Variation Characteristics of Aspect Ratio and Migration Rate of Barchan Dunes on the Periphery of Minqin Oasis: Postprint

Authors: He Chenchen, Wu Yingying, Tian Yongsheng, Ma Rui, Wang Zhenting, He Chenchen

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Abstract

Understanding the morphological evolution processes and migration patterns of barchan dunes on the periphery of the Minqin Oasis constitutes a critical prerequisite for local windbreak and sand fixation efforts as well as ecological restoration. This study investigates the relationships among morphological parameters of barchan dunes and their correlation with migration rates in the upwind marginal area of the Minqin Oasis periphery, utilizing field measurements and high-resolution remote sensing imagery analysis. The results indicate that: (1) The width-to-height ratio of the dunes has remained constant at 16 for 16 a. (2) Large dunes exhibit an annual average migration distance of less than 3 m, classified as moderate migration speed, with their morphology remaining essentially unchanged except for noticeable variations at the windward slope baseline, crest line, and wing tips. Small dunes migrate more rapidly, with an annual average migration distance exceeding 10 m, classified as extremely rapid migration speed. (3) The downwind migration rate of dunes is inversely proportional to their width, with a proportional constant of 718.52 $m^2 \cdot a^{-1}$. Barchan dunes in this area are dominated by rapid migration speeds, with migration rates exceeding 5 $m \cdot a^{-1}$, accounting for 52.63% of the total. (4) During the process of sand particle erosion on the windward slope and deposition on the leeward slope, large dunes maintain stable morphology and migrate slowly. Small dunes undergo dramatic morphological changes and migrate rapidly, with dune development exhibiting a trend toward further size reduction.

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Variation Characteristics of Width-Height Ratio and Migration Speed of Barchans at the Margin of Minqin Oasis

HE Chenchen[1,2], **WU Yingying**[1,2], **TIAN Yongsheng**[3], **MA Rui**[3], **WANG Zhenting**[1]

[1]Key Laboratory of Desert and Desertification, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, Gansu, China

[2]University of Chinese Academy of Sciences, Beijing 100049, China

[3]College of Forestry, Gansu Agricultural University, Lanzhou 730070, Gansu, China

Abstract

Understanding the morphological evolution and migration patterns of barchan dunes in the periphery of Minqin Oasis is an important prerequisite for local windbreak and sand fixation efforts and ecological construction. This study investigates the relationships between morphological parameters of barchan dunes and their migration rates in the upwind marginal area of Minqin Oasis through field measurements and high-resolution remote sensing image analysis. The results show that: (1) The dune width-to-height ratio remains constant at approximately 16 over 16 years. (2) Tall dunes have an average annual migration distance of less than 3 m, representing a medium movement speed, with their morphology essentially unchanged except for noticeable changes at the windward slope baseline, crest line, and wing tips. Low dunes move faster, with an average annual migration distance exceeding 10 m, representing an extremely fast movement speed. (3) The downwind migration rate of dunes is inversely proportional to their width, with a proportionality constant of 718.52 $m \cdot a^{-1}$. Barchan dunes in this region are dominated by fast movement speeds (>5 $m \cdot a^{-1}$), accounting for 52.63% of the total. (4) During the process of sand erosion on the windward slope and deposition on the leeward slope, large dunes maintain stable morphology and move slowly. Small dunes exhibit dramatic morphological changes and rapid movement, showing a tendency toward further reduction in size.

Keywords: Minqin Oasis; barchan dune; geometric parameters; migration pattern

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Introduction

The Hexi Corridor borders three major deserts—Tengger, Badain Jaran, and Kumtag—and suffers severely from wind-sand hazards, making it crucial for ecological security barrier construction in northern China. At the eastern end of the corridor, the Minqin region has a history of sand control spanning over sixty years. Despite remarkable achievements [1], the situation of land desertification remains severe. Water resources are scarce in the periphery of the oasis, winds are strong, and wind erosion desertification occurs easily. Taking the Liangucheng National Nature Reserve, which semi-circularly surrounds the Minqin Oasis, as an example, 98.41% of its total area consists of wind-eroded desertified land [2]. Understanding the formation and movement patterns of wind-sand landforms is an important prerequisite for scientifically designing and implementing wind-sand engineering projects. In the upwind area surrounding Minqin Oasis, wind-sand landforms are dominated by fixed and semi-fixed shrub coppice dunes, followed by barchan dunes and dune chains, with small wind erosion pits occasionally distributed. While moving, mobile dunes also provide material sources for nearby wind-sand activities, posing the greatest practical threat to the existence and development of the oasis.

