Changes in wind erosion over a 25-year restoration chronosequence on the south edge of the Tengger Desert, China: Implications for preventing desertification

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Abstract Wind erosion is a primary cause of desertification as well as being a serious ecological problem in arid and semiarid areas across the world. To determine mechanisms for restoring desertified lands, an unrestored shifting sand dune and three formerly shifting sand dunes (desertified lands) that had been enclosed and afforested for 5, 15 and 25 years were selected for evaluation on the south edge of the Tengger Desert, China. Based on sampling heights between 0.2 and 3 m, the critical threshold average wind speed was 6.5 m s^{-1} at 2 m where the sand transport rate was reduced from $285.9 \text{ kg m}^{-2} \text{ h}^{-1}$ on the unrestored dunes to $9.1 \text{ kg m}^{-2} \text{ h}^{-1}$ and $1.8 \text{ kg m}^{-2} \text{ h}^{-1}$ on the sites afforested and enclosed for 5 years and 15 years, respectively. The percentage of wind eroded area was reduced from 99.9% on the unrestored dune to 94.5%, 9.0% and 0.5% on the sites afforested and enclosed for 5, 15 and 25 years, respectively. Wind erosion was effectively reduced after 15 years. Although there were different driving factors for wind erosion mitigation on the different restoration stages, an increase in the vegetation cover, surface roughness, soil shear strength, soil clay content, organic matter, and reduction in the near surface wind speed were the primary variables associated with the restoration chronosequence. We conclude that reducing the wind speed and developing a biological crust through vegetation restoration were the critical components for restoration of desertified land.

Keywords Sand transport rate · desertified land · sand-binding vegetation · *Hedysarum scoparium* · afforestation

1 **Introduction**

2 Wind erosion – the detachment, transport, and redeposition of soil particles by wind – is a soil
3 degradation process which causes serious environmental and agricultural problems on a global scale
4 (Buschiazzo et al. 2008; Masri et al. 2015). Wind erosion can physically remove the most fertile portion
5 of the soil, pollute the air, fill road ditches, reduce seedling survival/growth, lower marketability of
6 vegetable crops, and, at its most extreme, create new desert landforms and landscapes in a process known
7 commonly as desertification (Masri et al. 2015). Wind erosion and desertification have continued to
8 increase as more arid and semi-arid lands become vulnerable to erosion due to climate change, population
9 growth, urbanization, farming of marginal lands, and overgrazing (Fang et al. 2003). Although wind
10 tunnel research has improved the understanding of sand transport mechanisms under unsteady wind
11 conditions, field investigations better represent the more complex situations found under natural
12 conditions (Keiko 2009). Due to the complexity of wind-sand flow, however, various methods have been
13 developed for field studies. Major methods for wind erosion measurement include wind erosion pans,
14 traps, collectors, cyclic collectors, tracers, remote sensing, erosion pins, sand samplers, and a variety of
15 sensors (Zhao et al. 2008; Dai et al. 2011; Yue et al. 2015). The sand sampler has been a commonly used
16 field method and represents a good compromise between accuracy and reliability for measuring sand
17 transport rates (Fryrear et al. 1991; Chen 2004; Wang and Zhao 2008). The sand transport rate directly
18 assesses the wind erosion of soil (Cheng 2004; Keiko 2009).

19 Sand transport involves the interaction between entrained grains in near-surface wind flow and the
20 sand bed (Merrison 2012). Substantial sand transport only occurs under specific conditions when: soil is
21 loose, dry and finely granulated; vegetative cover is sparse or absent; the susceptible area is sufficiently
22 large; and the wind speed is high (Shi et al. 2004; Yi et al. 2007). Measures which control wind flow or
23 stabilize the sand bed could effectively weaken wind erosion intensity (Chen 2004; Ci and Yang 2010).
24 The principles for controlling wind erosion include: stabilizing sites with various materials; producing a
25 rough, cloddy surface; reducing effective field width with barriers; and establishing and maintaining
26 sufficient vegetative cover (Skidmore 1986). Research and practices have shown that adding vegetation
27 has been shown to be an economical and effective measure for controlling wind erosion by both reducing
28 the wind speed at the soil surface and decreasing soil erodibility (Wolfe and Nickling 1993; Hupy 2004;
29 Li et al. 2007; Wang et al. 2008; Hugenholtz 2010; Mendez and Buschiazzo 2015). Biological soil crusts
30 also have played a crucial role in ecological restoration in arid and semi-arid areas (Li et al. 2002;
31 Goossens 2004; Li et al. 2008; Kidron et al. 2012) with soil shear strength having been proposed as an
32 index of susceptibility to erosion (Zimbone et al. 1996).

33 The most commonly cited components as critical to understand the restoration ecology of arid and
34 semi-arid areas have included induced vegetation succession, soil crust formation, and wind erosion
35 changes after afforestation (e.g. Kidron et al. 2012; Gong et al. 2014; Mendez and Buschiazzo 2015).
36 While the protective role of sparse vegetation in wind erosion have also been cited (e.g. Buckley 1987;
37 Wolfe and Nickling 1993), previous research has generally focused on high-density artificial forests (with
38 more than 5000 plants/ha²) and their role in preventing wind erosion (Buckley 1987; Ma et al. 2006; Ci
39 and Yang 2010; Ma et al. 2013; Gong et al. 2014). While there have been some successes in preventing
40 wind erosion, especially using high input methods such as high-density afforestation, the challenge of
41 mitigating and reversing damage to lands desertified through wind erosion remains (Wang et al. 2012;
42 Guo et al. 2014). One particular method, lower-density afforestation, has not been well studied and

appears to offer the potential for fostering sand-binding vegetation and reducing wind erosion on sand dunes.

This study, using the restoration of the desertified lands at the south edge of Tengger Desert as an example, was designed to document the changing conditions across four sites: on three formerly desertified sites afforested with lower-density sand-binding vegetation for 5, 15 and 25 years and an adjacent unrestored shifting sand dune. We hypothesized that wind erosion variation would have a consistent relationship with changing vegetation cover, soil properties and wind speed in the reversion process of desertified lands after lower-density afforestation. Specifically, the aims of the study were to: 1) quantify wind erosion rates and processes across the chronosequence, and 2) determine the key driving factors of wind erosion reduction.

