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The protective effects of nebkhas on an oasis

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ABSTRACT

Oases are of great importance to the sustainable development of economies and societies in desert regions. Thus, it is important to understand how many oases have survived for hundreds and even thousands of years. Oases in Northwest China include nearly all of the types found across the world. Among these oases, the Minqin Oasis, surrounded by mobile sandy deserts, is a stereotypical natural oasis that has been developed for more than 2000 years, making it ideal for a case study. Our investigation indicates that the nebkhas belt at the fringe of the Minqin Oasis, which consists of three sub-belts semi-mobile, semi-fixed and fixed nebkhas from desert to the oasis, plays a key role in its stability. The fractional speed-up ratio (δ_s) of wind generally fell within the range of −0.15 to −0.55 below the height of 0.6 m. Above the height of 0.6 m, wind velocity in the semi-mobile nebkhas was 5–27% weaker with a maximum reduction of 65% in the other two sub-belts. When wind carrying sand and dust from the desert passes through each sub-belt, its velocity is weakened by vegetation and dunes, and almost all sand and dust is deposited in the nebkha belt incrementally by grain size, ranging from coarse to fine. As such, nebkhas serve as a protection belt and ensure the existence of oases.

1. Introduction

From the perspective of integrated physical geography, an oasis is a unique geographical unit with stable water supply, fertile soil, and suitable for the growth of plants; it can provide the ideal habitats and production space for human, and is clearly different from the landscape of the surrounding desert in arid area (Shen et al., 2001). In an oasis, stable water supplies depend on river or groundwater with water table no more than 15 m; soils are derived from river alluvium and aeolian fine sediments (Kocurek and Lancaster, 1999; Beveridge et al., 2006); vegetation is mainly composed of natural plants and crops. Oases occupy a small area but bear a disproportionate amount of economic and social developmental pressure in desert regions. Due to their unique landscape and important role in agricultural production, oases have become the focus of an increasing amount of research, and important progress has been made in many fields. For example, previous literature has focused mainly on the economical use of water and soil resources in an oasis (Chen and Zhan, 1995; Zhou, 1994; Misak et al., 1997; Shen et al., 2001), with the goals of maintaining vegetation stability and water-thermal equilibrium (Bornkamm, 1986; Abd El-Ghani, 1992; Jia and Ci, 2003; Ma et al., 2003), and on the impact of environmental change on oases (Zhang and Wang, 1994; Zhao et al., 2001; Pan and Chao, 2003; Zhang et al., 2003). These studies are important for guiding the use of natural resources in oases. However, due to increasing populations in oases, especially in developing countries, water and soil resources tend to be overused, and it is difficult to implement scientific guidelines for best water and land use into agricultural practice (Shen et al., 2001). For a natural oasis at the edge or inside of a moving sand desert, a population increase puts pressure on water and soil resources, making the oasis appear to be “moving” rather than vanishing (Desai and Nelson, 2005). Previous studies have reported that nebkhas at the fringe of an oasis are the primary line of defense to prevent blown sand from invading the oasis (Sun, 1995; Gao, 2003). However, this protective function of the nebkhas has not been explained in detail. Although many reports have described the morphology of nebkhas and the airflow field over an isolated nebkha (Arens, 1996; Tengberg and Chen, 1998; Nishimori and Tanaka, 2001), few studies have been conducted on the airflow field over randomly distributed nebkhas or nebkhas at the fringe of an oasis. In the arid zone of northwestern China,

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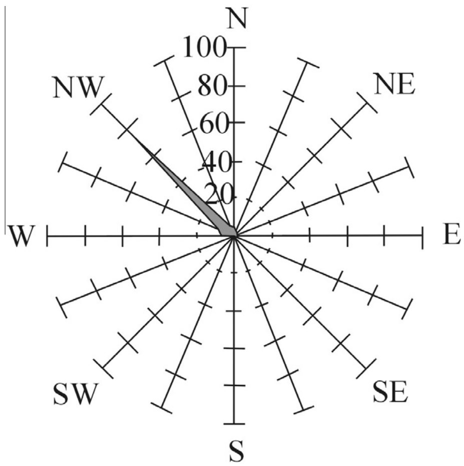

Fig. 1. Annual winds stronger than 6 m s^{-1}.

there are many different types of oases covering a total area of 86,419 km^2 (Shen et al., 2001). Thus, this region is ideal for studying the protective role of nebkhas at the fringe of an oasis.

