Correlation between nebkhas formation ability and silhouette layer parameters of desert plants

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Abstract. To determine why certain desert plants form nebkhas whereas others do not, we investigated common sand-fixing plants of the Minqin desert region, with 108 plants and nebkha samples set up at the edge of the above region. Measurement and comparative analysis of markers such as silhouette layer width, area, and center height revealed the following trends: (i) The silhouettes of nebkha-forming plants are triangular or cylindrical, i.e., the width of these silhouettes decreases with increasing height, and the silhouette centers are positioned 30 cm above the ground. Thus, these plants are shrubs. Plants that do not accumulate sand to form nebkhas are rhombus-shaped, and their silhouette centers are located more than 30 cm above the ground. (ii) Drifting sand flux and sandstorm particles are mainly concentrated in the region between 0 and 30 cm above the ground, explaining why plants with lower silhouettes can easily accumulate sand to form nebkhas. (iii) After being buried in sand, plants whose stems are capable of producing adventitious roots can form nebkhas/sand dunes dozens of times higher than the plant. Although other plants can still form nebkhas, the height of the produced dunes does not exceed the height of the plant. (iv) Silhouette area size is an important marker reflecting wind-breaking and sand-fixing ability, i.e., the ability of a plant to accumulate sand and form nebkhas. However, plants that cannot accumulate sand to form nebkhas, e.g., Haloxylon ammodendron, Calligonum mongolicum, and Artemisia desertorum also exhibit wind-breaking and sand-fixing abilities.

1. Introduction
Sand mounds formed due to the blocking effect of shrubs are generally termed as nebkhas. Sand dunes and nebkhas of different sizes are commonly observed in deserts, with some of them forming due to the wind-breaking and sand accumulation effects of plants, as exemplified by the sand dunes/nebkhas of Nitraria tangutorum and Tamarix ramosissima and the nebkhas of Ephedra przewalskii (figure 1).

Figure 1. Nebkhas along an oasis fringe in the Minqin desert.
Nebkhas are extensively documented in both local and overseas reports, which mainly deal with distribution environments [1-6], morphology characteristics and evolution [7-10], and ecological issues [11-17]. However, studies on the conditions required for nebkha formation are relatively few. Nebkhas form in arid, semi-arid, and semi-humid desert areas when wind-drift sands are blocked and accumulated by shrubs [4]. The richness of the sand supply source plays a key role in the genesis of aeolian landforms, also affecting the spatial dimensions and survival periods of nebkhas [4]. Shrub type and characteristics are important factors determining nebkha shape, since vegetation affects the surface flow field by surface coverage, wind dissipation, and quicksand blocking, accumulating sand around the shrub and protecting the sand underneath the shrub from erosion. The morphologies of nebkhas formed by different vegetation types differ from each other, with tall dense shrubs having a higher blocking ability [3,4]. Nebkhas at the edge of Lake Ebi in Xinjiang mainly formed in late Holocene and are currently still abundant [18]. As indicated by some overseas investigations, nebkha height and length are fairly well correlated to shrub height [19]. Generally, nebkhas are formed by sand accumulation in regions with reverse airflow at the leeward side of bushes [20], with their morphology depending on the bush width and the nebkha repose angle.

Different plant architectures have different quicksand blocking abilities, as has been extensively documented in numerous studies [21-25]. Nebkha formation is believed to be mainly controlled by vegetation coverage, wind intensity, and sand source type [3,4], with the wind-breaking effects of plants being mainly related to their silhouette area at the windward side [22-25]. Comparison studies on the sand-fixing ability of Caragana microphylla and Caragana stenophylla shrubs in the desert steppes of the Inner Mongolia plateau show that the area, height, and volume of nebkhas, as well as sand-fixing efficiency, show a significant positive linear correlation with the fresh weight of ground branches [7]. In addition, the plant architecture characteristics and wind-breaking/sand-fixing effects of three Artemisia species in the Horqin desert have been investigated [26].

