

# Wind tunnel experiments of air flow patterns over nabkhas modeled after those from the Hotan River basin, Xinjiang, China (II): vegetated

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**Abstract** This paper examines the results of wind tunnel experiments on models of nabkha, based on those studied in the Hotan River basin. Semi-spherical and conical models of nabkhas were constructed at a ratio of 40:1 in light of the on-site observation. Artificial vegetation of simulated *Tamarix spp.* was put on top of each model. Parameters of the shape, including height, width, and diameter of vegetated semi-spherical and conical nabkha, were measured in the Hotan River basin. Wind tunnel experiments on the semi-spherical and conical nabkha used clean air devoid of additional sediments at five different wind speeds (6–14 m/s) to study the influence of vegetation on airflow patterns. Results of the experiments indicate that vegetation at the top of the nabkhas enhances the surface roughness of the sand mounds, retards airflow over the sand mounds, reduces airflow energy, eliminates erosional pits occurring on the top surface of non-vegetated sand mounds and enhances the range of influence of the vortex that forms on the leeward slope. Vegetation changes the airflow pattern upwind and downwind of the sand mound and reduces the transport of sand away from the nabkha. This entrapment of sediment by the vegetation plays an important role in sustaining the nabkha landscape of the study area. The existence of vegetation makes fine materials in wind-sand flow to possibly deposit, and promotes nabkha formation. The imitative flow patterns of different morphological nabkhas have also been verified by on-site observation in the river basin.

**Keywords** nabkhas, artificial vegetation, wind tunnel experiment

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## 1 Introduction

Nabkhas are sand mounds that form in arid, semi-arid and sub-humid climates in desert and coastal locations with sufficient sand sources. Cook et al. (1993) classified nabkhas as phytogenic dunes since vegetation plays an important role in their development. Along with vegetation, wind speed and availability of the sand source are the primary factors that influence nabkha development (Zhu and Wu, 1981; Cook et al., 1993; Nickling and Wolfe, 1994; Wu, 2003). The formation of nabkhas was simulated in a series of wind-tunnel experiments by Zhu et al. (1994). He et al. (2003) studied the function of wind-blown sand disturbance in the development of *Tamarix* communities in nabkha areas. Yue et al. (2005) examined the shape, vegetation and airflow patterns of nabkha in the grassland and agricultural area of the southeast Mongolian plateau. Hesp (1981) investigated foredunes in a coastal location, and found that the shape of the foredune is dependent on plant width and the angle of repose, with deposition occurring on the leeward slope from vortex development. The physical characteristics of vegetation on the top of dunes affect the pattern of wind-blown sand flow on the surface of sand mounds, leading to morphological change of nabkha development (Khalaf et al., 1995; Arens, 1996; Tengberg and Cheng, 1998; Hesp and McLachlan, 2000).

Following previous experiments conducted on semi-spherical and conical sand mounds without vegetation (seen in this issue), additional studies on the wind tunnel were undertaken using clean air devoid of additional sediment on models with artificial vegetation. This study on the influence of vegetation on airflow patterns permitted a better understanding of the impact of vegetation on wind-erosion, wind-deposition and morphological nabkha development.

