more than 95% of the population and more than 90% of social wealth (Han, 1999). To maintain the stability of oasis ecosystem, therefore, has become an important issue for sustainable development in the arid region.

Oasis evolution in arid and semi-arid regions has two opposite processes, oasification and desertification (Zhang et al., 2003). Under the overexploitation and irrational use of water and soil resources by humans, the stability of oasis system is mainly affected by both desertification in the oasis–desert ecotone and soil salinization in the interior of the oasis (Han, 1999; Pan, 2001). In the arid regions of northwest China, the transitional zones between oasis and desert or oasis–desert ecotones have become the ecological rift zones to jeopardize oases due to intensive anthropogenic disturbance such as overgrazing and fuel collection in conjunction with highly erodible soils and a harsh climate. Therefore, an effective way of maintaining the stability of oasis is to recover the relatively stable ecological zone from the destroyed ecological rift zone (Pan and Chao, 2003).

Over the past several decades, the ecological restoration and desertification control of the oasis–desert ecotone has become a principle strategy to maintain the ecological security of the oasis ecosystem in the northwest China (Research Group of "Study on Combating Desertification/Land Degradation in China", 1998). Some successful experiences and significant achievements pertaining to establishment of sand-protecting system and desertified land reclamation have been obtained in some areas of the desert–oasis ecotone. This paper presents a typical case of successful efforts in ecological restoration and desertified land reclamation in the middle of the Hexi Corridor, northwest China, which is a representative of oasis–desert ecotone in arid regions. We attempt to evaluate the long-term effects of ecological restoration by investigating soil development and environmental improvement following ecological restoration of 28 years. The aim is to provide an effective and feasible model for ecological restoration in oasis–desert ecotone of arid region.

2. Method and materials

2.1. Description of study area

The study area, covering Wulidong village, Pingchan town, Linze county in the middle of Hexi Corridor region of Gansu province, is located between 39°19′–39°19′N and 100°02′–100°21′E at the southern edge of Badain Jaran Desert, with an altitude ranging from 1368 to 1380 m. Pingchan town is a narrow stretch of oasis and Wulidong village is located at the fringe of the oasis, which is connected with dense moving and denudation residual dunes as well as Gobi. This region has a typical temperate desert climate: dry and hot in summer, cold in winter, plenty of sunshine, very little precipitation, strong winds, and frequent drifting sands. According to the statistics of the Linze Weather Station, the annual mean air temperature is about is 7.6 °C, with an absolute maximum of 39.1 °C and an absolute minimum of 27 °C. The normal annual precipitation is 117 mm. Mean annual pan-evaporation is around 2390 mm, 20 times greater than the annual precipitation. The frost-free season lasts 165 days on average. Accumulated temperature of ≥10 °C is about 3088 °C. Mean annual wind velocity is 3.2 m s^{-1}, and prevailing wind direction is northwest. Gales with wind velocity >17 m s^{-1} occur 15 or more days per year (Su et al., 2004). The depth of groundwater level ranges from 4 to 10 m. The main soil types are Aripsamment and Calciorthids with loose structure and very low organic matter, and are very susceptible to wind erosion (Chen et al., 1998). The natural vegetation at the edge of oasis is composed of *Calligonum mongolicum* Turcz., *Calligonum gobicum* (Bge.) A. Los., *Nitraria sphaerocarpa* Maxim., *Reaumuria soongorica* (Pall.) Maxim., *Haloxylon ammodendron* (C.A. Mey.) Bge., *Caragana korshinskii* Kom., *Hedysarum scoparium* Fisch. et Mey., and *Tamarix chinensis* Lour. The staple crops are spring wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.) in the oasis.

2.2. Features of desertified land priori to restoration in the study area

Desertification and oasification are two extreme opposite geographical processes in arid regions (Zhang et al., 2003). Irrational reclamation of land and over utilization of natural resources in oases by humans can led to deterioration in oasis environments, resulting in development of desertification. Desertification around Pingchuan oasis margin was developed rapidly during the second half of the 20th century and reached climax in the mid-1970s. At its peak, the original fixed shrubby sand dunes at the fringe of the oasis were mobilized as a result of vegetation devastation due to over-gathering of fuelwood and overgrazing, leading to encroachment of shifting sand on the oasis. The farmlands endangered by shifting sand from residual dunes of Gobi led to soil erosion, and the resulting abandonment of cultivated land further induced a southward retreat of the oasis by 200–300 m. Severe desertified land made up 54.6% of the total land area (Research Group of "Study on Combating Desertification/Land Degradation in China", 1998).

2.3. Techniques of ecological restoration

In 1975, Lanzhou Institute of Desert Research, Chinese Academy of Sciences established the Linze Station of Desertification Research at Pingchuan to monitor desertification processes and develop effective techniques to restore vegetation and rehabilitate desertified land. According to the topographical features and desertification extent in the study area, plan for ecological rehabilitation was made and some stabilization and reclamation techniques including shelterbelts, land enclosure, straw checkerboards planted with indigenous shrubs, shelter belt establishment, dune level and irrigation were applied. The specific way of technical application in the study area was as follows.