The above studies on nebkhas rarely consider the relationship between nebkha formation and plant architecture. On the other hand, studies on plant architecture are generally focused on the relationship between architecture characteristics and environmental conditions, overlooking the role of architecture in nebkha formation. For instance, the better sand-blocking ability of tall and dense shrubs [3,4] does not explain why saxaul (Haloxylon ammodendron (C.A. Mey.) Bunge), which is a small tree/large shrub distributed in the Hexi Corridor desert region and the Minqin desert region in Gansu, does not form nebkhas. Apparently, simple plant height and architecture considerations cannot reveal the mechanisms of nebkha formation. Therefore, this work aims to investigate the influences of plant architecture and related parameters on the genesis of nebkhas.

2. Study area and methods

2.1. Study area
Minqin county (area = 16016 km²) is a classical arid desert region in China located at the western edges of the Tengger desert downstream of the Shiyang river catchment area in the northeast of the Hexi Corridor in Gansu (101 Gans–104 Gansu, 384 Gan–394 Gans) (figure 2). According to data provided by the Minqin county statistics department, deserts, gobis, saline-alkali wastelands, and low mountains/residual hills account for 94.2% of the total land area, with the individual shares of deserts, gobis, and desert wastelands equaling 55.03, 5.00, and 34.13%, respectively. The average annual precipitation and evaporation in Minqin county equal 116.52 and 2351.79 mm, respectively. On average, winds or sandstorms exhibiting speeds above 17 m s⁻¹ are annually observed on 28.2 and 25.8 days, respectively, with sand and dust storms annually observed on 37.8 and 30.2 days on average, respectively. Currently, the ground water level inside oases and on their edges has decreased to ~20 m.
2.2. Study methods

Local natural vegetation includes *Nitraria tangutorum* Bobr., *Artemisia arenaria* DC. Prodr., *Ephedra przewalskii* Stapf, *Nitraria sphaerocarpa* Maxim., *Calligonum mongolicum* Turcz., and *Tamarix ramosissima* Ledeb., whereas non-native vegetation is dominated by *Haloxylon ammodendron* and *Caragana korshinskii* Kom. Both natural and non-native vegetation show a patchy distribution. At the edge of the western Minqin desert, two sample lines were set up in the main wind direction (NW) and parallel to oasis edges. Mature plants (trees/bushes) were selected on the above sample lines, and plants with nebkhas were examined using the sand mound as a unit while plants without nebkhas were examined using individual plants as a unit, with 108 plants and nebka samples examined in total (table 1). Vegetation crowns were modeled by ellipses, the long/short axes of which were used to calculate the corresponding areas. The vegetation coverage of nebkhas was defined as the percentage of nebkha area covered with vegetation relative to the total nebkha area. The projective cover was defined as the percentage of vegetation and sample areas after deduction of gaps, which were estimated visually. The area of silhouette layers was obtained by sequentially dividing the plant into layers limited by heights of 10, 30, 50, 100, and 200 cm using a vertical ruler placed at the windward side of the plant. Subsequently, silhouette widths were measured at the above heights (the actual height of the last layer was used even if the total plant height was smaller than these pre-defined values). The silhouette fraction corresponded to the visually estimated percentage of the silhouette outline area occupied by branches (formula (1)). A vertical ruler was placed at the windward side of every plant/bush and photographed (figure 3). Gap areas were sketched and calculated using AutoCAD to correct the visually estimated silhouette fraction. The length of nebkhas was measured directly, and their width was determined perpendicular to their length at the widest point. Finally, the highest point of nebkhas was used to measure their height. The height of plant underbranches was defined as the distance from the stem to the growing parts of branches in the lowest layer. The area of silhouette layers was calculated as follows (formula (2)):

\[
\text{Silhouette rate} = \frac{\text{silhouette contour area} - \text{void area}}{\text{silhouette contour area}} \quad (1)
\]

\[
\text{Silhouette area of one layer} = \text{trapezoid area of layer} \times (1 - \text{silhouette fraction}) \quad (2)
\]

