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Aeolian Activities and Protective Effects of Artificial Plants in Re-vegetated Sandy Land of Qinghai Lake, China

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Abstract: Land desertification and aeolian activity are currently the greatest threats to alpine ecological environments and are also the primary challenges of desertification control and ecological restoration projects. Afforestation of sandy lands around the Qinghai Lake in China has effectively controlled the desertification of this watershed. However, certain issues remain which challenge its overall success, including lack of diverse biological species and poor theoretical understanding of aeolian processes, such as controlling wind-sand flow in relation to complex alpine ecological factors. Therefore, to help improving afforestation techniques, this research focused on *Hippophae rhamnoides*, *Salix cheilophila*, *Pinus sylvestris*, *Populus simonii* and *Artemisia desertorum* vegetation implanted in the mobile dunes on the eastern shore of Qinghai Lake. Aeolian transport characteristics and annual changes to community ecological factors from 2010–2016 were monitored in comparison with uncontrolled sand dunes. Based on simultaneous observations using gradient anemometers and sand samplers, it was found that the aeolian activities exhibited the following features: 1) In re-vegetated lands, the logarithmic growth of wind speed was disrupted by the wind speed amplification in the middle and high layers and wind speed reduction in the low layers, while vegetation had significant wind-breaking (> 37%) and sand-fixing (> 85%) effects in 2016. 2) Wind speeds in re-vegetated lands and mobile dunes showed a linear correlation, especially in lower layers of *H. rhamnoides* and *S. cheilophila*, while sand transport in re-vegetated land increased linearly or exponentially with increasing wind speed. 3) The four artificial shrubs and forests had greater sand deposition with intensities of 280–860 t/(ha·yr), largely concentrated during winter and spring which accounted for 60%–85% of the annual cycle, while *A. desertorum* experienced significant root undercutting; and 4) Intensity of aeolian activity in re-vegetated lands, except for *A. desertorum*, was significantly negative with respect to plant growth structure, community cover, topsoil moisture, and regional precipitation. Overall, these five sand-binding species produced optimistic wind-sand protection effects for the alpine sandy lands, which relied on the plants' physical disturbance of wind-sand flow during the early stages of community development. In comparison, *H. rhamnoides* and *S. cheilophila* individually maintained stable wind-sand protection effects, while *P. sylvestris* and *P. simonii* were better in mixing with other shrubs and herbs to achieve a comprehensive ecological system for future control of aeolian activity.

Keywords: artificial vegetation; protective effect; wind-sand flow; wind erosion intensity; vegetation-soil factor

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1 Introduction

Artificial afforestation is an important measure to prevent land desertification and restore the vegetation ecology of mobile sand dunes (Wolfe and Nickling, 1993). This approach is affordable, applicable, and effective in sand-fixation, and provides comprehensive socio-economic services (Pye and Tsoar, 2009; Ci and Liu, 2010). In past decades, various natural vegetations are regarded as research subject around the world, primarily in exploring their desert ecology adaption and vegetation community development. There are rarely close attention in artificial vegetation, neither in researches of field aeolian preventing mechanism and effects (Pasternak and Schlissel, 2001; Zhang et al., 2004). Sand-binding vegetation reduces wind energy through obstructive effects and actions such as the swinging of branches and leaves (Raupach and Lu, 2004; Zuazo and Pleguezuelo, 2008). In addition, these plants resist environmental stresses like drought, low temperatures, strong winds, and dust due to their unique physiological functions, which allow improvement of the local soil properties and microclimate, thus promoting the revival of natural vegetation. It is important to investigate the speed, stability, and complexity of ecological restoration via artificial plants compared with natural desert plants, especially for the revival of sand dune ecosystems (Nicoll, 1996; Moulton et al., 2018). At present, evaluation of the ecological restoration effect of sand-fixing plants is mostly focused on the adaptability and endurance of the artificially planted species for aeolian processes and soil environments (Li et al., 2013; Ewane and Lee, 2017). Furthermore, selection of afforestation species and evaluation of their protective effects are thought to be dependent on the characteristics of aeolian activity in forests and changes to the ecological factors (Arens, 1996). Therefore, the ability to summarize characteristics and trends of aeolian activities, and to assess the protective benefits of these forests against aeolian processes based on long-term monitoring would be strongly beneficial. This is extremely important for the formulation, refinement, and application of biological measures for desertification control (Li et al., 2014a; Zhang, 2017). Alpine mobile sand dunes are ecologically fragile, especially when facing severe risk of desertification. Current regional desertification control measures have some weakness, such as lack of knowledge of suitable afforestation species, slow rates of progress, relatively small areas of applicability, and inadequacies in theoretical guidance. Since the 1950s, only a few low-growing shrubs like *Hippophae rhamnoides*, *Caragana microphylla* and *Tamarix chinensis* have been used in artificial anti-desertification measures, applied in the form of living sand barriers, or strips and patches. These plants are usually tested and installed in low-lying lacustrine basins or shelterbelt networks with suitable site conditions, and have been mainly focused on protective benefits (Yang and Zhang, 1997; Zhao, 2015; Li et al., 2017). In comparison, research on features and mechanisms of re-vegetated lands' aeolian processes and protection effects are under-developed. In the desert artificial ecosystem, changes in aeolian environment inside the artificial re-vegetated lands are closely related to vegetation growth, as well as community succession and properties of sand surface soils (Wang and Lee 2015; Li et al., 2019). Therefore, it is necessary to conduct long-term field monitoring studies to investigate characteristics of sand transport within forests among different species at different wind speeds, and assess the changes in aeolian prevention and soil amelioration that accompany community succession.

Vegetation restoration effect is mainly influenced by the canopy and root, as the former disturbs surface airflow and reduces wind energy around a single plant, while the latter stabilizes soil to strengthen its ability of anti-erosion (Okin, 2008; Burri et al., 2012). In arid and semi-arid deserts, researchers have explored wind dynamics and sand flux features around vegetation, and developed models for evaluating erosion intensity using wind tunnel experiments (Leenders et al., 2011; Zhang et al., 2014a; Walter et al., 2017). Particularly in alpine sand land, the mechanisms of wind-sand activity and protective effects of vegetation are lacking in field experiment and long-term detection with multiple spatial scales (from single plant, vegetation community quadrat to artificial forests), additionally in understanding relationships between wind and sand changes and reactions within the overall artificial ecosystem (Zhang et al., 2014b; Li, 2018; Yang et al., 2019). Therefore, this study selected five re-vegetated lands featuring the artificial species *H. rhamnoides*, *Salix cheilophila*, *Pinus sylvestris*, *Populus simonii*, *and Artemisia desertorum* as representatives of alpine sandy land vegetation. Continual observation in the field of wind-sand flow characteristics and changes to the soil and vegetation community environments was carried out, mainly to assess: 1) the protective mechanism against wind and sand activity; 2) the ecological restoration effects induced from different plantation species; and 3) factors which may be changing re-vegetated lands' wind-sand environment. Innovatively, the three artificial vegetation species of *S. cheilophila*, *P. sylvestris* and *P. simonii* were firstly transplanted to Ketu Sandy Land for afforesting and field observing in plots. In particular, a continual monitor of aeolian activity change was focused on airflow structure, sand flux and vegetation community ecological interactions, and finally served to explore different artificial vegetation resistance and adaption to wind-sand hazards, and to evaluate their regional application for improving alpine desert-control system.