Among the various dune types, barchan dunes have been relatively well studied. Early field observations mainly consisted of textual descriptions [3], involving heavy workload, long time consumption, and insufficiently accurate morphological descriptions. Later, traditional monitoring methods such as stake insertion, repeated measurements, and aerial photo analysis were widely applied [4]. Currently, advanced technologies including remote sensing imagery, GPS, total stations, real-time kinematic (RTK) differential GPS, 3D laser scanners, and UAV oblique photogrammetry have been applied to dune morphological characteristics [5], providing valuable data for in-depth exploration of dune morphodynamic processes. The morphological parameters of barchan dunes include dune height, width, windward slope length, lee slope length, windward slope gradient, wing length, opening degree, and symmetry [6]. Relationships among these parameters include correlations between dune width and height, windward slope length and width, wing length and width, lee slope angle and height, base area and perimeter or volume, etc. Among these, the relationship between dune width and height has been most extensively studied. Empirical relationships derived from large amounts of measured data show that dune width is positively correlated with height and can be described by a linear relationship [7]. Based on the ratio of windward slope length to width, barchan dune morphology has been classified as fat, short, standard, or slim [8], and by horn shape as linear, beaded, or knotted [9]. In addition to morphological characteristics, the evolution process and migration rate of dunes constitute another research focus. Dunes result from the interaction of wind force, sand particles, and underlying surfaces [10]. Their morphological evolution and migration rates are influenced by multiple factors including sand source abundance, wind speed, wind direction, topography, and vegetation, with different regions exhibiting different manifestations of wind-sand transport characteristics. Seemingly universal empirical and theoretical relationships often show significant regional variations.

Remote sensing images from various periods show that barchan dunes in the Minqin area move the fastest [11]. Building on previous work, this study uses field measurements and high-resolution remote sensing image analysis to examine dune morphological characteristics and migration rates, providing quantitative relationships between morphological parameters and their correlation with migration rates for barchan dunes in the upwind marginal area of Minqin Oasis. This research not only directly serves local windbreak and sand fixation efforts and ecological construction but also provides important reference value and guidance for related work in other areas of the Hexi Corridor.

1.1 Study Area Overview

The study area is located approximately 30 km northwest of Minqin County in Gansu Province, extending from the northern edge of the Hongyashan Reservoir in the south to the foot of the Laifu Mountains in the north (38°25 –38°50 N, 102°45 –103°50 E) [Figure 1: see original paper]. The region has a temperate arid desert climate, characterized by perennial dryness, scarce precipitation, strong evaporation, and frequent strong winds with abundant sand. The average annual precipitation is 113.2 mm, average annual temperature is 7.8°C, and there are 139 windy days per year. The terrain is flat with no surface runoff, the wind direction is singular, vegetation is sparse, and plants such as *Haloxylon ammodendron*, *Calligonum mongolicum*, and *Nitraria tangutorum* are sporadically distributed. Land use types are dominated by sandy land, with a certain proportion of forest land, and cultivated land and grassland are scattered. Soil types are mainly desert soils. Wind-eroded desertified land includes both historically natural formations and recently abandoned cultivated land that has degraded over the past decades. The relatively open foreland and backland areas are necessary environmental conditions for the existence of barchan dunes and dune chains. Located downwind of the prevailing winds from the Badain Jaran Desert, the area has relatively abundant sand supply. Consequently, barchan dunes and dune chains are the main dune types in this region [12] and have historically been the focus of local windbreak and sand fixation efforts. Currently, sand control measures mainly consist of large-scale afforestation and enclosure for natural recovery, forming artificial *Haloxylon ammodendron* forests of varying sizes along rural roads within 3–5 km and in some areas on the oasis margin.

