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The trade-off in the establishment of artificial plantations by evaluating soil properties at the margins of oases

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ABSTRACT

The establishment of forest plantations in oasis–desert ecotones is crucial for reducing wind erosion, sand fixation, and for maintaining the stability of oases. In such oasis–desert ecotones in the arid regions of northwestern China, the dominant forest plantations are *Haloxylon ammodendron*, *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. However, the effects of these plantations on soil properties remain unknown. We undertook soil properties surveys on soils under native desert land, 21-year-old *Haloxylon ammodendron*, 27-years-old *Populus simonii* Carr. and 33-years-old *Pinus sylvestris* var. *mongolica* Litv. plantations. We found that the *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations significantly improved the porosity, physical stability index, water-holding capacity, and macroaggregates of the soil as well as soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), microbial biomass carbon (MBC), and nitrogen (MBN) contents, and urease, β-glucosidase and alkaline phosphatase activities. The 21-year-old *Haloxylon ammodendron* plantation (no irrigation) significantly increased urease and β-glucosidase activities and MBC content—but not soil porosity, bulk density, water-holding capacity,or SOC, TN and TP contents—when compared with the desert land. Based on these results, it was concluded that establishment of *Populus simonii* Carr. and *Pinus sylvestris* var. *Mongolica* Litv. plantations could significantly ameliorate soil properties with the necessary irrigation input. While establishment of a *Haloxylon ammodendron* plantation does not require irrigation, it did not have the desired effect on the physical and chemical properties of the soil. An artificial *Haloxylon ammodendron* plantation degenerates after about 30 years, and will not withstand wind erosion due to its low soil physical stability index and scarce carbon and nitrogen sequestration capacities. Water resources are extremely scarce in this region so a balance between ecological benefits and irrigation inputs should be considered in the design and establishment of artificial plantations in the oasis–desert ecotones. A single, large *Haloxylon ammodendron*, *Populus simonii* Carr. or *Pinus sylvestris* var. *mongolica* Litv. plantation is not recommended—the complex forest systems of these plantations should be properly designed and established in the desert–oasis areas.

1. Introduction

Desert ecosystems cover approximately one-fifth of the total land surface in China and are widely distributed in the northwestern and northern regions (Institute of Soil Science, Academia Sinica, 1978). A desert ecosystem is characterised by sparse vegetation and severe water stress. Generally speaking, an oasis–desert ecosystem is a matrix consisting of both desert and oasis areas, with a transitional belt (desert–oasis ecotone) between these areas. This ecotone acts as an interactive zone between irrigated farmland and the natural desert ecosystem (Shen et al., 2014; Yang et al., 2016).

A transitional belt between oasis and desert areas lies in the middle of the Hexi Corridor in northwestern China and represents an oasis–desert ecotone in an arid region (Su et al., 2007). Since the early 1970s, rapid population growth in these arid regions has led to large-scale conversions of desert areas into agricultural land at the edge of the oasis. At the same time, large areas of desert within the desert–oasis transitional zone have been converted into *Haloxylon ammodendron*, *Populus simonii* Carr., and *Pinus sylvestris* var. *mongolica* Litv. plantations to protect the oasis ecosystems. These plantations are the three main artificial plantations used for wind reduction and sand fixation in the oasis–desert ecotones (Zhao et al., 2004). The ecotone plays an important ecological role for the oasis by ensuring its ecological security and maintaining its internal stability (Wang and Li, 2012; Bo and

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Zheng, 2013; Dong et al., 2016), which is likely to be sensitive to human activities such as land exploitation and over-grazing.

Land use changes generally affect the physical, chemical and biological processes in soil and alter the soil environment (Gispert et al., 2013; Dessalegn et al., 2014; Mganga et al., 2016; Singh et al., 2016). Irrigated, newly reclaimed alfalfa forage land and farmland significantly ameliorated soil properties on desert land (Dong et al., 2016), and shrubs (*Caragana microphylla* and *Salix gordejevii*) create significant ‘islands of fertility’ which maintain or augment the richness of herbaceous species in shifting sand dunes. Therefore, the land use of mentioned above could potentially improve soil properties and facilitate vegetation recovery in the control of desertification processes (Zhao et al., 2007). As previously mentioned, the irrigated *Populus simonii* Carr., and *Pinus sylvestris* var. *mongolica* Litv. plantations and nonirrigated *Haloxylon ammodendron* plantation are the three main artificial plantations used for wind reduction and sand fixation in the oasis–desert ecotones of China's northwestern and northern regions. However, there is limited information on the soil environmental response to the establishment of these plantations. Therefore, the objective of this study was to evaluate the changes in soil physical, chemical and microbiological properties after the long-term establishment of *Haloxylon ammodendron*, *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations in a Chinese oasis–desert ecotone. This study tested the following hypotheses: (1) *Haloxylon ammodendron*, *Populus simonii* Carr., and *Pinus sylvestris* var. *mongolica* Litv. plantations ameliorate soil properties when compared with desert land; (2) Irrigated *Populus simonii* Carr.and *Pinus sylvestris* var. *mongolica* Litv. plantations are more propitious for amending soil environments than nonirrigated *Haloxylon ammodendron* plantations.

2. Materials and methods

2.1. Description of the study site

This study was conducted in a desert area located in the central region of the Heihe River Basin (39°20′N, 100°08′E, 1380 m asl). This basin is the second largest inland river basin (135,000 km^2) in China's arid regions. The climate in this region is strongly continental, with long, cold winters and dry, hot summers. In the past 30 years, the mean annual precipitation has been 117 mm, with > 70% occurring from June to September, and accounts for only one-twentieth of the mean annual pan potential evaporation (2390 mm). The mean annual air temperature is 6 °C and ranges from − 10.7 °C in January to 23.8 °C in July. The annual mean wind velocity is 3.2 $m\ s^{-1}$ with the prevailing winds from the northwest. Gales, with a wind velocity of > 17 $m\ s^{-1}$, occur for approximately ~15 days each year (Su et al., 2007). The main soil types are Calcaric Arenosols and Haplic Calcisols (FAO taxonomy), which have a loose structure and very low organic matter content. They are, therefore, very susceptible to wind erosion (Su et al., 2007).