The height of the center of the layer with the greatest silhouette area was taken as the silhouette center height. Data analysis was performed using SPSS 13.0 software.
3. Results

3.1. Morphological characteristics of nebkhas

The obtained results indicated that only five local plants (N. tangutorum, N. sphaerocarpa, T. ramosissima, E. przewalskii, and Stipa glareosa P. Smirn.) could form nebkhas, whereas A. arenaria, H. ammodendron, C. mongolicum, and C. korshinskii could not. N. tangutorum nebkhas were round or oval, those formed by E. przewalskii and S. glareosa were elongated triangular, whereas other nebkhas had irregular shapes.

Table 1. Morphological characteristics of plants and nebkhas.

| Plants            | Nebkhas/ plant quadrat | Sandpile | Mean height (cm) | Mean Length (cm) | Coverage (%) | Projective cover (%) | Shape of nebkhas | Vegetation projective cover (0–1) |
|-------------------|-------------------------|----------|------------------|------------------|--------------|----------------------|------------------|----------------------------------|
| N. tangutorum     | 17                      | 135.5 ± 12.9 | 863.8 ± 15.2     | 0.51 ± 0.1       | 0.10 ± 0.0   | Round or oval         | 0.23 ± 0.02      |
| N. sphaerocarpa   | 11                      | 28.8 ± 2.75 | 305.8 ± 19.6     | 0.34 ± 0.0       | 0.10 ± 0.0   | Long patchy           | 0.30 ± 0.00      |
| T. ramosissima    | 7                       | 193.6 ± 19.6 | 1297.1 ± 141.5   | 1.05 ± 0.5       | 0.61 ± 0.3   | Irregular             | 0.52 ± 0.07      |
| E. przewalskii   | 10                      | 45.5 ± 4.6  | 441.5 ± 45.1     | 0.30 ± 0.0       | 0.21 ± 0.07  | Elongated triangular  | 0.70 ± 0.01      |
| S. glareosa       | 7                       | 9.3 ± 1.4  | 74.1 ± 12.5      | 0.34 ± 0.0       | 0.11 ± 0.0   | Elongated triangular  | 0.34 ± 0.03      |
| A. arenaria       | 12                      | 0         | 0                | 0                | 0            | (No nebkha)           | 0.29 ± 0.06      |
| H. ammodendron    | 11                      | 0         | 0                | 0                | 0            | (No nebkha)           | 0.44 ± 0.03      |
| C. mongolicum     | 17                      | 0         | 0                | 0                | 0            | (No nebkha)           | 0.19 ± 0.01      |
| C. korshinskii    | 16                      | 0         | 0                | 0                | 0            | (No nebkha)           | 0.30 ± 0.03      |

Figure 3. Schematic plant silhouette diagram.
The above nebkhas had uniform vegetation cover, with their three other sides and the top covered by vegetation in addition to the leeward side in the case of *N. tangutorum* and *N. sphaerocarpa*. The average vegetation projective covers of *N. tangutorum* and *N. sphaerocarpa* equaled 0.30 and 0.23, respectively. *T. ramosissima* nebkhas were almost fully covered by vegetation, with only insignificant areas on the leeward side being exposed, showing an average vegetation projective cover of 0.52. *E. przewalskii* and *S. glareosa* covered their nebkhas at the top of the windward side, leaving other areas exposed, with the respective average vegetation projective covers equalling 0.70 and 0.34. The average projective covers of non-nebkha-forming plants were as follows: *A. arenaria* = 0.30, *H. ammodendron* = 0.44, *C. mongolicum* = 0.19, and *C. korshinskii* = 0.30 (table 1). The obtained results showed that the average vegetation projective cover of plants forming nebkhas was greater than that of non-nebkha-forming plants, however, this difference was not significant (*P > 0.05*).

