Relationship Between Stratified Plant Profiles and Sand Dune Formation in Desert Plants: A Postprint

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Abstract

Several common sand-fixing plants in the Minqin sandy area were selected, and 108 plant and sand mound quadrats were established at the edge of the Xishawo Desert in Minqin. Through measurement and comparative analysis of different plants' stratified silhouette width, stratified silhouette area, silhouette center, and other indicators, the following results were obtained: 1) The silhouettes of plants capable of accumulating sand into mounds are triangular or columnar, i.e., the silhouette width decreases from the ground upward, and the silhouette center is within 30 cm height from the ground. Plants meeting this condition are clustered shrubs. In contrast, plants incapable of accumulating sand into mounds have diamond-shaped silhouettes, with silhouette centers at heights above 30 cm from the ground. 2) Sand particles in wind-sand flows and dust storms are mainly concentrated in the near-surface layer at 0-30 cm height, which is one of the important reasons why plants with lower silhouettes more easily accumulate sand into mounds. 3) Plants whose stems can produce adventitious roots after sand burial can form sand mounds/dunes several to dozens of times higher than the plant itself, whereas plants lacking this attribute, although some can form sand mounds, are limited by plant height, i.e., the sand mound height will not exceed the plant height. 4) Silhouette area size is a very important indicator reflecting plants' windbreak and sand fixation functions. The ability to accumulate sand into mounds is the material manifestation of plants' capacity to block and stabilize shifting sand. The taller and larger the sand mounds formed, the stronger the plant's function in blocking and stabilizing shifting sand. However, plants incapable of accumulating sand into mounds, such as Haloxylon ammodendron, Calligonum mongolicum, and Artemisia desertorum, also possess certain windbreak and sand-blocking effects.

Full Text

Preamble

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Relationship Between Sand-Mound Formation and the Layered Silhouette of Desert Plants
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Abstract

We selected several common sand-fixing plants in the Minqin desert area and established plant and sand-mound quadrats along the edge of Minqin Xishawo. Through measurement and comparative analysis of layered silhouette width, layered silhouette area, and silhouette center of different plants, we obtained the following results: (1) The silhouettes of plants that can accumulate sand into mounds are triangular or cylindrical, meaning the silhouette width decreases from ground level upward, with the silhouette center located within 30 cm of the ground surface. Plants with this characteristic are clumping shrubs. (2) The silhouettes of plants that cannot accumulate sand into mounds are diamond-shaped, with the silhouette center 30 cm or more above ground. (3) Sand particles in aeolian sand flow and dust storms are primarily concentrated within the 0–30 cm layer above the surface, which is an important reason why lower plant silhouettes more easily form sand mounds. (4) Plants whose stems can produce adventitious roots after sand burial can form sand mounds or dunes several to dozens of times higher than the plant itself. Although some plants that lack this characteristic can still form sand mounds, the mound height is limited by plant height and will not exceed it. (5) Silhouette area is a crucial indicator reflecting a plant' s windbreak and sand-fixing function; the ability to accumulate sand into mounds is the material manifestation of a plant' s capacity to block and stabilize mobile sand, with taller mounds indicating stronger sand-blocking and fixation functions. However, plants that cannot accumulate sand into mounds, such as *Haloxylon ammodendron* and *Artemisia arenaria*, also possess certain windbreak and sand-blocking effects.

Keywords: desert plants; layered silhouette; nebkhas; sand-mound accumulation; Minqin desert area

1. Introduction

In deserts, dunes of various sizes can be observed, many of which form due to plant obstruction and interception of mobile sand. These dunes, such as *Nitraria* dunes and *Ephedra* mounds, are generally termed nebkhas (coppice dunes) [Figure 1: see original paper]. Numerous studies on nebkhas have been reported both domestically and internationally, primarily covering their distribution environment [1-5], morphological characteristics and evolution [6-9], and ecological properties [10-16]. However, research on the formation conditions of nebkhas remains limited.