2.2. Experimental design

The native desert land areas are shown in Fig. 1A. This area, at the oasis margin, comprises a 21-year-old *Haloxylon ammodendron* plantation (Fig. 1B), a 27-year-old *Populus simonii* Carr. plantation (Fig. 1C) and a 33-year-old *Pinus sylvestris* var. *mongolica* Litv. plantation (Fig. 1D) to convert native desert land into vegetated areas. These vegetated areas were selected for the study to allow us to quantify the long-term impacts on soil properties after conversion from desert land to plantation.

The native desert land was dominated by shrub species—*Calligonum mongolicum, Nitraria sphaerocarpa* and *Nitraria sibirica*—along with herbaceous species such as *Agriophyllum squarrosum, Bassia dasyphylla, Halogeton glomeratus* and *Pugionium cornutum*. The *Haloxylon ammodendron* plantation received no irrigation while the annual mean irrigation for *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations ranged from 12,000 to 15,000 $m^3\ ha^{-1}$ (in 2–3 applications from April to September). A large portion of the irrigation water is pumped from the Heihe River. From 2009 to 2011, the fine sediment in the irrigation water was collected andmeasured from ten replications of 25 L of irrigation water every 30 min during irrigation of the *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations. One ton of irrigation water contained approximately 0.15 kg of fine soil particles (< 100 μm).

2.3. Sampling and measurements

Three replicate sites, each with a sampling area of 100 × 150 m and at least 100 m apart, were selected for each land use type (12 sites in total). Three replicate plots (30 × 30 m) within each site were randomly selected. For each replicate plot, five soil cores (8 cm diameter × 10 cm high) were taken using a coring tube (total of 15 soil cores per replicate site) in early September 2011. The 15 soil cores were combined into a composite sample (Fig. 2). To prevent the loss of soil from the coring tube, a soil profile was dug adjacent to the coring ring, and the coring tube bottled were sealed after collecting the soil samples. The samples were air-dried, ground, and sieved (at < 2 mm) for analysis of soil particle fractions, available phosphorus (AP), NO_3-N, NH_4-N and pH, and then sieved again (at < 0.15 mm) for the determination of total carbon (TC), total nitrogen (TN) and total phosphorus (TP). To determine microbial biomass C (MBC) and soil enzyme activities, the samples were brought to the laboratory and stored at 4 °C for subsequent analysis.

The soil bulk density (SB) at 0–10 cm depth was determined according to Robertson et al. (1999). Using the same sampling method mentioned above, 15 soil core samples per site were collected in early September 2011, immediately weighed, dried at 105 °C for 24 h to a constant weight, and then reweighed. The soil specific gravity (SG) was calculated by determining the weight of the solid particles per weight of an equal volume of water. Detailed laboratory procedures for SG determination are outlined by Lu (2000). Soil total porosity (SP) was calculatedas follows:

SP (%) = (1–SB/SG) × 100.

For each land use type, nine soil samples were collected from 0 to 10 cm depth for the determination of soil water potential (3 sites × 3 plots per site) in early September 2011. The soil water potential was measured in undisturbed samples in a laboratory. A sample saturation was performed in a sandbox, by slowly adding water to approximately half way up the sample ring, which was left to soak overnight. Before soaking, cheesecloth was fastened to the lower end of each ring using rubber bands to avoid any loss of soil during the manipulations. When saturation was reached, soil water retention curves were measured at desorption after saturation using an H-1400 pF (Kokusan, Japan). The matric potentials of − 1, − 3, − 6, − 9, − 10, − 30, − 50, − 90, − 120, − 150, − 300 and − 1500 kPa were successively determinedfor the same undisturbed cube samples, up until which time the water ceased to flow from the pressure chambers.

Particle size distributions in < 2 mm soil fractions were determined using a laser detection technique on a Microtrac S3500 Particle Size Analyzer (Microtrac Inc., USA). The soil samples were pretreated by destroying the organic matter using H_2O_2 (30%, *w*/w) at 72 °C. The aggregates were then dispersed using sodium hexametaphosphate ($(NaPO_3)_6$, 0.5 mol L^{-1}) and ultrasonics for 30 s (Gui et al., 2010). Particle size distribution was determined for the1000–250 μm, 250–100 μm, 100–50 μm, 50–2 μm and < 2 μm dimensional classes. A soil physical stability index (St) was used to estimate the stability of the soil matrices, calculated as follows (Pieri, 1992):

St (%) = SOM % × 100/(silt + clay %).

where SOM is soil organic matter content and silt + clay % represents the silt and clay-sized fractions in the soil. SOM was calculated as follows: % SOM = % SOC × 1.724.