1.2 Research Methods

1.2.1 Dune Morphological Parameters Field measurements and high-resolution remote sensing image analysis are the primary methods for obtaining dune morphological parameters. Dune height and width were directly measured using an NTS-352 total station. The measurement objects were primarily complete, well-defined, and relatively independent barchan dunes. A local coordinate system was adopted for field measurements. Dune height was defined as the vertical distance from the highest point of the lee slope to the ground surface. Width was measured as the sum of the horizontal distances between the two wing tips along a straight line parallel to the main wind direction between the wings. The two field measurement campaigns were conducted in August 2005 and August 2021, with 31 and 46 dunes measured, respectively. Compared with the first measurement, the second covered a larger spatial range, essentially encompassing the entire study area.

1.2.2 Remote Sensing Image Sources and Analysis High-resolution remote sensing image data were purchased from the Gansu Data and Application Center of the High-Resolution Earth Observation System. The August 13, 2013 image was from the GF-1 satellite with a spatial resolution of 2 m; the September 28, 2017 image was from the GF-2 satellite with a spatial resolution of 0.8 m; and the September 26, 2021 image was from the GF-6 satellite with a spatial resolution of 2 m. Image preprocessing for each period included orthorectification, fusion, mosaicking, and geometric correction. Appropriate resampling methods were selected during mosaicking, and ground control points and geometric correction mathematical models were used to correct errors caused by non-systematic factors in geometric correction. After completing these steps, ArcGIS software was used to extract the outline of mobile barchan dune bases, from which dune width and centroid position were calculated. As barchan dune morphology in this area is constantly changing, it is difficult to select specific points on the outline to represent dune positions. Therefore, the base centroid position was used to calculate interannual migration distance. Dunes measured from remote sensing images were mainly located west of Xuebai Town and Daba Town, with only two dunes at the foot of Laifu Mountain on the northern oasis margin [Figure 1: see original paper].

Image analysis employed a global coordinate system with the following procedures: (1) Using a straight-line approximation for curves, the coordinate values of multiple points along each dune base outline were measured in the WGS-84 coordinate system and converted to three-dimensional Cartesian coordinates; (2) The optimal plane containing all dune base outline points was fitted using the least squares method; (3) Any point on this optimal plane was selected as the coordinate origin, with the main wind direction as the x-axis direction, to establish a plane rectangular coordinate system, and all measurement points were projected onto this coordinate system. Dune width and centroid position were then calculated based on the projected outline. The base area and first-order moment required for determining centroid coordinates were calculated using the trapezoidal method. Because the study area is small and the terrain is very flat, this image analysis method can accurately extract dune base outlines. For morphological parameters such as windward slope length and wing width, the relative error between field measurement and remote sensing image measurement results is within an acceptable range.

1.2.3 Wind Regime Characteristics Hourly wind speed data from the Minqin meteorological station from 2013 to 2021 were obtained from the China Meteorological Data Network (http://data.cma.cn) for wind regime characteristic analysis. Drift potential (DP) is commonly used to evaluate wind regime characteristics and potential sand transport intensity, calculated as [1]:

$$DP = \sum_{i=1}^{16} U_i^2 (U_i - U_t) t_i$$

where DP is drift potential in vector units (VU), U_i and U_t are wind speed at height i and threshold wind speed, respectively (U_t = 6 m · s^{-1}), and t_i is the duration of sand-driving wind, generally expressed as frequency. Wind energy environment assessment includes total drift potential (DP), resultant drift potential (RDP), resultant drift direction (RDD), and direction variability (RDP/DP). According to vector synthesis principles, RDP and RDD are obtained by synthesizing DP from 16 directions, while the ratio of RDP to DP represents direction variability. Based on DP magnitude, wind energy environments are classified as low energy (DP < 200 VU), medium energy (200–400 VU), and high energy (>400 VU). Based on direction variability, wind energy environments are classified as high variability (RDP/DP < 0.3), medium variability (0.3–0.8), and low variability (>0.8).

