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ORIGINAL ARTICLE

Ecological benefit of different revegetated covers in the middle of Hexi corridor, northwestern China

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Abstract Desertification is one of the major obstacles to the development and utilization of oases in arid and semiarid regions of China. Revegetation of oases is an effective means of protecting oases from sand invasion (the main cause of desertification) and enhancing the ecological stability of oasis. In order to assess the effects of revegetated plant communities, 21-year-old *Haloxylon ammodendron* shrubland (Shrubland), 28-year-old *Populus simonii* Carr. land (Poplar land) and 33-year-old *Pinus sylvestris var. mongolica Litv* land (Pine land) were selected as study objects. The topsoil properties and material changes were monitored, taking the native desert shrubland (Desert land) as a basis. The results show that different revegetated covers can lead to significant changes in soil organic carbon (SOC), as well as soil inorganic carbon (SIC) and total nitrogen (TN). SOC, SIC and TN content can be significantly increased from 0.56, 0.06, and 4.93 g kg^{-1} in Desert land to 5.85, 0.47, and 7.26 g kg^{-1} in revegetated covers, respectively. Different revegetated covers can also change plant species richness, productivity, and plant C and N content. It is also found that Poplar land and Pine land were more effective than Shrubland in improving soil fertility and plant productivity. In addition, this study confirmed that the establishment of revegetated covers can reduce the rates of wind erosion on soil surface up to 74.83–94.15 % compared to natural desert shrubland. The atmospheric dust fall was also affected significantly by the different covers. The results show that there are significant advantageous changes in soil characteristics and vegetation parameters, as well as the reduction of soil erosion and retention of atmospheric dust fall in the revegetated covers and habitat conditions. The results suggested the appreciable ecological effects of the different revegetation covers on soil development and restoration process of plant communities. Additionally, some rational management practices could also cause positive influence on the quality of soil, e.g. irrigation. Understanding these ecological effects may be helpful for designing and establishing protective forest systems in desert–oasis areas.

Keywords Carbon · Desertification · Ecological effect · Nitrogen · Revegetation

Introduction

Desertification has become one of the most serious environmental and socioeconomic problems. China is suffering the most from desertification, especially in the northwest, where desertification is rapidly increasing (Zhu and Chen 1994; Zhao et al. 2008; Wang et al. 2013; Cheng et al. 2014). Desertification can cause deterioration of soil and reduce the productivity of land (Zhu and Chen 1994). It hinders the sustainable development of oases, and seriously affects the livelihood and environment of people in the neighborhood (Su et al. 2007a; Wang et al. 2013). In order to reduce the desertification and its impacts on the natural environment in these regions, local governments have implemented a variety of measures to restore vegetation on desertified land

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since the middle of 1970s (Zhu and Chen 1994). These measures include the control of stocking rates and adjustment of grazing regimes, the enclosure of desertified grassland and use of various artificial sand arresters (e.g. wheat and maize straw checkerboards), as well as planting of indigenous trees (e.g. poplar), shrubs, and semi-shrubs (e.g. *Artemisia halodendron*) on severely desertified areas (Zhu and Chen 1994; Li et al. 2002; Stokes et al. 2010). Over the past decades, the control of desertification has become the primary strategy to safeguard the ecological security of oasis ecosystems, and some progress has been made, for example, the protection system of Pingchuan oasis to control the development of desertification and preventing the movement of dune in the oasis–desert ecotone in Hexi Corridor (Zhu and Chen 1994; Zhao et al. 2008; Su et al. 2007a; Li et al. 2009; Cheng et al. 2014).

Many researchers (Dong et al. 1983; Stockton and Gillette 1990; Su et al. 2007a; Zhao et al. 2008) have investigated the effect of revegetation in reducing wind speed and soil erosion in sandy lands, and several studies have focused on soil microhabitat improvement by trees through addition of organic litter to surface soils in temperate and boreal areas (France et al. 1989; Paul 2001; Su et al. 2010; Li and Shao 2014). There are also some studies about the effects of sand-retaining vegetation on increasing vegetation cover, species richness and biomass (Moreno and Gallardo 2002; Li et al. 2003a, 2013a, b; Schilling et al. 2014). However, further field studies of the integrated ecological roles of forest in soil amelioration and restoration of plant community, soil erosion reduction and atmospheric dust retention are still needed. In particular, no study has focused on the effects of different revegetated plant communities in desert–oasis ecotone from an interdisciplinary ecological perspective.

In this study, a hypothesis is proposed that revegetated plant communities have a significant ecological function, which can change the soil quality, decline wind erosion and increase the vegetation species richness, and then be favorable to the restoration of vegetation and desertification control. Furthermore, it is assume that the effects would be more obvious with the increase in age of vegetation, along with the different tree species. Therefore, the objectives of this study are to investigate: (1) the effects of different revegetated plant communities on soil physicochemical properties, vegetation restoration, surface wind erosion, and atmospheric dust deposition in this region; (2) the relationship between the effects of different covers. To understand the ecological effects of revegetated plant communities on soil properties it is essential to understand the relationship between afforestation and sustainable woodland management, to provide hard data for the establishment of sustainable shelterbelts to combat desertification not only in this place, but also in other dry lands.