The distributions of soil water-stable aggregates (WSA) were

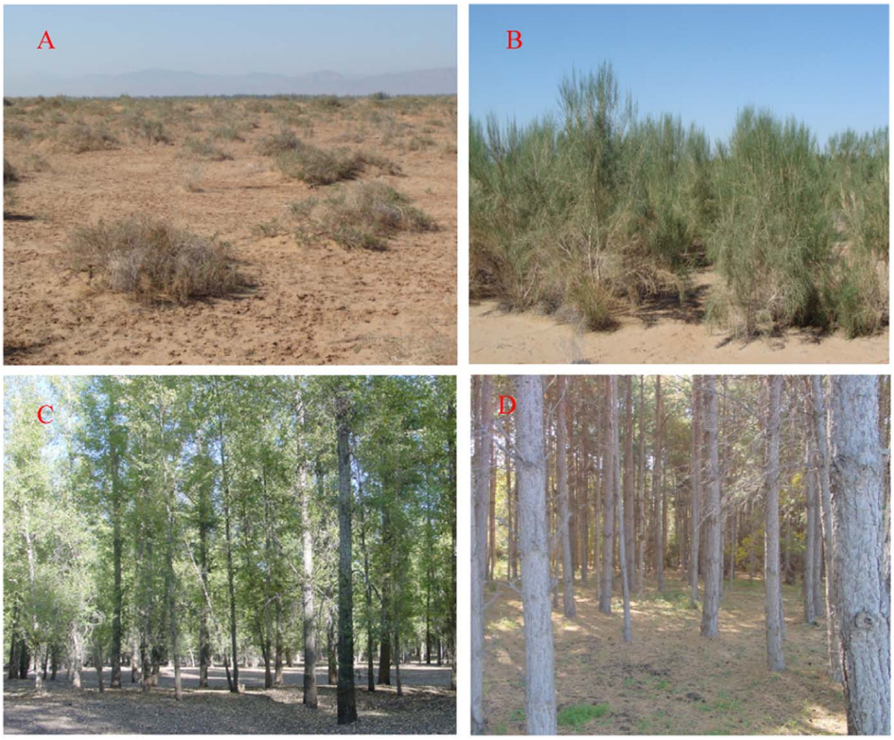

Fig. 1. Photographs showing the different cover types. A: native desert land; B: *Haloxylon ammodendron* plantation; C: *Populus simonii* Carr. plantation; D: *Pinus sylvestris* var. *mongolica* Litv. plantation.

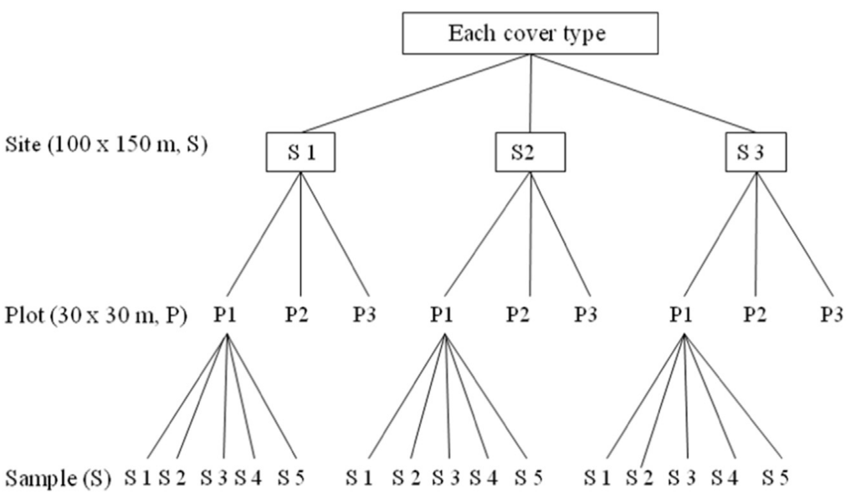

Fig. 2. Sketch of sampling design in each cover type.

determined by placing the soil samples on a nest of sieves with > 2 mm, 2–1 mm, 1–0.5 mm and < 0.5 mm mesh.The sieving process was conducted, and a 100 g sample of bulk soil (8-mm sieved) was slaked by submersion into deionised water on the top 2.0 mm sieve for five minutes at room temperature. The WSA were then separated by moving the sieve up and down 30 times per minute for 15 min (Blanco-Canqui and Lal, 2007). The retained soil in each sieve was oven dried at 50 °C and weighed. The proportion of WSA in each of the classes mentioned above was calculated (Nimmo and Perkins, 2002) and the organic carbon content in the WSA of each particle size was determined. A mean weight diameter (MWD) was used to estimate the stability of the soil aggregates, as follows (Castro Filho et al., 2002):

$MWD = \sum_{i=1}^{n} XiWi$;where X_i is the mean diameter of each size fraction (mm), W_i represents the proportion of the total sample (WSA) in the corresponding size fraction, and n is the number of size fractions.