Materials and methods

Study site

This study was conducted at the Mingshazui Desert Control Station (37°33'18"N, 103°41'06"E), Gansu Province, China, in an ecotone between desert and oasis on the south edge of the Tengger Desert (37°32'-43°33'N, 103°39'-103°42'E; Fig. 1). The elevation was 1780 m asl with a mean annual temperature of 6.0 °C, a maximum temperature of 36.6 °C and a minimum temperature of -27.3 °C. There are 2726 sunshine hours per year on average and the growing season averages 192 days. The mean annual precipitation of 175 mm falls mainly from July to September. The annual potential evaporation is about 3080 mm (1996-2013, data from Jingtai County Meteorological Station). The soil was 99% sand. The study site was an area of sand dunes approaching an oasis at a rate of 3-5 m year⁻¹ before afforestation. The groundwater was 67 m below the surface and natural precipitation was the only source of water for plant growth. The main plant species in the study area included *Nitraria tangutorum*, *Artemisia ordosica*, *Psammochloa villosa* and *Agriophyllum squarrosum*. In 1982, an artificial vegetation belt with a length of 2 km, and a width of 100-150 m was established. The belt included surface application of wheat straw and seedlings of *Hedysarum scoparium* (afforestation density was 1650 plants ha⁻¹) on the lower parts at the windward slopes of the shifting sand dunes. The entire area was fenced against livestock immediately after the belt was completed. Two similar belts were built in 1993 and 2002, and were about 2 km and 4 km away from the first enclosed area, respectively (Wang, et al. 2004).

Fig. 1 Location of the study area showing the distribution of the desertified lands

Establishment of study plots and methods

In 2007, three 20 m × 20 m plots, 50 m apart, were established at three formerly desertified sites afforested with sand-binding vegetation 5, 15 and 25 years ago and at an adjacent unrestored shifting sand dune site for a total of four sites. One of the three plots at each site was divided into four hundred 1 m × 1 m quadrats (Fig. 2).

To evaluate wind erosion at each plot in April 2007 and 2008, sand transport rates were measured with three vertical stepped sand samplers which had ten observation layers each with an area of 2 cm × 2 cm across a 20 cm observation height. Sand sediments in each observation layer were collected with a glass pipe in the sampler and weighed separately to calculate the sand transport rate (Chen 2004). In order to further measure the wind erosion level, the percentage of eroded area was also assessed. In April 2008, two perpendicular, 200 m long, horizontal sample lines were established at each site and observed every 1 m for evidence of erosion for a total of 400 observation points. A point without soil crust or with surface sand was recorded as eroded. The percentage of eroded area was calculated as the ratio of the eroded to un-eroded points. The thickness of biological soil crust was also measured with a Vernier caliper each 1 m along the sample line. In April 2007 and 2008, wind speed (m s^{-1}) was measured with a portable wind speed measurement system (ZL 02261931.3, China) simultaneously with the sand transport measurements. Wind-cups were set up at heights of 20 cm, 50 cm, 100 cm, 150 cm, 200 cm and 300 cm, and wind speed was recorded with a data logger at a rate of one observation every 10 s (Ma et al. 2006). Surface roughness was defined as the geometric height where average wind speed reduced to zero. The wind speed at the height of 200 cm and 50 cm for each of the sites was used to calculate the surface roughness by an equation of $\lg Z_0 = (\mu_1 \lg Z_2 - \mu_2 \lg Z_1) / (\mu_1 - \mu_2)$ (in the equation, Z_0 was surface roughness, μ_1 and μ_2 were wind speed at the height of Z_1 and Z_2 , respectively; Zhang and Zou 1989).

In September 2007 and 2008, 100 of the 1 m × 1 m quadrats at each site were systematically selected (every fourth quadrat) from the 400 quadrats available to investigate plant communities. In each quadrat,

species richness, shrub cover, herbaceous cover and aboveground biomass were measured and recorded (Li et al. 2005). Vegetation height was determined and recorded by measuring heights of dominance plants in each quadrat (Richard et al. 2013). The Simpson index was used to estimate plant species diversity (Li et al. 2005).

Fig. 2 The experimental layout

In September 2008, 50 quadrats at each site were systematically selected (every second quadrat) for soil analysis from the 100 vegetation investigation quadrats. On clear days one week following rain, a soil pit was dug and sampled for soil bulk density (g cm^{-3}), water content, and soil properties at the center of each quadrat surrounded by a iron frame with an area of $1 \text{ m} \times 1 \text{ m}$. Bulk density samples with three replications were taken at depths of 0-5, 5-20, 20-40, 40-60 cm using stainless steel bulk density rings with a 5 cm diameter and a 5 cm height. The soil bulk density and water contents were tested using the oven-dry method in the laboratory at 105°C for 24 h (Bao 2005). Particle size was analyzed using a Malvern laser particle size analyzer (MALVERN-S, UK); soil organic matter (SOM) was determined by the dichromate oxidation method; total N (TN) was measured using a Kjeltex method; and electrical conductivity (EC) was measured using a portable conductivity meter (Bao 2005; Li et al. 2007). During soil sampling, roots within the iron frame were collected on a 1-mm sieve, oven-dried at 70°C for 48 h, and weighed to the nearest 0.01 g.

At each site in September 2008, 20 quadrats were selected systematically (every fifth quadrat) from the 100 vegetation investigation quadrats and soil shear strengths were measured 3 times at the center of each quadrat with a 14.10 Pocket Vane Tester (Eijkelpkamp Agrisearch Equipment, Netherlands; Du et al. 2008). Using simulated rainfall, the effect of soil water content on soil shear strength was measured at the unrestored and 15-year-old sites.

Data analysis

1 A one-way analysis of variance (ANOVA) was used to evaluate changes in the sand transport rate, the
2 percentage of wind erosion area, the vegetation properties, the soil properties, and the soil shear strength.
3 Duncan's test was applied at a 5% probability to test for differences among the treatment means. The
4 analyses and figures were performed with Microsoft Excel, OriginPro 8.0 and SPSS (SPSS 13th ed.,
5 Chicago, USA).

6 Results

7 When the average wind speed at 2 m above the surface reached 6.5 m s^{-1} , the sand transport rate within
8 the near-surface ground layer (0-20 cm) of the unrestored dune was $285.9 \text{ kg m}^{-2} \text{ h}^{-1}$. In comparison, the
9 sand transport rate was only $9.1 \text{ kg m}^{-2} \text{ h}^{-1}$ and $1.8 \text{ kg m}^{-2} \text{ h}^{-1}$ on the 5-year and 15-year sites, respectively,
10 which is 3.2% and 0.6% of the unrestored dune rate. No wind erosion was observed at the 25-year site
11 (Fig. 3). The spatial distribution of sand transport within the range of 0-20 cm above the surface also
12 differed among the sites. While sand transport on the unrestored dune was mostly within the 0-4 cm
13 surface layers where the sand transport rates reached $249.8 \text{ kg m}^{-2} \text{ h}^{-1}$ (87.4% of the total), the 5- and
14 15-year sites had reduced sand transport rates at heights of 0-4 cm, while sand transport at heights above
15 4 cm increased (Fig. 4) in a polynomial decay function.