## 2 Wind tunnel experiments

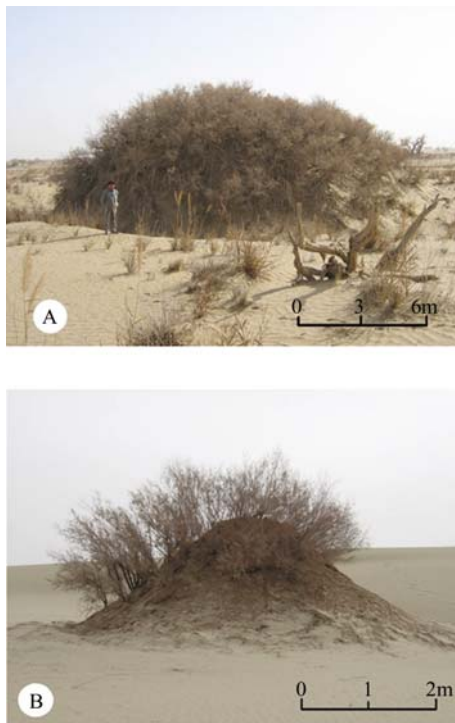
### 2.1 Experimental design

Field measurements included the wind velocity and corresponding nabkha shape and size in the Hotan River basin. This information was transferred to the laboratory experiments to ensure similarity between the field and laboratory conditions, consistent with research methods utilized by other researchers (Liu, 1995; Wu, 2003). Natural field conditions were taken into consideration as much as possible while simulating the wind tunnel experiments, including wind velocity, air pressure and air temperature. To examine the flow pattern around the nabkha without the influence of mobile sand that obscures the results, airflow in the wind tunnel used clean air without sediment.

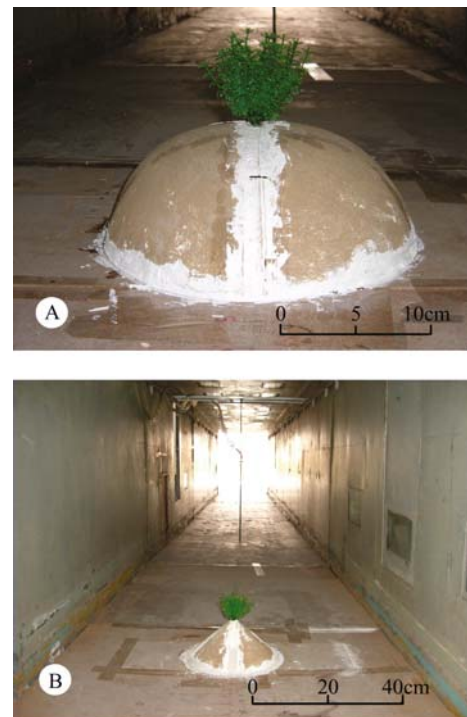
Vegetated nabkha measured in the Hotan River basin was used as the prototype for the experimental models at a 40:1 ratio (field to laboratory size) and had *Tamarix spp.* growing on their surfaces. Nabkha in the Hotan River basin is generally divided into two shapes: semi-spherical and conical (Fig. 1A and B). Since the length of the upwind slopes slightly shorter than the leeward ones, this minor difference was eliminated in the wooden model to simplify the experiment. In the field, the average height of semi-spherical nabkha is 4.74 m, and the average diameter at the base is 12.73 m. Using the 40:1 ratio, the

model had a height ( $H_1$ ) of 12 cm and a diameter ( $D_1$ ) at the base of 32 cm. Likewise, the average field height of conical nabkha is 5.10 m, while the average diameter at the base is 11.95 m. The wooden wind tunnel models had a height ( $H_2$ ) of 13 cm and a diameter ( $D_2$ ) of 30 cm.

It is more difficult to simulate the influence of vegetation on airflow patterns. Hesp and McLachlan (2000) indicated that the coppice with a vertical, dense, multi-branching growth habit was four times aerodynamically rougher, with the ability of trapping sand over a significantly greater per unit area than another with a prostrate growth habit. Khalaf et al. (1995) considered that the height of nabkhas was related to the height of the shrub crown, and the length related to the total shrub height. Changes in plant height and density and degree of coverage led to the complexity of the field situation, which could not be completely replicated in the wind tunnel experiments. The type, shape, height, width and density of the artificial plant did not change in the experiments; the artificial plant was chosen to simplify the experiments. Vegetation coverage plays an important role on the airflow pattern around nabkhas and can affect wind-speed and surface pressure on the windward side and leeside of the sand mound model. Plastic *Tamarix* models of 10 cm in height, with a crown width of 10 cm  $\times$  10 cm, were attached at the top of the sand mound models to imitate the vegetated nabkha (*Tamarix*) in the Hotan River basin (Fig. 2A and B).