The soil TC, SOC of the bulk soil, and water-stable macroaggregates C were determined using an HT1300-micro N/C3100-Analyzer (Jena, Germany). Before analysing SOC, sufficient 1 M HCl was added to 1–2 g of air-dried soil to cover and the samples left until no bubbles were generated. This process was repeated three times to remove all of the carbonates. Subsequently, the soil samples were dried at 60 °C for 12 h to remove water. About 50 mg of the soil sample was weighed and analysed in an HT1300-microN/C3100-Analyzer to determine TOC content (Hedges and Stern, 1984). A KJ (Kjeldahl) Auto Analyzer (Tecator Product, Sweden) was used to measure soil TN after digestion with salicylic acid-H_2SO_4 (Jia et al., 2006). Soil TP was determined colorimetrically after digestion with perchloric acid, and soil AP was determined using the method of Olsen et al. (1954). Dried samples, each weighing 10 g were added to 50 mL of 2 M KCl, shaken for one hour, and analysed with a FIAstar 5000 Analyzer (FOSS Tecator, Sweden) to determine nitrate-nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N) contents (Su et al., 2007; Zhang and Zhao, 2015). Soil pH was measured with a pH meter (PHS-3C, Shanghai Leici Instrument Factory, China) at a soil to water ratio of 1:2.5 (*w*/*v*). The calculation of $CaCO_3$ content was derived from inorganic carbon, by subtracting the SOC content from the TC content. The equation is $CaCO_3$ (g kg^{-1}) = (TC–SOC) × 8.33 (Bao, 2000). Microbial biomass carbon (MBC) and nitrogen (MBN) in the soil were estimated using a fumigation-extraction method (Brookes et al., 1985) which included a purified $CHCl_3$ treatment, followed by a 0.5 M K_2SO_4 extraction of fumigated and unfumigated soil (Singh and Singh, 1993). After which, soil samples (equivalent to 25 g of soil dry weight) were fumigated for 24 h at 25 °C with $CHCl_3$ (ethanol-free). Following the fumigant removal, the soil was extracted with 100 mL of 0.5 M K_2SO_4 by shaking for 1 h at 200 rpm, followed by filtering. The non-fumigated portions were extracted at similar time intervals. Following the extraction, MBC and MBN contents were measured by determining the C and N masses in the filtrate using a Multi N/C 3100 Analyzer (Jena, Germany). Microbial biomass carbon was calculated as follows: MBC = (C_{org} (fum) − C_{org} (non))/0.38 (Ocio and Brooks, 1990). Microbial biomass nitrogen was calculated as follows: MBN = (TN (fum) − TN (non))/0.45 (Ocio and Brooks, 1990). The ratios of MBC to total carbon (MBC/SOC) and MBN to total nitrogen (MBN/TN) were then calculated. The activities of β-glucosidase, urease and alkaline phosphatase were assayed, as described by Tabatabai (1994). To determine β-glucosidase activity, 1 g of moist soil was incubated for 1 h at 37 °C with *p*-nitrophenyl glucosidase and toluene in a pH 12.0 $CaCl_2$ solution and Tris hydroxyl methyl amino methane (THAM) buffer. The product, p-nitrophenol (PNP), was colorimetrically determined at 420 nm and expressed as mg pNP $kg^{-1} h^{-1}$. To determine urease activity, an aliquot of a moist sample was incubated with THAM buffer at optimal pH (pH 9.0), with or without toluene and urea (0.2 M), for 2 h at 37 °C. Urease was expressed as mg NH_4^+-N $kg^{-1} h^{-1}$. To determine phosphatase activity, 1 g of moist soil was incubated for 1 h with *p*-nitrophenyl phosphate and toluene in a pH 11.0 modified universal buffer. The product, p-nitrophenol (PNP), was colorimetrically determined at 420 nm and phosphatase expressed as mg pNP $kg^{-1} h^{-1}$.

2.4. Statistical analysis

One-way analyses of variance (ANOVAs) were performed to compare the effects of different cover managements on the biological, chemical and physical properties of the soil (SAS Institute, 1990). An LSD procedure was used to separate the means of the soil properties at $P \leq 0.05$. The relationships between soil particle size and SOC and TN, as well as soil water content and microbial activities were tested using a Pearson's correlation analysis.

3. Results

3.1. Soil $CaCO_3$, pH and physical properties

The conversion of desert land to shrub, poplar and pine land significantly reduced soil pH, but had no effect on soil specific gravity (Table 1). Poplar and pine land areas had significant increases in $CaCO_3$, porosity, and MWD of water-stable aggregates when compared with desert land and shrub land. Moreover, bulk density significantly decreased in the poplar and pine land plantations. Conversion of desert land to shrub land did not increase soil porosity but significantly increased the MWDs of water-stable aggregates. In contrast, the soil physical stability index decreased sharply from 20.63% in desert land areas to 9.50% in shrub land areas (Table 1).

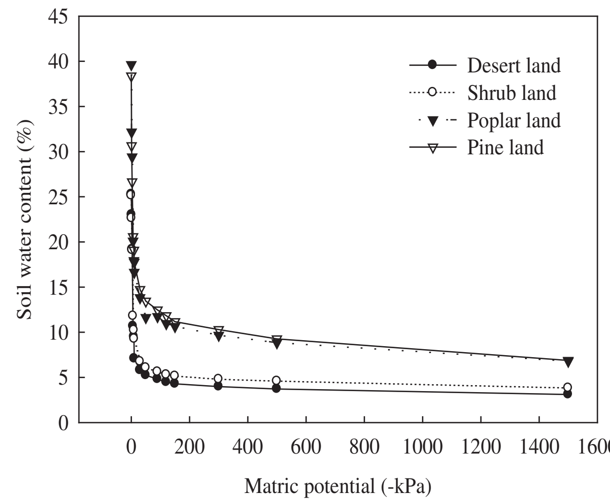

Fig. 3. Water retention curves in different land use types in the 0–10 cm soil layer. Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation.

The conversion of desert land to poplar and pine land significantly increased soil water-holding capacity (Fig. 3) compared with the other land use types. Shrub land areas had similar values to desert land areas. The soil water content of desert land areas decreased sharply from 25.3 to 5.8% at 0 to − 30 kPa, and from 5.8 to 3.1% at − 30 to − 1500 kPa. On average, water retention in the poplar and pine land areas increased by 128% compared with the desert and shrub land areas.

Macroaggregates (> 0.5 mm) in the 0–10 cm soil layer increased significantly after conversion from desert land to shrub, poplar, and pine land areas (Table 2), with respective increases of 4.66%, 14.08% and 17.91%.

The conversion of desert land to poplar and pine land significantly reduced soil particle content in the 1000–250 μm aggregate class (Table 2), but significantly increased fine particle content in the 100–50 μm and 50–2 μm aggregate classes in the 0–10 cm soil layer. In contrast, shrub land areas only increased fine particle content in the 50–2 μm aggregate class.