### 3.2. Silhouettes of plants in the main wind direction

#### 3.2.1. Silhouette layers

In the windward direction, the average silhouette width of the 0–10 cm layer decreased in the following order: *T. ramosissima* > *N. tangutorum* > *E. przewalskii* > *N. sphaerocarpa* > *C. mongolicum* > *C. korshinskii* > *H. ammodendron* > *S. glareosa* > *A. arenaria*; with the corresponding order for the 10–30 cm layer being *T. ramosissima* > *N. tangutorum* > *E. przewalskii* > *N. sphaerocarpa* > *C. mongolicum* > *C. korshinskii* > *H. ammodendron* > *S. glareosa*. The average silhouette width of the 30–50 cm layer decreased as follows: *T. ramosissima* > *E. przewalskii* > *C. mongolicum* > *C. korshinskii* > *H. ammodendron* > *N. tangutorum* > *N. sphaerocarpa* > *A. arenaria*. Finally, the average silhouette width of the 50–100 cm layer decreased in the following order: *T. ramosissima* > *C. korshinskii* > *H. ammodendron* > *C. mongolicum* > *E. przewalskii* > *A. arenaria*.

In the windward direction, the average silhouette height of the 0–10 cm layer decreased in the following sequence: *H. ammodendron* > *E. przewalskii* > *T. ramosissima* > *A. arenaria* > *C. mongolicum* > *C. korshinskii* > *S. glareosa* > *N. sphaerocarpa* > *N. tangutorum*; the average silhouette height of the 10–30 cm layer decreased in the following sequence: *E. przewalskii* > *T. ramosissima* > *H. ammodendron* > *C. korshinskii* > *A. arenaria* > *N. sphaerocarpa* > *N. tangutorum* > *C. mongolicum* > *S. glareosa*; the average silhouette height of the 30–50 cm layer decreased as follows: *E. przewalskii* > *T. ramosissima* > *H. ammodendron* > *C. korshinskii* > *A. arenaria* > *N. sphaerocarpa* > *C. mongolicum* > *N. tangutorum*. Finally, the average silhouette height of the 50–100 cm layer decreased in the following sequence: *T. ramosissima* > *H. ammodendron* > *E. przewalskii* > *C. korshinskii* > *C. mongolicum* > *A. arenaria*.

In the windward direction, the average silhouette area of the 0–10 cm layer decreased in the following sequence: *T. ramosissima* > *N. tangutorum* > *E. przewalskii* > *N. sphaerocarpa* > *H. ammodendron* > *C. mongolicum* > *C. korshinskii* > *S. glareosa* > *A. arenaria*; the average silhouette area of the 10–30 cm layer decreased as *T. ramosissima* > *E. przewalskii* > *N. tangutorum* > *N. sphaerocarpa* > *H. ammodendron* > *C. korshinskii* > *C. mongolicum* > *A. arenaria* > *S. glareosa*; the average silhouette area of the 30–50 cm layer decreased in the following order: *T. ramosissima* > *E. przewalskii* > *C. korshinskii* > *H. ammodendron* > *C. mongolicum* > *N. sphaerocarpa* > *A. arenaria* > *N. tangutorum*. Finally, the average silhouette area of the 50–100 cm layer decreased in the following sequence: *T. ramosissima* > *H. ammodendron* > *C. korshinskii* > *E. przewalskii* > *C. mongolicum* > *A. arenaria* (figure 4).