Fig. 3 Sand transport rates at the different restoration stages (mean±S.D.; different letters indicate significant differences at $P < 0.05$)

Fig. 4 Spatial distribution of sand transport at the different restoration stages

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17 After afforestation, the wind eroded area decreased gradually. The wind eroded area of the
18 unrestored dune was 99.9% and was not significantly different from the 5-year site at 94.5%. The 15- and
19 25-year sites were significantly different with only 9.0% and 0.5% wind eroded areas, respectively (Fig.
20 5).

Fig.5 Eroded area at the different restoration stages (mean±S.D.; different letters indicate significant differences at $P < 0.05$)

On our sites, the dominant species in the composition of sand-binding vegetation changed from annuals to shrubs, and then to sub-shrubs with perennial herbs. After 25 years, native species such as *Artemisia ordosica* and herbs dominated the communities. The species richness increased from 3 on the unrestored dune to 10 on the 25-year site (Supplement 1 lists the plant species at each restoration stage). The total vegetation cover, shrub cover, total biomass, aboveground biomass, and belowground biomass all had an increasing trend through the 15-year site and then decreased on the 25-year site (Table 1). After 15 years since afforestation, vegetation cover increased to 40.23% which was 6.6, 2.2 and 1.1 times that of the unrestored dune, the 5-year and 25-year sites, respectively. Analysis of the relationship between the sand transport rate and vegetation cover showed that the sand transport rate decreased more than 97% with a 6.5 m s^{-1} wind speed at the 2 m height when sand-binding vegetation cover approached 20% (Table 2) which implies that fostering vegetation to at least 20% reduced the impacts of wind erosion. Based upon the composition and quantitative characteristics of dominant species, the restoration succession order of natural sand-binding vegetation went from *A. squarrosus* and *Artemisia aphaerocephala* to community of *H. scoparium*, *A. aphaerocephala* and *A. ordosica*, then to community of *A. ordosica* and annual herbs, and finally to *A. ordosica*, annual and perennial herbs. The cover and biomass of herbaceous plants increased gradually, which strongly indicated that site conditions improved gradually in this assisted restoration chronosequence (Table 1). In comparison to the unrestored sand dune, vegetation height increased to the maximum in the 5-year site, and then decreased. Species diversity increased in the 5-year site, decreased in the 15-year site and then increased in 25-year site. The community similarity with nearby native vegetation also gradually increased over time and reached 50% after 25-years (Table 1).

Table 1 Changes in sand-binding vegetation at the different restoration stages (Mean ± S.E.)

Vegetation properties	Restoration stage			
	Unrestored	5-year	15-year	25-year
Species richness	3	9	10	10
Vegetation cover (%)	6.14±1.5 ^c	18.11±2.4 ^b	40.23±2.5 ^a	36.44±1.9 ^a
Vegetation height (cm)	14.8±2.6 ^d	64.6±4.4 ^a	55.9±2.8 ^b	48.1±1.3 ^c
Shrub cover (%)	4.88±1.5 ^c	12.89±2.2 ^b	32.21±2.4 ^a	27.48±2.0 ^a
Herbaceous cover (%)	1.26±0.3 ^b	5.22±1.5 ^a	8.02±1.3 ^a	8.96±1.9 ^a
Total biomass (kg ha ⁻¹)	493.8±247.5 ^c	3762.8±850.8 ^{ab}	5734.4±720.4 ^a	4025.2±332.2 ^a
Aboveground biomass (kg ha ⁻¹)	91.9±113.6 ^c	2095.0±669.0 ^b	3790.4±645.3 ^a	2305.2±275.6 ^b
Belowground biomass (kg ha ⁻¹)	401.9±222.8 ^b	1667.8±603.5 ^a	1944.0±336.8 ^a	1720.0±106.1 ^a
Herbaceous biomass (kg ha ⁻¹)	29.8±1.6 ^{bc}	82.6±19.7 ^b	136.0±23.7 ^{ab}	206.5±63.3 ^a
Species diversity	0.40±0.05 ^b	0.85±0.06 ^a	0.42±0.04 ^b	0.82±0.06 ^a
Similarity with zonal native vegetation	0.00	0.20	0.28	0.50

Note: Different letters in the same row indicate significant differences at $P < 0.05$.

Table 2 Regression equation between sand transport rate (y , $\text{kg m}^{-2} \text{h}^{-1}$) and key factors (x)

Factors	N	a	b	R^2	P
Vegetation cover (%)	12	87535.38	-3.167	0.99	<0.001
Surface roughness (cm)	12	12.254	-0.5422	0.79	<0.001
Soil shear strength (kg cm^{-2})	12	4.729	-4.641	0.99	<0.001

Note: The regression equations are of the form: $y = a * x^{-b}$, where a & b are significant coefficients. N , R^2 and P stand for sample size, mean squared error, and P value, respectively.

With the restoration of the desertified lands, wind speed near the ground was effectively reduced (Fig. 6). Compared to the unrestored dune, wind speeds were reduced 58.39%, 54.29% and 83.68% at the 20 cm height, and 46.91%, 37.98% and 67.77% at the 50 cm height on the 5-, 15-, 25-year sites, respectively (Table 3). The wind speed profiles of the restored sites better fit quadratic curves while the wind speed profile of unrestored dune site was more consistent with fitting a logarithmic curve (Fig. 6). The wind speed profiles generally show that the wind speed increased with increasing height above the ground, but the change in wind speed was very small for heights over 2 m. Sand-binding vegetation afforestation and restoration not only weakened the wind speed, but also changed the spatial distribution of wind speed across different heights. With the reduction of wind speed, the sand transport rate also showed a corresponding decrease (Fig. 3).

Fig. 6 Vertical variation of wind velocity at the different restoration stages

Table 3 Changes in wind speed and roughness at the different restoration stages

Restoration Stage	Percentage reduction of wind speed at different heights (%)				Roughness (cm)
	20 cm	50 cm	100 cm	200 cm	
Unrestored	0	0	0	0	0.003
5-year	58.39	46.91	30.33	2.84	11.43
15-year	54.29	37.98	15.50	3.08	6.04
25-year	83.68	67.77	37.20	4.10	17.73

The surface roughness of the 5-year site reached 11.43 cm which was 3810 times greater than the unrestored dune. This surface roughness was associated with a 96.8% reduction in sand transport rate

compared to the unrestored dune site. The surface roughness of the 15-year site only reached 6.04 cm due to mortality of the afforested species but the sand transport rate was reduced by 99.4%, nonetheless. The 25-year site surface roughness reached 17.73 cm, and reduced the sand transport rate by 100% (Table 3). The sand transport rate showed a general trend of decreasing with increased surface roughness. As the surface roughness approached 2 cm, the sand transport rate reduced rapidly by more than 80% (Table 2).