Nebkhas are geomorphic features formed when wind-sand flow encounters shrub obstruction and accumulates in arid, semi-arid, and semi-humid desert regions [3]. The abundance of sand supply plays a key role in any aeolian landform, affecting the spatial scale and survival time of nebkhas [3]. Shrub type and characteristics are important factors shaping nebkha morphology. Vegetation influences near-surface flow fields through three mechanisms: surface coverage, wind force decomposition, and sand flow obstruction, causing sand deposition within shrubs while protecting underlying sand from erosion. Different vegetation types produce different dune morphologies, with larger, denser shrubs having greater interception capacity [2-3].

In the Ebinur Lake region of Xinjiang, nebkhas mainly developed during the Late Holocene, with widespread development since that period [17]. Foreign scholars have found that nebkha height correlates well with shrub height, while length shows high correlation with overall shrub height [18]. Dune morphology on the leeward side of grass clumps depends on clump width and the sand's angle of repose, with dunes forming in areas with reverse airflow [19]. Different plant architectures exhibit varying capacities for intercepting and accumulating sand. Numerous studies have reported on desert plant architecture [20-24], generally concluding that vegetation, wind intensity, and sand source are the three main factors controlling nebkha formation. A plant' s wind-blocking effect primarily depends on its silhouette area on the windward side [21-24]. Comparative studies on sand-fixing capacity of *Caragana stenophylla* and *C. microphylla* in the Inner Mongolian Plateau desert steppe show that both nebkha volume and sand-fixing efficiency are significantly positively correlated with aboveground branch fresh weight, and nebkha height is significantly linearly correlated with shrub height [6]. Some scholars have studied the relationship between plant architecture and windbreak/sand-fixing effects for three *Artemisia* species in the Horqin Sandy Land [24].

Previous nebkha research has rarely considered the relationship between dune formation and plant architecture, while desert plant architecture studies have often focused on architectural characteristics and their relationship with environmental conditions, neglecting different outcomes resulting from different plant architectures. *Haloxylon ammodendron* (C.A. Mey.) Bunge is a small tree or large shrub in the Hexi Corridor and Minqin sandy areas of Gansu, yet why cannot it accumulate sand into mounds? Simple plant height and architecture cannot reveal the mechanism of nebkha formation. Nebkhas are the result of plants intercepting sand flow and represent the concrete manifestation of sand-fixing function. Different plant architectures inevitably lead to different dune formations. Among desert plants, why can some accumulate sand into mounds while others cannot, and what architectural characteristics does this reflect? This paper attempts to address these questions.

2. Methods

Minqin County is located in the arid desert region of northwestern China, on the western edge of the Tengger Desert in the lower Shiyang River basin on the northeastern side of the Hexi Corridor in Gansu Province [Figure 2: see original paper]. According to statistical data, Minqin County covers 16,016 km², with desert accounting for 55.03% of total land area, Gobi 34.13%, saline-alkali flats and low hills 5.00%, and desert grassland 11.84%. The county' s multi-year average precipitation is 116.52 mm, with 28.2 days of strong wind (17 m/s), 25.8 days of sandstorms, and 37.8 days of floating dust. Currently, groundwater levels within and at the edge of the oasis have dropped to 30.2 m.

Natural vegetation in the area includes *Nitraria tangutorum*, *N. sphaerocarpa*, *Artemisia arenaria*, *Ephedra przewalskii*, *Calligonum mongolicum*, *Tamarix ramosissima*, and *Stipa glareosa*, primarily *Haloxylon ammodendron* and *Caragana korshinskii.* Both natural vegetation and plantations are patchily distributed. Along the edge of Minqin Xishawo, we established two transects parallel to the oasis edge. Vegetation with sand mounds was surveyed by mound unit; vegetation without sand mounds was surveyed by individual plant. A total of 108 plant and sand-mound quadrats were investigated.