2 Materials and Methods

2.1 Study area

Ketu Sandy Land, located in the eastern shore of the Qinghai Lake in China (Fig. 1), is unique with its high altitude (3176–3340 m) and alpine climate; the average annual temperature and precipitation are 0.70 ℃ and 370 mm, respectively. Every spring and winter, the westerly wind has a velocity of over 4.5 m/s and a frequency of nearly 35%, leading a strong wind-sand activity in this sand area. Precisely because of such serious aeolian activity, Ketu Sandy Land develops the largest land degradation distribution with clumped mobile dunes around the lake. Since 2005, over 20 artificial vegetation species were transplanted into different types of sand dunes, and most of the shrubs and trees formed stable vegetation communities after 3–5 yr (Wu et al., 2019). After more than 10 years' afforestation and pilot construction, the sandy land becomes the most diverse artificial ecosystem and representative experimental demonstration area of alpine desert control.

2.2 Field experiment design

In 2009, we enclosed a field area of the Ketu Sandy Land containing six experimental plots of consistent primary topography and soil conditions (Table 1). The field was widely re-vegetated with artificial plants, all grafted to mobile sand dunes in 2009. The re-vegetated lands of *H. rhamnoides*, *S. cheilophila*, *P. sylvestris*, *P. simonii*, and *A. desertorum* were observed with respect to annual changes of regional environment factors, and compared with a bare mobile sand dune (LSD) for analyzing the artificial vegetation's ecological restoration potential.

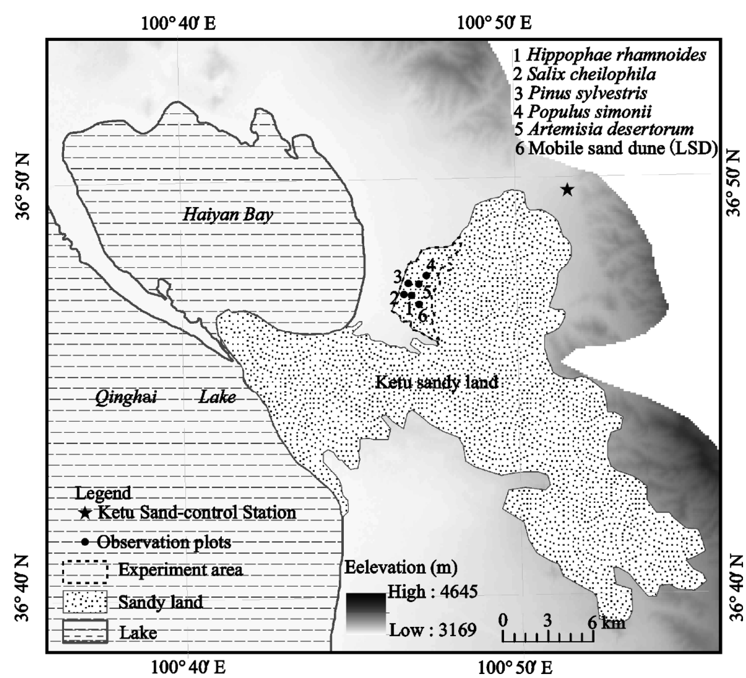

Fig. 1 Location of the Ketu Sandy Land and distribution of obervation plots

Table 1 Primary site conditions of each experimental plot of the Ketu Sandy Land in 2009

Site conditions	*H. rhamnoides*	*S. cheilophila*	*P. sylvestris*	*P. simonii*	*A. desertorum*	Mobile sand dune (LSD)
Altitude (m)	3187.52	3186.68	3183.27	3188.01	3185.53	3190.63
Slope degree (°)	1.20	4.57	3.12	3.46	1.99	3.36
Dune height (m)	5.49	6.43	3.45	6.48	3.78	7.43
Land area (ha)	7.02	3.39	1.84	2.86	3.33	2.31
Transplant technique	Seedling	Seedling	Seedling	Seedling	Direct seeding	–
Plant number per hectare	4500	5000	4500	2500	10000	–
Re-vegetated structure	Pure shrub	Pure shrub	Pure tree	Pure tree	Pure scrub	–
Survival rate (%)	63.47	76.44	77.28	57.61	70.52	–
Plant height (m)	0.43	0.59	0.25	1.06	0.29	–
Crown diameter (m)	0.42	0.24	0.28	0.58	0.22	–
Community cover (%)	25.74	35.68	38.00	16.43	62.86	–
Species number	2	3	3	2	3	0
Soil particle-size Φ	1.89	1.71	2.15	1.79	1.78	1.97
Soil moisture (%)	3.72	3.54.	3.09	3.45	3.67	2.88
Soil organic matter (g/kg)	9.86	10.65	8.05	9.56	15.73	5.48
Soil bulk density (g/m^3)	1.64	1.61	1.58	1.60	1.64	1.54

2.3 Methods

From 2009 to 2017, aeolian activity of each experimental plot was observed in every April and December. Specificly, wind speed was measured by field gradient anemometer (independently designed by Beijing Normal University) with nine cup-anemometers (RS485modbus, produced in China) vertically distributed at nine heights (0.1, 0.2, 0.5, 1.0, 1.5, 2.0, 2.5, 3.5, and 4.5 m). Wind data were sampled in 30-sec intervals and average values were registered every 10 min. Sediment transport amout was measured by vertical sand sampler (independently designed by Beijing Normal University) with 30 catchers (2 cm high × 5 cm wide) placed at 0–60 cm above the surface. Sand samples were collected every 10 min, and the process was repeated at least three times. The wind and sand collecting process were launched synchronously. We selected wind-sand flow datus of 2010 (1-yr-aged forests) and 2016 (7-yr-aged forests) as comparative time, since of the wind velocity data of 2017 was too small to induce blow sand.

Based on the plot of LSD (base point), the other re-vegetated lands' wind-sand activities (move point) were iteratively monitored in different field wind velocities. Since the shifting plots were measured at different time, a standardization Formula (1) allowed for simultaneous observation of updated wind velocity ($V'(z)$).

$$V'(z)=\frac{V_m(t_0,z=2)}{V_m(t,z=2)}\times V(t,z) \quad (1)$$

where V' (z) is the standardized wind velocity (m/s) at height z (m); and V_m (t_0, z = 2), V_m (t, z = 2) are the LSD measured wind velocity at 2 m height at time t_0 and t, respectively. V (t, z) is the wind velocity of other forest points at height of 2.0 m.