First of all, sand breaks 10–50 m wide were built along trunk canals at the peripheries of the oasis by planting poplar (*Populus gansuensis*) and narrow-leafed oleaster (*Elaeagnus angustifolia*). Since *Populus gansuensis* functions more effectively in providing shelter from the wind, it is mostly planted in places overlaid with soil horizons, while *E. angustifolia* is luxuriant and works better as barrier protecting against sand, it is suitable to be planted in infertile soil layers. Meanwhile, forest grids of 300 m × 500 m in size were built in the interior of the oasis with *Populus gansuensis*, *E. angustifolia*, *Populus nigna var. thevestina*, *Salix matsudana* and *Ulmus pumila* in domination. Dune stabilization plant species of various types were planted in interdune lowland or on dunes in the peripheries of the oasis. First, barriers composed of straw and reeds protecting against sand were set up on mobile dunes, then, some drought-tolerant desert shrub species with big stomata resistance, namely *H. ammodendron*, *C. korshinskii* and *Hedysarum scoparium*, were planted on sand dunes, and *T. chinensis* were planted in the depression between sand dunes. Thus, a protection system was formed by separating every strip and encircling every piece of farmland at the peripheries of the oasis. In order to stop exotic sand source, grass reservation belts were built outside of the protection system, and grazing and firewood gathering were forbidden to facilitate natural vegetation recovery. In winter, surplus irrigation water was diverted to the closed areas to accelerate vegetation rehabilitation. In the interior of the forest grids, sand dunes were leveled, irrigating channels were dredged. The large part of the leveled land was used as cropland and small part was used for planting *Picea sylvestris*, which is well adapted for sandy land environment. Thus, a protection system with 5 km width was established in the transitional zone between oasis and desert. This system formed a buffering strip from fringe to periphery of the oasis.

2.4. Investigation of long-term effects of ecological restoration

An attempt is made to investigate the vegetative cover, soil development, and sand transportation rate during sandstorm events in the restoration area and the untreated control area to assess the long-term effects of the ecological restoration engineering on oasis environment.

2.4.1. Measurements of sand transportation rate

In late April 2002, three types of land cover (i.e. the reclaimed cropland in the interior of shelter forest grid, artificial sparse shrubland and adjacent untreated control area at the edge of oasis) were selected as observation sites. At the sites, the windblown sand flux profiles (the distribution of sand transportation rate with height) were measured during three windstorm events with the step-like passive sand samples developed by the Institute of Desert Research, Chinese Academy of Sciences (Li et al., 2003a). These samplers have 10 openings, each 2 cm wide and 2 cm high, so a sand flux profile can be obtained for 0–20 cm with a successive of 2 cm, representing sand transportation rate in several sandstorm events with sand collecting machines. During the three windstorm events in late April 2002, sand samplers were placed on each of the three observation sites, with the openings of the samplers facing the wind direction. Measurement lasted for 1 h during each of the three sandstorms. During each 1-h measurement, mean wind speed at 2-m height above the ground surface was 8.5–9.0 m s^{-1}. The amount of sediment trapped by each sampler was weighed by electronic balance. The sand flux was expressed as the sediment transportation rate per unit area per minute (g cm^{-2} min^{-1}). The suspended dust content, which was the particle fractions of <0.063 mm and considered as the main component of sandstorm (Pye and Tsoar, 1990), was obtained by dry sieve.

2.4.2. Investigation of vegetation status and measurement of soil development

In 2004, four land cover classes in the restoration area and in an untreated control area were selected (Table 1). Three sites with an area of 20 m × 20 m were laid out at random in each of the selected five land cover classes. Soil surface condition and vegetative coverage were investigated in each site of the selected shrubland and the untreated control area. In each site of *P. sylvestris* forestland, 20 *P. sylvestris* individuals were randomly selected, and the height and diameter at breast height were recorded. In each site of the two shrublands, the height, crown diameter and diameter at basal stem of all shrub individuals were measured. Within each site, five soil samples with uniform distribution separated by 5 m each were taken at depths of 0–10, 10–30, 30–60 and 60–100 cm and bulked to obtain a composite sample of each depth. Soil bulk density was determined using a soil core (100 cm^3) taken at four depths in each location.