Crown area was calculated using the elliptical area formula based on long and short axes. Sand mound coverage was expressed as the percentage of vegetation area covering the mound. Projection coverage was the percentage of vegetation area (excluding gaps) to quadrat area, with gaps between branches estimated visually. Layered silhouette area was measured from the main wind direction, starting at ground level at the base diameter and dividing plant height into layers at 10, 30, 50, 100, 150, and 200 cm. A vertical ruler was erected on the windward side to measure silhouette width at each height layer. For the top layer insufficient to reach the designated height, its width was also measured. Silhouette degree refers to the percentage of plant branch area within the silhouette outline [Figure 3: see original paper]. We photographed clump plants with a vertical ruler on the windward side. Sand mound length and width were measured directly at the widest point perpendicular to length. Maximum height was measured with AutoCAD used to delineate and calculate gap areas to calibrate visually estimated silhouette degrees, thereby representing sand mound characteristics.

Layered silhouette area was calculated using the trapezoidal area formula for each layer. The center height of the layer with maximum silhouette area was defined as the silhouette center height. Data analysis employed SPSS 13.0.

3. Results

3.1 Morphological Characteristics of Sand Mounds

Survey results indicated that only five local plant species can accumulate sand into mounds: *Nitraria tangutorum*, *N. sphaerocarpa*, *Tamarix ramosissima*, *Ephedra przewalskii*, and *Stipa glareosa*. Plants such as *Artemisia arenaria*, *Haloxylon ammodendron*, *Calligonum mongolicum*, and *Caragana korshinskii* cannot form sand mounds. Among surveyed sites, *Tamarix* mounds were the largest, followed by *Nitraria* mounds. *Tamarix* mounds measured 193.6 cm in height (range: 64–250 cm), *Nitraria* mounds 135.5 cm (range: 13–275 cm), *N. sphaerocarpa* mounds 45.5 cm (range: 15–48 cm), *Ephedra* mounds 28.8 cm (range: 17–77 cm), and *Stipa glareosa* mounds 9.3 cm (range: 5–15 cm).

The length-to-width ratio was greatest for *Ephedra* (2.10), followed by *Stipa glareosa* (2.42), while *Nitraria* and *Tamarix* mounds had small ratios. *Nitraria* mounds were generally circular or elliptical, *Ephedra* and *Stipa* mounds were long-triangular, and other mounds were irregularly shaped. Vegetation on these nebkhas was highly uniform. On *Nitraria* and *N. sphaerocarpa* mounds, vegetation covered almost all surfaces except the leeward slope. *Nitraria* had average projection coverage of 0.51, *N. sphaerocarpa* 0.34, and *Tamarix* mounds were nearly completely covered with average projection coverage of 0.70. *Ephedra* and *Stipa* mound vegetation was concentrated at the upwind head, with other parts bare. Average projection coverage was 0.30 for *Ephedra* and 0.34 for *Stipa*. Other non-mound-forming plants had average projection coverages of 0.23 for *Artemisia*, 0.30 for *Haloxylon*, 0.44 for *Calligonum*, and 0.19 for *Caragana*. Nebkha vegetation had slightly higher average projection coverage than non-mound vegetation, but the difference was not significant ($P > 0.05$) .

3.2 Layered Silhouette

The ranking of average silhouette width by height layer was: 0–10 cm > 10–30 cm > 30–50 cm for *Nitraria*, *N. sphaerocarpa*, *Tamarix*, and *Stipa*; 0–10 cm > 30–50 cm > 10–30 cm for *Ephedra*; and 30–50 cm > 10–30 cm > 0–10 cm for *Artemisia*, *Haloxylon*, *Calligonum*, and *Caragana*. The ranking of average silhouette degree by height was: 0–10 cm > 10–30 cm > 30–50 cm for *Nitraria*, *N. sphaerocarpa*, *Artemisia*, *Haloxylon*, and *Calligonum*; 30–50 cm > 10–30 cm > 0–10 cm for *Tamarix* and *Ephedra*; and 10–30 cm > 0–10 cm > 30–50 cm for *Stipa* and *Caragana*. The ranking of average silhouette area by height was: 0–10 cm > 10–30 cm > 30–50 cm > 50–100 cm for *Nitraria* and *N. sphaerocarpa*; 30–50 cm > 10–30 cm > 0–10 cm for *Tamarix* and *Ephedra*; 10–30 cm > 0-

10 cm > 30-50 cm for *Artemisia*; and 30-50 cm > 10-30 cm > 50-100 cm for *Haloxylon*, *Calligonum*, *Stipa*, and *Caragana* [Figure 4: see original paper].

