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Abstract

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Full Text

Preamble

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Morphological Change and Migration of Revegetated Dunes in the Ketu Sandy Land of the Qinghai Lake, China

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Abstract: Alpine revegetated dunes have been barely researched in terms of morphological change and migration within their regional aeolian environments. To reveal the sand-fixing and land-reforming mechanisms of artificial vegetation, we observed the morphology and migration of four dunes with four revegetated types (*Hippophae rhamnoides* Linn., *Salix cheilophila* Schneid., *Populus simonii* Carr., and *Artemisia desertorum* Spreng.) using unpiloted aerial vehicle images and GPS (global positioning system) mapping in 2009 and 2018. Spatial analysis of GIS (geographic information system) revealed that the revegetated dunes exhibited a steady progression from barchan dune shapes to dome or ribbon shapes mainly through knap planation, wing amplification, and slope symmetrization. Generally, conditions of northern aspects, smaller slope degree, and larger altitude of unvegetated dunes would suffer more serious wind erosion. The southward movement of dune wings with a migration speed of 2.0–5.0 m/a and the alternating motion of sand ridges in east-western directions led to greater stability in revegetated dunes. The moving distances of revegetated dunes remarkably changed in patterns of quadratic or linear function with depositional depth. Compared with unvegetated dunes, the near-surface wind velocity of revegetated dunes decreased by 20%–30%, which led to heavy accumulation in low-flat dunes and erosion in high-steep dunes, but all vegetation species produced obvious sand-fixing benefits (100%–450% and 3%–140% in the lower and higher dune scales of revegetated dunes, respectively) with decreasing sand transport rates and increasing coverages. In practice, the four vegetation species effectively anchored mobile dunes by adapting to regional aeolian environment. However, future revegetation efforts should consider optimizing dune morphology by utilizing *H. rhamnoides* as a pioneer plant, *S. cheilophila* and *P. microphylla* in windward and northward dune positions, and *A. desertorum* in a sand accumulative southward position. Also, we should adjust afforestation structure and replant some shrub or herbs in the higher revegetated dunes to prevent fixed dune activation and southward expansion.

Keywords: artificial vegetation; dune morphology; migration; aeolian factor; species difference

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1 Introduction

Revegetated dunes represent a manually restored dune type that is ecologically rehabilitated through artificial vegetation establishment. This dune pattern typically indicates heavy aeolian activity requiring urgent sand fixation control (Wang, 2000; Wang and Zhao, 2005). Revegetation alters dune morphology by influencing surface airflow, wind erosion, and sediment transport (Leenders et al., 2011; Follett and Nepf, 2012; Hesp et al., 2019). As vegetative growth progresses, revegetated dunes become fixed or semi-fixed, leading to obvious differences in dune morphology and migration compared to their pre-revegetation state (Durán and Herrmann, 2006; Barchyn and Hugenholtz, 2012). Subsequently, these dunes gradually develop into longitudinal or dome dunes as aeolian activity weakens (Zhu, 1963; Qian et al., 2019). Although the long-term ecological restoration effects of revegetation remain uncertain, they may be predicted through observations of dune morphology and aeolian characteristics (Miyasaka et al., 2014).

Previous research has primarily examined the geometric characteristics and morphodynamic processes of dunes in their bare state, without implementing any control measures (Anthonsen et al., 1996; Liu et al., 2018; Bhadra et al., 2019; Xiao et al., 2021). In China, the morphological evolution of sand dunes—including barchan, linear, and dome dunes—has been comparatively studied. Dome-shaped dunes may evolve into barchan dunes, and the latter can develop into linear dunes under the influence of wind regime, drift potential, sand supply, and migration rate (Momiji et al., 2002; Rozier et al., 2019). Additionally, natural sandy vegetation may play an important role in the formation of nebkhas, as well as linear and parabolic dunes (Hasi et al., 2013; Samuel et al., 2022). Artificial vegetation communities conserve soil and water by restraining sand blowing and wind erosion (Xu et al., 2015). Microtopography and microclimate lead to aeolian differences in various parts of revegetated dunes, such that strong wind erosion typically occurs in the upwind portion and dune knap, while heavy sand accumulation appears in the downwind portion and bilateral slope toes (Gillies et al., 2014; Walker et al., 2022). Therefore, studies of revegetated dune morphology and aeolian feature changes should focus on vegetation-air-soil interactions (Pike et al., 2009; Li et al., 2021; Yamasaki et al., 2021).