2 Results and Analysis

2.1 Wind Regime Characteristics Drift potential is an important indicator reflecting wind-sand activity intensity in a region [27]. The drift potential rose diagram for the Minqin area from 2013 to 2021 is shown in [Figure 2: see original paper]. Sand-driving winds primarily originated from west-northwest and northwest directions, with multi-year resultant drift directions ranging between 120°–135°, indicating an overall transport direction of ESE–SE and a narrow unimodal wind regime distribution. Annual drift potentials were 34 VU, 20 VU, and 20 VU for 2013, 2017, and 2021, respectively. Although interannual drift potential varied, the differences were small, indicating a basically stable wind energy environment. The multi-year average drift potential was 27.7 VU. According to wind energy environment classification standards [1], this region belongs to a low wind energy environment (DP < 200 VU). Additionally, resultant drift potential showed the same interannual variation trend as total drift potential. The direction variability was 0.77 in 2013, 0.68 in 2017, and 0.92 in 2021 [Figure 3: see original paper], with a multi-year average of 0.79, belonging to low variability and indicating relatively uniform wind direction. However, the 2021 direction variability was less than 0.8, belonging to medium variability. Therefore, the study area has relatively small overall drift potential, though wind direction variation is significant in some years. Barchan dune movement is mainly influenced by west-northwest and northwest winds.

2.2 Height-Width Relationship Barchan dune height and width data can be fitted by either proportional functions [28] or power functions [29]. For convenience, proportional fitting was applied, yielding a correlation coefficient of 0.92 [Figure 4: see original paper]. Overall, although the two measurements were 16 years apart, the morphological parameter relationship remained essentially unchanged, with a dune width-to-height ratio of approximately 0.06. Previous studies have shown this value generally ranges between 0.05–0.15 [30], and this study conforms to this pattern. The constant ratio maintained over many years indicates that the width-to-height ratio is a characteristic parameter of barchan dunes. Dune morphology is influenced by wind regime, sand supply, and topography. For the same region, the above wind regime characteristics indicate little change in multi-year drift potential, belonging to a low wind energy environment. The multi-year average direction variability is low, with relatively uniform wind direction. Without human interference, the parameter relationships of barchan dunes should show no significant changes. The 2021 measured data are slightly more dispersed for two main reasons: First, artificial vegetation on the windward slopes of some dunes measured in 2021 affects their morphodynamic processes. Second, wind conditions and surface conditions differ slightly in different regions. The windward slope airflow acceleration is stronger for larger dunes, resulting in greater wind erosion at the dune crest, with more complex and diverse sand source abundance and surface conditions.

2.3 Migration Rate and Morphological Parameters When dune morphology and incoming flow conditions remain constant, mass conservation laws can derive a theoretical inverse relationship between migration speed and dune height [31]. Sometimes, the overall movement of barchan dunes over several months is almost entirely caused by one or two strong sandstorms. Meanwhile, the existence of reverse winds and annual differences in remote sensing image acquisition timing also create difficulties in determining dune migration rates along the main wind direction. To reduce uncertainty from year-by-year calculations, this study used the 2013 centroid position as a reference point and calculated the average migration rate from 2013–2021 based on the maximum centroid displacement, with dune width taken as the average of three image analyses.

2.3.1 Individual Dune Migration Trajectories and Morphological Changes Dune migration rate can estimate sand transport volume and provide guidance for windbreak and sand fixation practice. Under wind action, dunes typically move through erosion on the windward slope and deposition on the leeward slope. Although the width-to-height ratio remains constant, the morphology of individual dunes continuously changes during movement. In traditional aeolian geomorphology research, the average migration distance of one or several characteristic points on the outline is often used to represent the movement of the entire dune. When morphological changes are significant, errors are substantial. Therefore, using the base centroid to identify dune position is more reasonable.