3.2. Soil C, N and P

Land use modification from desert land to poplar and pine land had significant effects on SOC content and total N and P levels (Table 3). The poplar and pine land areas had significantly higher SOC, TN and TP contents than the other land types. No significant differences were observed between the desert and shrub land areas. The pine land areas had significantly higher AP contents than the other land use types, with no significant differences observed between the desert, shrub and poplar land areas. Significant positive correlations were found between SOC and the particle contents of 250–100, 100–50 and 50–2 μm (Fig. 4), and TN and the particle contents of 250–100, 100–50 and 50–2 μm (Fig. 5).

Table 1
Soil porosity, bulk density and mean weight diameter of water-stable aggregates and physical stability index for three cover types at 0–10 cm soil depth (means ± SD, n = 3).

Cover types	$CaCO_3$ ($g\ kg^{-1}$)	Soil pH	Soil specific gravity ($g\ cm^{-3}$)	Soil total porosity (%)	Soil bulk density ($g\ cm^{-3}$)	Mean weight diameter (mm)	Soil physical stability index (%)
Desert land	40.9 ± 1.4b	9.35 ± 0.22a	2.66 ± 0.03a	39.63 ± 0.19b	1.57 ± 0.02a	0.25 ± 0.00d	20.63 ± 1.10b
Shrub land	39.5 ± 1.3b	8.11 ± 0.01b	2.67 ± 0.14a	40.19 ± 0.15b	1.52 ± 0.01a	0.27 ± 0.01c	9.50 ± 2.75c
Poplar land	54.8 ± 8.9a	8.40 ± 0.07b	2.63 ± 0.01a	48.20 ± 1.25a	1.28 ± 0.08b	0.43 ± 0.01b	25.50 ± 1.90a
Pine land	62.7 ± 10.6a	8.21 ± 0.24b	2.61 ± 0.04a	47.34 ± 1.77a	1.28 ± 0.02b	0.45 ± 0.01a	16.47 ± 1.09b

Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation. Values within a column followed by the same letter do not differ significantly at $P \leq 0.05$.

Table 2
Soil water-stable aggregate size classes (%) and particle-size for different cover types in the 0–10 cm soil layer (means ± SD, $n = 3$).

Cover types	Macroaggregates (> 0.5 mm)				Microaggregates	Particle size distribution (%)				
	> 2 mm	1–2 mm	0.5–1 mm	Sum	< 0.5 mm	1000–250 μm	250–100 μm	100–50 μm	50–2 μm	< 2 μm
Desert land	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c	0.0 0 ± 0.00d	100.00 ± 0.00a	24.50 ± 3.15a	66.09 ± 2.73c	8.92 ± 0.93c	0.49 ± 0.09d	0.00 ± 0.00a
Shrub land	0.00 ± 0.00c	0.28 ± 0.06c	4.38 ± 0.52b	4.66 ± 0.56c	95.34 ± 0.56b	21.47 ± 1.40a	67.13 ± 1.07bc	9.91 ± 1.07c	1.49 ± 0.19c	0.00 ± 0.00a
Poplar land	6.63 ± 0.51a	3.71 ± 0.44b	3.74 ± 0.68b	14.08 ± 0.94b	85.92 ± 0.94c	3.17 ± 0.39b	69.84 ± 0.54ab	23.00 ± 1.18a	3.99 ± 0.41b	0.00 ± 0.00a
Pine land	5.56 ± 0.38b	5.23 ± 0.36a	7.13 ± 0.42a	17.91 ± 0.48a	82.09 ± 0.48d	2.96 ± 0.356b	71.47 ± 0.99a	20.26 ± 0.20b	5.31 ± 0.28a	0.00 ± 0.00a

Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation. Values within a column followed by the same letter do not differ significantly at $P \le 0.05$.

The conversion of desert land to poplar and pine land significantly increased the SOC content of water-stable aggregates in all classes on desert land, though poplar and pine land exhibited irregular behaviour (Table 4). In the < 0.5 mm aggregate class, the desert land had on organic carbon content of 0.58 g kg^{-1}, which increased by 34%, 600% and 337% in shrub, poplar and pine land, respectively.

The contribution of the organic carbon in water-stable aggregates to total SOC is shown in Table 5. In the desert land, the contribution of organic carbon to total SOC in the different aggregate classes was 0, apart from the < 0.5 mm class which was 100% because the soil material was accumulated under wet-sieving. Contributions varied for the > 2, 2–1, 1–0.5 and < 0.5 mm aggregates classes with respective values of 0, 1.5, 5.6 and 92% for shrub land, 15.8, 11.1, 14.1 and 59% for poplar land, and 13.0, 22.6, 23.0 and 41.4% for pine land. Poplar land and pine land depicts a higher ability of afforestation treatments to sorting aggregates classes, organic carbon content and structural stability.

3.3. Soil microbial biomass C (MBC), nitrogen (MBN) and enzyme activities

Microbial biomass carbon increased sharply from 47.5 mg kg^{-1} in desert land areas to 60.1 mg kg^{-1} in the shrub land, 87.5 mg kg^{-1} in the poplar land, and 97.9 mg kg^{-1} in the pine land (Table 6). Microbial biomass nitrogen followed a similar trend increasing from 11.2 mg kg^{-1} in desert land areas to 20.2 mg kg^{-1} in the pine land. The poplar and pine land areas had significantly lower ratios of MBC/SOC and MBN/SOC than the other land types (Table 6). All enzymatic activities increased significantly from desert land to pine land (Table 6)—urease by 672%, β-glucosidase by 540% and phosphatase by 1294%—verifying the positive effect of treatments on soil biochemical properties. In addition, MBC, MBN and soil enzymes were positively correlated with water-holding capacity (WHC) (Fig. 6).