2.4.3. Soil analyses

Soil samples were air-dried, ground and passed through a 2 mm sieve. Particle size distribution was determined by the pipette method in a sedimentation cylinder, using sodium hexametaphosphate as the dispersing agent (Gee and Bauder, 1986). Soil pH and electrical conductivity (EC) were measured in a soil–water suspension (1:1 and 1:5 soil–water ratio, respectively). Part of the air-dried and sieved samples was further ground and passed through a 0.1 mm sieve for chemical analysis. Soil organic carbon (SOC) was determined by dichromate oxidation of Walkley–Black (Nelson and Sommers, 1982), total nitrogen (total N) was measured by micro-Kjeldahal procedure and total phosphorous by UV-2450 spectrophotometer after H_2SO_4–$HClO_4$ digestion (Institute of Soil Sciences, 1978). Available soil N was determined by the alkaline diffusion method, available P by the Bray method and available K by using flame spectrophotometry (Institute of Soil Sciences, 1978).

Table 1 – The selected land cover type and management as the study site

Land cover type	Management
Picea sylvestris forestland	Irrigation four to five times annually, without fertilizers, less disturbance
Reclaimed cropland	Spring wheat–maize rotation, irrigation six to seven times annually, chemical fertilizer with about 150 kg N, 75 kg P_2O_5 hm^2 annually, without farmyard manure, straw removal when harvest, conventional tillage
T. chinensis shrubland	No irrigation, planted in depression or lowlands between sand dunes
H. ammodendron shrubland	No irrigation, planted on sand dunes
Untreated control shifting sand land	No any measurements as control area

Statistical analysis (ANOVA with LSD and regression analysis) was carried out by using SPSS 10.0 for Windows at a $p < 0.05$ significance level.

3. Results

3.1. *Sand surface and vegetative characteristics*

Investigation shows that the untreated control area still exhibits the characteristics of severely desertified mobile sandy land. The total vegetative coverage is less 5% with some natural *Phragmites australis* and *Nitraria tangutorum* individuals occurred on the depression between sand dunes. Soil crust occurs around sparse plant individuals. In the restoration area at the edge of oasis, the total cover of artificial shrubs reaches about 30% and sand surface is basically stable. Soil crust thickness is about 1–2 cm on sand dunes and 2–5 cm in the depression. The mean height, crown diameter and the diameter of basal stem for *T. chinensis* individual are observed 2.2 m, 220 cm × 230 cm and 13 cm, respectively, and these parameters for *H. ammodendron* individual reach 1.8 m, 150 cm × 160 cm and 9.5 cm, respectively. In the leveled and irrigated land, the mean height and the mean diameter of breast height for artificial *P. sylvestris* individual reach 15 m and 20 cm, respectively (Fig. 1).

3.2. *Sand transportation rate*

Vegetative reconstruction and desertified land reclamation can significantly reduce soil erosion by wind, which can be testified by measurement of sand transportation rate. On the three measurement dates in late April 2002, the mean sand transportation rate in the 0–20 cm height was 1.25 g min^{-1} cm^{-1} at the untreated control site, 7.4 and 4.3 times greater than the artificial shrubland and the spring-ploughed bare cropland, respectively. Mean suspended dust content (particle size <0.063 mm) was 0.192 g min^{-1} cm^{-1} at the untreated control site, 6.9 and 2.3 times greater than the artificial shrubland and the spring-ploughed bare cropland, respectively (Fig. 2). The ratios of the suspended dust content to the total sand transport rate were averaged on 15.4, 30.5 and 16.5% on the shifting sand land, the bare cropland and the sparse shrubland, respectively. Within the 0–20 cm height above ground surface, sand transportation rate decreased with increasing height by an exponential function in the three measurement sites. Most of the sediment trapped by samplers occurred within 12 cm height of surface and their proportions were 89.3, 91.3 and 97.6% for the shifting sand land, the bare cropland and the sparse shrubland, respectively (Fig. 2).

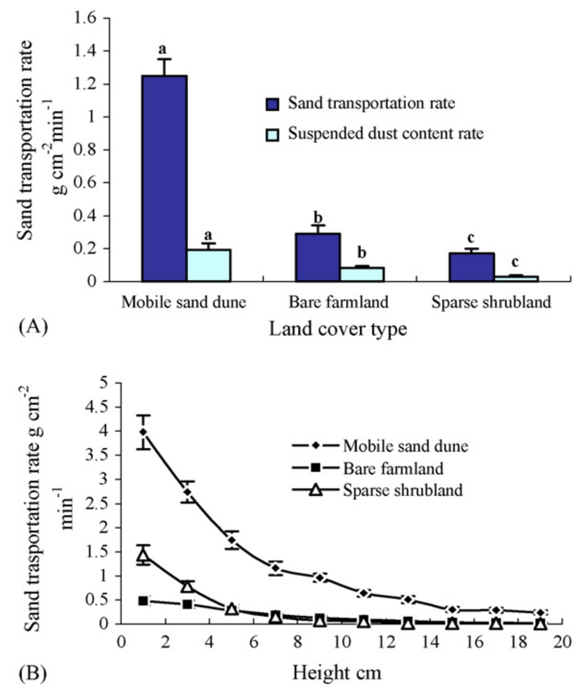

Fig. 2 – (A) Measured mean sand transportation rates at 20 cm above surface for the three land cover types during the three sandstorm events. Means with different letters indicate significant differences at $p < 0.05$. (B) Distribution of sand transportation rate with height for the three land cover types. Bars represent ±1 S.D., $n = 3$.