Minqin Oasis is located downstream of the Shiyang River in the arid zone of northwest China and is surrounded by the Badan Jaran and Tengger Deserts, with a total area of 267 km^2. There used to be a large inland lake in the north and center of the Minqin Oasis (Feng, 1963), a large amount of fine sediments brought by the river and aeolian flux had deposited and formed claypan here (Shi et al., 1999). Due to climate change and irrigation consumption, the inland lake area has gradually been reduced, and finally dried up (Chen et al., 2001). Minqin Oasis is a typical developed natural oasis that has been used for more than 2000 years (Chen and Zhan, 1995). According to data from the Minqin meteorological station, the annual precipitation in the oasis is 113 mm, and the annual evaporation is 2644 mm. Minqin Oasis has persisted under conditions of increasing population (Li, 2003) and severe aridity. Is the vitality of the oasis related to the ring distribution of nebkhas of width 1–5 km at the fringe of the oasis? If so, understanding the protective role of the nebkha belt is of great importance for protecting oases in general. We chose to study the area abutted by the northwest nebkha belt of the Minqin Oasis adjacent to the Bardan Jaran Desert for two reasons First, among winds with velocities greater than 6 m s^{-1}, 97.9% blow between N and W, and 74.6% of these blow due NW (Fig. 1). The nebkha belt runs from NE to SW, which is perpendicular to the local prevailing NW wind direction. Second, the study area is the main route by which blown sand invades the Minqin Oasis and is a stereotypical region containing nebkhas including mobile dunes, semi-mobile dunes, semi-fixed dunes, and fixed dunes and cropland from desert to the oasis (Fig. 2). The objective of this study was to clarify how the nebkhas prevent the invasion of blown sand by investigating the airflow field over nebkhas and the size distribution of aeolian topsoil particles on nebkhas.

2. Methods

2.1. Investigation of nebkhas and vegetation

Nebkha morphology was investigated within an observation area falling between mobile dune and cropland (Fig. 3). According to the method proposed by Tengberg and Chen (1998), the obtained dimensions of the nebkhas include horizontal length (l) and width (w), vertical height (h), and a horizontal parameter (cl) equal to $(l + w)/2$. In addition, vegetation coverage (VC) of nebkhas was measured. For each site (1, 3, 4, 5, 6, 7 and 8), a 25 m × 25 m sample plot was selected and designated plot 1, plot 3, plot 4, plot 5, plot 6, plot 7, or plot 8, respectively. The plant species in each plot were identified, and the average height and coverage of each plant species were measured. The fixation degree of a dune is classified according to the VC, where $VC < 5\%$ for a mobile dune, $5\% < VC \leqslant 20\%$ for a semi-mobile dune, $20\% < VC \leqslant 50\%$ for a semi-fixed dune and $VC > 50\%$ for a fixed dune (Zhu, 1984). In this study, VC refers to the coverage of vertical projection by shrub branches because vegetation greening had not begun by the end of the investigation.

2.2. Wind profiling

To understand the impact of nebkhas on the wind field, we chose a section downwind from the mobile dunes inside the oasis and an observation area covered by typical Tangut Nitraria (*Nitrario tangutorum Bobr.*) nebkhas for observation. For the duration of the observation period, wind consistently originated from the NW direction. The observation section spanned from the mobile dunes to the cropland of the oasis. Site 1 was located on flat terrain within the mobile dunes and served as the reference observation site, sites 2–9 were located at tops of the dunes, and site 10 was located in the cropland inside the oasis (Fig. 3). The straight-line distance between sites 1 and 2 was 135 m. The typical Tangut