**Fig. 1** Nabkhas in the Hotan River basin, Xinjiang, China  
(A) Semi-spherical nabkha; (B) Conical nabkha



**Fig. 2** Nabkha models with vegetation in the wind tunnel  
(A) Semi-spherical model; (B) Conical model

## 2.2 Experimental methods

All of the experiments were conducted in a 'blowing-type' soil deflation wind tunnel at the Desert Experiment Station of the Key Laboratory of Desert and Desertification of the Chinese Academy of Sciences, Ningxia Hui Autonomous Region of China. The wind tunnel has a working section 21 m long, 1.2 m wide and 1.2 m high, and was set at a 1° angle. The highest controlled wind velocity is 29 m/s. The working section of the wind-tunnel is made of seven movable aluminum alloy plates, which can be easily assembled and moved. Air temperature was measured by a digital thermometer and atmospheric pressure by an aneroid barometer, which imports data automatically into the computer. The wind-speed of the working section was gathered by a wind velocity profile collector, which automatically records the data once every 2 seconds over a 60 second period. The working section wind-speed is the average of the values collected over the period.

The wooden semi-spherical and conical sand mound models were hollowed out of whole tree trunks. Sand from the Hotan River basin was glued onto the models so that the surface roughness would be the same as that of the field. Plastic *Tamarix* was glued to the top of the sand mounds, replicating field vegetation conditions. Measurements of the airflow patterns over the semi-spherical and conical sand mounds were determined using the following procedure. The models were placed along the main axis of the work section, with air velocity measuring points distributed along the mid-point line of the sand mound model.

Measurements were taken along the line at the bottom and middle of the upwind slope, the top of the mound and the middle and bottom of the leeward slope of the conical and semi-spherical mounds. In addition, 18 other measuring points were selected along the line upwind and downwind of the semi-spherical mound at distances of 6, 12, 18, 24, 36, 60, 120, 180, and 240 cm. For the conical models, the 18 other measuring points were made at 6.5, 13, 19.5, 26, 39, 65, 130, 195, and 260 cm upwind and downwind. Ten measurements were made at each point at logarithmic intervals above the sand surface at 0.3, 0.6, 1.0, 3.0, 6.0, 12.0, 20.0, 35.0, and 50.0 cm to measure the wind velocity profile for both the semi-spherical and conical models (Qu et al., 1992; Li and Chen, 1995; Li and Guan, 1996; Ling et al., 1997; Zhang et al., 1998; Hu et al., 2002; Liu and Dong, 2002; Ling et al., 2003; Liu and Dong, 2003). From previous field observations and experimental results, the minimum wind speed required to initiate sand movement is 6 m/s (Liu, 1995; Wu, 2003). Experimental airflow speeds in the working section of the wind tunnel were run at 6, 8, 10, 12, and 14 m/s ( $V_1$ – $V_5$ ) to survey the flow pattern with different wind speeds over the models. Flow patterns of the semi-spherical and conical models are drawn using the Surfer (R) 8.0 software package. In this

paper, airflow patterns are shown for semi-spherical and conical nabkhas air velocities of 6, 10 and 14 m/s (Figs. 3(a)–(f)).