To analyze the wind increasing extent (C) of different vertical layers in wind profiles, a division of two layers was established, the 'below canopy' and the 'above canopy' (the canopy separatrix height changed with plants average growing height, the height of 1.0 m was for the *H. rhamnoides* and *P. sylvestris* plots, 1.5 m was for *S. cheilophila* plot, and 2.0 m was for *P. simonii*, *A. desertorum* and LSD plots), and their C values were marked as C_1 and C_2, respectively, given by the following Formula (2).

$$C=\frac{V_b-V_a}{V_a\times(b-a)}\times 100\% \quad (2)$$

where V_a and V_b are the wind velocities (m/s) at the height of a and b, respectively.

Compared with the referenced plot of LSD, every re-vegetated land wind-breaking effect I could be calculated by Formula (3).

$$I = \frac{V_n - V_m}{V_n} \times 100\% \tag{3}$$

where V_m and V_n are average wind velocity (m/s) of move points and base point at the same height layer, respectively. In details, the wind protective effect of the low (0–1.5 m), middle (1.5–2.5 m) and high layers (2.5–4.5 m) were differentiated as I_1, I_2, and I_3, respectively.

The sand samples were fetched back with valve bags from the sand catchers and weighted using a 1/1000 balance scale. The sand transport rate (*TR*, g/(cm^2·min)) was transferred from the total sand amount of the 30 catchers by the following Formula (4).

$$TR = \frac{\sum T_i}{s \times t} \tag{4}$$

where the T_i is the sand amount of the i layer fetcher (i :1, 2, 3···30), s (s = (60 × 5) cm^2) is the vertical sectional area of the sand sampler, and t (t = 10 min) is the time of collecting sand. In the vertical sand transport structure, three height layers were divided into the low (0–10 cm), middle (10–40 cm), and high (40–60 cm) layers, and the sediment discharge proportion for each layer was labeled P_1 (%), P_2 (%)and P_3 (%).

In January of 2010, 3–5 polyvinchlorid tubes (Pvc, 40 cm long, 3 cm in diameter) were inserted surface soil with 25 cm buried and 15 cm exposure in west slope, top and east slope of plots. Until to the December of 2017, We measured the exposure length (l) of tubes every month, and looked the exposure length change (Δl) of adjacent months as monthly erosion depth for judging wind erosion ($\Delta l < 0$) or sand deposition ($\Delta l > 0$). Beside the Pvc pipe, five 250 cm^3-volume plastic bottles were buried at the top of each plot for evaluating erosion or deposition amount (m, g: collecting sand and weighting every month). Based on seasonal aeolian activity difference, we calculated winter (January to March), spring (April to June),summer (July to September) and Autumn (Octorber to December) erosion intensity Q (t/(ha·yr)) given by Formula (5).

$$Q = \frac{\sum_{1}^{12} m_i}{s} \times 100 \tag{5}$$

where m_i (g) was the bottle sand amount in the i (i : 1, 2, 3···12) month, s (28.3 cm^2) was the sand entrance area of each bottleneck.

In addition, three vegetation community quadrats with 5 m × 5 m specification were installed at each re-vegetated land, and 80 cm deep soil profiles were dug for soil property test samples in the same positions with wind-sand activity observation points. In July of 2010 and 2017, we investigated the artificial vegetation community features for analyzing species diversity including coverage, species numbers, Shannon-Wiener index *etc*., and sent soil samples to experimental center of Qinghai University for grain size, moisture, soil bulk density and nutrients analyses. All meteorological datus were obtained from regional automatic weather station installed in LSD plot from the January of 2010 to the December of 2017.

3 Results

3.1 Wind environment

3.1.1 Wind profiles

Airflow movements within the re-vegetated lands were directionally disordered and graded in velocity. The wind profile was influenced by plant height and crown width, which resulted in wind speed differences vertically (Fig. 2). The layers below the canopy experienced a sustained, steadier, and weaker wind environment, compared to land surfaces of mobile sandy lands. Contrasting to the logarithmic patterns of LSD wind profiles, the vertical wind velocity of re-vegetated lands was affected by a variety of disturbances, primarily showing decreased accuracy of fit for logarithmic functions, and increased difference of the wind increasing extent (C) between different height layers (Table 2). Given the same period and height, C in the middle and low layers of re-vegetated lands was always lower than those of LSD. Plants with large crown widths and low ventilation coefficients (e.g., *H. rhamnoides* and *P. sylvestris*) usually developed ‘calm zones’ or ‘eddy zones’ behind and under canopy, which resulted in wind profiles with the lowest fit accuracy of logarithmic functions (R^2 < 0.80). In 2010–2016, the C value of below canopies (C_1) and above canopies (C_2) decreased dramatically almost in all re-vegertated lands, and the gaps between layers narrowed obviously.

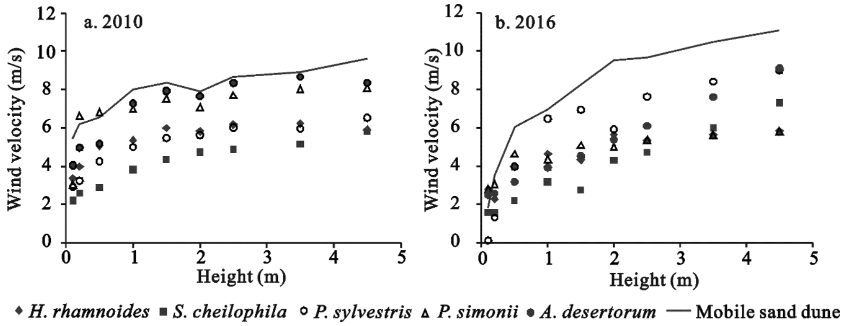

Fig. 2 Wind profiles of each plot of Ketu Sandy Land in 2010 (a) and 2016 (b)

Table 2 The plot wind profile feature and wind increasing extent (C, m/s) of different layers in Ketu Sandy Land

Plot	Year	R^2	C_1	C_2	C'
H. rhamnoides	2010	0.9268	3.48	0.27	1.48
	2016	0.8788	0.62	0.38	0.47
S. cheilophila	2010	0.9873	2.18	0.61	1.20
	2016	0.7879	1.31	0.93	1.07
P. sylvestris	2010	0.9568	2.69	0.51	1.33
	2016	0.8687	0.84	0.74	0.78
P. simonii	2010	0.7291	5.64	0.35	2.34
	2016	0.7345	2.47	0.49	1.23
A. desertorum	2010	0.9355	4.69	0.43	2.03
	2016	0.8021	1.40	1.47	1.45
Mobile sand dune (LSD)	2010	0.9501	3.81	0.45	1.71
	2016	0.9912	5.66	1.38	2.98