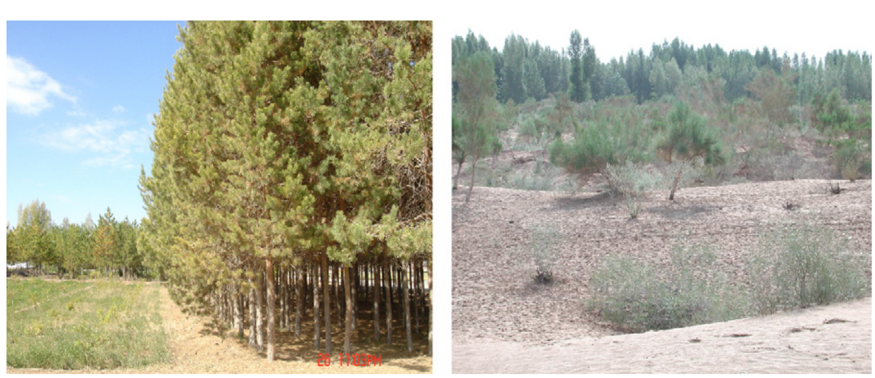

Fig. 1 – Landscape characteristics in the restoration area following desertification control and vegetation construction: left: 28-year-old *Picea sylvestris* planted on the leveled desertified sandy land; right: 28-year-old *T. chinensis* shrubland and *H. ammodendron* shrubland planted on desertified mobile sand dunes.

3.3. Soil development

3.3.1. Soil particle size distribution and bulk density

The soils in the study area have a sandy layer 1 m or more in thickness, mainly consisting of well sorted fine sand and have weakly developed profiles and loose consistence. In the untreated control area, soil particle composition exhibits a uniform distribution in the whole 0–100 cm profile and the 0.5–0.05 mm fine sand content occupies more than 96%. For the artificial shrubland and forestland with less disturbance, changes in soil particle size distribution relative to the control area only occur in the 0–10 cm surface layer. While, tillage practices in the cropland allow fine particles to mix in the 0–30 cm plough layer, which results in higher fine particle content in the 10–30 cm layer in the cropland than in the other lands. The fine particle fraction (clay + silt) in the 0–10 cm surface layer are 9.3, 14.1, 16.2 and 37.3% in the *H. ammodendron* shrubland, *T. chinensis* shrubland, irrigated cropland and irrigated *P. sylvestris* forestland, respectively. In comparison with the untreated control area, fine particle size fraction at the 0–10 cm depth in the restoration areas increased by 3.6–14.3 times. The greatest increase in fine particle fraction occur in the irrigated *P. sylvestris* forestland and an irrigated Ap horizons of 10 cm in thickness has been formed under the long-term irrigation of silt-laden water and litter input. Owing to the changes in soil mechanical composition, the bulk density in the 0–10 cm sand layer in the restoration area decreased, especially in the irrigated forestland and cropland (Table 2).

3.3.2. Soil chemical properties

Soil organic C and nutrients exhibit a very low contents and a relatively uniform distribution in the whole 0–100 cm profile of the untreated control soil. Changes in soil organic C and nutrients concentrations following vegetation recovery and desertified land reclamation occur mainly in the 0–10 cm surface layer and their levels declined sharply at the 10 cm below (Fig. 3). These parameters at the 10–30 cm depth are higher in the irrigated cropland and the *P. sylvestris* forestland than those found at a corresponding depth in the untreated control area. No significant differences in soil organic C and nutrients of the 30 cm below are observed among the different land cover classes. Soil organic C concentrations in the 0–10 cm layer at the restoration sites are 1.88, 2.64, 5.15 and 9.70 g kg^{-1} in the *H. ammodendron* shrubland, *T. chinensis* shrubland, irrigated cropland and irrigated *P. sylvestris* forestland, respectively, which are 3.0, 4.2, 8.2 and 15.4 times greater than that of the untreated control area (0.63 g kg^{-1}). Total N and P and available N concentrations show a similar trend of variation to that of soil organic C. However, the variation of available P and K among the land cover classes differed to that of soil organic C and total P. The highest level of available P concentration is observed in the irrigated cropland because of long-term

Table 2 – Particle size distribution and bulk density of soils in different land cover type after 28 years of land reclamation for desertified sand land, non-vegetated shifting sand land as untreated control, $n = 3$