Nitraria, *N. sphaerocarpa*, *Ephedra*, and *Stipa* had maximum silhouette width near ground level. *Ephedra* and *Tamarix* had relatively large silhouette degrees near ground level, and *Ephedra* also had large near-ground silhouette area. *N. sphaerocarpa* and *Stipa* had thick main stems but sparse near-ground branches. Silhouette width decreased gradually from ground upward for *Nitraria*, *N. sphaerocarpa*, *Tamarix*, *Ephedra*, and *Stipa*. For *Calligonum* and *Artemisia*, silhouette width first increased then decreased from ground upward. *Stipa* silhouette area peaked in the 10-30 cm layer, while other species peaked in the 30-50 cm layer. Except for *Ephedra* and *Tamarix*, where silhouette degree first increased then decreased from ground upward, all other species showed decreasing trends.

3.3 Silhouette Center Height

Further calculations of silhouette area for each height layer showed that the silhouette centers of *Nitraria*, *N. sphaerocarpa*, *Tamarix*, *Ephedra*, and *Stipa* were within 10 cm of ground level. Specifically, *Nitraria* and *N. sphaerocarpa* centers were in the 0-10 cm layer, *Tamarix* and *Stipa* in the 10-30 cm layer, and *Ephedra* in the 30-50 cm layer. In contrast, plants that cannot form sand mounds—*Artemisia*, *Calligonum*, *Haloxylon*, and *Caragana*—had silhouette centers above 30 cm: *Artemisia* and *Calligonum* at 50-100 cm, *Caragana* at 100-150 cm, and *Haloxylon* at 100-150 cm [Figure 5: see original paper].

3.4 Relationship Between Sand Mounds and Plant Silhouette

Analysis of all sample points revealed that sand mound height, width, and length were all extremely significantly positively correlated with plant silhouette width and silhouette area ($P < 0.01$). Silhouette degree at 10-200 cm height was significantly positively correlated with sand mound height ($P < 0.05$), while silhouette degree at 200-250 cm was extremely significantly positively correlated with plant silhouette area ($P < 0.01$). Correlations with other indicators were weaker.

Plant silhouette width on the main wind direction was extremely significantly positively correlated with sand mound height, width, and length ($P < 0.01$). Width at ground level showed extremely significant positive correlation with sand mound height and width ($P < 0.01$). Numerically, correlations were stronger for sand mound width and length with plant silhouette width. The correlation coefficients between sand mound width and length with plant silhouette width were larger when closer to ground level, as were those with plant silhouette area. Correlation coefficients between sand mound width and plant silhouette degree were larger when closer to plant center height. Silhouette degree at 0-10 cm and 200-250 cm was not correlated with sand mound morphology ($P > 0.05$), indicating greater variation in silhouette degree at plant top and bottom. Sand mound width showed stronger correlation with plant silhouette area than did height or length. Both sand mound width and length were extremely significantly negatively correlated with plant under-branch height ($P < 0.01$) [TABLE:2, TABLE:3].

4. Discussion

The above analysis indicates that plants capable of forming sand mounds have triangular or cylindrical silhouettes—wide at the base and narrow at the top, with silhouette centers near ground level. Plants with this triangular silhouette are clumping shrubs without obvious main stems. *Tamarix* is also a clumping shrub with a roughly cylindrical silhouette. Plants that cannot accumulate sand have diamond-shaped silhouettes with centers at some height above ground.