Three years after afforestation, soil crusts began to form on the surface of the sand dunes. On the 5-year site, the thickness of soil crust reached 0.34 mm, but it only covered about 20% of the sand dune which was still semi-mobile. On the 15-year site, the average thickness of soil crust reached 3.3 mm and the crust covered more than 90% of the site. On the 25-year site, the soil crust thickness reached 5.3 mm and it covered virtually all of the site (Fig. 7).

Fig. 7 The thickness of sand crust at the different restoration stages (mean±S.D.; different letters indicate significant differences at $P < 0.05$)

The soil shear strength increased gradually from 0.0078 kg cm⁻² on the unrestored dune to 0.0164 kg cm⁻², 0.103kg cm⁻² and 0.243 kg cm⁻² on the 5-, 15- and 25-year sites, respectively (Fig. 8). There was a significant difference among the restoration stages in the soil shear strength ($P < 0.05$), but the difference between the unrestored dune and the 5-year site was not significant, which indicated the reduction of wind erosion on the 5-year site had less of a relationship with the increased the soil shear strength. The sand transport rate was reduced rapidly as soil shear strength increased to 0.02 kg cm⁻² (Table 2). Soil shear strength above 0.02 kg cm⁻² was associated with little additional reduction in the sand transport rate.

The sand content of the topsoil significantly decreased from 98.48% on the unrestored dune to 68.18% on 25-year site, the silt content increased from 0.65% to 25.16%, and the clay content increased from 0.87% to 6.65% (Table 4). The SOM of the topsoil significantly increased from 0.143% on the shifting sand dune to 0.508% on the 25-year site (Table 4). The restoration of vegetation not only stabilized the sand but also improved the soil structure, fertility, and cohesion.

Fig. 8 The soil shear strength at the different restoration stages (mean±S.D.; different letters indicate significant differences at $P < 0.05$)

Table 4 Changes in topsoil at the different restoration stages (mean ± S.E.)

Soil properties	Restoration stage			
	Unrestored	5-year	15-year	25-year
Water content 5-60 cm layer (%)	2.97±0.36 ^a	1.92±0.34 ^b	1.46±0.29 ^c	1.79±0.27 ^b
Bulk density (g/cm ³)	1.56±0.03 ^a	1.51±0.04 ^b	1.49±0.07 ^c	1.37±0.09 ^d
Sand content (%)	98.48±0.13 ^a	94.62±1.33 ^a	77.52±2.64 ^b	68.18±3.35 ^c
Silt content (%)	0.65±0.10 ^c	3.67±1.40 ^b	18.14±2.13 ^a	25.16±3.42 ^a
Clay content (%)	0.87±0.06 ^b	1.70±0.32 ^b	4.34±0.51 ^a	6.65±0.40 ^a
Organic matter (%)	0.143±0.02 ^d	0.203±0.02 ^c	0.466±0.04 ^b	0.508±0.03 ^a
Total N (%)	0.013±0.001 ^c	0.026±0.003 ^b	0.039±0.005 ^a	0.043±0.003 ^a
EC (μs/cm)	81.2±0.5 ^d	90.5±2.2 ^c	123.8±3.0 ^b	133.4±3.3 ^a

Note: Different letters in the same row indicate significant differences at $P < 0.05$.

At our sites, the soil shear strength had a significant positive correlation with soil clay content, SOM, TN and EC; while it had negative correlation with soil bulk density and sand content (Table 5). On our unrestored dune site, the soil shear strength was significantly increased with increasing soil water content, but the maximum soil shear strength still did not reach 0.05 kg cm⁻² (Fig. 9). The relation between the soil shear strength and the soil water content was quadratic, when the soil water content was 6%, the soil shear strength increased more than 3 times, thus the threshold speed of sand-driving wind was markedly increased. At the 15-year site with a 3.3 mm soil crust, the soil shear strength was significantly increased with the increase in soil water content in the early stages, then decreased to a stable value with further increase in soil water content (Fig. 9).

Table 5 Correlation coefficient between the soil shear strength and soil properties

Items	Shear strength	Bulk density	Sand content	Clay content	SOM	TN	EC
Shear strength	1.00						
Bulk density	-0.90**	1.00					
Sand content	-0.65*	0.74**	1.00				
Clay content	0.58*	-0.77**	-0.99**	1.00			
SOM	0.67*	-0.75**	-0.79**	0.75**	1.00		
TN	0.64*	-0.59*	-0.59*	0.65*	0.45*	1.00	
EC	0.81**	-0.80**	-0.89**	0.89**	0.80**	0.67*	1.00

Note: ** $P < 0.01$, * $P < 0.05$.

Fig. 9 Effect of soil water content on surface soil shear strength (mean±S.D.; different letters indicate significant differences at $P < 0.05$)

(A) UNRESTORED SHIFTING SAND DUNE; (B) THE DESERTIFIED LAND AFFORESTED FOR 15 YEARS

Discussion

The expansion of wind eroded areas alters the environment and reduces the standard of living in these desertified regions (Ci and Yang 2010; Duan et al. 2014). This human and environmental cost gives rise to measures to combat wind erosion, including shelterbelts, fences, and upright sand barriers but these measures have been aimed at decreasing wind speed (Morgan 2005; Ci and Yang 2010) while our research indicated the importance of both reducing wind speed and preventing soil movement.

When wind speed at 2 m above the surface was 6.5 m s^{-1} , the sand transport rate was reduced from $285.9 \text{ kg m}^{-2} \text{ h}^{-1}$ on the unrestored dunes to $9.1 \text{ kg m}^{-2} \text{ h}^{-1}$ and $1.8 \text{ kg m}^{-2} \text{ h}^{-1}$ on the sites afforested and enclosed for 5 years and 15 years, respectively. The percentage of wind eroded area was reduced from 99.9% on the unrestored dunes to 94.5%, 9.0% and 0.5% on the sites afforested and enclosed for 5, 15 and 25 years, respectively. Our results were consistent with previous studies on wind erosion intensity. For example, Wang et al. (2008) found that the sand transport rate of the shifting sand dune was 4.9 times and 22.8 times of those of the semi-fixed and fixed sand dunes. Ma et al. (2013) found that *Ulmus pumila*, *Platycladus orientalis*, and *Populus simonii* forests, each with different levels of cover, all significantly decreased the wind transport rate of desertified lands. However, most of previous studies focused on wind erosion at a particular site or time, or used change of wind speed to evaluate wind erosion (Liu et al. 1992; Wang et al. 2005; Wang et al. 2008; Ma et al. 2013). Our studies found wind erosion intensity was gradually reduced with the restoration of the sand-binding vegetation.