Materials and methods

Experimental site

The Experimental site is located at Pingchuan town, the southern edge of Badan Jaran Desert in the middle of Hexi Corridor in Gansu province (39°21′N, 100°08′E; 1380 m a.s.l.), see Fig. 1. Pingchuan town is a narrow stretch of oasis with large shifting sandy dunes. This region has a typical desert climate, hot in summer, cold in winter, dry and windy in spring. The mean annual precipitation is 117 mm, and the annual mean air temperature is 7.6 °C, with a recorded maximum of 39.1 °C in July and a minimum of 27 °C in February. The annual mean open-pan-evaporation is around 2390 mm. The annual mean wind velocity is 3.2 $m\ s^{-1}$, and the prevailing wind direction is from the northwest. Gales with wind velocities greater than 17 $m\ s^{-1}$ occur on 15 or more days per year (Su et al. 2007b). The groundwater table ranges from 4 to 10 m. The main soil types are Aripsamment and Calciorthids with a loose structure and very low organic matter content, which are very susceptible to wind erosion (Chen et al. 1998). The local natural vegetation at the edge of oasis is composed primarily of *Calligonum mongolicum* Turcz., *Haloxylon ammodendron* (C.A.Mey.) Bge., *Calligonum gobicum* (Bge) A.Los., *Caragana korshinskii* Kom., *Hedysarum scoparium* Fisch. et Mey., and some small subshrubs such as *Nitraria sphaerocarpa* Maxim., and *Reaumuria soongorica* (Pall.) Maxim. The staple crops in the farmland are spring wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and cotton (*Gossypium hirsutum* L.).

Experimental plan

In 2009, native desert shrubland was selected as control area. Three typical revegetated areas, which were established separately in 1976, 1981 and 1988 by Linze Inland River Basin Research Station, Chinese Ecosystem Research Network (CERN), were selected as study areas, respectively. All the revegetated lands are developed from the native desert shrubland. Therefore, the experimental covers included one control (Desert land), one 21-year-old *H. ammodendron* shrubland (Shrubland), one 28-year-old poplar land (Poplar land), and one 33-year-old pinus land (Pine land) (Table 1).

Measurement of soil and vegetation properties

The soil properties were measured in mid-August. Within each site, three sample strips (which were about 300 m long) were selected with at least 1000 m between them. Within each strip, three 20 m × 20 m squares with 100 m

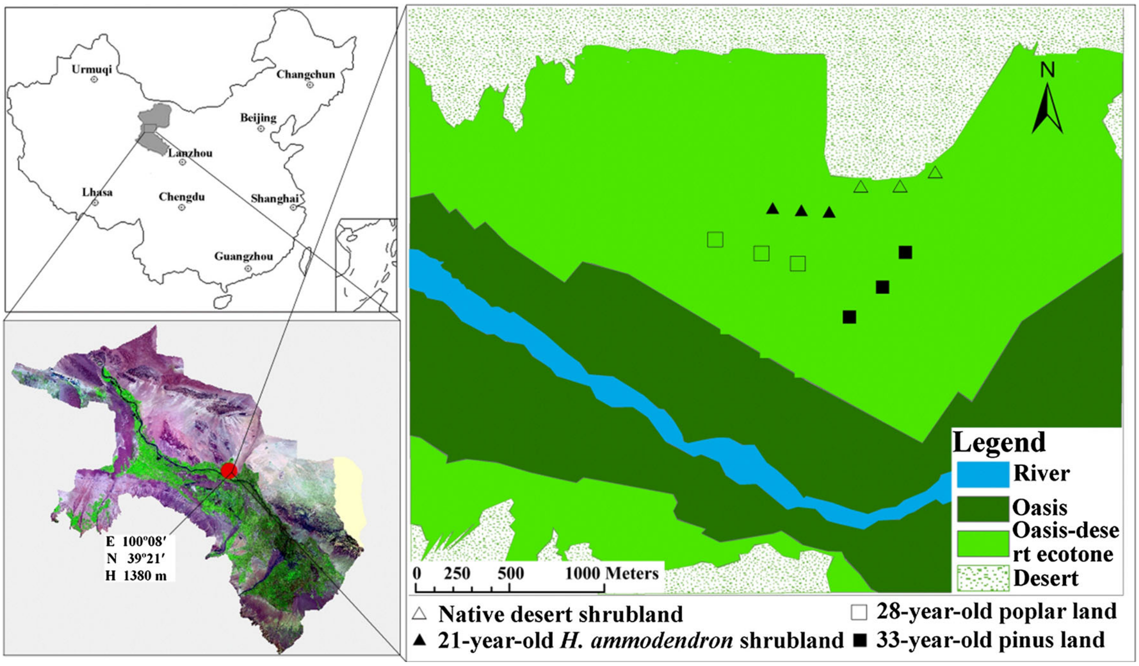

Fig. 1 Map showing the location of the study area in the middle of Hexi Corridor Region, Northwest China: **a** China, **b** the middle of Hexi corridor, **c** the schematic outlines of the three sampling sites in each cover