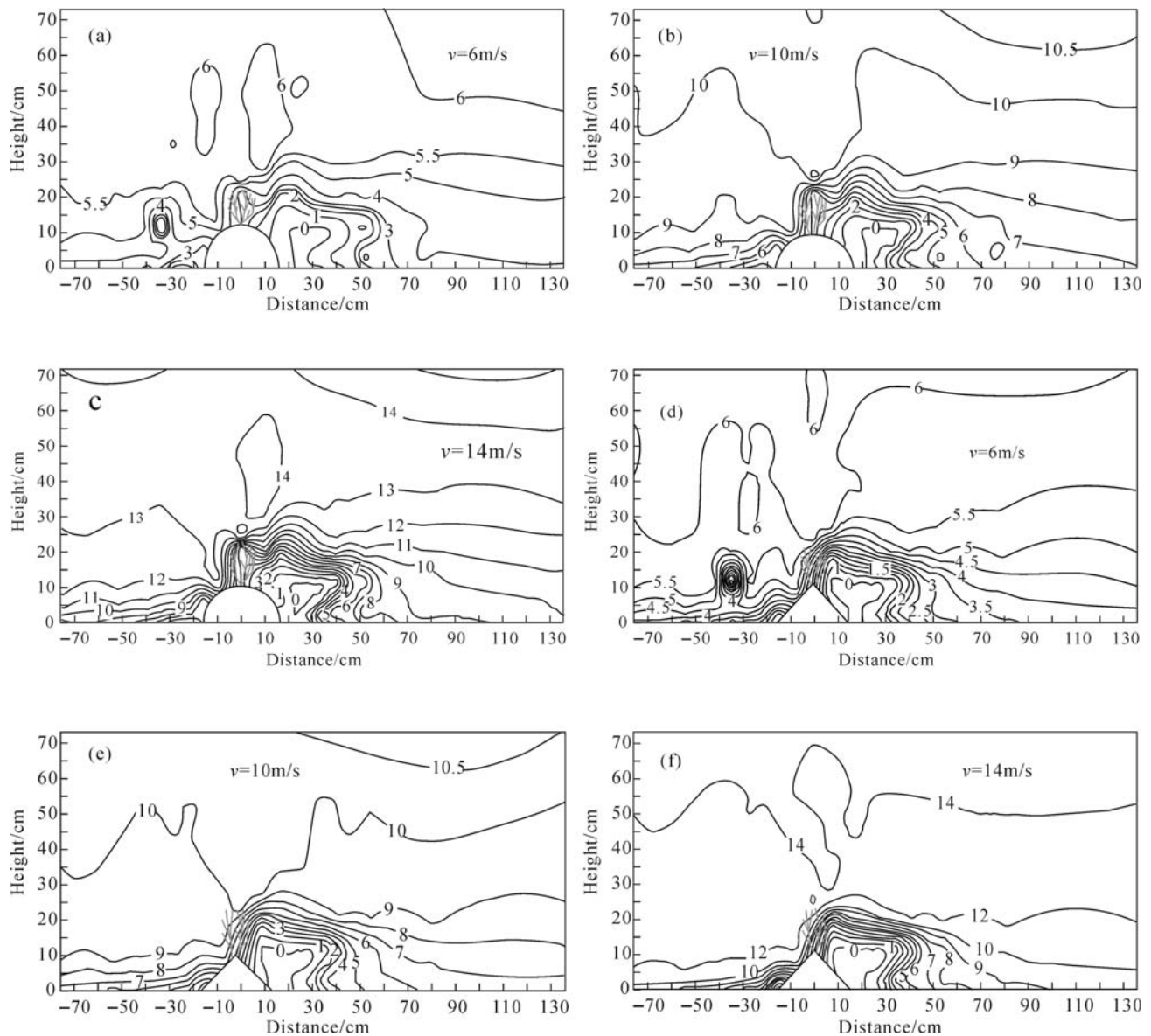
## 3 Results

### 3.1 Airflow patterns of vegetated semi-spherical nabkha

From the results of the wind tunnel experiments at all wind speeds, airflow patterns can be divided into two zones: a vortex and acceleration area in front of the upwind slope and a strong vortex area over the leeward slope (Fig. 3a–c).

A reflected vortex reaching a thickness of  $1/2 H_1$  developed at the foot of the upwind slope of the semi-spherical nabkha at all three experimental air velocities. The speed at the center of the vortex was  $<1/2 V$ . At all experimental wind speeds, at a distance  $1/4 H_1$  from the foot of the upwind slope, a return flow from the vortex meets the oncoming wind, resulting in an area of lower velocity where sand could be deposited in the work section. This is confirmed in areas of available sand sources at the Hotan River basin, where a crescent-shaped dune forms in front of an arc-shaped area of erosion at the foot of the upwind slope of semi-spherical nabkha. These morphological features are the product of a strong reflected vortex observed in the field. Confirmed by observations of nabkha in the Hotan River basin, the size of the crescent-shaped dune, the depth of the arc-shaped erosion area and the size of the semi-spherical nabkha are proportional. Wind-speed increases sharply over  $1/2 H_1$  on the upwind slope of the semi-spherical nabkha, accelerating from less than 50% of the given experimental speed in the work section to 1 m/s less than the experimental wind speed in the vortex core. With increasing experimental wind speeds from 6 m/s to 14 m/s, the speed of the centre of the vortex area increases gradually from less than 1 m/s to more than 7 m/s. This causes a shift in the areas conducive to sand deposition and erosion moving 1–2  $H_1$  distance away from the foot of the upwind slope.