Vegetation cover, along with wind speed, soil moisture, and surface material composition, have been found to be the important natural factors influencing soil erosion (Leys 1991; Liu et al. 1992; Wolfe and Nickling 1996; Levin et al. 2006) but even small changes in vegetation cover have been shown to have a direct impact on the effectiveness of windbreaks and sand fixation projects (Buckley 1987; Hupy 2004; Wang et al. 2008). In our project, the planting of the sand-binding vegetation initially increased the vegetation cover, especially shrub cover, aboveground biomass, and belowground biomass. Over time, the initial plantings of what became large shrubs died out likely due to the depletion of soil water in deeper soil layers. Nonetheless, the plantings stayed in place long enough to allow succession of

1 vegetation and development of the soil ecosystem. The large shrubs were naturally replaced by the
2 semi-shrub *Artemisia ordosica* that relies on water in the shallow root zone. At the 25-year site, *Artemisia*
3 *ordosica* became the dominant species and its cover was limited by the amount of vegetation the annual
4 rainfall can support.

5 This plant community change from large planted shrubs to smaller naturally occurring shrubs was also
6 associated with the notable changes in the interaction among soil water content, wind speed, and surface
7 roughness. Although the vegetation cover did not have a consistent linear relationship with the sand
8 transport rate, there was a power function relationship between them. In other studies, wind erosion rates
9 have shown a significant positive relationship with vegetation cover in spring and sharp decreases as
10 vegetation cover increased (Shi et al. 2004; Guo et al. 2014). However, even with the same wind speed,
11 wind erosion can increase with vegetation cover (Liu et al. 1992) and it is clear that the morphology of
12 the plants providing the cover makes a difference. For instance, grasses reduce the near-surface wind
13 speed more than other life forms with the same cover (Li et al. 2007). This complicates generalized
14 management prescriptions based on total cover such as those of Huang et al. (2001) and Dong et al.
15 (1996). Huang et al. (2001), based on a statistical model, found that vegetation cover of 40–50%,
16 effectively controlled wind erosion. Dong et al. (1996), based on wind tunnel testing, found that when the
17 vegetation cover was greater than 60%, there was little or no wind erosion, between 20 and 60% there
18 was moderate wind erosion; and less than 20% had strong wind erosion. Our results showed that wind
19 erosion was effected by vegetation cover, arrangement and species composition, and erosion was
20 controlled when the shrub cover was more than 20%.

21 Wind erosion can occur only when there is enough wind (Shi et al. 2004; Yi et al. 2007) and wind
22 erosion management has been designed to decrease the strength of the wind (Morgan 2005; Ci and Yang
23 2010). Our study found that lower-density afforestation significantly reduced the wind speed. Compared
24 to the unrestored dune, wind speeds were reduced 58.39%, 54.29% and 83.68% at the 20 cm height on the
25 5-, 15-, and 25-year sites, respectively. For the 5-year site, dominated by large, planted shrubs, the effect
26 of wind speed reduction was close to that of 15-year site.

27 The surface roughness has been shown to be a key indicator of wind-breaking and sand-fixation effect,
28 and has been used in wind erosion equations (Yang 1996). The surface roughness acts to absorb part of
29 the momentum of the wind which reduces the threshold friction speed and wind erosion (Ashrafi et al.
30 2015). In our study, afforestation also increased the surface roughness significantly. The surface
31 roughness of the 5-year site reached 11.43 cm which was 3810 times greater than the unrestored dune.
32 The greater the surface roughness of sand dunes, the greater the friction force acting on the air. The
33 higher surface roughness increased the threshold wind velocity for sand movement and reduced the
34 amount of wind erosion because the sand transport rate is proportional to the cube of wind friction speed
35 and increases rapidly above the threshold friction speed (Lorentz 2011; Merrison 2012). The surface
36 roughness not only depends on the atmospheric stability, soil particle diameters, and the soil moisture, but
37 also depends on the vegetation height, cover and distribution pattern. The surface roughness of the
38 15-year site with the most cover and biomass only reached 6.04 cm. Compared to the 15-year site, the
39 5-year site had the taller vegetation height, and the 25-year site had a more uniform distribution of
40 vegetation and soil fine particles. Sand transport rates vary between surfaces of different roughness
41 because the threshold friction speed required to initiate movement of sand particles varies with roughness
42 (Greeley et al. 1991). For example, Fryrear (1984) found that a surface roughness of 6 cm can reduce
43 wind erosion more than 50 percent. Havstad et al. (2006) found that surface roughness leading to
44 roughness lengths longer than 0.2 cm provided good protection against wind erosion.

At the south edge of the Tengger Desert, the primary concern was the movement of the wind eroded sand but the wind also brought finer dust from further away. The accumulation of deposited dust on our sites was associated with the formation of biological soil crusts which increased in both cover and thickness across our chronosequence. The most important function of biological soil crusts in arid ecosystems is preventing wind erosion of the soil (Rajot et al. 2003; Li et al. 2004; Kidron et al. 2010). Resistance to wind erosion has been shown to parallel biological soil crust development (Belnap and Gillette, 1998). Biological soil crusts form through the entanglement of cyanobacteria and algae filaments, lichen and moss thalli, and soil particles (Chartres, 1992; Belnap and Gillette, 1998; Kidron et al. 2012) which provides a “protective coat” on the sand surface due to its soil-binding qualities (Williams et al. 1995; Li et al. 2002). Li et al. (2002, 2009) indicated that the development of soil crusts passed through three stages after afforestation: (1) aeolian deposition and raindrop impact crust occurs 2-3 years after the sand-binding vegetation establishment; (2) a microbiotic crust stage enriched with bacteria and algae occurs 4-5 years after the sand-binding vegetation establishment; (3) a microbiotic crust dominated by algae, mosses and liverworts occurs 20 years after the sand-binding vegetation establishment. Biological soil crusts significantly increased species diversity of algae, algal cover/biomass and moss biomass which have been highly correlated with increases in available soil nutrients and organic matter (Li et al. 2003). The biological soil crust development can lead to a change from shrubs to herbs because of decreased soil moisture in deeper soil layers (Li et al. 2002), which could increase surface cover and reduce wind erosion (Li et al., 2008). Only undisturbed sandy soils and disturbed soils of all types would be expected to be erodible in normal wind storms (Marticorena et al. 1997).

Soil shear strength has been proposed as a measure of soil resistance to erosion, i.e. as the reciprocal of soil erodibility (Torri 1987; Brunori et al. 1989). The soil shear strength is the frictional resistance met by soil particles when they are forced to slide over one another or to move out of interlocking positions (Morgan 2005). In our study, soil shear strength generally increased with the restoration of sand-binding vegetation. However, the relationship was inconsistent. On the unrestored site, shear strength increased with increasing soil water content while on the 15-year site, soil shear strength first increased and then decreased with increasing water content. On the unrestored site, the effect seemed to be a physical effect. Soil moisture can significantly affect adhesion (soil shear strength) and indeed sand entrainment thresholds are seen to increase with increased relative humidity (Zimbone et al. 1996; Cornelius and Gabriels 2003). For example, Liu et al. (1992) found that when the water content was less than 2%, the ability of the soil to resist wind erosion increased with the increase of water content, and its change was more stable when the water content is more than 2%. On the 15-year site, the additional water caused the soil biotic crust to breakup which reduced the shear strength.