[Figure 5: see original paper] shows the migration trajectories and morphological changes of two typical dunes located at 38.68°N, 102.99°E and 38.79°N, 102.83°E. In 2005, the dune heights were 9.3 m and 5.1 m, with wing widths of 150 m and 45 m, respectively. Using 2013 as a reference, the base outline changes reflect detailed interannual migration processes. Overall, dune morphology remains relatively intact, with minimal lateral displacement and clear crescent shapes. Centroid changes reflect slow overall dune movement. Interannual morphological changes are mainly evident at the windward slope baseline, crest line, and wing tips. The windward slope baseline and crest line represent the dune's forward movement, while wing tip changes reflect the influence of lateral winds.

Dunes generally move along the main wind direction, but reverse movement occurs in some years. Dune movement patterns include forward, swaying, and swing-forward types [32]. When sand supply is insufficient, wind-sand flow becomes unsaturated, and the perennial occurrence of multiple wind directions can lead to reverse development of barchan dunes. The dune in [Figure 5: see original paper] has wing widths of approximately 45 m. The base outline reflects dramatic morphological changes, with large variations in all morphological parameters, and the dune rapidly moves forward along the main wind direction. During 2013–2021, the dune primarily exhibited forward movement along the main wind direction, with reverse movement occurring in a few years. Under reverse wind erosion, reverse accumulation appears at the top of the lee slope and the crest line moves backward, promoting reverse dune development. According to migration rate classification [33], mobile dunes are divided into four categories: slow ($<1\ \mathrm{m \cdot a^{-1}}$), medium ($1$–$5\ \mathrm{m \cdot a^{-1}}$), fast ($5$–$10\ \mathrm{m \cdot a^{-1}}$), and extremely fast ($>10\ \mathrm{m \cdot a^{-1}}$). The tall dune has an average annual migration distance of 5.1$±$2.0 m, belonging to medium speed; the low dune has an average annual migration distance >10 m, belonging to extremely fast speed.

The centroid trajectories in [Figure 5: see original paper] show significant reverse movement for both dunes. Such movement only occurs when the main and secondary wind directions are roughly opposite. Chang et al. [34] found that a single main wind direction is the key factor maintaining barchan dune morphology, promoting coincidence between the dune vertex and crest line, while reverse winds cause separation between them. Statistical analysis of wind speed and direction data for the Minqin sand area [35] shows that sand-driving winds are primarily northwest winds in spring, followed by southeast winds in summer. In addition to causing overall reverse movement, reverse winds also change the wind-sand flow structure at the crest line and cause relative position changes between the dune top and crest line [36]. Dune movement is mainly influenced by wind speed and direction. Combined with wind regime analysis, the study period had relatively small drift potential, belonging to a low wind energy environment. The migration trajectory of individual dunes reflects overall forward movement, but the 2021 dune showed obvious reverse movement, with direction variability of 0.92, belonging to medium variability, indicating significant wind direction changes. Variable wind direction is an important factor causing reverse dune movement. Since the Minqin area is perennially controlled by northwest winds, east and southeast winds are weak and insufficient to completely compensate for the effects of northwest winds. Even though wind direction variability was large in 2021, the annual drift potential was too small to cause reverse dune movement. Therefore, interannual reverse movement may be caused by strong sandstorm events. Taking the April 23–25, 2021 sandstorm as an example [37], monitoring before and after the event revealed: crest line height decreased (7.00$\pm$2.00 m), length increased by 5–10 m, and dune volume decreased by 15$\pm$5 m^{3}. This demonstrates that strong sandstorm events significantly impact dune migration rates and morphological characteristics and are an important cause of reverse dune movement. Additionally, the base area of low dunes continuously shrinks over time, indicating volume reduction during movement and a developmental trend toward further size reduction. Large dunes remain relatively stable, a result related to their own volume.