Compared to the increasing velocity of wind observed for a semi-spherical sand mound without vegetation, those with vegetation show a reduction in velocity. Plants at the top of the semi-spherical nabkha retard the airflow passing over the top surface which reduces the wind speed. On the top surface, non-vegetated semi-spherical sand mounds resulted in air flow speeds typically exceeding the experimental wind velocity by 1 m/s, leading to an area of wind-erosion. However, with the vegetated model, airflow speed at the top is reduced by 1–3 m/s below the experimental wind speed. Vegetation plays a significant role in maintaining the upper surface by stabilizing the sediment and protecting the nabkha from wind-erosion. During the development of a *Tamarix* community, the plants trap the sand. This burial



**Fig. 3** Flow patterns of different morphological nabkhas at three wind speeds. (a)–(c), semi-spherical nabkha; (d)–(f), conical nabkha

then facilitates the stability and growth of the *Tamarix* and promotes enlargement of the nabkha (He et al., 2003).

A strong vortex area lies behind the leeward slope of the vegetated semi-spherical model. The airflow easily separates to form a vortex at the leeside of plants (Hesp and McLachlan, 2000). This is confirmed in the wind tunnel experiment where a strong vortex forms on the leeside of the nabkha, with the thickness of the vortex reaching  $2 H_1$ . Within the central area of the vortex at  $1/2-1 H_1$ , airflow speed range is  $\leq 1-3\text{ m/s}$ . The vortex is initiated by the plant and its range of influence on the leeside extends over  $5 H_1$  in a downwind direction, a much larger area of influence than that seen on non-vegetated mounds. In the field, development of this vortex on the leeward slope permits deposition of fine sand within the plant cluster at the top of the nabkha and the upper part of

the leeward slope to promote enlargement of the mound. For semi-spherical sand mounds without vegetation, the center of the vortex at the foot of the slope on the leeside has a velocity of  $\leq 1-3\text{ m/s}$ . The area of influence of this vortex is smaller and extends to a distance of  $3-4 H_1$  in a downwind direction. The influence of the leeward vortex of the semi-spherical sand mound without vegetation is much less than that of the vegetated one. Therefore, the role of vegetation is significant in interfering in the wind-blown sand flow, thereby enhancing nabkha growth. By increasing the experimental wind speed, the vortex intensity on the leeside increases and its range of influence expands. The wind-speed gradient also increases from the core of the vortex to its outer edge, thus enhancing wind-erosion with distance from the vegetation on the leeside.

### 3.2 Airflow patterns of vegetated conical nabkha

Results of the wind tunnel experiments on airflow patterns over vegetated conical nabkha at different speeds are shown in Fig. 3(d)–(f). Airflow patterns on the conical nabkha are divided into two zones: an accelerating area on the upwind slope and a strong vortex area on the leeward slope.

A zone of acceleration forms on the upwind slope of conical nabkha as the airflow climbs the slope. Airflow accelerates evenly along the lower upwind slope, and then increases rapidly to the given experimental wind speed near the top of the nabkha. No vortex forms at the foot of the upwind slope. This is confirmed by observations in the field in the Hotan River basin, where no crescent-shaped dunes or arc-shaped area of erosion were found in front of vegetated conical nabkha despite sufficient sources of sand. Vegetation at the top extends the zone of acceleration at the base of the plant on the upwind slope. Near the top of the vegetated conical model, the wind-speed is close to the experimental one. Eventually, the plant begins to interfere with the airflow and wind-speed slows sharply. Near the foot of the dune on the windward side, large changes in surface roughness and topography can generate turbulence and upward flow, causing a small amount of fine sand to be transported in suspension. The patterns of sediment transport associated with the mound are closely related to the pattern of airflow, which in turn is related to the dune topography and density of the vegetation (Arens, 1996).

A strong vortex area develops on the leeside of vegetated conical nabkha. The thickness of the vortex approaches  $2 H_2$ . The central area of the vortex has a velocity  $\leq 1\text{--}3$  m/s at a height ranging from  $1/2 H_2$  to  $1 H_2$ . The vortex initiates from the disturbance from the plant cluster on the leeside, and the range of influence of this vortex area spreads over a distance  $3\text{--}4 H_2$  along the leeside of the mound. Fine sediment is deposited within the plant cluster on the leeward slope, illustrating the importance of vegetation in reducing airflow speed, entrapment of fine sediments and maintaining the development of conical nabkha.