Remote sensing image sources such as Landsat, Google Earth, SPOT (small programmable object technology), and QuickBird are widely used for large-and medium-scale dune identification and quantification (Bubenzer and Bolten, 2008; Hugenholtz et al., 2012). Traditional field observation and gauging methods such as DGPS (differential GPS), 3D laser scanning, UAV (unmanned aerial vehicle), and fingerprint techniques are employed for vegetated dune morphology observation and 3D modeling (Louis, 2019; Rominger and Meyer, 2019; Zheng et al., 2022). Advanced field gauging devices can improve the resolution of small-scale dune morphology and migration observation in revegetated areas (Telbisz and Orsolya, 2018).

Sandy lands in China experience high frequency and velocity of sand-moving winds, causing strong wind erosion and sand burial in alpine barchan and dome dunes (Zhang et al., 2018; Pang et al., 2020; Hu et al., 2021; Cao et al., 2022). However, there is a lack of morphological and aerodynamic analysis of revegetated dune formation and evolution associated with aeolian factors (Li et al., 2017; Chang et al., 2021). Therefore, we examined the morphology and migration characteristics of revegetated alpine dunes through detailed analysis of dune scales and positions and vegetation species differences, with the aim of identifying the relationships between regional microtopography and aerodynamics with vegetation, and making further predictions of revegetated dune evolution and stabilization.

2.1 Study Area

The Ketu Sandy Land is located on the eastern shore of Qinghai Lake in northwestern China (Fig. 1a [Figure 1: see original paper]). The local climate integrates the East Asian monsoon with the northwestern arid and alpine climate of China. Data from the regional meteorological station indicate a cold, windy, and semi-arid climate, with an annual mean temperature of 0.7°C and precipitation of 370.0 mm. The prevailing northerly wind has a velocity exceeding 4.5 m/s and a frequency of nearly 35%. Strong wind-sand activity in this sandy land is reflected by a high sand drift potential of nearly 300 VU/a, dominated by west and northwest wind directions (Zhang et al., 2016). Large areas of the Ketu Sandy Land belong to severe and extremely severe desertification lands, and mainly consist of short barchan dunes, mega-dunes, and transversal sand ridges. Since the early 1980s, the local government has implemented numerous measures, including enclosure, mechanical barriers, and vegetation afforestation, to control desertification and accelerate ecological restoration. Since 2008, over 20 artificial vegetation species have been transplanted to different types of sand dunes. Most revegetated dunes developed into vegetation communities after 3–5 years, becoming a vegetative experimental demonstration area (VEDA) of alpine desert control (Wu et al., 2019).

Fig. 1 Location of study area (a) and design of sample dunes (b and c) in the Ketu Sandy Land of the Qinghai Lake, China. Hr-1, Hr-2, and Hr-3, *H. rhamnoides* dunes; Sc-1, Sc-2, and Sc-3, *S. cheilophila* dunes; Ps-1, Ps-2, and

Ps-3, *P. sylvestris* dunes; Ad-1, Ad-2, and Ad-3, *A. desertorum* dunes; CK-1 and CK-2, reference sand dunes. The abbreviations are the same in the following tables and figures.

2.2 Sample Design

In September 2008, four revegetated dune types (*H. rhamnoides*, *S. cheilophila*, *P. sylvestris*, and *A. desertorum*) in the VEDA were selected as sample dunes (Fig. 1b and c). They were almost purely bare shifting dunes with similar regional aeolian climate and soil properties before plantation. Two or three topographic scales (low-flat scale, medium scale, and high-steep scale) were arranged for each revegetated dune type, differing in primary dune absolute height, relative height, and slope gradient (Table 1). Additionally, two shifting bare dunes (CK-1 and CK-2) were established as reference sand dunes. All sample dunes were originally barchan formations stretching from northeast to southwest, with windward slopes facing northern and northwestern directions.