Figure 4 reveals that *T. ramosissima*, *N. tangutorum*, *E. przewalskii*, and *N. sphaerocarpa* exhibited the greatest silhouette width, whereas *E. przewalskii* and *T. ramosissima* exhibited the greatest silhouette fraction (the stem of *H. ammodendron* is thicker but has fewer branches near the ground). *T. ramosissima*, *N. tangutorum*, and *E. przewalskii* had the largest silhouette areas. The silhouette widths of *N. tangutorum*, *E. przewalskii*, *N. sphaerocarpa* and *S. glareosa* gradually decreased with increasing height, whereas those of *T. ramosissima*, *H. ammodendron*, *C. korshinskii*, *C. mongolicum*, and *A. arenaria* initially increased and then decreased. Except for *E. przewalskii* and *T. ramosissima*, which showed an initially increasing and subsequently decreasing silhouette fraction with increasing
height, the corresponding values for all other plants decreased with increasing height. The silhouette area of *S. glareosa* was the largest at a height of 0–10 cm, whereas that of *E. przewalskii*, *N. tangutorum*, and *N. sphaerocarpa* was maximal at 10–30 cm. The silhouette area of *A. arenaria* was the largest at a height of 30–50 cm, with all other plants exhibiting the greatest silhouette area at a height of 50–150 cm.

**Figure 4.** Silhouette parameters of nebkha-forming plants.

3.2.2. **Height of silhouette center.** Based on table 2, the silhouette area was further calculated in 10-cm height intervals, revealing that the silhouette centers of *N. tangutorum*, *N. sphaerocarpa*, and *S. glareosa* were located at 0–10 cm, that of *E. przewalskii* at 10–30 cm, and that of *T. ramosissima* at 30–50 cm height. The silhouette centers of plants not forming nebkhas were all positioned above 30 cm, i.e., at 50–100 cm (*A. arenaria* and *C. mongolicum*), 50–100 cm (*C. korshinskii*), and 100–150 cm (*H. ammodendron*) (figure 5).

**Figure 5.** Height profile of silhouette areas.

3.3. **Relationship between nebkha parameters and plant silhouettes**

Analysis of all 115 quadrats showed that the height, width, and length of nebkhas were positively correlated with the width and area of plant silhouettes (*P* < 0.01), silhouette fraction at 10–200 cm
height \( (P < 0.01) \), silhouette fraction at 200–250 cm height \( (P < 0.05) \), and the silhouette area \( (P < 0.01) \). In comparison, the correlation between the silhouette overall and nebkha morphological parameters (table 2) was weaker.

### Table 2. Correlations between silhouette and nebkha parameters.

| Nebkha parameters | Silhouette height/cm |
|-------------------|----------------------|
|                   | 0–10                 | 10–30                | 30–50                | 50–100               | 100–150              | 150–200              | 200–250              |
| Silhouette height | 0.95**               | 0.95**               | 0.93**               | 0.85**               | 0.75**               | 0.71**               | 0.65**               |
| Nebkha width      | 0.97**               | 0.96**               | 0.95**               | 0.88**               | 0.80**               | 0.76**               | 0.70**               |
| Nebkha length     | 0.90**               | 0.90**               | 0.88**               | 0.80**               | 0.70**               | 0.66**               | 0.63**               |
| Silhouette fraction | 0.04                | 0.29**               | 0.43**               | 0.48**               | 0.40**               | 0.35**               | 0.24*                |
| Nebkha width      | 0.05                | 0.31**               | 0.44**               | 0.50**               | 0.42**               | 0.38**               | 0.26*                |
| Nebkha length     | 0.04                | 0.33**               | 0.46**               | 0.47**               | 0.36**               | 0.34**               | 0.24*                |
| Silhouette area   | 0.90**               | 0.87**               | 0.80**               | 0.76**               | 0.72**               | 0.57**               | 0.49**               |
| Nebkha width      | 0.94**               | 0.92**               | 0.86**               | 0.83**               | 0.78**               | 0.63**               | 0.56**               |
| Nebkha length     | 0.86**               | 0.83**               | 0.76**               | 0.71**               | 0.69**               | 0.57**               | 0.49**               |

Table 2 allows the following conclusions to be drawn:

- The silhouette width in the windward direction and the height, width, and length of nebkhas showed a significant positive correlation \( (P < 0.01) \), similar to that observed between the width of the plant stem and nebkha dimensions \( (P< 0.01) \). The above data indicate that nebkha and silhouette widths were most strongly correlated to each other.
- The correlation between nebkha dimensions and plant silhouette width improved with decreasing height, similarly to that between nebkha dimensions and plant silhouette area.
- The correlation between nebkha height/width and silhouette fraction improved with decreasing distance to the silhouette center \( (50–100 \text{ cm}) \), being significant and positive \( (P < 0.05) \) at a height of 200–250 cm. However, no corresponding correlation was observed at a height of 0–10 cm \( (P > 0.05) \). Therefore, changes in the silhouette fraction at both extremes of the plant showed great variation.
- Among the three nebkha morphology indicators (i.e., dimensions), the greatest correlation with silhouette area was observed for nebkha width.

All nebkha morphology indicators showed a significant negative correlation with underbranch height \( (P < 0.01) \) (table 3).

### Table 3. Correlations between nebkha morphology indicators and underbranch height.

| Underbranch height | Nebkha height | Nebkha length | Nebkha width |
|--------------------|---------------|---------------|--------------|
|                    | -0.32**       | -0.35**       | -0.31**      |

### 4. Discussion

The above analysis reveals that nebkha-forming plants exhibit triangular or cylindrical silhouettes, i.e., their silhouette width is largest at the bottom and lowest at the top, with the silhouette center lying close to the ground. Plants with triangular silhouettes are shrubs with no obvious main stem, e.g., *N. tangutorum*, *N. sphaerocarpa*, *E. przewalskii*, and *S. glareosa*, with *T. ramosissima* being a shrub with a cylindrical silhouette. Conversely, plants that do not form nebkhas have rhombus-shaped silhouettes, i.e., those with a broad middle, and narrow top/bottom, with the silhouette center lying at a certain height above the ground. These plants include *A. arenaria*, *H. ammodendron*, *C. mongolicum*, and *C. korshinski*. Interestingly, it has been reported that *C. mongolicum* can form nebkhas in Xinjiang [10], *A. sphaerocephala* Krasch. can form nebkhas in the Ulan Buh Desert [8], and *A. ordosica* can form nebkhas in the Kubuqi Desert [11], which can be related to the local growth conditions of these plants. Although the deserts in Minqin county and the Hexi Corridor are populated with *C. mongolicum* and *A.*...
arenaria, these plants do not generally form nebkhas in those areas. This observation is rationalized by the fact that the weather conditions (i.e., precipitation) in the Minqin desert region are less favorable than those in the abovementioned areas, resulting in plants with sparser branches that are not able to form nebkhas.

The height of nebkhas is determined by certain plant attributes. Thus, plants such as N. tangutorum, T. ramosissima, and N. sphaerocarpa produce adventitious roots when buried in sand, allowing nebkhas to increase concomitantly with plant growth. Although E. przewalskii and S. glareosa can form nebkhas, they do not produce adventitious roots, which limits the corresponding nebka height to the height of these plants. Conversely, C. mongolicum can produce adventitious roots, but its sparse near-ground branches and high-lying silhouette center (50–100 cm above ground) make sand accumulation unfavorable. Nebkhas formed by N. tangutorum, T. ramosissima, and N. sphaerocarpa can be covered by vegetation, except for the northern windward slope, where vegetation is sparse. Nebkhas of E. przewalskii and S. glareosa are long triangles, and these plants are located at the top 1/5 of their nebkhas at the upwind side, with other nebka parts being exposed. According to our analysis, this behavior can be explained by the ability of plants to produce adventitious roots. Branches of N. tangutorum and T. ramosissima can form adventitious roots after being buried in sand, and the shrub becomes larger as sand accumulates. On the other hand, E. przewalskii and S. glareosa do not have this capability, and the size of their nebkhas is limited by the size of the corresponding shrub. Therefore, these plants can only form exposed triangular nebkhas at the downwind side of the shrub.