Notes: C_1 and C_2 are wind increasing extents below and above plant canopy relatively, C' is average wind increasing extent in the whole 4.5 m high, R^2 is logarithmic fit accuracy of wind profiles

3.1.2 Wind velocity relationships among plots

At each height layer, there was a linear correlation between wind velocities in re-vegetated lands and mobile sandy land (LSD). The differences manifested in the following traits (Fig. 3; Table 3): 1) when V_n at 2.0 m in LSD was less than 9 m/s, V_m at each height layer of re-vegetated lands was generally lower, and the significant linear correlation between V_m and V_n weakened as re-vegetated lands aged; 2) the fit accuracy of the linear model in descending order was low layer > high layer > middle layer (except in *A. desertorum* land). Compared to 2010, the fits of the middle and lower layers were substantially lower in 2016; and 3) the linear trend of each re-vegetated land indicated that the wind speed in *H. rhamnoides* lands was greater than that of mobile sandy lands at each height ($a > 1$), if the V_n reached a certain threshold. In 2016, this phenomenon was observed in the low and high layers of *S. cheilophila* land and the low layer of *A. desertorum* land. In 2016, the middle- and low-layer wind speeds of *P. simonii* land were negatively related with V_n.

3.1.3 Wind-breaking effect (I)

In 2010, differences in wind velocities between re-vegetated lands and LSD were relatively small (Fig. 4). Based on a stratification analysis, it was found that $I_1 > I_2 > I_3$ in all plantation plots, and the wind-breaking efficacies of the low layer were 2–7 times those of the middle layer. In particular, *P. sylvestris* and *S. cheilophila* had the largest I_1. The I values of *P. simonii* and *S. cheilophila* increased with increasing V_n, whereas the I values of *H. rhamnoides*, *P. sylvestris,* and *A. desertorum* decreased with increasing V_n. The I_3 values of all re-vegetated lands were less than 10%, with *H. rhamnoides* having the lowest value ($I_3 < 1\%$). In 2016, a sudden increase was observed in the I_1 of the re- vegetated lands; the layer of wind-breaking effects was *P. sylvestris* > *S. cheilophila* > *A. desertorum* > *H. rhamnoides* > *P. simonii*, in descending order. As V_n increased, the I_1 values of *H. rhamnoides* and *A. desertorum* gradually eclipsed those of *P. sylvestris* and *S. cheilophila*. In the

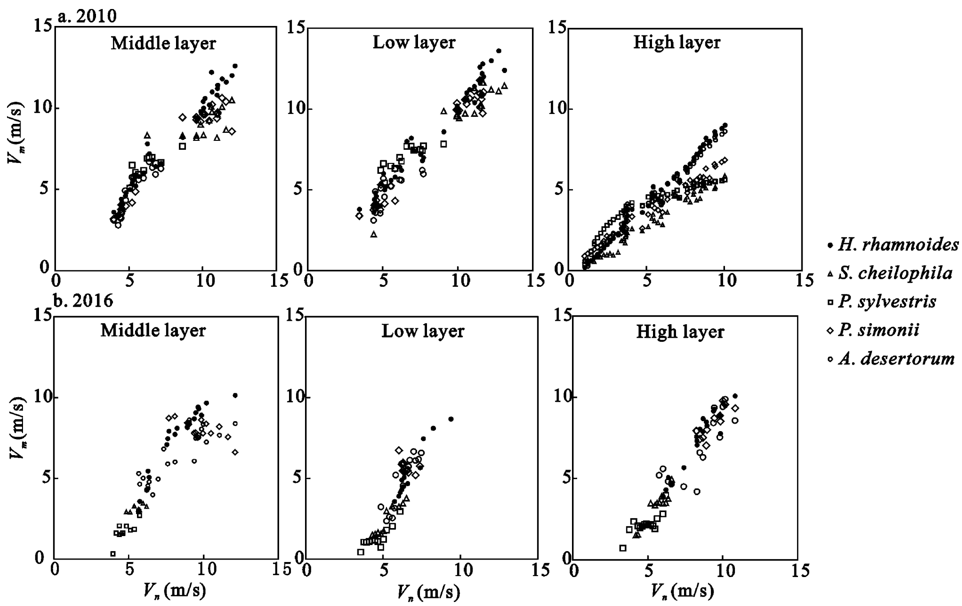

Fig. 3 Scattered distributions of wind velocity between the re-vegetated lands and mobile sand dune of Ketu Sandy Land in 2010 and 2016; V_m and V_n are wind velocities of re-vegetated lands and mobile sandy land, respectively

Table 3 Linear fitting model of wind velocity between the re-vegetated lands and mobile sand dune of Ketu Sandy Land in 2010 and 2016

Year	Re-vegetated lands	Low layer			Middle layer			High layer		
		a	*b*	R^2	*a*	*b*	R^2	*a*	*b*	R^2
2010	*H. rhamnoides*	0.97	−0.77	0.99	1.06	−0.46	0.97	1.03	−0.10	0.96
	P. sylvestris	0.47	1.48	0.85	0.59	2.75	0.67	0.50	3.73	0.71
	S. cheilophila	0.61	−0.33	0.97	0.33	5.76	0.30	1.03	−1.01	0.86
	P. simonii	0.65	0.22	0.98	0.95	−0.41	0.94	0.99	−0.43	0.97
	A. desertorum	0.88	−0.25	0.97	1.20	−1.53	0.78	0.73	0.95	0.63
2016	*H. rhamnoides*	1.46	−4.49	0.90	1.07	−1.32	0.88	1.29	−3.44	0.92
	P. sylvestris	0.74	−2.14	0.73	0.93	−2.67	0.65	0.63	−0.89	0.59
	S. cheilophila	1.14	−3.60	0.88	0.98	−2.42	0.71	1.19	−3.34	0.86
	P. simonii	−0.52	9.09	0.25	−0.36	11.56	0.55	0.96	−0.55	0.71
	A. desertorum	1.80	−6.37	0.78	0.72	0.43	0.76	0.99	−1.45	0.66

Notes: $V_m = aV_n + b$, V_m and V_n are wind velocities of re-vegetated lands and LSD, respectively; *a* and *b* are gradient and intercept of the fitted lines, respectively