Land cover class	Particle size distribution (%)			Bulk density (g cm^{-3})
	Sand	Silt	Clay	
	0.5–0.05 mm	0.05–0.002 mm	<0.002 mm	
0–10 cm depth				
P. sylvestris forestland	62.7 e	29.6 a	7.7 a	1.45 c
Reclaimed cropland	83.8 d	11.7 b	4.5 b	1.30 d
T. chinensis shrubland	85.9 c	9.3 c	4.8 b	1.50 b
H. ammodendron shrubland	90.7 b	5.5 d	3.8 c	1.53 b
Non-vegetated shifting sand land	97.4 a	1.5 e	1.1 d	1.61 a
10–30 cm depth				
P. sylvestris forestland	94.3 b	3.0 b	2.7 b	1.56 b
Reclaimed cropland	89.7 c	6.5 a	3.8 a	1.55 b
T. chinensis shrubland	94.8 ab	2.8 b	2.4 b	1.57 a
H. ammodendron shrubland	95.6 a	2.3 b	2.1 b	1.57 a
Non-vegetated shifting sand land	96.3 a	2.0 b	1.6 b	1.60 a
30–60 cm depth				
P. sylvestris forestland	96.8 a	1.8 a	1.4 a	1.57 a
Reclaimed cropland	96.0 a	2.1 a	1.9 a	1.53 a
T. chinensis shrubland	95.9 a	2.3 a	1.8 a	1.53 a
H. ammodendron shrubland	96.9 a	1.7 a	1.4 a	1.56 a
Non-vegetated shifting sand land	97.2 a	1.6 a	1.2 a	1.58 a
60–100 cm depth				
P. sylvestris forestland	96.9 a	1.6 a	1.5 a	1.58 a
Reclaimed cropland	96.0 a	2.2 a	1.8 a	1.55 a
T. chinensis shrubland	95.8 a	2.4 a	1.8 a	1.54 a
H. ammodendron shrubland	96.9 a	1.5 a	1.6 a	1.56 a
Non-vegetated shifting sand land	96.8 a	1.9 a	1.3 a	1.56 a

Values are means of three measurements; means in line with the same depth followed by the same letter are not significantly different ($p > 0.05$).