Our study found that water content first decreased and then increased with the restoration of sand-binding vegetation. This result was different than that of the small shrub forests of Li et al. (2004), but consistent with that of the planted *Haloxylon ammodendron* forest of Ma et al. (2007). Change in soil water content has been not only related to plant species composition but also to plant density and arrangement. In general, soil water content can be first reduced due to high afforestation density, and then later increase with the death of afforestation plants. The death of afforestation plants has been a common and serious problem in the afforestation in Northern China (Cui 1998; Ma et al. 2007; Feng et al. 2015) but our research at least implies that even the dead plants may continue to provide some wind erosion protection.

Our restoration of sand-binding vegetation effectively changed the soil particle composition from 99% sand to 68% sand, 25% silt, and 7% clay through the capture of dust which in addition to the vegetation

cover and soil crusts resulted in a soil surface layer much better able to resist wind erosion. Even without considering vegetation, topsoil properties such as moisture content, bulk density and dry aggregate size distribution affect wind erodibility (Zobeck 1991; Zobeck et al. 2013). This is because wind erosion decreases with both increasing and decreasing grain size. The reduction from larger particles comes from their size and weight, and that of the finer particles is due to their cohesiveness and the protection afforded by surrounding coarse grains (Morgan 2005). As described by Borrelli et al. (2014), soils with higher clay content led to the formation of a resistant soil surface crust that effectively limited the erosive power of the wind. Similarly, SOM has been associated with the reduction in movement of sand by wind (Malakouti et al. 1978). Other studies showed that the soils with lower bulk density, higher SOM, TN and clay content tended to have higher adhesion and shear strength at the same water content, and the soil shear strength was a function of the physical and chemical properties (Brunori et al. 1989; Zhang et al. 2001). The soil shear strength has been shown to be affected by the soil particle composition, soil organic matter, vegetation cover, and root density (Fredlund et al. 1978; Zhang et al. 2001). The soils of higher bulk density and soil organic matter had lower adhesion at the same water content (Zhang et al. 2001). The soil formation was in concert with vegetation establishment and soil formation has been shown to be closely related to the emergence, propagation and evolution of natural vegetation on sand dunes (Chen and Dong 1990; Li et al. 2012).

Conclusions

Wind erosion is a major cause of land degradation, and a significant concern in arid and semi-arid regions worldwide. After low-plant-density afforestation and enclosure on the shifting sand dunes at the southern edge of Tengger desert, wind erosion intensity was gradually reduced with the restoration of the sand-binding vegetation which, over time allowed the development of topsoil and the establishment of a stable native plant community. To extend measures of wind-erosion prevention and control beyond a formulaic adoption of what has worked before, it is necessary to identify the causes of wind-erosion mitigation. Although there were different driving factors for wind erosion mitigation of the different restoration stages, an increase in the vegetation cover, ground roughness, soil shear strength, soil clay content and organic matter, and reduction in the near surface wind speed were the primary reasons in an assisted restoration chronosequence. The lower-density afforestation was by any measure a success with the critical factors being a restored structure and sand-fixing function of the desert vegetation system in order to control wind erosion.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

References

- Ashrafi, K., Kalhor, M., Shafie-Pour, M., Esfahanian, V. (2015). Numerical simulation of aerodynamic suspension of particles during wind erosion. *Environmental Earth Sciences*, 74, 1569–1578.
- Bao, S.D. (2005). *Soil and agricultural chemistry analysis*. Chinese Agricultural Publishing House, Beijing.
- Belnap, J., Gillette, D.A. (1998). Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance. *Journal of Arid Environments*, 39, 133–142.
- Borrelli, P., Ballabio, C., Panagos, P., Montanarella, L. (2014). Wind erosion susceptibility of European soils. *Geoderma*, 232–234, 471–478.
- Brunori, F., Penzo, M.C., Torri, D. (1989). Soil shear strength: its measurement and soil detachability. *Catena*, 16, 59–71.
- Buckley, R. (1987). The effect of sparse vegetation on the transport of dune sand by wind. *Nature*, 325, 426–428.
- Buschiazzo, D.E., Zobeck, T.M. (2008). Validation of WEQ, RWEQ and WEPS wind erosion for different arable land management systems in the Argentinean Pampas. *Earth Surface Processes and Landforms*, 33 (12), 1839–1850.
- Chen, H.Z., Dong, G.R. (1990). Some preliminary discussions on aeolian sandy soil. *Geographical Research*, 9(3), 80–86.
- Chen, W., Fryrear, D.W. (1996). Grain-size distributions of wind eroded material above a flat bare soil. *Physical Geography*, 17, 554–584.
- Cheng, G.T. (2004). *Control Technology for Sand Disaster*. Chemical Industry Press, Beijing, pp. 96–98.
- Ci, L.J., Yang, X.H. (2010). *Desertification and Its Control in China*. Higher Education Press/Springer-Verlag, Beijing/Berlin–Heidelberg, pp.500.
- Cornelius, W.M., Gabriels, D. (2003). The effect of surface moisture on the entrainment of dune sand by wind: an evaluation of selected models. *Sedimentology*, 50, 771–790.
- Cui, G.F. (1998). Water balance of dune fixation forest and suitability of artificial vegetation. *Journal of Beijing Forestry University*, 20(6), 89–94.
- Dai, H.L., Jin, F.X., Zhang, K.L. (2011). A review of field measurement on wind erosion. *Advances in Earth Science*, 26 (4), 401–408.
- Dong, Z.B., Chen, W.N., Dong, W.L., Dong, G.R., Chen, G.Q., Li, Z.S., Yang, Z.T. (1996). Influences of vegetation cover on the wind erosion of sandy soil. *Actaentiae Circumstantiae*, 16(4), 437–443.
- Du, J.H., Yan, P., Zhan, X.L., E, Y.H. (2008). Surface erosion resistance of *Nitraria tangutorun* nebkhas at different succession stages in Minqin oasis and related affecting factors. *Chinese Journal of Applied Ecology*, 19(4), 763–768.
- Duan, H.C., Wang, T., Xue, X., Liu, S.L., Guo, J. (2014). Dynamics of aeolian desertification and its driving forces in the Horqin Sandy Land, Northern China. *Environmental Monitoring & Assessment*, 186, 6083–6096.
- Feng, W., Yang, W.B., Dang, H.Z., Li, W., Han, H., Song, X.D., Zhang, X.L. (2015). Soil Moisture characteristics of sand fixation forest of *Pinus Sylvestris* var. *mongolica* with different plantation densities. *Bulletin of Soil & Water Conservation*, 35(5), 189–194.
- Fredlund, D.G., Morgenstern, N.R., Widger, R.A. (1978). The shear strength of unsaturated soils. *Canadian Geotechnical Journal*, 15(3), 313–321.