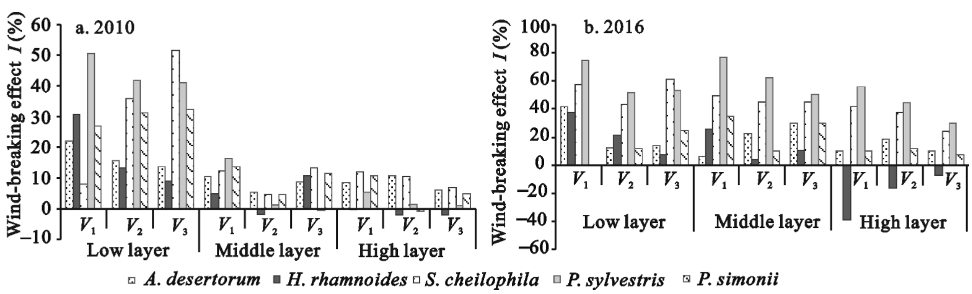

Fig. 4 The wind-breaking effect of artificial vegetation under three field wind velocities of Ketu Sandy Land in 2010 and 2016. V_1, 4–6 m/s; V_2, 6–9 m/s; V_3, 9–13 m/s

middle layer, the I_2 value of *P. simonii* increased most rapidly. In the high layer, the I_3 values of all re-vegetated lands decreased significantly, with the I_3 values of *P. sylvestris* and *S. cheilophila* decreasing by 10–30%. In summary, the wind-breaking effects of artificial vegetation were the most significant in the middle and low layers (18% < I < 76%), and species in descending order was *P. sylvestris* > *S. cheilophila* > *H. rhamnoides* > *A. desertorum* > *P. simonii*.

3.2 Sand transport characteristics

3.2.1 Sand transport structures

Changes of sand transport structures and wind profiles were synchronized in time, and these showed inversed functions between each other (Fig. 5). In re-vegetated lands, the sand transport amount in the lower layer (0–10 cm) accounted for a smaller proportion of the total sediment flux than in LSD, whereas the middle layer (10–40 cm) accounted for a larger proportion. When V_n was 9 m/s in 2010, the low layer of *A. desertorum* and *P. simonii* lands had the largest percentage of sand amount (P_1 > 80%), the other re-vegetated lands produced sand flow mainly accumulated in the middle layer (P_2 > 40%), whereas the high layer of all plots took the lowest (P <10%). Given the same field wind velocities in 2016, the P_1 values of *A. desertorum* and *P. simonii* lands reduced by 35%–60%, whereas slight increases occured in *H. rhamnoides* and *P. sylvestris* lands. During the same period, the P_2 and P_3 values of each plot increased by 10%–30%. These results indicated that plant growth and community development effectively improved the resistance of land surfaces against wind erosion.

Changes in sand transport rate (*TR*) directly revealed the sand-fixing effects of artificial vegetation in 2016 compared with 2010 (Table 4). When the V_n ranged from 8.0–9.0 m/s, the *TR* values of all re-vegetated lands experienced sharp declines with a scope of 40%–90%, particularly in the *H. rhamnoides* and *P. simonii* lands. In 2010, the *TR* values of re-vegetated lands were only 1/2 to 1/3 of LSD, but in 2016, the rate decreased to 1/40 to 1/8, thus, the artificial vegetation sand-fixing benefit increased by 14 to 40 times. Correspondingly, threshold wind velocity of sand movement (V_t) in re-vegetated lands increased by 0.5–1.5 m/s from 2010 to 2016. In contrast, the *H. rhamnoides* and *S. cheilophila* lands were better protected from wind erosion.

3.2.2 Sand transport amount at different wind velocities

There was usually positive correlation between the changes in sediment discharge and wind velocity. In LSD, sand transport amount usually increased exponentially with field wind velocity (Fig. 6). In re-vegetated lands, sand transport amount increased linearly with wind velocity in *H. rhamnoides* and *P. simonii* lands, whereas in other vegetation lands and LSD exhibited exponential increases. Based on the fitted growth models analysis, the increase trend of LSD was the most rapid, followed by *A. desertorum*, *P. simonii*, *H. rhamnoides*, *P. sylvestris*, and *S. cheilophila* lands. In comparison, the sand transport amount in *H. rhamnoides, S. cheilophila,* and *P. sylvestris* lands were 94%–98% lower than that in LSD, and these decreases were 30%–65% greater than those of *A. desertorum* and *P. simonii* lands. The extent of sand-transport-decrease (as compared to mobile dunes) expanded with increasing field wind velocity. In 2016, the relationship between sand transport amount in re-vegetated lands and wind velocity was generally dominated by positive linear relationships with mild slopes.

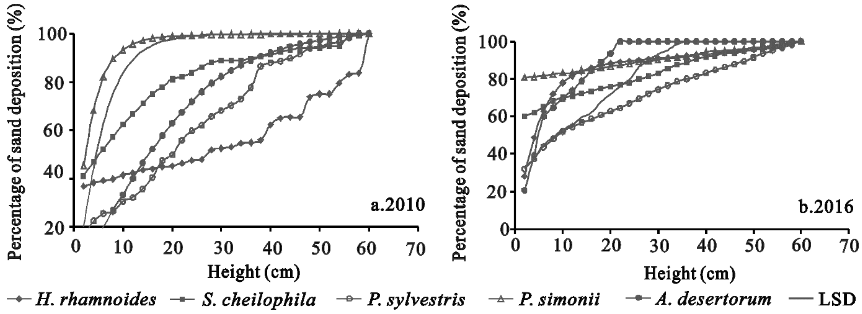

Fig. 5 Sand deposition percentage under a wind velocity of 9 m/s in different plots of Ketu Sandy Land in 2010 (a) and 2016 (b); LSD, mobile sand dune

Table 4 The sand transport rate (*TR*) and threshold wind velocity of sand movement (V_t) in each plot of Ketu Sandy Land

Plot	*TR* (g/(cm·min)) (V_n=8–9 m/s)		V_t (m/s)	
	2010	2016	2010	2016
H. rhamnoides	0.0051	0.0008	6.16	9.07
S. cheilophila	0.0021	0.0014	6.70	9.48
P. sylvestris	0.0082	0.0008	6.30	8.13
P. simonii	0.0118	0.0017	6.27	8.56
A. desertorum	0.0208	0.0066	6.00	8.59
Mobile sand dune (LSD)	0.0663	0.0688	5.40	6.32

Note: V_n means the field wind velocity of LSD at 2.0 m, V_t means the threshold wind velocity of sand movement

3.2.3 Wind erosion and sand deposition intensity

Compared with mobile dune (LSD), the surface of re-vegetated lands encountered weaker wind erosion and heavier sand accumulation, which demonstrated impressive wind-breaking and sand-fixing benefits. In erosion/deposition intensity (Table 5), the four artificial trees and shrubs had greater sand deposition with intensities of 280–860 t/(ha·yr), largely occurring during winter and spring, which accounted for 60%–85% of the calendar year. In contrast, the *A. desertorum* land was eroded with an intensity of 400 t/(ha·yr). Over the last seven years, sand accumulated on the surface of re-vegetated lands with a depth of 0.5–2.7 cm/yr, especially at the top position of sand dunes. Under the same circumstances, the *S. cheilophila* and *P. simonii* sand dunes had larger sand deposition than the *H. rhamnoides* and *P. sylvestris* lands, while the *A. desertorum* land experienced significant root undercutting.