Research shows that *Calligonum* can form nebkhas in Xinjiang [9], and *Artemisia sphaerocaphala* can accumulate sand in the Ulan Buh Desert [7], while *A. ordosica* can form mounds in the Kubuqi Desert [10]. These differences may relate to local plant growth conditions. Both *Calligonum mongolicum* and *A. arenaria* generally cannot form sand mounds in Minqin and the Hexi Corridor, possibly because Minqin' s poorer climate conditions (especially precipitation) result in sparser branching.

Nebkha height is determined by plant properties. Shrubs that produce adventitious roots can develop mounds that grow with the plant, reaching several times the plant height. Although *Ephedra* and *Stipa* can accumulate sand, they do not produce adventitious roots, so mound height is limited by plant height. *Tamarix* and *N. sphaerocarpa* mounds are nearly completely covered by vegetation except on the leeward slope, while *Ephedra* and *Stipa* mounds are long-triangular with vegetation only at the upwind head, leaving other parts bare.

Why does this occur? Based on observations, this is determined by adventitious root production. *Tamarix* branches can produce adventitious roots after burial, allowing mounds to grow taller with vegetation, while *Ephedra* and *Stipa* cannot. Limited by shrub size, mounds cannot widen and only form long-triangular bare sand piles on the leeward side.

According to observations at Minqin Desert Control Experimental Station, 75% of sand particles in wind-sand flow move within 20–30 cm of the surface, and 76–200 cm height accounts for only 0.035% of total sand transport. Sand particles, including those in dust storms, concentrate near the surface, which is why lower plant silhouettes more easily form sand mounds. The 0–10 cm silhouette layer is critical for sand accumulation, and its structure likely represents post-burial plant structure. Studies in southern New Mexico show nebkhas generally form 1-6.5 km downwind of sand sources [26]. While sand source is necessary for nebkha formation, it is not sufficient, as *Calligonum* and *Haloxylon* cannot form mounds under the same local conditions. Some scholars note that abundant sand sources produce larger mounds [3], but this is relative to similar vegetation and wind conditions—not the primary factor.

Some researchers suggest that the relationship between nebkha horizontal scale and height is an important indicator for dividing development stages [28], while others propose nebkhas as important indicators of wind erosion and land degradation [29]. Sand mounds formed by shrubs represent material manifestation of sand interception and stabilization. Silhouette area, especially perpendicular to the main wind direction, is a crucial indicator of windbreak and sand-fixing function. The notion that plants unable to form sand mounds cannot prevent wind erosion is clearly incorrect—such plants still increase surface coverage and reduce near-surface airflow velocity.

In summary, plant silhouette, particularly within the 0–30 cm near-ground layer, is a key factor in nebkha formation. This conclusion advances beyond previous findings that vegetation coverage is a main factor [2–3] and provides deeper insight than studies focusing solely on silhouette area' s wind-blocking effect [21–24]. Since nebkha surfaces generally lack soil crusts, they can store precipitation and benefit plant growth. Whether some nebkhas might transition to barchan dunes after vegetation degradation, given appropriate environmental and sand source conditions, remains a question for further research.

5. Conclusion

Plants capable of accumulating sand into mounds have triangular or cylindrical silhouettes, meaning silhouette width decreases from ground upward and the silhouette center is located near ground level (within 30 cm). Plants with this characteristic are clumping shrubs. Plants unable to accumulate sand have diamond-shaped silhouettes with silhouette centers more than 30 cm above ground. Sand particles in wind-sand flow and dust storms concentrate primarily within the 0–30 cm near-surface layer, which is an important reason why lower plant silhouettes more easily form sand mounds. Plants whose stems can produce adventitious roots after sand burial can form mounds several to dozens of times taller than the plant itself, while those lacking this characteristic form mounds limited by plant height. Silhouette is an important architectural feature, and silhouette area is a crucial indicator of windbreak and sand-fixing function. Taller sand mounds indicate stronger sand-blocking and stabilization capacity. However, plants that cannot form sand mounds still possess certain windproof effects.

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