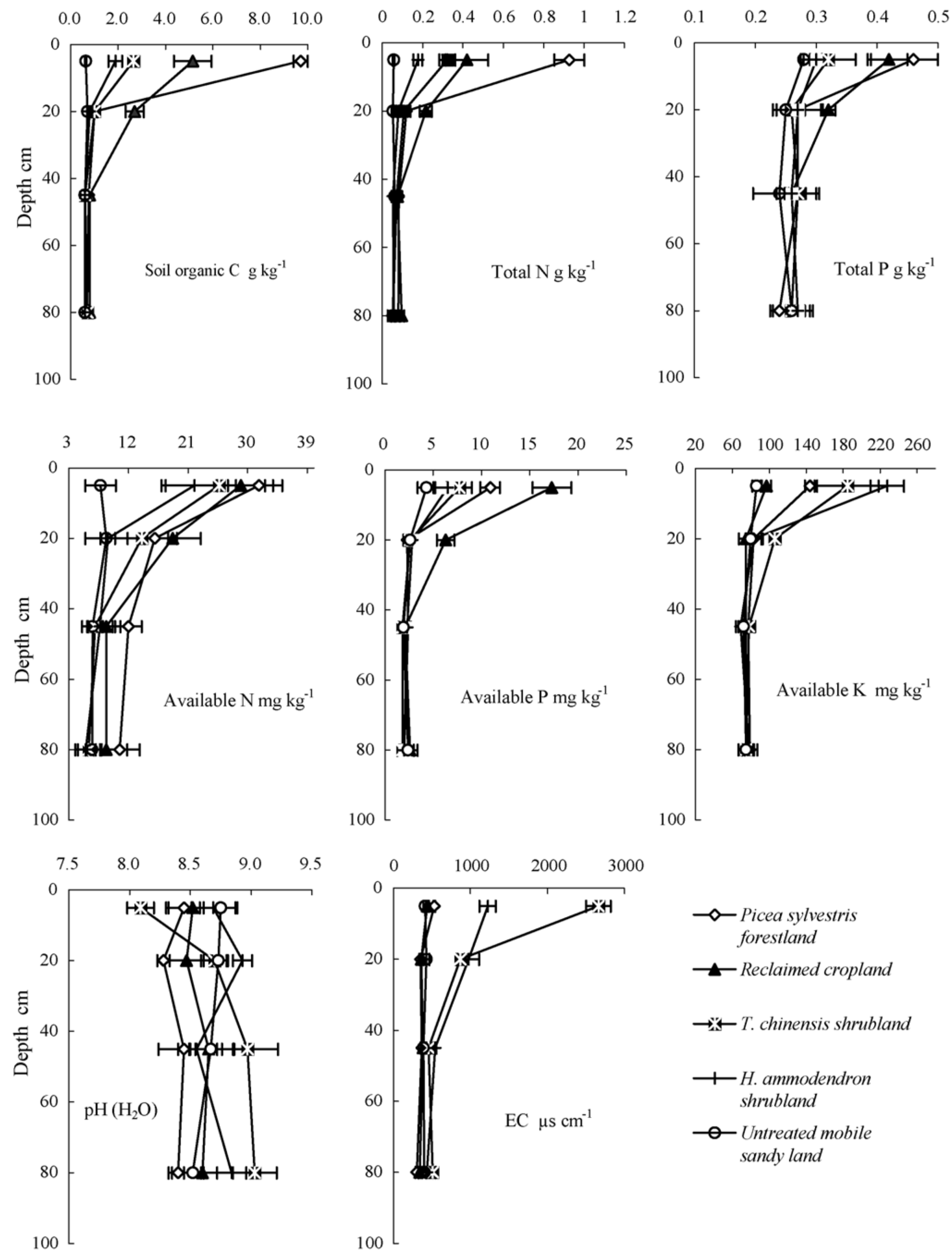

Fig. 3 – Soil chemical properties in different land cover types after 28 years of land reclamation for desertified sand land, non-vegetated shifting sand land as untreated control. Bars represent ±1 S.D., $n = 3$.

phosphorus fertilization, whereas, available K concentration was significant lower in the cropland than in the forestland and the shrubland, despite it was higher than in the untreated control soils. This was probably because of the long-term output of K nutrient associate with the crop harvesting. At the 10–30 cm depth, the irrigated cropland soils had significant higher soil organic C and nutrients except available K than the other sites due to the tillage effect.

Soil pH has a slight decline at the 0–10 cm surface layer in the restoration areas compare to the untreated control area, with lower values in the irrigated cropland and *P. sylvestris* forestland. However, soil pH increase at the 30 cm below in the *T. chinensis* shrubland relative to the untreated area. In comparison with the untreated control area, soil salt content (EC) has no significant changes in the irrigated cropland and *P. sylvestris* forestland. While, the EC values are 6.7 and 2.9 times higher at the 0–10 cm depth and 2.6 and 1.9 times at the 10–30 cm depth in the *T. chinensis* shrubland and the *H. ammodendron* shrubland, respectively, exhibiting a significant salt accumulation (Fig. 3).

4. Discussion

An effective way of combating desertification around an oasis and maintaining the stability of an oasis in arid regions is to establish an integrated protecting system in the transitional zone between oasis and desert. This system consists of forest grids to protect farmland in the interior of the oasis, forest-shrub integrated sand breaks at the fringe of the oasis, and sand breaks in dune areas of periphery of the oasis as well as dune stabilization belt by planting sand binders within the break and grass reservation by closing dunes outside the stabilized belt. The visual success of this system has been clearly demonstrated by preventing further sand encroachment, reinstating a stable ecosystem on dunes and providing new land suitable for cultivation. In the restoration area, the rate of shifting sand area have declined from 54.6% in pre-treatment to 9.4% and the land used for agricultural and forestry purposes in desertified area have increased from 6.1 to 43% through establishment of protecting system and improved land management (Research Group of “Study on Combating Desertification/Land Degradation in China”, 1998).

The ultimate success of these reclamation techniques is their sustainability (Mitchell et al., 1998), which can be assessed partially through vegetation and soil development and environmental improvement (Vance and Entry, 2000). The results investigated in 2004 indicate that the artificially planted *T. chinensis* and *H. ammodendron*, two of the anti-drought indigenous shrub species with big stomata resistance (Su et al., 2004), had formed a sparse and stable community and still sustained a well-balanced growth in arid environment after 28 years. This artificial community had formed a buffering zone between oasis and desert, which protect the oasis from sand encroachment, modify the roughness of the underlying surface in ecosystem (Pan and Chao, 2003), reduce effectively wind speed and enhance sand surface stabilization and soil development (Su and Zhao, 2003; Duan et al., 2004).

Sand transportation rate during the sandstorm events reduced significantly in the sparse shrubland and in the bare farmland in comparison with the unvegetated control area, suggesting the significant effect of ecological restoration on environmental improvement. Measurements indicate that most of the trapped sediments occurred within 12 cm of the surface, showing that sand transportation and deposition by wind is a near-surface phenomenon. This agrees with conclusions from other studies (Dong et al., 1999; Li et al., 2003a). The bare cropland showed a higher value in the proportion of the suspended dust content than the sparse shrubland and the mobile sand land, suggesting that spring bare croplands contribute significantly to the formation of sandstorms in this erosion-prone area. Therefore, the conservative tillage management is needed to mitigate soil erosion by wind.