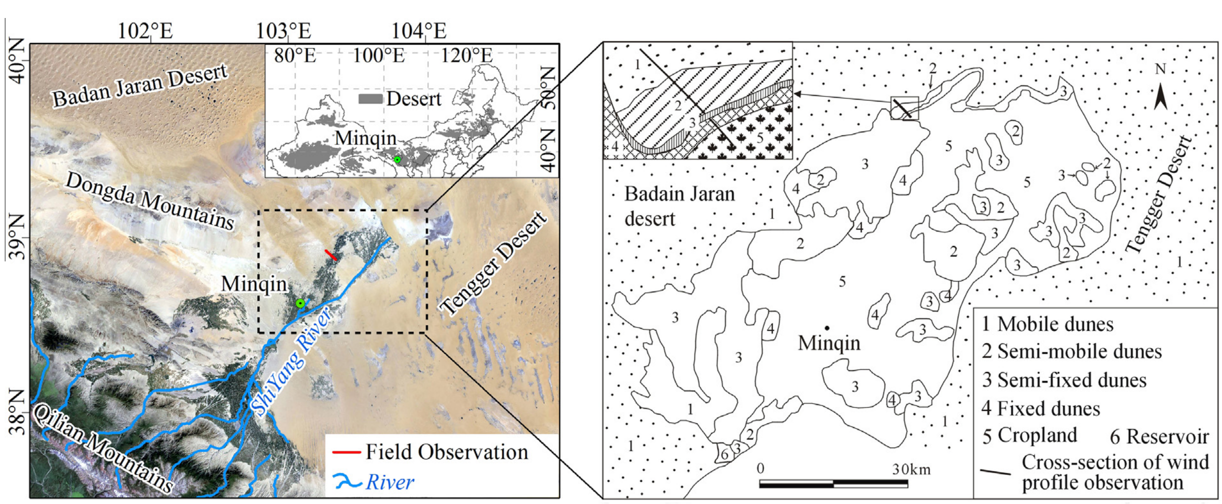

Fig. 2. The location of the Minqin Oasis and of the study area.

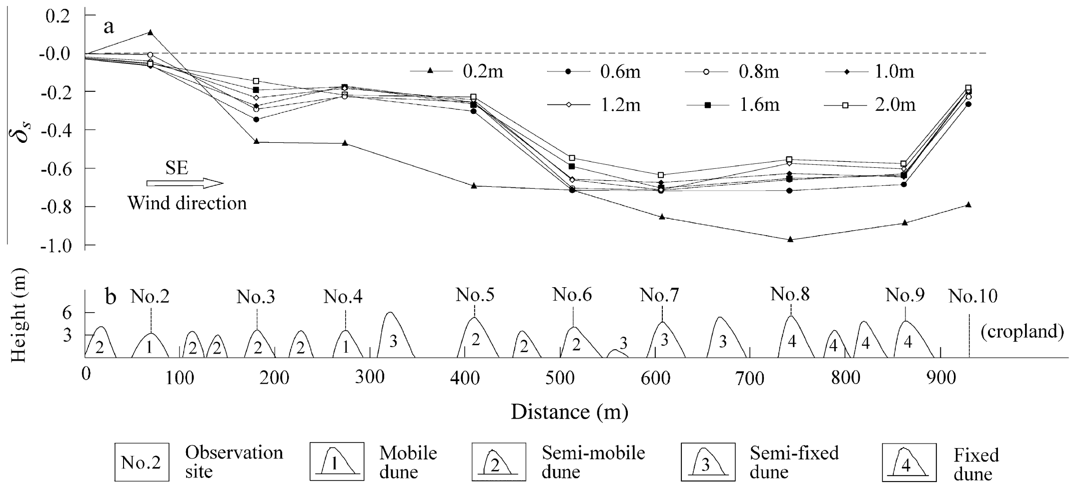

Fig. 3. Layout of wind profile observation sites between mobile dune and cropland.

Nitraria nebkha observation area was near site 7, and the associated observation points were located upwind between dunes, at the toe of the stoss slope, at the middle of the stoss slope, at the top of the dune, at the middle of the lee slope and downwind between dunes, for a total of 75 observation points. The fixed reference observation point was located at the top of Dune II (Fig. 4).