2.3.1 Dune Morphology and Migration

In October 2009 and 2018, high-resolution images of the VEDA were obtained by UAV (Dajiang Spirit 4, Shenzhen Dajiang Innovation Technology Co. Ltd., Shenzhen, China), equipped with a camera lens of 4 mm focal length. We controlled a flying height of 120 m and a tracing velocity of 3 m/s. The UAV camera took photos vertically with a shooting interval of 3 s, ensuring both course overlap and lateral overlap higher than 70%. During these periods, we used a GPSmap 60CSx global positioning system receiver (Garmin, 2D positioning accuracy of 1.0 m) to track the dunes' outer edges, slopes, and sand ridges at an average interval of 5 m (Zhang et al., 2018). All GPS sampling data were matched and corrected with UAV image points. After importing the UAV images to PhotoScan software and performing a series of image processing steps including target point alignment, mesh generation, and texture recognition, we obtained digital orthoimages (DOM) and 3D terrain data for all sample dunes. The DOM and GPS sampling points were then managed with ArcGIS v.10.2 software to extract various dune morphology parameters such as sand dune area (A, m^2), dune ridge length (L_0, m), bilateral slope degrees (S_1, westerly slope degree, °; S_2, easterly slope degree, °), and slope lengths (L_1, westerly slope length, m; L_2, easterly slope length, m). When each sample dune's spatial position and outline were extracted and overlaid with 3D terrain elevations (E), the dune's absolute height (H_0) and relative heights (H_1 and H_2) were identified using Equation 1. In the differences between the two periods' DEM (digital elevation model) data (ΔE), the erosion positions ($\Delta E<0$) and sand deposition positions ($\Delta E>0$) of sample dunes were clearly presented in the changed elevation grid net under the spatial analysis function of ArcToolbox.

where H_0 (m), H_1 (m), and H_2 (m) are the elevation differences between the highest point of the dune knap (E_0, height above sea level) and the base point (EB, beside the road approaching the lake level altitude), the lowest point of the westerly slope toe (E_1), and the easterly slope toe (E_2), respectively.

Dune volume (V, m^3) was calculated using the surface function of 3D Analyst Tools in ArcGIS v.10.2. By performing volume subtraction between the two periods (ΔV), the sand expansion area ($\Delta V>0$) and direction were determined, and sand deposition amount (W) and intensity (Wi) were calculated using Equations 2 and 3. Migration of different dune positions was determined by comparing the two periods' spatial locations of outline edges and sand ridges, with annual migration speed (M, m/a) averaged from 5–10 space distance lines under spatial distance analysis in ArcGIS v.10.2.

where , A, and n are the dunes' soil density (kg/m^3), vertical projected area (m^2), and number of years, respectively. If W and Wi are larger than 0, it indicates sand deposition; conversely, it indicates wind erosion and sand transport.

2.3.2 Wind Velocity and Direction

In December or March of 2009 and 2018, five sets of portable anemometers (with a self-counting wind speed interval of 30 s and errors of velocity and direction less than 0.5 m/s and 5°, respectively) were applied to collect surface wind velocity and direction. One set was installed at a fixed height of 1.0 m to serve as a base station for mobile point calibration under the same time (Eq. 4), while the other four sets were installed on a homemade bracket (steel material, 2.5 m high) as a mobile device, placed on four side bars of the bracket at heights of 0.5, 1.0, 1.5, and 2.0 m, respectively. The fixed device stood at the base point, and the mobile device worked at each sample dune part including the knap, easterly and westerly toe-slope and mid-slope, and north and south wings. Wind data exceeding 6.0 m/s averaged over continuous 10-min periods were screened for comparisons of dune position, vegetation species, and yearly change. Threshold wind velocity of sand-driving (Vt) for all sample dunes and surface roughness (z_0, Eq. 5) were observed and calculated from field wind profiles.