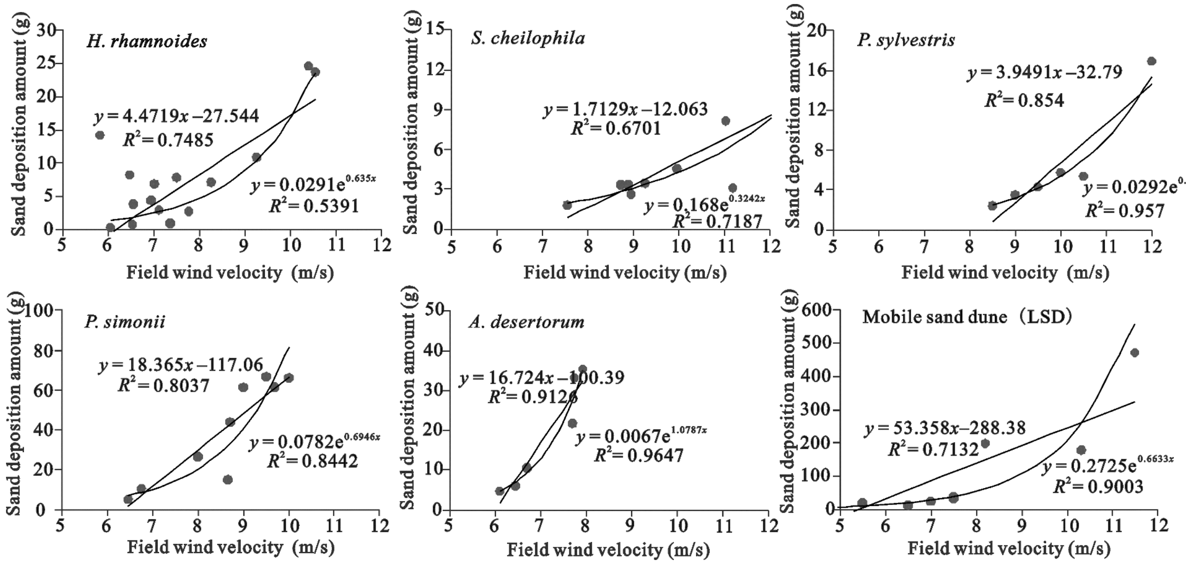

Fig. 6 Sand transport amount of different plots in different field wind velocities in Ketu Sandy Land

Table 5 Wind erosion/deposition intensity and sand deposition depth of each plot of Ketu Sandy Land from 2010 to 2017

Plot	Seasonal erosion/deposition intensity *Q* (t/ha)				*Q′* (t/ha)	Annual sand deposition depth (cm)		
	Winter	Spring	Summer	Autumn		West slope	Top	East slope
H. rhamnoides	93.63	84.82	66.51	35.81	280.77	1.07	0.30	0.43
S. cheilophila	109.82	122.72	42.31	90.13	364.98	1.27	2.00	1.90
P. sylvestris	82.42	85.19	34.44	90.25	292.30	2.67	2.17	1.00
P. simonii	588.85	83.65	113.47	73.52	859.50	0.77	1.30	0.67
A. desertorum	−180.90	−156.65	36.23	−98.31	−399.63	−0.93	−1.17	0.27
Mobile sand dune (LSD)	−18660.51	−4115.87	−2429.47	−8711.02	−33916.86	−110	−137	−77

Notes: *Q′* means annual deposition intensity; the positive value means sand deposition; negative value means wind erosion

3.3 Natural factors affecting aeolian activity

3.3.1 Vegetation community

The aeolian activities of re-vegetated lands were deeply influenced by regional climate, soil properties and artificial vegetation community features and their interactions. From previous investigations and data organization of these six plots ecosystem changed from 2010 to 2017 (Fig. 7), each artificial vegetation had different adaptability for wind-sand environmental stresses like aeolian processes and droughts. In fact, the growth trends of artificial plants and the features of community succession directly determined the plants wind-breaking and sand-fixing capabilities. Compared with 2010, the number of species in each re-vegetated land increased from 5 to 9 in 2017, while community coverage increased by 5 to 16-fold, and the Shannon-Wiener diversity index also increased by 40%–80%. Meanwhile, the surface roughness (z_0) of re-vegetated lands was increased by 1–10 times, causing sand transport rate to decrease by 40%–85% during 2010–2017. Under the field wind velocity of 8.5–9.0 m/s, the artificial vegetation wind-breaking and sand-fixing functions had relatively increased by 10%–30% and 35%–75%. According to correlation analysis (one-way ANOVA), most of the re-vegetated lands displayed positive correlations between wind-sand proof benefits and vegetation growth structures, and community coverage and diversity, particularly in *S. cheilophila*, *P. simonii*, and *P. sylvestris* lands. Comparatively, *A. desertorum* lands showed a weaker relationship with surface roughness and sand transport intensity.

3.3.2 Soil properties

The re-vegetated lands soil properties determined the wind erosion resistance of surface soils (Zhao et al., 2012). In 2010–2017 (Fig. 7), the average particle size of each re-vegetated land was slightly refined, the soil organic matter, water moisture, and soil nutrients were increased by different scales with species variation. According to all soil indices, *S. cheilophila* produced the best soil amelioration, while the soil property improvements