Due to airflow acceleration caused by compression as the air climbs the stoss slope of the dune, the wind profile on the stoss slope presented a non-logarithmic-linear change (Frank and Kocurek, 1996; Lancaster et al., 1996; Wiggs et al., 1996a,b). For dunes without vegetation cover, the internal boundary layer thickness was <1 m (Frank and Kocurek, 1996; Lancaster et al., 1996), while the inner boundary layer thickness increased to 1–2 m for nebkhas of the same size due to increasing surface roughness caused by vegetation (Wiggs et al., 1996a). Thus, the upper limit of the wind field observation height was 2.5 m.

Three sets of multi-channel wind anemometers were used to measure wind velocities, and each set simultaneously obtained the wind velocity at heights of 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.6, 2.0 and 2.5 m (Fig. 5). During observation, one set was fixed as a reference at all times, and the other two sets were alternated among other measurement sites or points, with the observation time at each site or point lasting for approximately 5 min. The wind velocity was recorded every 30 s at each site or point a total of three times, from which the average velocity was calculated. Meanwhile, topsoil samples at a depth of 0–5 cm were collected at sites 1, 3, 4, 5, 6, 7 and 8 and were designated TS1, TS3, TS4, TS5, TS6, TS7 and TS8, respectively.

2.3. Calculation

2.3.1. Fractional speed-up ratio

The fractional speed-up ratio was defined by Jackson and Hunt (1975) and has been used to observe the wind field over nebkhas in the Southwest Kalahari Desert (Wiggs et al., 1996a). Here, wind velocity data were standardized as previously described:

$$\delta_s = \frac{u_z - u_\infty}{u_\infty} \tag{1}$$

where δ_s is the relative acceleration used to express wind velocity fluctuation at a given site compared with the reference site; u_z is the wind velocity at the observation site at a height z; and u_∞ is the wind velocity at the reference site at a height z.

2.3.2. Aerodynamic roughness

Aerodynamic roughness (z_0) was derived and calculated according to the wind profile formula proposed by Bagnold (1941):

$$U_z = \frac{U_*}{k} \ln \frac{z}{z_0} \tag{2}$$

where U_z is the wind velocity at the height z; U_* is the friction velocity; and k is von Karman's constant (0.4). Under neutral atmospheric stratification conditions, the wind profile can also be described by the following formula (Wiggs et al., 1996a; Lancaster and Baas, 1998):

$$U_z = a \ln z + b \tag{3}$$

where a and b are the coefficients fitted by least square method. By combining Formulas (2) and (3), $U_* = kb$, then:

$$z_0 = \exp(-b/a) \tag{4}$$

In practical application, this method has been proven to be reliable (Zhang et al., 2007; Wu et al., 2011).

3. Results and discussion

3.1. Nebkha morphology and vegetation

Our measurements indicated that the density of nebkhas in the study area was 4780 dunes per square kilometer. The development stage of nebkhas is divided into the growing stage, the stable stage and the dying stage (Tengberg and Chen, 1998) and is approximated by morphological characteristics, which met the following formula:

$$h = a \cdot cl - b \cdot cl^2 \tag{5}$$

where a and b are fitting coefficients. Formula (5) shows that as cl increased, h first increased and then decreased, corresponding to the three development stages of nebkhas. Therefore, the ratio of the vertical parameter to the horizontal parameter h/cl could reflect the development stage of nebkhas: the larger the value, the more stable the morphology of the nebkha. The value of h/cl for mobile dunes, semi-mobile dunes, semi-fixed dunes and fixed dunes was 0.024, 0.037, 0.039 and 0.041, respectively (Table 1), indicating that the morphological stability of semi-fixed and fixed dunes is higher than that of mobile dunes. When a mobile dune was disturbed, its morphology was more easily altered.