$V'(z) = V(t, z) \times [Vm(t_0, z=1) / Vm(t, z=1)]$

where V'(z) is the standardized wind velocity (m/s) at height z (m); $Vm(t_0, z=1)$ and $Vm(t, z=1)$ are the measured wind velocities at the base point at 1 m height at times t_0 and t, respectively (m/s); and V(t, z=1) is the wind velocity at revegetated dune points at 1 m height (m/s).

$z_0 = (z_1 - z_2) / \ln(V_{2\cdot0}m / V_{0\cdot2}m)$

where $V_{2\cdot0}m$ and $V_{0\cdot2}m$ are the wind velocities at heights z_1 and z_2, respectively (m/s).

2.3.3 Sediment Transport and Deposition

From 2009 to 2018, sand transport amount was measured using a vertical sand sampler with 30 catchers (2 cm high × 5 cm wide) placed at different dune positions. Each sampling event collected sands from wind-sand flow for 10 min, with the work repeated at least three times. Sand samples were then retrieved with valve bags from the sand catchers and weighed using a 1/1000 balance scale. Sand transport rate (TR, g/(cm^2 • min)) was calculated from the total sand amount of 30 catchers using Equation 6.

$$TR = (\Sigma Ti) \ / \ (s \times t)$$

where Ti is the sand amount from the i-th layer catcher (i=1, 2, 3, …, 30); s is the vertical sectional area of the sand sampler (s=300 cm^2), and t is the collection time (t=10 min).

In January 2010, 3–5 polyvinylchloride (PVC) tubes (40 cm long and 3 cm in diameter) were inserted into surface soil with 25 cm buried and 15 cm exposed in the westerly slope, top, and easterly slope of sample dunes. We measured the exposure length (l) of tubes monthly and tested the exposure length change (Δl) over the past 10 years to judge wind erosion ($\Delta l<0$) or sand deposition ($\Delta l>0$). In addition to PVC pipes, five 250 cm^3 plastic bottles were buried at the top of each plot to evaluate erosion (collecting sand) or deposition amount (weighing monthly). Based on seasonal aeolian activity differences, we calculated yearly deposition intensity Wi (t/(hm^2 • a)) using Equation 7.

$$Wi = (\Sigma mi) \ / \ (s \times n)$$

where mi is the bottle sand amount in month i (i=1, 2, 3, …, 12) (g); and s is the sand entrance area of each bottleneck (28.3 cm^2).

To analyze significant differences and relationships among morphology, migration, and aeolian activity, we used Origin v.18.0 software for significance testing (t-test and P-value) and curve fitting (R^2, fitting coefficient). Correlations from bivariate analysis (correlation coefficient, r) and one-way ANOVA (analysis of variance) were used to explain parameter differences.

3.1.1 Shape, Area, and Volume

Most barchan dunes developed into dome or ribbon dunes, with two-dimensional area (A) and volume (V) changes of revegetated dunes being more stable than those of reference dunes. Sand dune area variation (ΔA) between 2009 and 2018 showed a slight increase ($\Delta A<0.2$ hm^2) in most dunes, except for low-flat scales of *S. cheilophila* and *A. desertorum* dunes (Fig. 2 [Figure 2: see original paper]). Positively correlated with 2D-area (r>0.88), dune volume mainly showed increases of 0.01\$$\times10^{\{6\}-0.20\times10}$\{6\}\$ m^3, except in some high-steep scales of *H. rhamnoides*, *S. cheilophila*, and reference sand dunes. In general, most low-and medium-scale dunes expanded horizontally, demonstrating obvious sand accumulation functions.

Fig. 2 Area (A) and volume (V) of the sample dunes in 2009 and 2018.