### 3.3 Impact of vegetation on airflow patterns

Hesp (2000) found that a plant with a vertical growth habit is conducive to the formation of conical nabkha, whereas a plant with a prostrate growth habit leads to the formation of semi-spherical nabkha. The differences in growth habits of vegetation result in different airflow patterns that control the entrapment of sand and give rise to unique shapes of nabkhas. Wasson and Hyde (1983), Wasson and Nanninge (1986) and Ling et al. (2003) observed the flow pattern changes a single artificial plant. An erosion area formed on the upwind side of the plant, and areas of acceleration formed as the air flowed around and over the top of the vegetation. Sand accumulated in

the area behind the plant on the leeside of the mound where the airflow streams came together. They concluded that even artificial vegetation changes the speed of wind-sand flow and its range of influence.

Lines of constant velocity were closely distributed and the wind-speed increased sharply near the foot of the artificial vegetation on the windward side of the semi-spherical and conical nabkha in the experiments (Figs. 3(a)–(f)). Field observations found that the sediment appears compacted and limited accumulation on the windward slopes of the two types of nabkha in the Hotan River basin. Strong airflow and resultant erosion in this region are the likely causes. At the top of the vegetated models, although the airflow velocity was higher, it did not reach the experimental wind speed. Thus, in the field at the effective speed of sand-movement, when the airflow passes through the vegetation, the fine sand is deposited. Although wind speed can reach 8.36 m/s at the top of the dune, sand transport mainly occurs above the vegetation at the top of the dune. At the same wind speed, the upwind acceleration ratio among a transverse sand dune, non-vegetated alluvial plain and nabkha field shows considerable difference with relative values of 118: 100: 87 in the Taklimakan Desert (Han et al., 2003).

Artificial plants at the top of the sand mounds enhance the surface roughness, reduce the airflow velocity at the sand mound surface, and enlarge the range of influence of the vortex on the leeside compared to sand mound without vegetation. Tengberg and Chen (1998) indicated that sediment transport and supply are related to the density of the vegetation cover in semiarid areas, and differences in plant growth habits play an important role on the rate of development of nabkhas. Thus, the type and density of vegetation influence nabkha formation, which results in variability of the mound morphology even in the same environment. The distance of sediment saltation within the vegetation depends on vegetation density and wind speed. When the plant density is high, the nabkha traps much more sand and grows vertically in place (Hesp, 1983; Hesp et al., 1989). Hesp et al., (1989) notes that a positive feedback exists between vegetation and deposition, i.e., where sand deposition is the greatest, plant growth is encouraged, leading to greater aerodynamic roughness and deposition (Arens, 1996).

## 4 Conclusions

Results of airflow experiments in the wind-tunnel using artificial vegetation on model sand mounds were compared with semi-spherical and conical nabkhas observed in the Hotan River basin of China. The main conclusions can be drawn as follows:

(1) Airflow patterns of semi-spherical nabkha are divided into two zones: a vortex and acceleration area in front of the upwind slope and a strong vortex area over

the leeward side. The presence of vegetation at the top of the mound negates strong wind-erosion at the top of semi-spherical nabkha. Airflow patterns on the conical nabkha are divided into two zones: an accelerating area on the upwind slope and a strong vortex area on the leeward slope. Vegetation at the top increases the vortex intensity and enlarges the range of influence of the vortex on the leeward slope of semi-spherical and conical nabkhas.

(2) According to the experimental results and field investigations, vegetation at the top of sand mounds enhances surface roughness, impeding airflow over the nabkha, reducing the available energy allowing deposition, eliminating wind-erosion at the top, and reinforcing the range of influence of the vortex on the leeside of the mound. These factors combine to change the structural characteristics of wind-sand flow. Vegetation plays an important role in changing airflow pattern, interfering with sand transport, trapping fines, and promoting and maintaining the shape of the nabkha.

(3) The type, height, density, and coverage of vegetation play a fundamental role on the development of semi-spherical and conical nabkha.

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