Table 1 Characteristics and management of different study covers

Treatments	History and characteristics	Management
Desert land	Natural desert shrubland with dominant species of *N. sphaerocarpa* Maxim and *Calligonum gobicum* (Bge) A.Los., and several herbs such as *A. squarrosum* (L.) Moq., *B. hyssopifola* (Pall.) O. Kuntze and *Salsola Colliaris* Pall	Natural desert shrubland
Shrubland	In 1988, 1 × 1 m straw checkerboards were built on sand dunes and *H. ammodendron* seedlings were planted within checkerboards; during the 21 years, nearly half of the individuals naturally died. The dominant species in Shrubland were *Haloxylon ammodendron* (C.A.Mey.)Bge., and several herbs such as *A. squarrosum* (L.) Moq., *Halogeton arachnoideus* Moq., and *Pugionium cornutum* (Linnaeus) Gaertn	Irrigated 3–5 times at the first year of planting seedling, the amount of irrigation is about 20 m^3 ha^{-1} after seedlings survived, no irrigation and fertilization
Poplar land	In 1981, poplar seedlings were planted on dunes randomly, the row spacing was 2–4 m; in 2009, the average diameter at breast height (BDH) of individuals was 16 cm. The dominant species in Poplar land were *Populus simonii* Carr., and several herbs such as *Setaria viridis*, *Eragrostis pilosa, B. hyssopifola* (Pall.) O. Kuntze and *Sonchus oleraceus* Linn	Forbidding pasturing for 5 years, no fertilization and irrigation 2–3 times each year; the amount of irrigation is about 10,000 m^3 ha^{-1}
Pine land	In 1976, *Pinus sylvestris var. mongolica Litv* seedlings were planted on dunes randomly, the row spacing was 2–3 m; in 2009, the average diameter at breast height (BDH) of individuals was 13 cm. Plant community at the Pine land was dominated by *Pinus sylvestris var. mongolica Litv*, *B. hyssopifola* (Pall.) O. Kuntze, *Cleistogenes squarrosa*, *Artemisia scoparia and Agropyron cristatum* (Linn.) Gaertn	Forbidding pasturing for 5 years, no fertilized and irrigated 3 times each year; the amount of irrigation is about 12,000 m^3 ha^{-1}

between each other were selected as soil sampling plots. Five soil samples at 0–0.2 m layer, evenly distributed 5 m apart, were taken and pooled into a composite sample within each quadrat. Soil bulk density measurements were made from un-disturbed soil samples taken at each site and depth. After drying each composite sample was split into two subsamples. One subsample was sieved to <2 mm for the analysis of soil texture and the other was sieved to <0.1 mm to determinate the soil organic C (SOC), soil inorganic C (SIC), and total N (TN).

The soil texture was determined by dry sieve method using 0.05, 0.25, and 2.0 mm mesh sieves. SOC was determined by dichromate oxidation of Walkley–Black (Nelson and Sommers 1982); TN was measured using the micro-Kjeldahl procedure (Su et al. 2007b); the content of carbonate was expressed as $CaCO_3$, which was determined by the CO_2 volumetric method.

The vegetation was surveyed using the quadrat method (quadrat size 1 m × 1 m) in late August 2010 (Zhao et al. 2003; Li et al. 2009). Within each soil sampling plot, nine 1 m × 1 m squares evenly distributed 5 m apart were selected. Some of these squares were beneath the shrubs or tree canopies, and the others were between them. The species composition and frequency of each species were determined using a round area (1 m in diameter) and 9 replicates at each site. The plant cover was estimated by the point frame method (Mueller-Dombois and Ellenberg 1974), and plant density was determined by counting the number of plants in each square. The aboveground living plant biomass was determined by clipping off at ground level, oven-drying at 75 °C for 48 h and weighing. The belowground biomass was collected by five replica soil cores, 0.1 m in diameter and 0.3 m in depth after the aboveground biomass had been measured. The soil cores were washed with a gentle water spray over a fine mesh screen until roots were free of soil. The roots were dried at 75 °C for 48 h and then weighed. The plant litter mass was measured using 1 m × 1 m square harvesting method in the early September 2010. Subsamples from the plant litter, above and belowground biomass were analyzed for SOC and TN contents.

Measurements of sand transport and atmospheric dust deposition

For each site, the transport of sand by wind was measured using fixed traps method over an erosive period from April to May in 2009 with 5 traps with a small modification of the method used by the predecessor (Li et al. 2004, 2009). The traps are cylindrical enamel containers, each with a diameter of 0.25 m and height of 0.15 m. The trap was put in a bracket with the up edge 10 mm above soil surface. After several days, sediment in the traps was sampled. Some small gravel covering the entire base of the trap was put into the traps to avoid removal of dry sediment. The collected sediment was weighted and sand transport rate was expressed as collected sediment per unit area per day (g m^{-2} day^{-1}). Using the data collected, the wind erosion rate was calculated. Airborne dust deposition was measured over the spring, summer and autumn using three dust traps that mounted at the same height on the concrete pole (2 m), located at a distance of approximately 10 m from the erosion observation site. The size of the traps is the same as those used for the windblown sediment collection. The dust deposited in the traps was collected after about 10-day intervals in spring, summer and autumn. The rate of dust deposition was expressed as the amount of the deposited dust per unit area per day (g m^{-2} day^{-1}) (Li et al. 2004).

Data analysis

Statistical analysis was done using SPSS 10.0 (ANOVA with LSD and regression analysis) at a $P < 0.05$ significance level.

Results

Effects of revegetated covers on soil properties

The highest content coarse sand was of course in the Shrubland, followed by the Desert land, Poplar land, and Pine land. The fine sand content in the Shrubland was much lower than that in other covers. The contents of silt and clay (<0.05 mm) were significantly higher in the Poplar land and Pine land than in the other two covers (Table 2). The soil bulk density was significantly lower in the Poplar land and Pine land. Regression analyses indicated significant positive associations could be drawn. One is between the soil bulk density and SOC and the other is between soil bulk density and total N, see Fig. 2a and b.