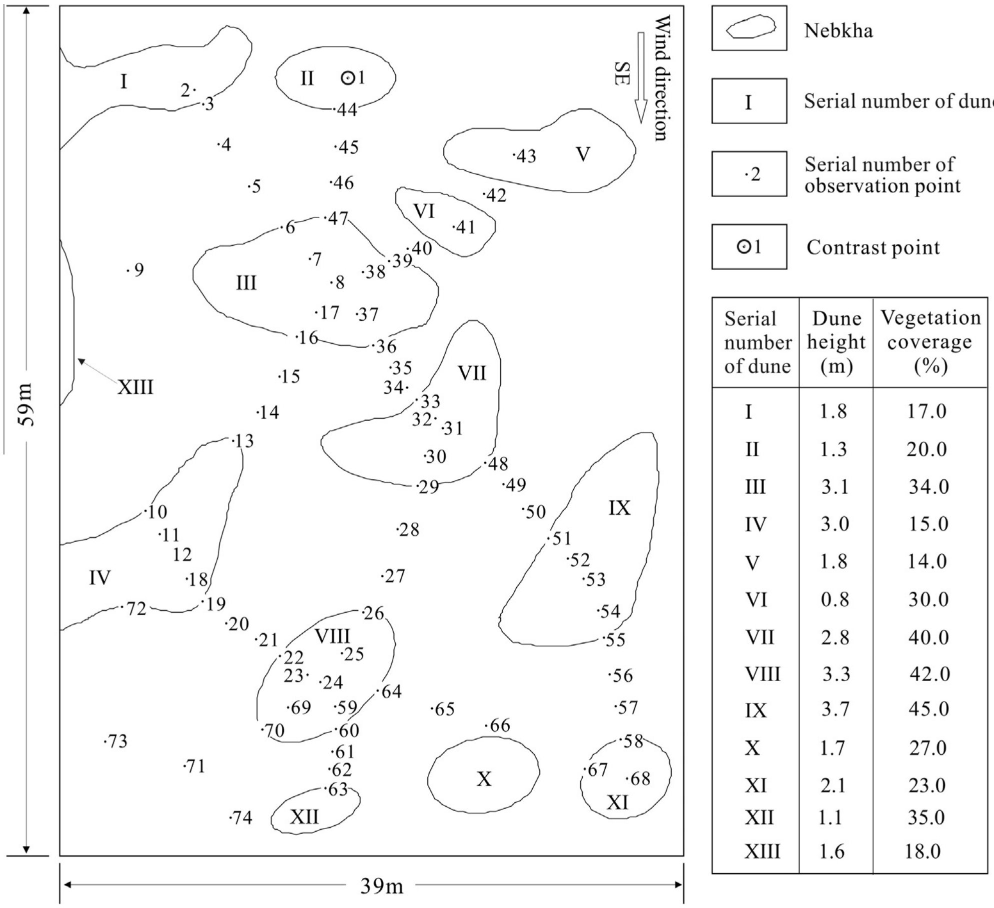

Fig. 4. Layout of wind profile observation points within the typical nebkha area.

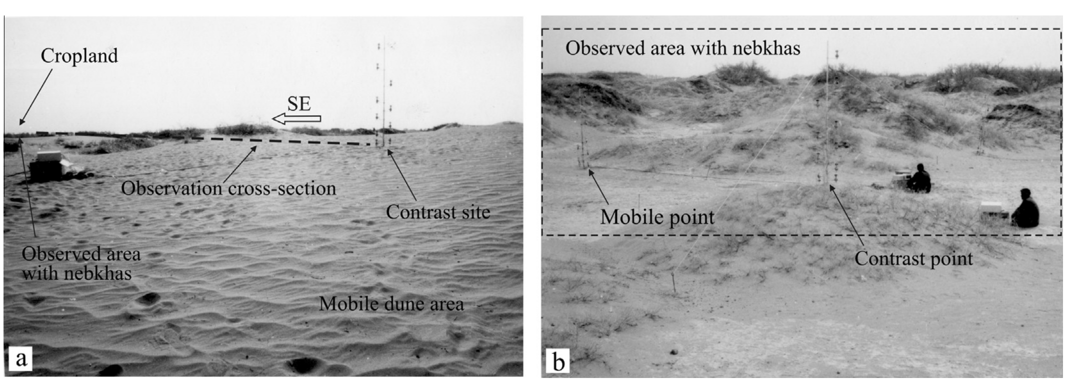

Fig. 5. Wind profile observation in the fields. (a) Wind profile observation along the section from mobile dune to cropland; (b) wind profile observation in the typical nebkha area.