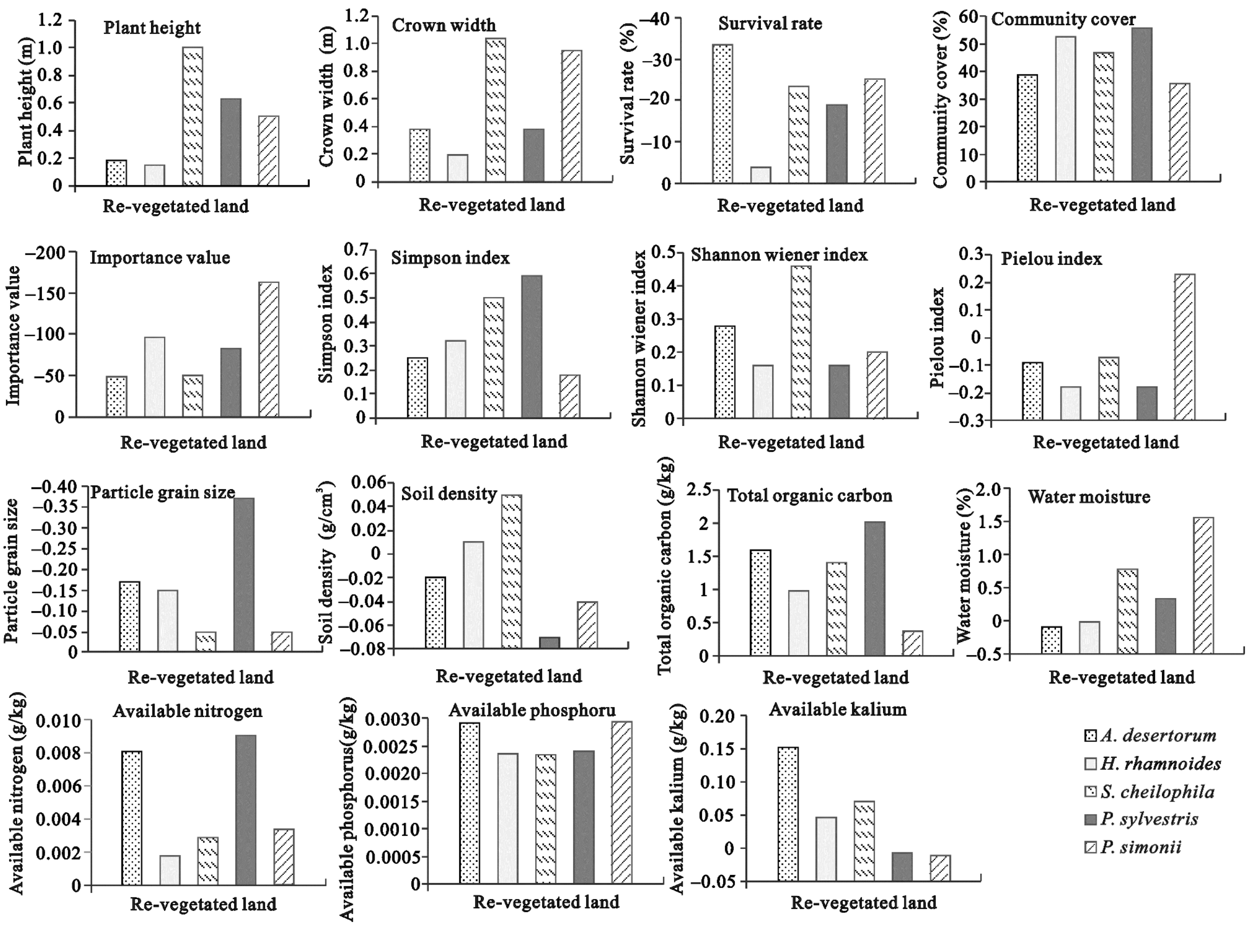

Fig. 7 Soil and vegetation community feature changes from 2010 to 2017 in different re-vegetated lands of Ketu Sandy Land

of *P. sylvestris* and *P. simonii* lands were relatively focused on the organic matter and soil water moisture. In the same period, the sand transport rate decreased yearly for all five plantation plots, and exposed obviously negative correlations (–0.98 < *CR* < –0.72) with soil nutrients and organic matters (Table 6), while showed mildly positive correlations (0.32 < *CR* < 0.92) with soil density and grain size. Indeed, the annual *TR* and erosion intensity declined with increasing soil water content. According to annual investigations of sand deposition intensity and topsoil (0–80 cm) moisture (Fig. 8), linear increasing trends between the two indications were significantly reflected (0.55 < R^2 < 0.90, P < 0.05) in the five re- vegetated lands, particularly in the *P. sylvestris* and *A. desertorum* lands.

3.3.3 Climate factors

The re-vegetated lands wind erosion was derived largely by sand-blowing wind velocity and frequency. From 2006 to 2017, the mobile sandy lands in this area was significantly linearly correlated with the average regional wind frequency (R^2 = 0.785) and exponentially related to average sand-blowing wind velocity (R^2 = 0.816) (Fig. 9). Furthermore, wind energies and sand transport intensities in re-vegetated lands maintained statistically positive correlations with the regional wind factors throughout this period. In terms of temperature and precipitation, the re-vegetated lands' threshold wind velocity and erosion intensities changed unpredictably without definite correlations. However, when in strong wind-sand activity years like 2009–2012 and 2015–2017, the precipitation and annual average temperature were always at a low value and kept a decreasing trend. In comparison, the *P. sylvestris* and *A. desertorum* lands' wind erosion had more insensitive feedback with regional precipitation.

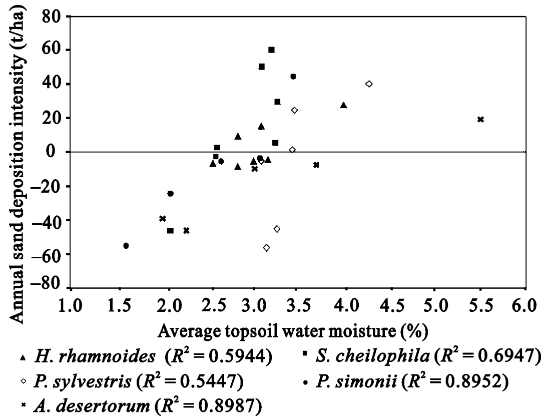

Fig. 8 Scatter distribution of annual sand deposition intensity with change of average topsoil water moisture in Ketu Sandy Land. R^2 means fitting accuracy of linear curves between topsoil sand deposition intensity and moisture

Table 6 Relationships (*CR*) between sand deposition intensity and soil properties in Ketu Sandy Land

Plot	Soil density	Percentage of silt and clay	Organic matter	Average sand grain size	Soil water moisture
H. rhamnoides	0.6219	−0.7245	−0.8221	0.3166	0.3905
S. cheilophila	0.6159	−0.7548	0.2349	0.8790	0.5425
P. sylvestris	0.5924	−0.7580	−0.7230	0.6541	−0.1288
P. simonii	0.6397	−0.8166	−0.9798	−0.5068	−0.7581
A. desertorum	0.9228	−0.9066	−0.8824	0.9859	−0.9989