According to observations of the Minqin sand control comprehensive test station, 80% of sand particles in a drifting sand flux circulate at a height of 20–30 cm above the ground, with half of these particles circulating at a height of 0.3–0.5 cm. At a wind speed of 7 m s⁻¹, the sediment load at a height of 10 cm above the ground comprises 75% of the total load, with the corresponding value for a height of 200 cm equaling 0.035% [25]. Thus, we can see that drifting sand flux particles (including those of sandstorms) are mainly concentrated near the ground, which is one of the important reasons why plants with lower silhouettes can easily form nebkhas. Combining the observations of plant silhouettes and the vertical structure of the drifting sand flux, we can see that the height of 0–10 cm is a crucial threshold for silhouettes to accumulate sand and form nebkhas. Therefore, we can further hypothesize that the plant structure of this layer can also represent that after the next sand burial. Studies performed in the southern parts of New Mexico in the US show that nebkhas are typically formed 1–6.5 km downwind of the sand source [27]. The sand source is a necessary but not sufficient condition for nebka formation, e.g., N. tangutorum, T. ramosissima, and N. sphaerocarpa can form nebkhas, whereas A. arenaria and C. mongolicum cannot, even in the same local environment with identical sand source parameters. In addition, a number of studies revealed that the drifting sand flux in gobis is non-saturated [28], although nebkhas of T. ramosissima and N. tangutorum can be sometimes observed in these regions. Some researchers have pointed out that the nebka volume increases under the conditions of a rich sand supply, and vice versa [4]. However, this only applies to approximately similar vegetation and wind conditions. It has also been reported that the horizontal scale and height of nebkhas are important markers differentiating their development phases [29]. Moreover, nebkhas are known to be important indicators of wind erosion and land degradation, playing an important role in the evaluation of desertification [30]. However, the formation of nebkhas is a direct manifestation of blocking and interception of quicksand by plants. Although silhouette parameters, especially the vertical silhouette area at the windward side, are important indicators of plant wind-breaking and sand-fixing performance, the opinion that plants unable to accumulate sand and form nebkhas do not exhibit wind-breaking and sand-fixing activity is obviously wrong, since such plants increase the cover of the sand surface and reduce the surface air velocity.

The above analysis demonstrates that plant silhouettes, especially those within a height of 30 cm above the ground, are an important factor for nebka formation, being better correlated with nebka formation ability than vegetation cover [3,4] and thus indicating that nebka formation is more dependent on the wind blocking effects of plant silhouette areas [22-25]. As nebkhas typically lack a soil crust, they can accumulate precipitation and thus benefit plant growth. Upon partial degradation,
nebkhas can be transformed into crescent-shaped dunes under suitable environmental and sand source conditions, which, however, requires further research.

5. Conclusion

Plants capable of forming nebkhas (shrubs) were demonstrated to have triangular or cylindrical silhouettes, i.e., those whose width decreases with increasing height and whose silhouette center lies 30 cm above the ground. Conversely, plants that do not accumulate sand to form nebkhas are rhombus-shaped, with their silhouette center lying more than 30 cm above the ground.

Numerous observations indicate that drifting sand flux and sandstorm particles are mainly concentrated in the region 0–30 cm above the ground, explaining why plants with lower silhouettes can easily form nebkhas.

After being buried in sand, plant stems capable of producing adventitious roots can form nebkhas/sand dunes that are dozens of times higher than the plant itself. Although plants incapable of such behavior can still form nebkhas, the height and shape of these nebkhas are determined by the height of the plant.

Thus, silhouette parameters are important characteristics of plant architecture. For instance, silhouette area is an important marker reflecting the wind-breaking and sand-fixing ability of plants, which is manifested in their ability to accumulate sand and form nebkhas, i.e., taller nebkhas are formed by plants with stronger wind-breaking and sand-fixing abilities. However, plants that cannot accumulate sand to form nebkhas also exhibit wind-breaking and sand-fixing effects.

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