Table 1
Morphological parameters of nebkhas in the research area.

Dune type	Average value of h (m)	Average value of l (m)	Average value of w (m)	Average activity of dunes	Vegetation coverage on dunes (%)	h/cl	h/l	h/w	l/w
Mobile dunes	3.25	44.00	24.00	1	0.00	0.024	0.074	0.135	1.833
Semi-mobile dunes	3.90	31.33	20.83	2	13.33	0.037	0.124	0.187	1.504
Semi-fixed dunes	3.73	28.71	18.54	3	35.00	0.039	0.130	0.201	1.549
Fixed dunes	3.75	29.67	16.53	4	82.13	0.041	0.126	0.227	1.795

Table 2
Results of a quadrat survey of nebkhas along the observation section.

Plot number	Landscape	Main plant species (Latin names)	Average vegetation height (m)	Coverage (%)	
				Coverage of single species	Total coverage
Plot 1	Mobile dunes	*Nitrario tangutorum Bobr.*	0.59	3	3
Plot 3	Semi-mobile dunes	*Nitrario tangutorum Bobr.*	0.27	13	13
		Zygophyllum dumosum	0.70	0	
Plot 4	Semi-mobile dunes	*Nitrario tangutorum Bobr.*	0.37	15	16
		Reamuria soongorica	1.00	1	
Plot 5	Semi-mobile dunes	*Nitrario tangutorum Bobr.*	0.23	10	18
		Reamuria soongorica	0.43	8	
		Zygophyllum dumosum	0.60	0	
		Lycium ruthenicum	0.76	0	
Plot 6	Semi-fixed dunes	*Tamarix ramosissima Ledeb.*	1.50	30	38
		Reamuria soongorica	0.38	7	
		Nitrario tangutorum Bobr.	0.42	1	
Plot 7	Semi- fixed dunes	*Tamarix ramosissima Ledeb.*	1.10	35	40
Plot 8	Fixed dunes	*Reamuria soongorica*	0.38	4	
		Nitrario tangutorum Bobr.	1.00	1	
		Reamuria soongorica	2.25	84	84

The results of our investigations in 7 sample plots within the observation section showed that plant species grew mostly on semi-mobile and semi-fixed dunes and less on fixed dunes (Table 2). Possible explanations are that semi-mobile and semi-fixed dunes greatly changed the habitat and plant species capable of utilizing the altered environment. For fixed dunes, the longer the dune remained fixed due to human protection, the more stable the habitat; as a result, interspecific competition led to low diversity in vegetation, often with one species dominating. Plot 1 was located on mobile dunes, where Tangut Nitraria (*Nitrario tangutorum Bobr.*) was the dominant species with an average height of 0.59 m and average coverage of 3%. Plots 3, 4 and 5 were located on semi-mobile dunes, where Tangut Nitraria was the constructive plant species with an average height of 0.27–0.41 m and average coverage of 13–18%. Plots 6 and 7 were located on semi-fixed dunes, where Tamarix ramosissima (*Tamarix ramosissima Ledeb.*) was the constructive plant species, with an average height of 1.03–1.27 m and average coverage of 38–40%. Plot 8 was located on fixed dunes, where vegetation was mostly pure Songory Reaumuria (*Reamuria soongorica*), with an average height of 2.25 m and average coverage of 84%.