Soil chemical properties also exhibited significant differences in SOC and TN among the four covers (Table 2). The SOC contents in the Poplar land and Pine land were approximately 9 times greater than that of the Desert land and Shrubland. The highest SOC level was in Poplar land, followed in decreasing sequence by Pine land, Desert land, and Shrubland. A power regression indicated a close relation between SOC and silt and clay contents. Likewise, the TN had a significant positive relationship on silt and clay contents (Fig. 2c, d). The SOC content was also correlated positively with the above and belowground biomass (Fig. 2e, f). For example, the above and belowground biomass in Poplar land was 18,890 ± 6104 and 5312 ± 1716 g m^{-2}, respectively, which was about 276 and 246 times greater than in Desert land. The same trend was obtained, in that the content of SOC in Poplar land was about 10 times greater than in Desert land.

SIC was also found to increase by 34.3 and 47.26 % in the Poplar land and Pine land, compared to the Desert land (Table 2). The smallest change of SIC occurred in the

Table 2 Soil aggregate distribution and contents of C and N in different revegetated covers in the 0-0.2 m soil layer

Treatments	Coarse sand (%) 2–0.25 mm	Fine sand (%) 0.05–0.25 mm	Silt + clay (%) <0.05 mm	Bulk density 10^3 kg m^{-3}	SOC g kg^{-1}	TN g kg^{-1}	SIC g kg^{-1}	C/N ratio
Desert land	15.64 ± 1.70b	83.77 ± 1.68a	0.59 ± 0.09c	1.58 ± 0.01a	0.56 ± 0.02b	0.06 ± 0.001c	4.93 ± 0.31b	9.83 ± 0.18b
Shrubland	24.11 ± 1.42a	74.76 ± 1.38b	1.13 ± 0.09c	1.55 ± 0.003a	0.55 ± 0.02b	0.09 ± 0.01c	5.00 ± 0.33b	6.17 ± 0.57c
Poplar land	10.75 ± 0.66c	84.53 ± 0.32a	4.72 ± 0.35b	1.41 ± 0.02b	5.85 ± 0.20a	0.47 ± 0.07a	6.62 ± 0.63a	12.76 ± 1.40ab
Pine land	9.95 ± 1.05c	83.24 ± 0.41a	6.81 ± 0.99a	1.31 ± 0.01cb	5.34 ± 0.77a	0.37 ± 0.07ab	7.26 ± 0.80a	15.23 ± 0.67a

Values are mean ± SD. Values with different letters within a variable indicate significant differences at $P < 0.05$

Shrubland. When SOC and SIC were transformed to mass per hectare, total soil C in the Desert land, Shrubland, Poplar land, and Pine land was 16.9 ± 1.3, 17.0 ± 1.2, 33.8 ± 2.3, and 34.8 ± 2.6 t ha^{-1}, respectively. It can be seen that the total soil C in Poplar land and Pine land was significantly higher than that in the Desert land and Shrubland (Fig. 3).

Effects of revegetated covers on plant communities

The vegetation data indicated greater change in the structure and composition of the plant communities in the three covers compared to the Desert land (Table 3). This can be seen from the following data. First, only 6 species were recorded at the Desert land, whereas the corresponding values were 8, 13, and 16 at the Shrubland, Poplar land, and Pine land. The Pine land had the greatest vegetation species richness, of which the main herbs were Gramineae and Chenopodiaceae. Second, vegetation coverage showed a dramatic increase in shelter forest lands, which was 85.0, 66.4, and 77.8 % in the Shrubland, Poplar land, and Pine land, respectively, but only 39.1 % in the Desert land. Third, the above and belowground biomass and litter production were all significantly greater in the Poplar land and Pine land than in Desert land and Shrubland (Table 3). The aboveground biomass was 68.5 ± 19.5, 845.3 ± 224.9, 18,890 ± 6104 and 14,495 ± 5449 g m^{-2} in the Desert land, Shrubland, Poplar land and Pine land, respectively, which are 12–275 times higher than in Desert land. The belowground biomass was 21.6 ± 5.9 g m^{-2} in the Desert land, 219.0 ± 58.0 g m^{-2} in the Shrubland, 5312 ± 1716 g m^{-2} in the Poplar land, and 2536 ± 953 g m^{-2} in the Pine land, an increase by a factor of 10–245 compared to the Desert land. Plant litter production increased from 21.8 ± 5.8 g m^{-2} in the Desert land to 38.4 ± 15.2 g m^{-2} in the Shrubland, 275.3 ± 51.6 g m^{-2} in the Poplar land and 3377 ± 233 g m^{-2} in the Pine land (Table 3).

Increasing plant biomass leads to a significant increase in C and N stored (Table 4). The aboveground biomass C store increased on an average from 25.5 ± 6.8 g m^{-2} in the Desert land to 300.4 ± 78.0 g m^{-2} in the Shrubland, 8838 ± 2694 g m^{-2} in the Poplar land, and 6959 ± 2616 g m^{-2} in the Pine land. The N store increased from 1.2 ± 0.3 g m^{-2} in the Desert land to 11.1 ± 2.8 g m^{-2} in the Shrubland, 114.1 ± 36.8 g m^{-2} in the Poplar land, and 120.9 ± 45.0 g m^{-2} in the Pine land. For the belowground biomass, C and N stored increased on an average from 8.4 ± 2.1 and 0.3 ± 0.1 g m^{-2} in the Desert land to 87.0 ± 23.1 and 1.1 ± 0.3 g m^{-2} in the Shrubland, 2118 ± 685 and 18.5 ± 6.0 g m^{-2} in the Poplar land, and 1185 ± 446 and 15.6 ± 5.9 g m^{-2} in the Pine land (Table 4). The same trend was observed for plant litter, C