The shrubland, forestland and cropland in the restoration area evolved from shifting sand land that the change in soil properties are very weak during a long period of time (Chen et al., 1998). Soil-forming environment was improved after artificial shrubs and shelter forest systems were established and desertified lands were reclaimed and the process of soil development was accelerated. First, development and establishment of artificial vegetation and subsequently increases in vegetation cover is efficient in the soil amelioration by interception and retention of more precipitation and aeolian dust including atmosphere dust (Fearnehough et al., 1998; Li et al., 2003b). The precipitation of fine particles and dust thereby altered the original soil mechanical composition (Fearnehough et al., 1998; Duan et al., 2004). Our results indicate that the *T. chinensis* shrubland on the interdune depression and leeward slopes had higher fine clay and silt content in soil surface layer than the *H. ammodendron* shrubland on the windward slopes and sand dunes. This agrees with the results from Shapotou region (Duan et al., 2004) and Horqin Sandy Land in north China (Shirato et al., 2004), which suggested that the interdune depression and leeward slopes received more fine particles from dust deposition than the windward slopes and sand dunes. When the shifting sand dunes were leveled and changed into the irrigated cropland and forestland, the long-term use of silt-laden water for irrigation increased significantly fine fractions in soil surface layer and thereby accelerated the development of the soil structure and improvement of soil fertility. Linear regressions indicated significant positive associations of soil organic C, total N and P, available N and P with fine particle content (Table 3), suggesting that the input of fine particle materials by dust deposition and the use of silt-laden water for irrigation is an important controlling factor in soil fertility improvement and soil development. A study at the Shapotou indicated that soil development generally increased with the length of the irrigation period and soil organic matter content in the 0–5 cm deep layer increased by a mean rate of 0.1–0.2% per year after sand dunes were leveled and cultivated (Mitchell et al., 1998).

Table 3 – Correlation coefficient (R^2) between fine particles and soil nutrients

	Silt + clay content (%)
Soil organic C ($g\,kg^{-1}$)	0.987***
Total N ($g\,kg^{-1}$)	0.996***
Total P ($g\,kg^{-1}$)	0.929***
Available N ($mg\,kg^{-1}$)	0.835***
Available P ($mg\,kg^{-1}$)	0.587**
Available K ($mg\,kg^{-1}$)	0.475*

* Significant at $p \leq 0.001$, $p \leq 0.01$, $n = 45$.
** Significant at $p \leq 0.05$.
*** Significant at $p \leq 0.001$, $p \leq 0.001$.

The change in soil salt content (EC) indicates that long-term irrigation in this arid region had not result in significant salt accumulation in the cropland and the *P. sylvestris* forestland. This was probably due to high infiltration of sandy soil. However, the *T. chinensis* and *H. ammodendron* shrublands without irrigation have significant salt accumulation, especially in the 0–10 cm surface layer. The *T. chinensis* and *H. ammodendron* are salt secrete halophyte and succulent halophyte, respectively (Xi et al., 2004), which can uptake amounts of salt ion from the soil in their growth. With the increase of their growth years, soil salt content in the canopies of shrubby halophytes tended to increase and accumulation due to the input and accumulation of litter enriched in salt content (Xi et al., 2004). Therefore, artificial regeneration of shrubs is needed to curtail the excessive accumulation of soil salt.

Although a stable ecosystem in the oasis–desert ecotone had been formed following the implementation of the desert reclamation project, the degree of soil development is very slow in this arid region. Soil organic C content in the 0–10 cm depth on the artificial shrublands ranged from 1.88 to 2.64 $g\,kg^{-1}$ and increased 3–4.2-fold compared to the shifting sand (the unvegetated control area) after 28 years of shrub establishment. The pedological effect of vegetation construction on desertified sandy land is significant lower in the studied area than in the semi-arid Horqin sandy land (Su and Zhao, 2003; Shirato et al., 2004) and in the Shapotou area located in a transitional zone between arid and semi-arid climate (Mitchell et al., 1998; Duan et al., 2004). This was because the studied area has more drought conditions and only few annual plants occurred. The development of annual herbs played an important role for accumulation of soil organic C and nutrients in sandy land (Mun and Whitford, 1998). For the reclaimed cropland, soil organic matter and nutrients showed relatively low levels (5.15 $g\,kg^{-1}$ organic C and 0.42 $g\,kg^{-1}$ total N) following the irrigation, fertilization and cultivation of 28 years. The accumulation of soil organic matter and nutrients depend mainly on input of organic materials and return of crop residuals, as well as the rational tillage management (Lal et al., 1999). But in the study area, conventional tillage practice was carried out, straw was removed after harvesting, few residuals were returned. Especially, farmyard manure was not applied for the reclaimed cropland. This resulted in a relatively slow accumulation in soil organic C on the irrigated cropland. With respect of soil fertility improvement, a rational cultivation management, i.e. manure application, residual return and conservative tillage, may be required in this erosion-prone area.

In conclusion, the ecological restoration techniques in the oasis–desert ecotone based on stabilization of mobile dunes and crop productivity of reclaimed agricultural land are successful. This can be reflected by formation of stable artificial shrub community, the improvement in soil properties and mitigation in soil erosion by wind. The results suggest that the ecological restoration approach is of practical significance for the rebuilding of rift zone ecosystem and maintenance of the stability of oasis in the arid regions of northwest China.