4. Discussion

Water shortages have become a major obstacle for revegetated covers and plant production, which tend to rely heavily on irrigation in oases (Kang et al., 2004; Shen et al., 2014). The study showed that the conversion of native desert land to *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations significantly increased soil water-holding capacity (Fig. 3) and water-stable macroaggregation (> 0.5 mm). The soil water-holding capability had a significant positive correlation with water-stable macroaggregates (Liu et al., 2013). Rawls et al. (2003) reported that the increasing organic matter content over time increased water retention in sandy soil. In our study, the conversion of native desert land areas into *Populus simonii* Carr. And *Pinus sylvestris* var. *mongolica* Litv.plantations increased SOC contents from 0.58 to 5.89 and 5.06 g kg^{-1}, respectively. Increasing the soil fine particle content is important for improving the water-holding capacity of sandy soil (Wilhelmi and Wilhite, 2002). In our study, the fine soil fractions significantly increased when the native desert land areas were converted into *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations. In addition, total soil porosity increased by 20% while bulk density decreased by 20% thus improving soil water retention. Our results agree with those of Abel et al. (2013), who suggested that the addition of biochar reduces bulk density, and increases total pore volume and water reserves at permanent wilting point in sandy soil. In contrast, the soil water-holding capacity in the *Haloxylon ammodendron* plantation had not increased after 21 years, which was largely due to low soil macroaggregation, SOC content and fine particle content. The poplar and pine land areas not only improved soil water-holding capacity but provided more available water for plant growth when compared to the native desert land areas and *Haloxylon ammodendron* plantation.

Soil fine fractions significantly increased when desertified sandy

Table 3
Soil nutrients for different cover types at 0–10 cm soil depth (means ± SD, n = 3).

Cover types	SOC (g kg^{-1})	TN (g kg^{-1})	MN (mg kg^{-1})	TP (g kg^{-1})	AP (mg kg^{-1})
Desert land	0.58 ± 0.10b	0.09 ± 0.02b	5.4 ± 0.7b	0.25 ± 0.04c	1.0 ± 0.1b
Shrub land	0.80 ± 0.16b	0.11 ± 0.01b	7.2 ± 0.6a	0.25 ± 0.04c	1.3 ± 0.3b
Poplar land	5.89 ± 0.60a	0.48 ± 0.05a	7.3 ± 0.8a	0.35 ± 0.02b	1.4 ± 0.4b
Pine land	5.06 ± 0.26a	0.46 ± 0.04a	8.1 ± 0.6a	0.42 ± 0.03a	13.5 ± 3.7a

SOC: soil organic C; TN: total nitrogen; MN: mineral nitrogen (sum of NH_4-N and NO_3-N); TP: total phosphorus; AP: available phosphorus. Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation. Values within a column followed by the same letter do not differ significantly at $P \leq 0.05$.

lands were converted into artificial sand-fixing shrub and forage lands (Su et al., 2005, 2007; Dong et al., 2016). In our study, the conversion of native desert land to *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations significantly increased the soil fine particle content (< 100 μm). When compared with the native desert land, the fine particle contents (100–50 and 50–2 μm aggregate classes) in the *Populus simonii* Carr., *Pinus sylvestris* var. *mongolica* Litv.and *Haloxylon ammodendron* plantations had increased by 1.9, 1.7and 0.2 times, respectively. In this geographical region, the fraction of clay particles < 2 μm is very low (Su et al., 2007); no clay particles < 2 μm were detected in our study. The injection volume of particle suspension was only 1–2 mm when soil particles were detected by a Particle Size Analyzer; the low injected sample volume may limit the detection of clay particles < 2 μm. The high fine particle contents in the *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations benefited from the surface organic litter which reduced the risk of wind erosion. The silt-laden irrigation water is important for increasing soil fine particles in the *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations (e.g., the input of fine particles was approximately 2 ton ha^{-1} y^{-1}). The bare soil was highly exposed in *Haloxylon ammodendron* plantation, which increased the risk of wind erosion.

These results are important because the increased fine fractions not only enhanced the formation of a stable soil crumb thus stabilizing the sandy surface (Li et al., 2002), but accumulated organic C in the soil. A significant linear regression between SOC and fine particles indicates positive associations of these important soil constituents (Su et al., 2007). Zhao et al. (2009) reported on the capacity of soil to reserve C and N via its association with silt and clay particles (< 50 μm). In this study, the 250–100 and 100–50 μm particle contents played an important role in SOC and TN accumulation, and with soil development in artificial plantations of desert–oasis areas. As mentioned above, the conversion of native desert land areas to *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations increased the SOC content significantly. This indicates that the soil fine particles (< 250 μm) are important for the sequestrations of SOC in these plantations.

The conversion of desert land to a *Haloxylon ammodendron* plantation reduced the soil physical stability index from 20.63% to 9.50%. An artificial *Haloxylon ammodendron* plantation may degenerate after about 30 years (Tao, 2002; Wang and Ma, 2003) and be unable to withstand wind erosion due to its low soil physical stability index. In contrast, the *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations had significantly higher soil physical stability indices than those observed in the *Haloxylon ammodendron* plantation, indicating stronger resistance to wind erosion.