3.1.2 Height and Slope

Artificial vegetation affected the outline edge position and shape of the dunes. Over the past decade, H_0 (absolute height) values of *H. rhamnoides* and *S. cheilophila* dunes changed less than those of other sample dunes (0.5 m<H_0<1.8 m) (Figs. 3 and 4a). H_0 of higher dunes consistently experienced greater reductions than those of lower and medium dunes ($0.010<P<0.014$). Additionally, variations in H_1 (relative height; 0.5 m<ΔH_1<1.2 m) were larger than those in H_2 (relative height; –1.5 m<ΔH_2<0.0 m) for the majority of sample dunes. In comparison, *S. cheilophila* and *P. simonii* dunes with higher scales suffered more serious wind erosion on their westward slopes, while *H. rhamnoides* and *A. desertorum* dunes at all scales experienced clear sand deposition on their eastward slopes.

Wind blowing and sand burial caused surficial undulation in different parts of sand dunes, primarily affecting slope degree (S) and aspect (D) (Fig. 4b [Figure 4: see original paper] and c). The slope degree of almost all lower and medium dunes' knap exhibited little variation ($-2°<\Delta S<2°$) except for higher *H. rhamnoides* and *S. cheilophila* dunes ($8°<\Delta S<12°$). Bilateral slope positions changed more substantially in slope degree from 5°–10° to 7°–20° over the past decade. There were large vegetation and dune position differences in slope degrees ($P<0.050$) for most sample dunes, with the greatest slope degree changes occurring in west slope positions and species of *S. cheilophila* and *P. simonii* dunes ($3°<\Delta S<9°$).

Changes in sand dune aspect corresponded to changes in surface height and slope degree (Fig. 4c). As all sample dunes fully stretched from northeast to southwest and fell slowly from north to south, the top position of dunes presented aspects of southwest-south-southeast and changed by less than 23°. The slope aspects shifted from west-southwest and east-northeast to northwest and southeast ($\Delta D<45°$), respectively, with the most significant changes occurring in high-steep *H. rhamnoides* and low-flat *S. cheilophila* dunes.

Fig. 3 Dune morphology parameters of height (a), slope degree (b), aspect (c), and length (d) in 2009 and 2018. H_0, S_0, D_0, and L_0 are the values of dune ridge of absolute height, slope degree, aspect, and length, respectively; H_1, S_1, D_1, and L_1 are the values of westerly slope of relative height, slope degree, aspect, and length, respectively; H_2, S_2, D_2, and L_2 are the values of easterly slope of relative height, slope degree, aspect, and length, respectively.

3.1.3 Dune Slope and Ridge Length

Prior to revegetation, all sample dunes faced heavy sand hazards characterized by sand ridge movement. Gradually, sharp ridges became flat and intermittent with increased sand-fixing function of artificial vegetation (Fig. 4d). After 10 years, most low-flat and medium sand dune ridge lengths increased by 20–90 m, especially those of *S. cheilophila* and *P. simonii* dunes ($\Delta L_0 > 55$ m). In contrast, high-steep sand dune ridges narrowed by 10–110 m, typically for *P. simonii* and reference dunes. Bilateral slope length corresponded to ridge change and reflected dome shape growth. There was a decrease ($\Delta L_1 < -10$ m) in west slope length and an increase (10 m$<\Delta L_2<$25 m) in east slope length of high-steep sand dunes. A continuous decrease in slope-length difference ($P<0.050$) led to the two slope forms becoming symmetrical. Slope morphology of *S. cheilophila* and *P. simonii* dunes changed more significantly than those of *H. rhamnoides* and *A. desertorum* dunes.

3.2 Migration

Revegetated sand dunes moved more slowly compared with unrestored shifting dunes. We observed comprehensive differences in dune positions and vegetation species according to outline edge monitoring of moving speed and direction (Fig. 4d). Three migration patterns were identified: north/northeast-to-south/southwest movement for north and south dune edges, west-to-east movement for westward slope edges, and east-to-west movement for eastward slope edges. Migration speed (M) varied by vegetation species and dune scales. *S. cheilophila* and *P. simonii* dunes (3.0 m/a<M<5.0 m/a) moved southward faster than *H. rhamnoides* (1.0 m/a<M<3.2 m/a) and *A. desertorum* dunes (M<1.0 m/a). With the exception of some high-steep scale dunes (2.0 m/a<M<4.0 m/a), most sample dune slope edges moved eastward or westward slowly (M<1.5 m/a).