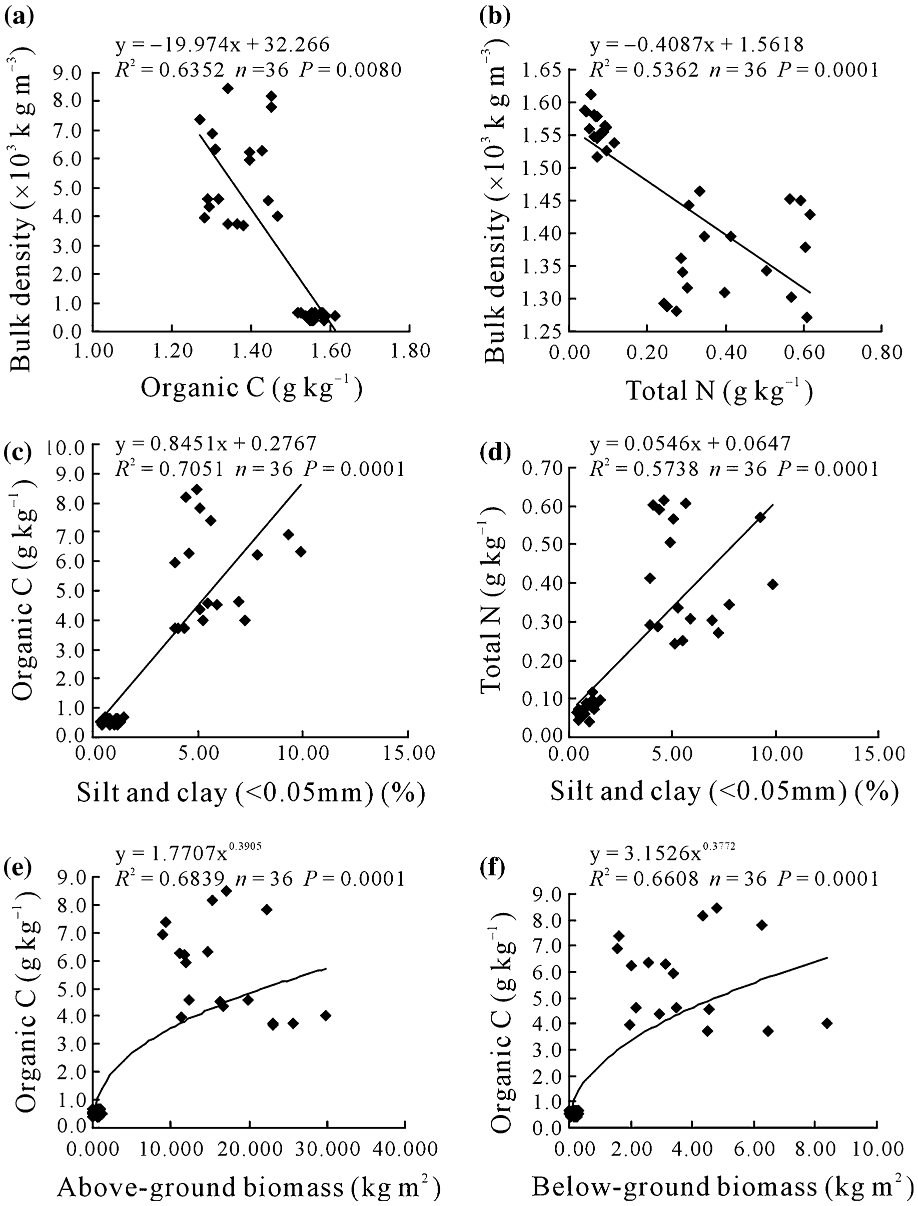

Fig. 2 Linear relationship between SOC and TN with bulk density (**a**, **b**), silt + clay content (**c**, **d**), above, and belowground biomass (**e**, **f**)

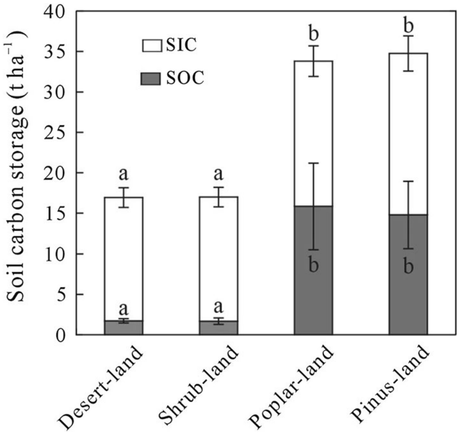

Fig. 3 SOC and SIC storage under different revegetated covers

and N stored increased significantly from 8.2 ± 0.7 and 0.4 ± 0.1 g m^{-2} in the Desert land to 10.6 ± 1.3 and 0.7 ± 0.1 g m^{-2} in the Shrubland, 117.2 ± 2.9 and 3.5 ± 0.2 g m^{-2} in the Poplar land, and 1609 ± 35 and 53.5 ± 1.2 g m^{-2} in the Pine land (Table 4).