2.3.2 Relationship Between Migration Rate and Morphological Parameters [Figure 6: see original paper] shows the variation of annual migration rate with dune width. Dune widths range from 45–300 m, with migration rates of 1–16 $m \cdot a^{-1}$. Fast-moving dunes account for 52.63%, extremely fast-moving dunes for 31.58%, and medium-speed dunes for 15.79%. Therefore, the region is dominated by fast-moving dunes with migration rates >5 $m \cdot a^{-1}$. The inverse relationship between migration rate and width can be explained by mass differences between dunes of different widths. Dune migration involves the process of sand particle erosion from the windward slope and redistribution to the leeward slope. Wider dunes require more time to reconstruct and balance this process, resulting in slower migration rates [38]. This process may cause morphological changes during dune movement. Dune dynamic model studies show that under constant sand supply conditions, barchan dunes of different sizes may exist in different non-equilibrium states within wind-sand flow [39]. After establishing the relationship between migration rate and width, measuring regional wind regime and dune width can quickly estimate dune migration rates. Using width to reflect migration rate greatly reduces research difficulty. Under the same wind conditions, dunes exhibit different migration rates, indicating that the influence of wind regime on migration rate is weakened by other factors, leading to rate differences [40]. The previous section confirmed the empirical relationship of constant dune width-to-height ratio. Therefore, migration rate should be inversely proportional to dune width. The fitting relationship obtained by least squares method is $y = 718.52x^{-1}$, with a proportionality constant of 718.52 $m \cdot a^{-1}$.

Studies on dune migration rate and width [41], migration distance [42], and migration speed [43] found that barchan dune migration rate is inversely proportional to both height and width, consistent with this study. Additionally, the ratio of migration rate to width shows that as width increases, the variation in migration rate tends to flatten. When dune width increases from 45 m to 150 m, migration rate varies from 3–16 $m \cdot a^{-1}$; when width increases from 200 m to 300 m, migration rate varies only from 2–7 $m \cdot a^{-1}$, indicating that after reaching a certain width, migration rate variation becomes smaller and dunes tend to be more stable under the same wind regime. For isolated barchan dunes, the inverse relationship between dune width and migration rate reflects sand mass differences between dunes of different widths. From the multi-year migration trajectories of individual dunes and the relationship between migration rate and width, dune width not only reflects migration speed but also, due to rate differences, causes dunes of different widths to develop in different directions. Over time, wide dunes maintain basically unchanged or enlarged morphology, while narrow dunes tend to shrink or disappear.

3 Discussion

3.1 Wind Regime Wind regime is an important dynamic factor affecting dune morphology development. Wind speed and direction determine dune height, width, volume, and migration rate. Dune evolution and movement are controlled not only by atmospheric circulation but also by local airflow [44]. Macroscopically, regional wind regimes are controlled by atmospheric circulation, and previous studies have established connections between wind regimes and different dune types. Narrow unimodal distributions are associated with barchan dunes, bimodal distributions with linear dunes, and complex distributions with star dunes [45]. Barchan dunes form in areas with low sand supply and low wind direction variability; increased sand supply leads to merging into transverse dunes, while increased wind direction variability leads to linear dunes under bidirectional wind conditions. The study area's wind regime characteristics show that sand-driving winds mainly originate from west-northwest and northwest directions, with a narrow unimodal distribution and low multi-year direction variability, favoring barchan dune formation and evolution. Therefore, the dune width-to-height ratio remains constant over many years [Figure 4: see original paper]. Dunes respond not only to regional wind regimes but also generate complex secondary flows locally. Lee slopes can form separated flow, reattached non-deflected flow, reattached deflected flow, and reverse flow [46]. When sand particles are eroded from the windward slope and deposited on the leeward slope, dunes move downwind. Some studies consider this process to be in equilibrium, while others consider it non-equilibrium. Analysis of two typical dunes' migration trajectories shows that tall dunes maintain stable morphology over many years with slow migration rates [Figure 5: see original paper], suggesting that sand erosion and redistribution can be considered an equilibrium state. Relatively low dunes exhibit dramatic morphological changes, with continuously decreasing base outlines reflecting volume reduction [Figure 5: see original paper], indicating that erosion exceeds deposition during movement, causing dunes to continuously shrink. This process can be considered non-equilibrium, and dunes may eventually shrink or disappear. Therefore, regional atmospheric circulation and locally generated secondary flows jointly shape dune morphology and influence dune movement.