Fig. 4 Changes and spatial distributions of deposition depth (a), slope degree (b), aspect (d), and sand ridge (d) of all sample dunes from 2009 to 2018.

Furthermore, most sample dune ridges moved similarly to outline edges in eastward or southward directions, changing more prominently in swing parts than in middle ridge sections. The eastward migration phenomenon was mainly observed in *S. cheilophila* and *H. rhamnoides* dunes with speeds exceeding 2.0 m/a, whereas slight westward movement (M<0.6 m/a) in the knap part of ridges occurred primarily in high-steep *P. simonii* and *A. desertorum* dunes. Compared with reference dunes (1.5 m/a<M_{low}-flat<3.0 m/a, 0.5 m/a<M_{high}-steep<2.0 m/a), revegetated dune ridges moved slightly slower for low-flat scales and slightly faster for high-steep scales. Revegetated sand ridges twisted and turned into two swings due to stronger sand-fixing benefits in north and south positions, with increasing knap deplanation in the middle. In contrast, reference dune ridges swayed easily with seasons and migration was blocked by adjacent dunes, moving more slightly and slowly than outline edges.

3.3 Wind Erosion and Sand Deposition

We calculated changes in dunes' wind erosive and sand accumulative positions, area percentage, and sand deposition rate and intensity based on outer edge contours and elevations of sample revegetated dunes. Different aeolian activities appeared across both dune scales and positions. First, almost all revegetated dunes exhibited sand accumulation in low-flat scales and erosion in medium and high-steep scales (Fig. 5a [Figure 5: see original paper]). The order of deposition intensity among all vegetation species from low to high was reference dunes, *P. simonii*, *S. cheilophila*, *H. rhamnoides*, and *A. desertorum* dunes. Second, knap and north wings were commonly erosive, while south and east slope toes experienced serious sand accumulation, especially in low-flat scales of *S. cheilophila*, *H. rhamnoides*, and *A. desertorum* dunes. Third, higher and steeper scale dunes generally had larger wind erosion areas (55%–95%) and smaller sand deposition intensities (–33.0\$×10^{3}\$ t/hm^2<Wi<–5.0\$×10^{3}\$ t/hm^2). In contrast, low-flat scale dunes presented 70%–90% deposition areas and moderate to severe deposition intensities (0.5\$×10^{3}\$ t/hm^2<Wi<110.0\$×10^{3}\$ t/hm^2). Considering dune scale differences, *A. desertorum* dunes were over-accumulative (Wi>100.0\$×10^{3}\$ t/hm^2), greatly exceeding the deposition intensities of other sample dunes. Fourth, compared with reference dunes, revegetated dunes exhibited heavier sand accumulation and weaker wind erosion. This was evidenced by low-flat revegetated dunes' distinctive sand-fixing benefits, which changed net sand loss to sand accumulation. Furthermore, medium and high-steep revegetated dunes showed smaller sand-fixing benefits ranging from 3% to 140%, with *P. simonii* and *A. desertorum* exhibiting better aeolian control functions than *H. rhamnoides* and *S. cheilophila.*

Fig. 5 Aeolian features of sample dunes. (a), Wi (yearly deposition intensity) and TR (sand transport rate); (b), Vm (wind velocity of base point), Vt (wind velocity of sand-driving), and z$_0$ (surface roughness).

Dune morphology and aeolian intensity were caused by wind velocity (Vm, 2 m high) and sand transport rate changes under open field wind velocity (Vt, 2 m high) (Fig. 5b). Revegetated dune near-surface wind velocities and sand transport rates decreased by approximately 20%–30% and 70%–100%, respectively. Wind velocity differences among three topographic scales confirmed stronger wind erosion in medium and higher scales, while sand transport rate was always higher in knap position and lower in slopes. Revegetated dunes exhibited slower changes in morphology and migration due to significant increases in threshold wind velocity (1.8 m/s<ΔVt<3.2 m/s) and surface roughness (2 cm<Δz$_0$<8 cm). In contrast, aeolian environments of low-flat *H. rhamnoides* and *A. desertorum* dunes were weaker than *S. cheilophila* and *P. simonii* dunes, though this inverse relationship was observed in medium and high-steep scales.