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REFERENCES

Chen, L.H., Li, F.X., Di, X.M., Zhang, J.X., 1998. Aeolian Sandy Soils in China. Science Publishing House, Beijing, China.

Cheng, G.D., Xiao, D.N., Wang, G.X., 1999. On the characteristics and building of landscape ecology in arid area. Adv. Geosci. 14 (1), 11–15 (in Chinese with English abstract).

Dong, Z.B., Fryrear, D.W., Gao, S.Y., 1999. Modeling the roughness properties of artificial soil clods. Soil Sci. 164, 930–935.

Duan, Z.H., Xiao, H.L., Li, X.R., Dong, Z.B., Wang, T., 2004. Evolution of soil properties on stabilized sands in the Tengger Desert, China. Geomorphology 59, 237–246.

Fearnehough, W., Fullen, M.A., Mitchell, D.J., Trueman, I.C., Zhang, J., 1998. Aeolian deposition and its effect on soil and vegetation changes on stabilized desert dunes in northern China. Geomorphology 23, 171–182.

Gee, W.G., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. American Society of Agronomy/Soil Science Society of America, Madison, WI, USA, pp. 383–412.

Han, D.L., 1999. The progress of research on oasis in China. Scientia Geographic Sinica 19 (4), 313–319 (in Chinese with English abstract).

Institute of Soil Sciences, Chinese Academy of Sciences, 1978. Physical and Chemical Analysis Methods of Soils. Shanghai Science Technology Press, Shanghai, pp. 7–59 (in Chinese).

Lal, R., Follett, R.F., Kimble, J., Cole, C.V., 1999. Managing U.S. cropland to sequester carbon in soil. J. Soil Water Conserv. 54, 374–381.

Li, F.R., Zhang, H., Zhang, T.H., Shirato, Y., 2003a. Variation of sand transportation rates in sandy grassland along a desertification gradient in northern China. Catena 53, 255–272.

Li, F.R., Zhang, H., Zhao, L.Y., Shirato, Y., Wang, X.Z., 2003b. Pedoecologicl effects of a sand-fixing poplar (*Populus simonni* Carr.) forest in a desertified sandy land of Inner Mongolia, China. Plant Soil 256, 431–442.

Mitchell, D.J., Fullen, M.A., Trueman, I.C., Fearnehough, W., 1998. Sustainability of reclaimed desertified land in Ningxia, China. J. Arid Environ. 39, 239–251.

Mun, H.T., Whitford, W.G., 1998. Changes in mass and chemistry of plant roots during long-term decomposition on a Chihuahuan Desert watershed. Biol. Fertil. Soils 26, 16–22.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L. et al. (Eds.), Methods of Soil Analysis, Part 2, ASA Publ. No. 9, 2nd ed. Madison, WI, pp. 539–577.

Pan, X.L., 2001. A preliminary study on the stability of oasis ecosystem in arid area. Quat. Sci. 21, 345–351 (in Chinese with English abstract).

Pan, X.L., Chao, J.P., 2003. Theory of stability, and regulation and control of ecological system in oasis. Global Planet. Change 37, 287–295.

Pye, K., Tsoar, H., 1990. Aeolian Sand and Sand Dunes. Academic Division of Unwin Limited, London, pp. 45–47.

Research Group of "Study on Combating Desertification/Land Degradation in China", 1998. Study on Combating Desertification/Land Degradation in China. China Environmental Science Press, Beijing, pp. 76–113.

Shirato, Y., Taniyama, I., Zhang, T.H., 2004. Changes in soil properties after afforestation in Horqin sandy land, north China. Soil Sci. Plant Nutr. 50 (4), 537–543.

Su, P.X., Liu, X.M., Zhang, L.X., Zhao, A.F., Li, W.R., Chen, H.S., 2004. Comparison of $\delta\,^{13}C$ values and gas exchange of assimilating shoots of desert plants *Haloxylon ammodendron* and *Calligonum mongolicum* with other plants. Isr. J. Plant Sci. 52, 87–97.

Su, Y.Z., Zhao, H.L., 2003. Soil properties and plant species in an age sequence of *Caragana microphylla* plantations in the Horqin Sandy Land, north China. Ecol. Eng. 20, 223–235.

Vance, N.C., Entry, J.A., 2000. Soil properties important to the restoration of Shasta red fir barrens in the Siskiyou Mountains. Forest Ecol. Manage. 138, 427–434.

Xi, J.B., Zhang, F.S., Chen, Y., Mao, D.R., Yin, C.H., Tian, C.Y., 2004. A preliminary study on salt contents of soil in root-canopy area of halophytes. Chin. J. Appl. Ecol. 15 (1), 53–58.

Zhang, H., Wu, J.W., Zheng, Q.H., Yu, Y.J., 2003. A preliminary study of oasis evolution in the Tarim Basin, Xinjing, China. J. Arid Environ. 55, 545–553.