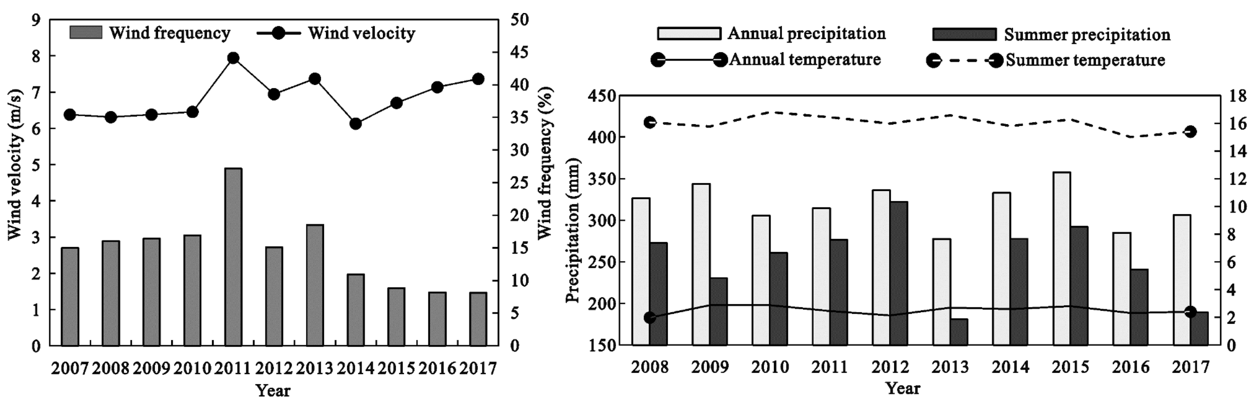

Fig. 9 Regional climate environment changes from 2010 to 2017 in re-vegetated lands of Ketu Sandy Land

4 Discussion

4.1 Wind-sand prevention mechanisms

In previous studies, the re-vegetated lands' wind-sand prevention mechanisms intrinsically relied on disturbing the wind profile law and increasing sand surface roughness (Buckley, 1987; Allgaier, 2008). With artificial plants' continued growth, the effective protection height and distance against headwind doubled and redoubled (Musick et al., 1996; Jakolien et al., 2011). In this study, the surface airflow and sand movement of re-vegetated lands experienced changes of wind direction and decreases of wind velocity, therefore, various plant sandpiles built up due to the different wind erosion and sand accumulation intensities. The *H. rhamnoides* and *A. desertorum* showed significant thicket effects around stem and concaves among four plants, however the other vegetation species mainly encountered weaker wind erosion and only moderate deposition (Wu, 2018). The formation process of sandpiles reflected weak trends of the wind-sand activity, and prominent effects of wind-prevention and sand-fixation.

For another, annual changes of wind-sand activity are sensitive and coadjutant to vegetation community development (Mclntyre, 1999; Greene, 2010). Analogous to the other sand-control deserts in China, the land surface sand transport rate and the degree of wind velocity decrease of alpine artificial shrubs and forests are positively related with community cover, diversity, and soil moisture, especially during the primary period of community development (Zuo et al., 2012; Li et al., 2014b). Based on our results, *S. cheilophila* exhibits rapid growth in plant height and develops flexible branches, and *S. cheilophila* lands have the highest community diversity, thus the sand dunes are able to retain stability and experiences only mild erosion and deposition. *P. sylvestris* and *H. rhamnoides* have dome-shaped canopies, thick soil crusts, and abundant litters, leading to significant wind speed reduction and soil amelioration. *P. simonii* has very few low branches and leaves, which results in weak sand accumulation around its roots and the 'funnel effect'existing in the airflow below the crown. The *A. desertorum* exhibits the unique ability of seed rebirth and breeding every year, while the community coverage increases quickly and forms relatively large sandpiles. However, due to its short structure, simple species configuration, and high death rate, the *A. desertorum* community was found to be extremely susceptible to soil drought and strong wind; therefore, these aeolian activities continue to threaten the *A. desertorum* lands (Wu 2018; Yang 2019).

4.2 Peculiarity of aeolian activity in alpine re-vegetated land

Compared with other artificial vegetation in arid and semi-arid deserts of China, the ability of alpine vegetation to prevent wind-sand flow is peculiar, including: 1) the preventing process is limited due to the slow growth of plants and time needed for optimal community development. The effective wind-prevention height is less than 2.0 m, and the horizontal distance against the windward direction behind plants ranges from 2–8 m, reflecting a large airflow difference above and below plant canopy (Tian et al., 2020). 2) the land surface around each plant experiences a stable and balanced aeolian process, which forms staggered features of erosive ditches, concaves, and sand ridges, useful for promoting natural seed breeding and community diversity. 3) considering ecological adaptation and reaction to environmental changes, alpine plants were found to be more sensitive to wind erosion and sand deposition intensity during the seedling and primary growth periods, and gradually became restricted by soil water content and community species competition during the elite and mature stages (He, 2018). 4) Through root breeding and expansion, and underground energy storage and transfer processes, the artificial plants could protect themselves from strong wind and sand hazards, mainly through enhancement of the stem and root renewing speed, leaf photosynthetic rate, and water use efficiency, which are different for arid and semi-arid afforestation regions.

Besides areal difference of wind-sand preventing mechanism, there also some unique biological sand-control techniques directed by aeolian activity theories (Cornelis et al., 2005). Most pure and mixed vegetation sand-binding models in alpine deserts require regular planting specifications, including higher plant density with smaller intervals between plant belts, more economical herb species, and replanting technology of shrub branches cutting (Di et al., 2018; Liu, 2019).

5 Conclusions

The five sand-binding plants produced optimal wind-sand protection effects in the alpine deserts. Artificial vegetation altered the logarithmic growth of wind profiles, resulting in lower wind velocities at lower layers and higher wind velocities in the middle-high layers. Artificial vegetation has significant wind-breaking effects (> 37%) in the lower and middle layers, the sequence from high to low was as follows: *S. cheilophila* , *P. sylvestris*, *P. simonii, H. rhamnoides*, and *A. desertorum* lands.

In corresponding with wind-breaking function, the sand transport rate of all re-vegetated lands exhibited sharp declines with a scope of 40%–90%, while their threshold wind velocity of sand movement increased by 0.5–1.5 m/s, and their sand-fixing effects (> 85%) increased by 14 to 40 times, with *P. simonii* and *H. rhamnoides* being the most effective. For these species, with an increasing field wind velocity, the extent of sand-transport-amount (as compared to mobile dunes) continuously decreased, and deposition intensity increased to 280–860 t/(ha·yr), promoting sand dunes stabilized and re-vegetated quickly from 2010 to 2016.

In terms of the impact factors, aeolian activity was closely related to ecological response with the vegetation community environment. Wind decreasing extent and sand deposition intensity were significantly negatively correlated with the plant growth structure, community cover, topsoil water moisture, and regional precipitation. In the earlier stage, survival and physical growth of plants directly affected the re-vegetated lands' ability to resist wind-sand hazards. However, in the later-stage, the growth of vegetation community took the leading role. Accordingly, the *H. rhamnoides* and *S. cheilophila* are thought to be the most effective species for effective regional afforestation, while the *P. sylvestris* and *P. simonii* may be mixed with other shrubs and herbs to achieve a comprehensive ecological system for future control of aeolian activity.

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