3.4.1 Original Topography and Deposition Depth

Original topography—including dune height, slope degree, and aspect—controlled surface airflow direction and velocity. Based on sand deposition depth distribution in dune configurations of original slope degree–altitude and slope degree–aspect (Fig. 6 [Figure 6: see original paper]), we found that deposition depth (ΔE) at different dune positions changed linearly or quadratically with original altitude and slope degree. A negative correlation ($r<–0.85$) between deposition depth and original altitude existed in the majority of revegetated dunes. Deposition depth increased positively with both steepened and flattened slope degree changes (ΔS). Slope aspects directly revealed dunes' aeolian positions in correspondence with regional leading wind directions, with almost all sample dunes showing apparent southeast-south-southwest aspects. Additionally, the impact of multiple interacting topographic factors was greater than that of single factors. Topographic conditions of northern aspects, smaller original slope degree, and larger original altitude led to more serious wind erosion, whereas dunes with southern aspects, larger original slope degrees, and smaller original altitude were more likely to experience sand accumulation. In terms of vegetation species, *S. cheilophila* and *P. simonii* dunes exhibited strong knap-erosion in northern directions and strong slope toe-deposition in southwestern directions, while *H. rhamnoides* and *A. desertorum* dunes showed medium slope-erosion and omni-directional medium deposition.

Fig. 6 Relationships of sand deposition depth between original altitude (a–e) and slope degree, and between original aspect and slope degree (f–j) of each sample dune.

3.4.2 Migration and Deposition Depth

Migration distance or speed at different positions of outline edge and sand ridge exhibited remarkable change patterns of quadratic or linear function with depositional depth (Δl) after significant testing ($P<0.050$) and square testing ($0.780<R^2<0.950$) (Fig. 7 [Figure 7: see original paper]; Table 2). For both southward and westward movement of revegetated dunes, migration distance generally increased with sand deposition depth and erosion depth, suggesting that excessive wind erosion and sand accumulation led to rapid dune movements. Balance values of deposition depth corresponding to the lowest migration distance reflected vegetation's ability to resist erosion or sand burial. All revegetated dunes moved more slowly under balance values of –3.0 to 3.0 cm. Comparatively, migrations of *A. desertorum* and *P. simonii* dunes were more sensitive to aeolian activity than *H. rhamnoides* and *S. cheilophila* dunes.

Fig. 7 Best fitting curves of sand deposition depth and migration distance of southward (a) and eastward (b) directions.

4.1 Factors of Revegetated Dune Reforming

Micro-topography and plant structures influenced dunes' aeolian differences fundamentally by changing the understory airflow field, and wind tunnel experiments have attempted to demonstrate and simulate aerodynamic and morphological processes (Hesp et al., 2019; Walker et al., 2022). The original area, volume, and intervals of dunes restrained their expansion speed, direction, and spatial location to a certain degree (Lancaster, 1988; Li et al., 2021). A previous study of crescent dune and linear dune morphology revealed less shifting and migration at larger dune scales and higher knaps, which corresponds to slower migration and expansion observed in high-steep scale sample dunes (Joanna and Andreas, 2008; Bishop, 2010). *H. rhamnoides* and *P. simonii* dunes with medium scales expanded southward but generally maintained their dome shape. *S. cheilophila* and *A. desertorum* dunes with low-flat scales variably changed from barchan to either dome or ribbon shapes due to their small original volume and heavy sand accumulation around outline edges. Wide dune intervals facilitate migration and expansion along dominant wind directions, whereas narrower and deeper intervals form wind erosion troughs that impel turbulent airflow, leading to steep slopes and deep interdunes (Meire et al., 2014). For example, *A. desertorum* dunes invaded lower *S. cheilophila* dunes from northeast to southwest, and high-steep *P. simonii* dunes showed a trend of covering lower dunes due to narrow dune spacing. Meanwhile, considerable east-west and north-south movement was observed for dunes with wide spacing.