Effects of revegetated covers on surface wind erosion and atmospheric dust deposition

The surface soil wind erosion rate decreased sharply with the age of revegetated covers. The average daily erosion rate over the 60 days was 214.7 ± 12.6 g m^{-2} in the Desert land to 54.1 ± 16.7 g m^{-2} in the Shrubland, 28.1 ± 8.3 g m^{-2} in the Poplar land, and

Table 3 Vegetation species richness, coverage, density, and productivity (mean ± SD) in different revegetated covers

Treatments	Vegetation species richness	Vegetation coverage (%)	Density (plants m^{-2})	Aboveground biomass (g m^{-2})	Belowground biomass (g m^{-2})	Plant litter (g m$^{-2)}$
Desert land	6	39.11 ± 9.81c	0.98 ± 0.17a	68.46 ± 19.49b	21.63 ± 5.94c	21.82 ± 5.76c
Shrubland	8	85.00 ± 5.0a	0.21 ± 0.08c	845.25 ± 224.87b	218.96 ± 57.95c	38.37 ± 15.17c
Poplar land	13	66.39 ± 9.61b	0.13 ± 0.03d	18890 ± 6104a	5312 ± 1716a	275.28 ± 51.59b
Pine land	16	77.78 ± 9.22a	0.37 ± 0.14b	14495 ± 5449a	2536 ± 953b	3377 ± 233a

Values are mean ± SD. Values with different letters within a variable indicate significant differences at $P < 0.05$

Table 4 C and N storage in the vegetation of different revegetated covers

Treatments	C storage in aboveground biomass (g m^{-2})	C storage in belowground biomass (g m^{-2})	C storage in plant litter (g m^{-2})	N storage in aboveground biomass (g m^{-2})	N storage in belowground biomass (g m^{-2})	N storage in plant litter (g m^{-2})
Desert land	25.54 ± 6.79b	8.44 ± 2.07c	8.24 ± 0.68c	1.18 ± 0.30b	0.29 ± 0.08c	0.42 ± 0.03c
Shrubland	300.4 ± 78.04b	86.95 ± 23.11c	10.60 ± 1.32c	11.13 ± 2.78b	1.05 ± 0.28c	0.74 ± 0.09c
Poplar land	8838.51 ± 2694.24a	2118.99 ± 685.27a	117.21 ± 2.90b	114.10 ± 36.82a	18.51 ± 6.01a	3.45 ± 0.20b
Pine land	6959.46 ± 2616.18a	1185.11 ± 446.03b	1609.77 ± 34.91a	120.92 ± 45.01a	15.64 ± 5.90b	53.46 ± 1.16a

Values are mean ± SD. Values with different letters within a variable indicate significant differences at $P < 0.05$

12.6 ± 7.5 g m^{-2} in the Pine land. These were significantly lower by 74.8–94.2 % relative to the Desert land (Fig. 4).

There was marked spatial variation in the rate of dust deposition during the measurement period (Fig. 4). The mean daily dust-fall rate was 1.2 ± 0.5 g m^{-2} in Shrubland, and decreased significantly to 0.7 ± 0.2 and 0.6 ± 0.2 g m^{-2} in Poplar land and Pine land. The three measurements are all significantly lower than in Desert land (1.0 ± 0.4 g m^{-2}).

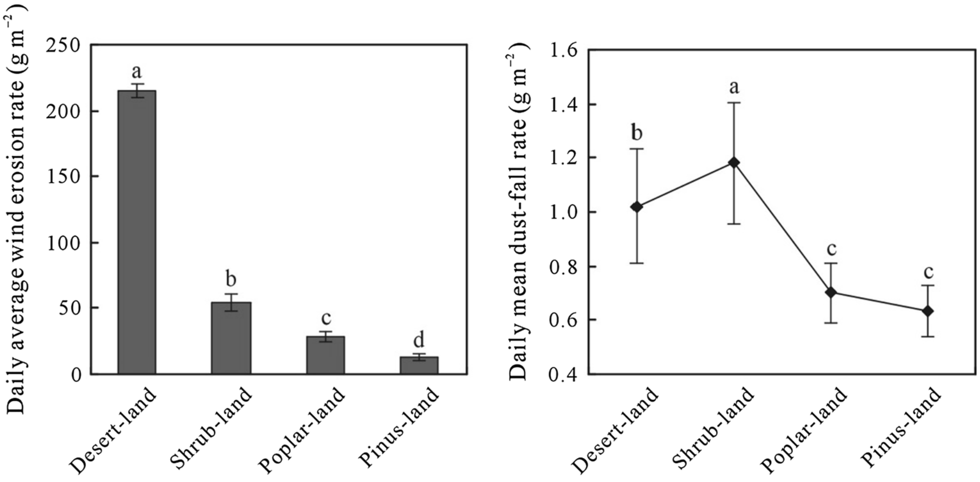

Fig. 4 Daily mean average wind erosion rate and daily dust-fall rates for different observation sites. Means with *different letters* indicate significant differences at $P < 0.05$. *vertical bars* represent ± 1 SD

Discussion

Effects of revegetated cover on soil amelioration

Revegetation has been proved of great importance in soil amelioration. For example, increasing fine particles, intercepting C and N and other nutrients promoted formation and development of topsoil. The top soil texture in Poplar land and Pine land was finer than in the Shrubland and Desert land. Moreover, the soil texture was found to become finer with the increase of the age of revegetation. Such significant textural differences may suggest perceptible ecological effect of the revegetated covers on soil amelioration and reflect the extent of sand land stabilization (Li et al. 2003b; Su et al. 2005).

The soil fertility parameters showed a significant increase in SOC and TN concentrations following the revegetation. This is in accordance with previous research (Lal 2001, 2002, 2004; Su et al. 2005, 2010; Sartori et al. 2007), which considered the rehabilitation of desert land and adoption of appropriate management practices to have significant effect on carbon and N sequestration of soil. In this research, the increases of SOC and TN changed under different revegetated covers. SOC and TN accumulation were lesser in the less managed Shrubland compared with other revegetated covers which were intensively managed. With the age of revegetation, the fertility of the revegetated lands increased more significantly.