3.2 Vegetation With the implementation of windbreak and sand fixation projects in Minqin Oasis [47], sand surface stabilization has limited sand supply for wind-sand flow and changed underlying surface properties. Sand fixation projects mainly achieve sand blocking, fixation, and transport reduction through biological, mechanical, and chemical measures that decrease sand supply and alter underlying surface properties. Main influencing factors include sand particle size changes, water content, binders, vegetation types, plant structure, morphology and density, and other surface roughness elements. As the main limiting factor for sand supply and wind-sand transport, vegetation in the study area is the primary factor affecting dune morphology and movement and is one reason for the dispersion in dune width-to-height ratios. Psammophytic plants have well-developed root systems that can bind surrounding sand particles. Vegetation decomposition facilitates organic matter accumulation, promotes soil formation and fixation, and changes soil chemical properties [48] and particle size distribution [49]. Plant canopies can also reduce the effectiveness of near-surface wind-sand transport. Monitoring of bare and vegetation-covered dunes [50] shows that vegetation-covered dunes have poorer correlation between migration rate and height compared to bare dunes. Compared with bare dunes, fixed dunes show different movement speeds at the wings, windward slope, leeward slope, and crest. Increased vegetation coverage limits surface sand transport capacity and sand supply, causing barchan dunes to gradually transform into parabolic dunes [51]. With only 10% vegetation coverage, 70% of sand particle transport is suppressed [52]. Plant canopy effects on wind-sand flow are profound [53], near-surface flow fields [54], and dune surface particle size distribution [55]. The impact depends on plant density, shape or morphology, distribution, and height [56], with tall, dense plants having stronger sand fixation capacity. Analysis of surface sediment particle size under different vegetation covers [57] shows that fine component content is positively correlated with plant canopy size, branch height, and branch number. At low densities, turbulence and vortex shedding formed by individual shrubs enhance surface wind-sand erosion [58]. Increased plant height leads to increased dune height and decreased dune length [59]. In the study area, good correlations exist among parameters of mobile dunes, with larger dune volume corresponding to slower migration rate. Additionally, migration rate is inversely proportional to dune width [Figure 6: see original paper], and dunes generally move southeastward, consistent with previous studies [60]. The difference is that some barchan dunes have artificial *Haloxylon ammodendron* forests, weakening correlations among parameters and dispersing the dune width-to-height ratio. Vegetation profoundly affects dune morphological characteristics and movement in terms of wind-sand flow structure, near-surface flow field, and dune surface particle size distribution. Vegetation increases surface roughness, intercepts sand material carried by airflow, and affects sand deposition near plants [61]. Simultaneously, vegetation reduces near-surface wind speed and decreases the amount of sand particles transported, both leading to insufficient sand supply and affecting dune morphology.

4 Conclusions

Through field measurements and high-resolution remote sensing image analysis, this study investigated the morphological characteristics and migration rates of artificially forest-fixed and fully mobile barchan dunes in the upwind area surrounding Minqin Oasis. The following conclusions are drawn:

(1) From 2005 to 2021, the dune width-to-height ratio remained constant at approximately 16. The dispersion in 2021 dune width-to-height ratio data is due to: first, artificial *Haloxylon ammodendron* forests on some dune windward slopes affecting their morphodynamic processes; second, different wind conditions and surface conditions in different measurement areas. Larger dunes have stronger windward slope airflow acceleration, greater wind erosion at the crest, and more complex and diverse sand source abundance and surface conditions.

(2) Tall dunes move slowly, with an average annual migration distance of 5.1$±$2.0 m, belonging to medium movement speed, with basically unchanged morphology; low dunes move rapidly, with an average annual migration distance >10 m, belonging to extremely fast movement speed.

(3) The annual downwind migration rate of dunes is inversely proportional to their width, with a proportionality constant of 718.52 $m \cdot a^{-1}$. In this region, fast-moving dunes account for 52.63%, extremely fast-moving dunes for 31.58%, and medium-speed dunes for 15.79%.

(4) Large dunes maintain stable morphology over many years. The process of sand erosion on the windward slope and deposition on the leeward slope is relatively stable, with slow dune movement. Small dunes exhibit dramatic morphological changes and rapid movement, showing a developmental trend toward further size reduction during migration.

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