3.2. Variation of wind velocity and topsoil particle size distribution along the observation section

The protective role of nebkhas is mainly reflected in airflow change caused by dune morphology and vegetation and is a weaking of wind–sand activity (Zhang et al., 2007). Thus, a change in the wind profile along the observation section is critically important to the evaluation of the protective efficiency of the nebkha belt. Vegetation can lift near surface airflow such that the surface wind profile has zero plane displacement *d* (Oke, 1988), resulting in variation of the near surface wind profile. According to Formula (1), calculations showed that except for the δ_s value at the height of 0.2 m at site 2, all δ_s values were negative. For both mobile and fixed dunes, δ_s values decreased and the rate of δ_s variation gradually increased with increasing distance, nebkha fixation and surface vegetation. However, the value of δ_s increased in cropland (Fig. 3).

According to Formulas (2), (3) and (4) and the wind profile at each observation site within the section, aerodynamic roughness (z_0) calculations showed that vegetation failed to influence the wind profile at some observation sites according to the logarithmic-linear law (Wiggs et al., 1996a). Values for z_0 varied in the range of 0.0002–0.0385 m, in agreement with previous research (Wiggs, 2011). Site 1 was located in a mobile dune area and its z_0 was 0.0002 m, the minimum value observed for the entire observation section. Sites 3, 4 and 5 were located in a semi-mobile dune area, and their mean z_0 was 0.0044 m, 22 times the z_0 value of the mobile dune area. Site 7 was located in a semi-fixed dune area, and its mean z_0 was 0.0069 m, 34.5 times the z_0 value of the mobile dune area. Site 8 was located in a fixed dune area, and its z_0 was 0.0385 m, the maximum value observed for the entire observation section. This value was 192.5 times the z_0 value of the mobile dune area and 8.75 times the z_0 value of the semi-mobile and semi-fixed dune areas. Site 10 was located in cropland, and its z_0 was 0.0024 m, close to the z_0 value of the semi-mobile and semi-fixed dune areas.

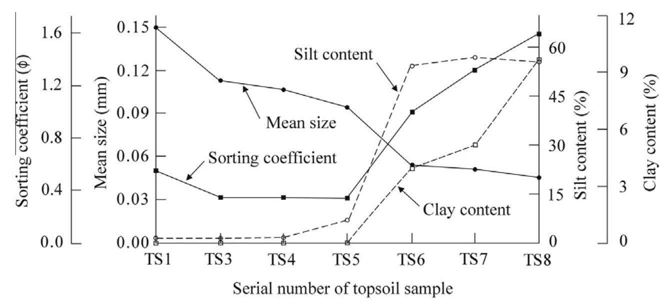

Fig. 6. Variation in topsoil particle size from mobile dune to cropland.

The topsoil particle size distribution might reflect the effect of vegetation and dune morphology on wind velocity (Zhang et al., 2011). The average particle size of topsoil collected from the observation section ranged from 0.046 to 0.148 mm; from mobile dunes to fixed dunes, the average particle size gradually decreased. This finding indicated that the near surface wind velocity decreased gradually. The topsoil particle-sorting coefficient, related to sand source and the degree of wind velocity change, was calculated according to the Φ value (Folk and Ward, 1957). From mobile dunes to fixed dunes, the topsoil particle-sorting coefficient varied within the range of 0.34–1.57, showing a gradual increase and implying that particle sorting gradually worsened. This indicated that with increases in *VC* and height, both coarse and fine particles from upwind were to a great extent intercepted (Fig. 6).

3.3. Variation in wind velocity in a typical nebkha observation area

According to the δ_s calculation method (Jackson and Hunt, 1975), which uses the wind velocity observed at the contrast point in the typical nebkha area as a reference, we calculated δ_s values at different heights at each observation point (Fig. 7). We found that δ_s values at almost all heights and positions were negative, except for those on the top of dunes. At the toe of the stoss slope, the wind velocity generally increased and the average δ_s value at each height of Dunes III, VII, and VIII was −0.201. At the middle of the stoss slope, the wind velocities above the height of 0.6 m further increased, with the average δ_s value reaching −0.130, while the wind velocity at the height of 0.2 m was slightly lower than that at the toe of the stoss slope. Except for the height of 0.2 m, wind velocities on the tops of dunes were generally the greatest for each dune, and the average δ_s value at heights above 0.6 m for Dunes III, VII, and VIII was 0.048. On the lee slope, due to the presence of a vortex (Walker and Nickling, 2002), δ_s values were negative, and wind velocity decreased rapidly. At the middle and toe of the lee slope and at the downwind inter-dune, the average δ_s value at each height for Dunes III, VII, and VIII was −0.402, −0.388 and −0.383, respectively. For the downwind inter-dune, due to increasing distance from the dune, airflow gradually recovered to the same level as on the upwind inter-dune, in agreement with previous studies (Wiggs et al., 1996a).