Soil microbial biomass is an ecological indicator sensitive to changes in soil nutrients due to land management strategies (Foote et al., 2015; Spohn et al., 2016). In this study, the *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations had significantly higher soil MBC than the native desert land areas and the *Haloxylon ammodendron* plantation, substantiating their ability to improve soil microbial activity on desert and shrub land at the oasis edge. The reduction in MBC/SOC is an effective measure of the efficiency of organic

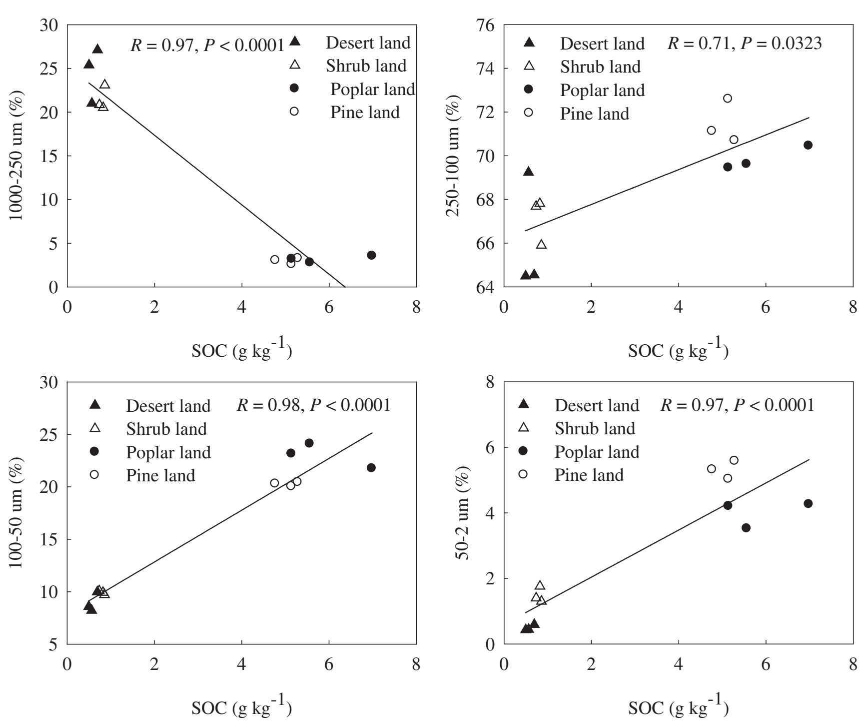

Fig. 4. Relationship between soil particle-size content and soil organic C (SOC). Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation.

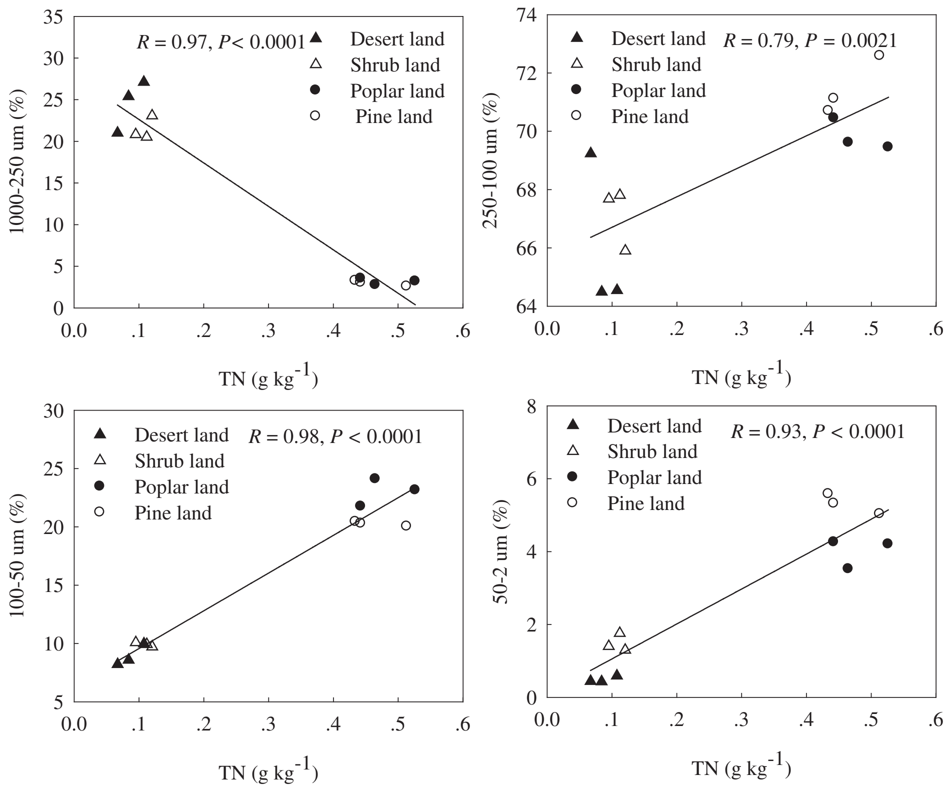

Fig. 5. Relationship between soil particle-size content and soil total N (TN). Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation.

Table 4
Organic carbon content in water stable aggregates of different particle sizes for three cover types at 0–10 cm soil depth (means ± SD, n = 3).

Cover types	Organic carbon content (g kg^{-1})			
	> 2 mm	2–1 mm	1–0.5 mm	< 0.5 mm
Desert land	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00c	0.58 ± 0.10c
Shrub land	0.00 ± 0.00b	4.46 ± 0.74b	1.03 ± 0.04c	0.78 ± 0.07c
Poplar land	13.86 ± 1.56a	17.44 ± 1.48a	22.03 ± 4.90a	4.06 ± 0.86a
Pine land	11.78 ± 2.76a	22.24 ± 5.24a	16.42 ± 2.11b	2.54 ± 0.25b

Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation. Values within a column followed by the same letter do not differ significantly at $P \le 0.05$.

Table 5
Contributing rates of organic carbon of water stable aggregates in total soil organic carbon (%) in three cover types at 0–10 cm soil depth (means ± SD, n = 3).