Artificial vegetation community development in revegetated dunes greatly enhanced their surface anti-erosion ability through soil reinforcement by roots and wind-breaking effects of branches. Evolving from mostly bare mobile dunes to fixed or semi-fixed revegetated dunes, they gradually deformed elliptically and exhibited reduced migration speed, mainly due to increased vegetation community coverage and species diversity (Follett and Nepf, 2012; Zhang et al., 2017). In alpine sandy lands, tall shrub-tree plantations dominate more community resources and suppress regrowth of native species; their simple community structures are more easily disturbed by wind-sand hazards, degrade faster, and the same holds true for high-steep scale dunes (Wu et al., 2020). Additionally, plant spacing, clear height (below-branch height), canopy porosity, and plant survival rate influenced the airflow field with increased velocity and effective protection distance (Okin, 2008; Leenders et al., 2011; Chen et al., 2012). Moreover, heightened wind-sand activity restrained natural revegetation, leading to lower species diversity. In contrast, *H. rhamnoides* and *A. desertorum* dunes experienced lower wind energy under plants and developed stable communities due to their high planting density and large horizontal canopy. The majority of high-steep scale dunes were subjected to excessive wind erosion and sand burial due to unstable vegetation communities (Wu et al., 2020; Che et al., 2022).

4.2 Morphology Evolution

Compared with regional tall barchan dunes without vegetation cover, revegetated dunes evolved more slowly and migrated wobbly (Momiji et al., 2002). Zhang et al. (2018) and Hu et al. (2021) found that high-steep mobile dune morphology changed quickly from barchan shape to dome or linear shape in less than 5 years. We found that prevailing winds from west-northwest-north directions caused bare shifting dunes to climb eastward and southward, forming higher sand hills with sharpened sand ridges. In contrast, revegetated dune morphology mildly transformed into spindle or dome shapes with a flat knap and 2–3 blurred ridges, then extended southward and northward to connect with other dune wings, forming barchan chains and longitudinal dunes. Revegetated dunes exhibited a pattern of "cut-top, extended-slope, stabilization, and internal unbalance," with the final phase typically presenting as an "ecological break" involving blowouts and the formation of erosion troughs and nebkhas in high-steep scales. In some cases, "ecological break" may be attributed to a new sand source that disrupts dune morphology (Zhu, 1963; Silc et al., 2020; Yamasaki et al., 2021).

Arid revegetated dunes quickly migrated and readily shifted into parabolic and linear shapes under the influence of wind storms and extreme drought, possibly dismembering into nebkha dunes within 10 years (Nickling and Wolfe, 1994; Hasi et al., 2013). The majority of semi-arid flat revegetated dunes evolved into fixed or semi-fixed sandy land due to ecological restoration function and stable community structure of artificially planted vegetation. Furthermore, dune outlines dispersed and connected to each other, propelling sand-fixing and plant-recovery effects (Li, 2003). Alpine *S. cheilophila* and *P. simonii* dunes evolved into semi-fixed dunes with fragmentation shapes, whereas *H. rhamnoides* and *A. desertorum* dunes tended to have dome or longitudinal shapes. However, all revegetated dunes showed little movement in east-west directions due to alternating dominant wind directions from northeast and northwest, though they faced potential dangers of dune activation and fragmentation, and presented threats of invading southern grassland and inter-dune lowland.

5 Conclusions

Revegetated dunes progressed steadily from barchan to dome or ridge shapes, with four vegetation types contributing to topography reforming through knap planation, wing amplification, and slope symmetrization. Southward migration of wings was observed, indicating the need for sand-control in these areas. *H. rhamnoides* was found to be adaptive to each dune type and position, mitigating wind erosion and slowing migration. *S. cheilophila* and *P. simonii* are recommended for afforestation efforts in medium and high-steep dunes' north wing and knap positions. *A. desertorum* revegetated dunes require additional reinforcement to increase anti-erosion and sand-fixing functions.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Note: Figure translations are in progress. See original paper for figures.