In this study, the dramatically higher levels of soil C and N in the revegetated lands could be attributed to not only the natural input, e.g. deposition of soil, but also the input of the artificial management (Li et al. 2003b, 2013a, b; Moreno and Gallardo 2002). The former can affect the level of soil C and N in both direct and indirect ways. Through the analysis, it could be largely caused by two factors. One is the significant reduction of soil erosion loss in these observation sites which may reduce the probability of plant litter dispersal by wind and increase the rate of accumulation of fine particles, compared with the Desert land (Pérez 1992; Li et al. 2003b; Su et al. 2005). Regression analyses revealed that both SOC and TN showed a strong linear relation to silt and clay contents ($R^2 = 0.71$ for SOC and $R^2 = 0.57$ for TN). The other factor is the addition of organic matter in the soils in these observation sites, for example, the irrigation could input many fine materials several times each year. It is worth mentioning that the high levels of soil C and N in the revegetated soil have some relationship to wind erosion and atmospheric dust deposition, which is rich in organic matter (Moreno and Gallardo 2002; Li et al. 2003b). In addition, amount of litter cover soil surface and the development of soil crust were beneficial to formation of topsoil and reducing the wind erosion (Zhao et al. 2010). Hence, we think that the changes of soil organic carbon and soil texture are due to direct and indirect effects of revegetation and irrigation input for maintaining plant normal growth in this region.

Many studies have shown that the increases in SOC levels are directly related to the return of fresh organic material to soil, especially the plantation residues. Therefore, the inclusion of trees and cover crops and the addition of manure and fertilizer linearly increase the SOC levels in a low organic matter soil (Kong et al. 2005; Rasmussen et al. 1980; Cole et al. 1993). Our measurements of vegetation characteristics showed significant increases of litter biomass, above and belowground biomass in the different observation sites than in the Desert land. As indicated by regression analysis, the contents of SOC and TN increased linearly with the amounts of above and belowground biomass (Fig. 2e, f). Such a positive correlation indicates that the rise in SOC level can mainly attributed to the addition of organic C from plant litter and root mass to the soil in these areas. This is consistent with the study of Pérez (1989), Li et al. (2003b, 2013a, b). In addition, there was no significant difference on SOC storage between the Poplar land and Pine land with irrigation management. This result suggests that the tree species had some effect on SOC and TN accumulation in this region. Some researchers had found tree species traits control litter decomposition rates and soil formation, and these may change SOC and TN accumulation, and litter decomposes faster in broadleaf than in coniferous forest (Wardenaar and Sevink 1992; William et al. 2008; Zhang et al. 2008). The SOC storage of a 28-year-old Poplar land was nearly equal to 33-year-old Pine land. The C/N ratios were consistently lower in the Shrubland than that in the other lands and the differences were significant between them in this study (Table 2). This suggested a greater rate of litter decomposition in the Poplar land and Pine land, and deposition of fine particles led to greater C and N accumulation in the revegetated cover lands compared to desert shrubland.

In this study, the contents of soil total carbon, organic carbon (SOC) and inorganic carbon (SIC) content were measured. The results showed that all were increased significantly in the revegetation covers compared with Desert land. A noteworthy question here is that whether the extra carbon stored in the soil is stabile or labile and to be subsequently lost. The stabilization of SOC is believed to be closely related to the sum content of silt and clay in soil. It has been suggested that the carbon sequestration potential of soil is dependent upon its carbon capacity level, which is the maximum amount of organic C associated with clay and silt particles (Su et al. 2007a; Six et al. 2002; Hassink 1997). In this research, the content of silt and clay (<0.05 mm) was significantly higher in the Poplar land and Pine land than that in the Desert land (Table 2), and the regression analyses revealed that both SOC and TN showed a strong linear relation to the silt and clay contents ($R^2 = 0.71$ for SOC and $R^2 = 0.57$ for TN). It seems that a part of carbon has been stored in the form of clay and silt particles in the soil. On the other hand, a large part of carbon is lost in the form of carbon dioxide (CO_2) output from these degraded sandy soils, such as soil respiration (Iqbal et al. 2009; Philippe and Angers 1999; Raich and Schlesinger 1992). In addition, it was also found that inorganic carbon (SIC) in the Poplar land and Pine land was higher than that in the Shrubland and Desert land. This result is not consistent with the previous reported result that forestation causes increase in acidity and that leads to consumption of $CaCO_3$ and decrease inorganic carbon content (Jobbágy and Jackson 2003; Duan et al. 2004). In this research region, the $CaCO_3$ content in the Poplar land (65.9 g/kg) and Pine land (68.6 g/kg) was not significantly lower than that in the Shrubland (60.8 g/kg) and Desert land (61.2 g/kg). It is concluded that the increase in SIC may be related to fine soil particles input from irrigation water (annual mean irrigation input was about 12,000 m^3 ha^{-1}, and three times every year in the Poplar land and Pine land over the past 20 years).

There are many investigations about the impact of water management on the soil quality, such as desertification and soil salinization. Some of these investigations indicated that the scientific and rational water management can conserve and restore the ecosystems, and prevent further desertification, especially in the inland river basin, for example, in Tarim and Heihe River Basion (Xu et al. 2007; Schilling et al. 2014; Gao et al. 2014). On the other hand, some investigations suggested that unreasonable water use could degrade soil quality and increase desertification (Li et al. 2008; You et al. 2011; Liu et al. 2012; Ali et al. 2014), especially the flood irrigation in arid and semi-arid areas (Gui et al. 2011). No significant soil salinization phenomenon was observed in the present experimental area. We are prepared to improve related research on irrigation needs/costs through cooperate with the ecological hydrology scholar.