Cover types	Macroaggregates (> 0.5 mm)				Microaggregates
	> 2 mm	1–2 mm	0.5–1 mm	Sum	< 0.5 mm
Desert land	0.00 ± 0.0b	0.0 ± 0.0c	0.0 ± 0.0d	0.0 ± 0.0c	100.0 ± 0.0a
Shrub land	0.00 ± 0.0b	1.5 ± 0.2c	5.6 ± 0.9c	7.1 ± 1.06c	92.9 ± 1.0a
Poplar land	15.8 ± 2.5a	11.1 ± 1.8b	14.1 ± 5.6b	41.0 ± 5.6b	59.0 ± 5.6b
Pine land	13.0 ± 3.3a	22.6 ± 3.2a	23.0 ± 1.8a	58.6 ± 6.1a	41.4 ± 6.1c

Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation. Values within a column followed by the same letter do not differ significantly at $P \le 0.05$.

carbon preservation, as well as soil carbon losses during SOM decomposition (Foote et al., 2015; Dong et al., 2016). In fact, a high MBC/SOC ratio indicates that the organic matter decomposed quickly, which would be harmful to the soil quality (Jiang et al., 2006). This suggests that soils of desert areas and the *Haloxylon ammodendron* plantation had limited carbon sequestration potential due to the high MBC/SOC ratio.

Soil enzymes are important components for soil biochemical functions since they are the driving force in nutrient cycling, and are commonly suggested to be indicators for detecting changes or disturbances in a soil ecosystem (Wallenius et al., 2011; Piotrowska and Wilczewski, 2012; Wahsha et al., 2017). The *Pinus sylvestris* var. *mongolica* Litv. plantation had the highest urease, β-glucosidase and phosphatase activities of the four land use types. The improved water-holding capacity in the *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations may have enhanced microbial biomass activity which would increase soil enzyme activity. In fact, the significant positive correlations (P < 0.0001) found between MBC, MBN, and soil enzyme activities, and soil water content (Fig. 6), indicate that stable vegetation and irrigation are paramount in promoting soil microbial activities and nutrient cyclingat the margins of the oases.

Table 6
Soil microbial biomass C and N contents, and enzyme activities for three cover types at 0–10 cm soil depth (means ± SD, n = 3).

Cover types	MBC (mg kg^{-1})	MBN (mg kg^{-1})	MBC/SOC (%)	MBN/TN (%)	Ure (mg NH_4^+-N kg^{-1} h^{-1})	Glu (mg pNP kg^{-1} h^{-1})	Pho (mg pNP kg^{-1} h^{-1})
Desert land	47.5 ± 3.2c	11.2 ± 1.7b	8.2 ± 0.9a	12.8 ± 1.2a	2.2 ± 0.2c	0.5 ± 0.1d	11.4 ± 0.8c
Shrub land	60.1 ± 8.0b	12.5 ± 1.6b	7.6 ± 1.1a	11.4 ± 0.1b	5.1 ± 0.5b	1.2 ± 0.1c	19.7 ± 2.9c
Poplar land	87.5b ± 4.9a	17.7 ± 2.6a	1.5 ± 0.1b	3.7 ± 0.7c	6.5 ± 0.5b	2.1 ± 0.5b	88.6 ± 12.4b
Pine land	97.9 ± 6.0a	20.2 ± 0.8a	1.9 ± 0.3b	4.4 ± 0.5c	17.0 ± 2.3a	3.2 ± 0.2a	159.0 ± 19.7a

MBC: soil microbial biomass C; MBN: soil microbial biomass N; MBC/SOC: ratio of MBC to soil organic carbon (SOC); MBN/TN: ratio of MBN to soil total nitrogen (TN); Ure: urease; Glu: β-glucosidase; Pho: alkaline phosphatase. Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation. Values within a column followed by the same letter do not differ significantly at $P \leq 0.05$

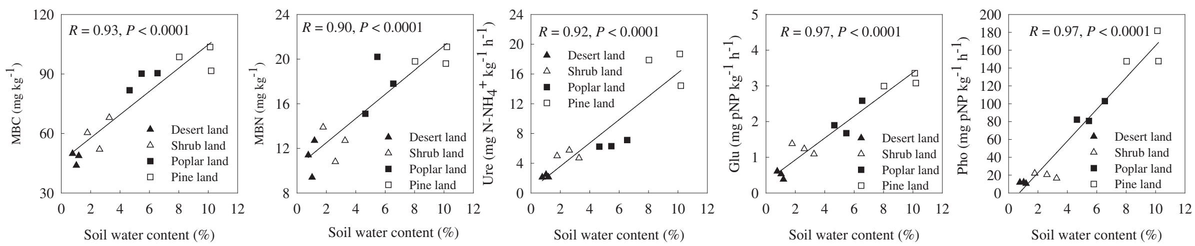

Fig. 6. Relationship between soil water content and soil microbial activity in the 0–10 cm soil layer. MBC: soil microbial biomass C; MBN: soil microbial biomass N; Ure: urease; Glu: β-glucosidase; Pho: alkaline phosphatase. Desert land: native desert land; Shrub land: *Haloxylon ammodendron* plantation; Poplar land: *Populus simonii* Carr. plantation; Pine land: *Pinus sylvestris* var. *mongolica* Litv. plantation.

5. Conclusions

The establishment of the *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. plantations significantly improved the soil physical, chemical, and microbial properties. However, irrigation input is required in these plantations. Water resources are extremely scarce in this region, with insufficient water to establish a large area of *Populus simonii* Carr. or *Pinus sylvestris* var. *mongolica* Litv. The establishment of a *Haloxylon ammodendron* plantation did not require irrigation input but had no significant improvement in soil physical or chemical properties. In addition, the *Haloxylon ammodendron* plantation may degenerate after 30 years due to the higher vulnerability to wind erosion. Considering the ecological benefits and irrigation inputs, we do not recommend a single or large area planted with *Haloxylon ammodendron*, *Populus simonii* Carr. and *Pinus sylvestris* var. *mongolica* Litv. As complex forest systems, these plantations should be designed and established in desert–oasis areas with consideration to costs and benefits.

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