- 1 Fryrear, D.W. (1984). Soil Ridges-Clods and Wind Erosion. *Transactions of the American Society of*
2 *Agricultural Engineers*, 27(2), 445–448.
- 3 Fryrear, D.W., Stout, J.E., Hagen, L.J., Vories, E.D. (1991). Wind erosion: field measurement and
4 analysis. *Transactions of the American Society of Agricultural Engineers*, 34(1), 155–160.
- 5 Gong, G.L., Liu, J.Y., Shao, Q.Q., Zhai, J. (2014). Sand-fixing function under the change of vegetation
6 coverage in a wind erosion area in northern China. *Journal of Resources and Ecology*, 5(2), 105–114.
- 7 Goossens, D. (2004). Effect of soil crusting on the emission and transport of wind eroded sediment: Field
8 measurements on loamy sandy soil. *Geomorphology*, 58, 145–160.
- 9 Guo, Z.G., Huang, N., Dong, Z.B., Pelt, R.S.V., Zobeck, T.M. (2014). Wind erosion induced soil
10 degradation in northern China: Status, measures and perspective. *Sustainability*, 6, 8951–8966.
- 11 Havstad, K.M., Huenneke, L.F., Schlesinger, W.H. (2006). *Structure and function of a Chihuahuan*
12 *Desert ecosystem: the Jornada Basin long-term ecological research site*. Oxford University Press,
13 New York.
- 14 Huang, F.X., Niu, H.S., Wang, M.X., Wang, Y.S., Ding, G.D. (2001). The relationship between
15 vegetation cover and sand transport flux at Mu Us sand land. *Acta Geographica Sinica*, 56(6),
16 700–710.
- 17 Hugenholtz, C.H. (2010). Topographic changes of a supply-limited inland parabolic sand dune during the
18 incipient phase of stabilization. *Earth Surface Processes and Landform*, 35, 1674–1681.
- 19 Hupy, J.P. (2004). Influence of vegetation cover and crust type on wind-blown sediment in a semi-arid
20 climate. *Journal of Arid Environments*, 58, 167–179.
- 21 Keiko, U. (2009). New method for estimation of aeolian sand transport rate using ceramic sand flux
22 sensor (UD-101). *Sensors*, 9(11), 9058–9072.
- 23 Kidron, G.J., Vonshak, A., Dor, I., Barinova, S., Abeliovich, A. (2010). Properties and spatial distribution
24 of microbiotic crusts in the Negev Desert, Israel. *Catena*, 82, 92–101.
- 25 Kidron, G.J., Barinova, S., Vonshak, A. (2012). The effects of heavy winter rains and rare summer rains
26 on biological soil crusts in the Negev Desert. *Catena*, 95, 6–11.
- 27 Leys, J.F. (1991). Towards a better model of the effect of prostrate vegetation cover on wind erosion.
28 *Vegetatio*, 91, 49–58.
- 29 Levin, N., Kidron, G.J., Ben-Dor, E. (2006). The spatial and temporal variability of sand erosion across a
30 stabilizing coastal dune field. *Sedimentology*, 53, 697–715.
- 31 Li, C.J., Lei, J.Q., Gao, P., Xu, X.W., Wang, Y.D., Fan, J.L. (2012). Research progress of soil forming
32 process of aeolian sandy soil under the effect of artificial shelter-belt. *Acta Pedologica Sinica*, 49(6),
33 1227–1234.
- 34 Li, J.R., Okin, G.S., Alvarez, L., Epstein, H. (2007). Quantitative effects of vegetation cover on wind
35 erosion and soil nutrient loss in a desert grassland of southern New Mexico, USA. *Biogeochemistry*,
36 85, 317–332.
- 37 Li, X.J., Li, X.R., Song, W.M., Gao, Y.P., Zheng, J.G., Jia, R.L. (2008). Effects of crust and shrub
38 patches on runoff, sedimentation, and related nutrient (C, N) redistribution in the desertified steppe
39 zone of the Tengger Desert, Northern China. *Geomorphology*, 96, 221–232.
- 40 Li, X.R., Chen, Y.W., Yang, L.W. (2004). Cryptogam Diversity and Formation of Soil Crusts in
41 Temperate Desert. *Annals of Arid Zone*, 43(3&4), 335–353.
- 42 Li, X.R., He, M.Z., Duan, Z.H., Xiao, H.L., Jia, X.H. (2007). Recovery of topsoil physicochemical
43 properties in revegetated sites in the sand-burial ecosystems of the Tengger Desert, northern China.
44 *Geomorphology*, 88, 254–265.