Effects of revegetated covers on vegetation restoration

The vegetation data indicated that all vegetation parameters measured have been altered considerably since the revegetated covers were established. The changes were characterized by an overall increase in vegetation cover, species richness, above and belowground biomass and litter biomass for the different revegetated cover lands in comparison with the Desert land. From the results, significant ecological effects of the revegetated cover can be observed on vegetation restoration and stabilization. These effects were reflected in the creation of microhabitat with high soil nutrient and water availability. First, the reduction of soil erosion and improvement of soil properties in revegetated covers formed a nutrient-rich, water-retaining substrate of land which provided a more suitable environment for the germination and establishment of herbaceous plant seeds. Second, the colonization of some pioneer plant species on bare mobile sand land made an 'island of fertility', especially for those species that have low nutrient requirements and adapt well to the sandy environment (Schlesinger and Pilmanis 1998; Su et al. 2002, 2005), it might also promote further invasion by other plant species. The key role of these pioneer colonizers might be to stabilize the moving sand dunes and to help wind-dispersed seeds of some plant species remain beneath their canopy, thus enhancing the possibility of their expansion (Li et al. 2002). This in turn encourages the restorative succession of plant community, and eventually leads the establishment of a more species-rich community in the rehabilitated sandy lands. The similar result had been also reported by Schilling et al. (2014) who modeled Environmental flow releases in the Tarim Basin to save the Populus forests along the river and prevent the further desertification (Xu et al. 2007; Schilling et al. 2014).

Rehabilitated vegetation also has important ecological implications for the soil development through increasing the addition of forest litter fall to the soil, and thus improved the properties of land (Jenny 1958; Plotnikoff et al. 2002; Reintam et al. 2002). In addition, the increased cover of vegetation and aboveground biomass may also be effective in improving the quality of soil through interception and increased retention precipitation (Danin and Ganor 1991; Moreno and Gallardo 2002; Li et al. 2003b). In the same way, the improved soil conditions could provide a better environment for the establishment and development of a more diverse community.

Effects of revegetated covers on sand fixation and dust interception

The effects of revegetated covers on sand fixation and atmospheric dust deposition are pronounced, such effects exhibited large variability in different revegetated lands. This variability can be addressed by comparing the differences in the measured sand transport (or dust deposition rates) between the revegetated cover lands and the Desert land.

This study found that the establishment of revegetated covers can affect the surface wind erosion significantly and lead to a dramatic reduction in daily sand transport rate compared to the Desert land, which is consistent with the previous observations from other studies (Wiggs et al. 1996; Dong et al. 2001; Li et al. 2014). In this study, the results indicated that the increased vegetation covers were the pivotal variable associated with the decreased rates of soil surface wind erosion as the development of habitat becomes stable. This may be because the increased plant cover can absorb more wind force and therefore the wind erosion is reduced, similar conclusion can also be found in (Buckley 1987). A regression analysis in another study demonstrated that the rate of soil surface wind erosion was greatly affected by the plant cover, which accounted about 48.1 % of the variation in erosion (Li et al. 2005).

Several studies suggest that the shelter forest has functioned as a dust trap that can deposit large amounts of atmospheric dust (Li et al. 2003b; Ouyang et al. 1999). Other studies also indicate that forest is very efficient in the air particles interception by impact due to the high aerodynamic resistance (Miller and Miller 1980; Lindberg et al. 1986; Moreno and Gallardo 2002; Li et al. 2013a, b, 2014). In this study, only the gravitational deposition was collected, which is only part of the total dust fall. The data show that there is significant spatial differentiation in the distribution of dust-fall rate. In the three types of revegetated cover lands, the Shrubland significantly increased the average daily dust deposition rate compared to the other land types. The reason could be that the Shrubland was next to the desert shrubland, which was the main source of dust storm, especially in the windy spring seasons, whereas the Poplar land and Pine land were set up later and further away from the source. In addition, it can also be affected by the vegetation species and habitat condition (Su et al. 2007a; Zhao et al. 2008; Li and Shao 2014).

Through the full text research, we could find that the vegetation influences the accumulation of carbon and nitrogen of soil through many aspects directly and indirectly, such as litter decomposition, soil erosion loss, and the dust and wind erosion. For example, the establishment of revegetated covers can decrease the surface wind erosion significantly and lead to a dramatic reduction in daily sand transport rate. The high content of C and N could be affected by not only the revegetation itself directly and indirectly, but also the input of natural and artificial. If the condition allows, the research will be improved quantitatively.

Conclusions

Revegetated covers have a great effect on the amelioration of soil physicochemical properties, especially they can increase C and N sequestration and improve the soil quality. Furthermore, revegetated covers play an important role in increasing the species richness, productivity and C, N accumulation of vegetation. In addition, different effects of three typical revegetated covers on wind erosion and atmospheric dust deposition were also shown. This study confirmed that the establishment of artificial forest on sandy land is one of the most effective measures against desertification. This study showed the importance of revegetation in combating desertification in arid regions. Different covers show different effects, revegetation forest by irrigation had a stronger effect on soil fertility and plant productivity than revegetation shrub without irrigation. Thus, there is a great need to study and monitor the long-term and different effects of different revegetated covers on controlling desertification and improving soil productivity to choose optimized revegetated covers.

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