- 1 Li, X.R., Jia, X.H., Dong, G.R. (2005). Influence of desertification on vegetation pattern variations in the
2 cold semi-arid grasslands of Qinghai-Tibet Plateau, North-west China. *Journal of Arid Environments*,
3 64, 505–522.
- 4 Li, X.R., Ma, F.Y., Xiao, H.L., Wang, X.P., Ke, C.K. (2004). Long-term effects of revegetation on soil
5 water content of sand dunes in arid region of Northern China. *Journal of Arid Environments*, 57,
6 1–16.
- 7 Li, X.R., Wang, X.P., Li, T., Zhang, J.G. (2002). Microbiotic soil crust and its effect on vegetation and
8 habitat on artificially stabilized desert dunes in Tengger Desert, North China. *Biology and Fertility of*
9 *Soils*, 35, 147–154.
- 10 Li, X.R., Zhang, Y.M., Zhao, Y.G. (2009). A study of biological soil crusts: recent development, trend
11 and prospect. *Advances in Earth Science*, 24(1), 11–24.
- 12 Li, X.R., Zhou, H.Y., Wang, X.P., Zhu, Y.G., O’Conner, P.J. (2003). The effects of sand stabilization and
13 revegetation on cryptogam species diversity and soil fertility in the Tengger Desert, Northern China.
14 *Plant and Soil*, 251, 237–245.
- 15 Liu, Y.Z., Dong, G.Y., Li, C.Z. (1992). Study on some factors influencing erosion by wind tunnel
16 experiment. *Journal of Desert Research*, 12 (4), 41–49.
- 17 Lorentz, R. (2011). On the statistical distribution of dust devil diameters. *Icarus*, 215, 381–390.
- 18 Ma, Q.L., Wang, J.H., Zhao, M., Zhan, K.J., Liu, H.J. (2006). Research on restoration technology of
19 degenerated artificial *Haloxylon ammodendron* Forest. *Forest Research*, 17(2), 151–158.
- 20 Ma, Q.L., Wang, J.H., Li, X.R., Zhu, S.J. (2007). Effects of precipitation, soil water content and soil crust
21 on artificial *Haloxylon ammodendron* forest. *Acta Ecologica Sinica*, 27(12), 5057–5067.
- 22 Ma, Z.W., Fan, S.H., Guan, F.Y., Xin, C.W. (2013). Study on soil properties of artificial forest in the
23 northern Hebei. *Journal of Zhejiang Forestry Science and Technology*, 33(4), 23–29.
- 24 Malakouti, M.J., Lewis, D.T., Stubbendieck, J. (1978). Effect of grasses and soil properties on wind
25 erosion in sand blowouts. *Journal of Range Management*, 31(6), 417–420.
- 26 Marticorena, B., Bergametti, G., Gillette, D., Belnap, J. (1997). Factors controlling threshold friction
27 velocity in semiarid and arid areas of the United States. *Journal of Geophysical Research*, 102(19),
28 23277–23287.
- 29 Masri, Z., Donk, S.V., Bruggeman, A., Turkelboom, F. (2015). Post-harvest summer tillage to control
30 wind erosion in the Khanasser Valley, Syria. *Aeolian Research*, 17, 219–229.
- 31 Mendez, M.J., Buschiazzi, D.E. (2015). Soil coverage evolution and wind erosion risk on summer crops
32 under contrasting tillage systems. *Aeolian Research*, 16, 117–124.
- 33 Merrison, J.P. (2012). Sand transport, erosion and granular electrification. *Aeolian Research*, 4, 1–16.
- 34 Morgan, R.P.C. (2005). *Soil Erosion and Conservation*. Blackwell Publishing Ltd. Malden.
- 35 Oke, T. (1987). *Boundary Layer Climates*. Methuen, London, pp. 54.
- 36 Rajot, J.L., Aifaro, S.C., Gomes, L., Gaudichet, A. (2003). Soil crusting on sandy soils and its influence
37 on wind erosion. *Catena*, 53, 1–16.
- 38 Richard, E.Z., Cynthia, B.M., David, B.W., Ronald, E. S., John, B.B. (2013). Precipitation and mowing
39 effects on highway rights-of-way vegetation height and safety. *Landscape and Ecological*
40 *Engineering*, 9, 121–129.
- 41 Shi, P.J., Yan, P., Yi, Yuan, Nearing, M.A. (2004). Wind erosion research in China: past, present and
42 future. *Progress in Physical Geography*, 283, 366–386.
- 43 Skidmore, E.L. (1986). Wind erosion control. *Climatic Change*, 9, 209–218.
- 44 Torri, D. (1987). A theoretical study of soil detachability. *Catena*, Suppl. 10, 15–20.

- 1 Wang, G.Q., Wang, X.Q., Wu, B., Lu, Q. (2012). Desertification and its mitigation strategy in China.
2 *Journal of Resources and Ecology*, 3 (2), 97–104.
- 3 Wang, J.H., Ma, Q.L., Yang, Z.H., Liu, H.J., Zhan, K.J. (2004). Space-time pattern and driving
4 mechanism of desertification land reversion in arid area. *Journal of Desert Research*, 24(6), 729–733.
- 5 Wang, J.L., Zhao, M.Q. (2008). Sand Sampler research analysis and reflection. *Journal of Agricultural*
6 *Mechanization Research*, 5, 216–218.
- 7 Wang, T., Wu, W., Xue, X. (2004). Temporal and spatial changes of desertified land in Northern China in
8 the past 50 years. *Acta Geographica Sinica*, 59, 203–212.
- 9 Wang, X.D., Yue, D.P., Liu, Y.B. (2005). Review of the Research on Soil Wind Erosion and Vegetation
10 Prevention. *Journal of West China Forestry Science*, 34(2), 108–112.
- 11 Wang, X.Y., Yuan, P.F., Ding, G.D., Shang, R.Y., Song, B.P., Zhang, Y.Q., Wu, B., Ma, S.L. (2008).
12 Study on mechanism between natural shrub-grass and soil wind erosion. *Research of Soil and Water*
13 *Conservation*, 15(5), 38–41.
- 14 Williams, J.D., Dobrowolski, J.P., West, N.E., Gillette, D.A. (1995). Microphytic crust influences on
15 wind erosion. *Transactions of the American Society of Agricultural Engineers*, 38, 131–137.
- 16 Wolfe, S.A., Nickling, W.G. (1993). The protective role of sparse vegetation in wind erosion. *Progress in*
17 *Physical Geography*, 17(1), 50–68.
- 18 Wolfe, S.A., Nickling, W.G. (1996). Shear stress partitioning in sparsely vegetated desert canopies. *Earth*
19 *Surface Processes and Landforms*, 21, 607–620.
- 20 Yang, M.Y. (1996). The analysis and study of determining earth surface rough degree. *Journal of Desert*
21 *Research*, 10(4), 383–387.
- 22 Yi, X.Y., Zhao, H.L., Li, Y.Q. (2007). Research progress on wind erosion control. *Chinese Journal of*
23 *Applied Ecology*, 18 (4), 905–911.
- 24 Yue, Y.J., Shi, P.J., Zou, X.Y., Ye, Y.X., Zhu, A.X., Wang, J.A. (2015). The measurement of wind
25 erosion through field survey and remote sensing: a case study of the Mu Us Desert, China. *Natural*
26 *Hazards*, 76(3), 1497–1514.
- 27 Zhang, B., Zhao, Q.G., Horn, R., Baumgartl, T. (2001). Shear strength of surface soil as affected by soil
28 bulk density and soil water content. *Soil & Tillage Research*, 59(3-4), 97–106.
- 29 Zhang, K.B., Zou, S.Y. (1989). *The Principle and Technology of Desert Control*. China Forestry
30 Publishing House, Beijing, pp.35–44.
- 31 Zhao, P.Y., Tuo, D.B., Zheng, D.W., Duan, Y., Li, H.C., Yan, W., Yao, J.Q. (2008). Study on the method
32 of quantitative observation on soil wind erosion in field. *Journal of Anhui Agricultural Sciences*,
33 36(29), 12810–12812.
- 34 Zhou, Y.L., Sun, X.M., Zhu, Z.L., Wen X.F., Tian, J., Zhang, R.H. (2007). Comparative research on four
35 typical surface roughness length calculation methods. *Geographical Research*, 26(5), 887–896.
- 36 Zimbone, S.M., Vickers, A., Morgan, R.P.C., Vella, P. (1996). Field investigations of different techniques
37 for measuring surface soil shear strength. *Soil Technology*, 9, 101–111.
- 38 Zobeck, T.M. (1991). Soil properties affecting wind erosion. *Journal of Soil and Water Conservation*, 46,
39 112–118.
- 40 Zobeck, T.M., Baddock, M., Pelt, R.S.V., Tatarko, J., Acosta-Martinez, V. (2013). Soil property effects
41 on wind erosion of organic soils. *Aeolian Research*, 10, 43–5.