4. Evidence for protection of an oasis by nebkhas

The formation of nebkhas at the fringe of an oasis is the result of the interception of windblown sand by vegetation. After the formation of nebkhas, surface relief and vegetation change the near surface wind field and enhance the interception of windblown sand interception. The nebkha belt at the fringe of the Minqin Oasis is divided into a Tangut Nitraria semi-mobile nebkha sub-belt, a *T. ramosissima* semi-fixed nebkha sub-belt, and a Songory Reaumuria fixed nebkha sub-belt. Changes in the plant species and *VC* in the nebkha belt indicated that the intensity of windblown sand invasion of the oasis was gradually weakened, and nebkhas played a crucial role in the maintenance of the oasis ecosystem.

4.1. Protective effects reflected by wind profile and topsoil particle size along the observation section

Sites 2, 3, 4 and 5 were located in the Tangut Nitraria semi-mobile nebkha sub-belt, which is close to the mobile dunes in the Badan Jaran Desert and is at the forefront of the nebkha protection system. In addition, there are a small number of mobile dunes between semi-mobile dunes (Fig. 3a, Table 2). From site 2 to site 5, *VC* increased gradually, but increases of less than 20% of the dunes' fixation were weak, z_0 values were low, and wind velocities over dunes were not significantly reduced. This indicated that strong blown-sand activity existed in this sub-belt. Compared with mobile dunes, the average diameters of TS3, TS4 and TS5 were lower, at 0.112 mm, 0.105 mm and 0.093 mm, respectively. However, the average particle size was second only to 0.148 mm observed in mobile dunes, and the silt content was, respectively, 1.13%, 1.46% and 6.10%, while the clay content was 0 (Fig. 6). This indicates that dune morphology and vegetation in this sub-belt significantly hindered windblown sand and intercepted most of the coarse particles, but fine particles continued to move forward. In fact, fine particles were able to move very far with airflow over the near surface, especially clay (<0.002 mm), which could be moved higher and farther by airflow (Tsoar and Pye, 1987). Overall, this sub-belt significantly weakened the flux of windblown sand, mainly through dune morphology. When airflow climbed along the stoss slope of a Tangut Nitraria dune, its acceleration and shear force caused by concave–convex dune morphology resulted in erosion from the slope toe to the stoss slope (Wiggs et al., 1996b; McKenna Neuman et al., 1997). When air crossed the dune top, expansion and separation over the lee slope caused the wind velocity to decrease and resulted in the deposition of windblown sand (Walker and Nickling, 2002).

Sites 6 and 7 were located in the *T. ramosissima* semi-fixed nebkha sub-belt, where *VC* increased to nearly 40% and the fixation of vegetation on the dune was enhanced (Fig. 3a, Table 2). z_0 increased to approximately 22 times that of the semi-mobile nebkha sub-belt, wind velocity was much weaker than those observed from site 2 to site 5, and the average δ_s value at each height over 0.6 m was, respectively, −0.646 and −0.693. This indicated that the effect of this sub-belt on reducing wind velocity was significantly enhanced. Compared with the mobile dune area and the semi-mobile nebkha sub-belt, the average particle size of TS6 and TS7 decreased significantly to 0.054 mm and 0.051 mm, respectively, while silt content increased significantly to 46.70% and 48.79%, and clay content increased to 4.13% and 5.43%, and the particle sorting of the topsoil worsened (Fig. 6). This indicated that coarse particles had been completely intercepted by the

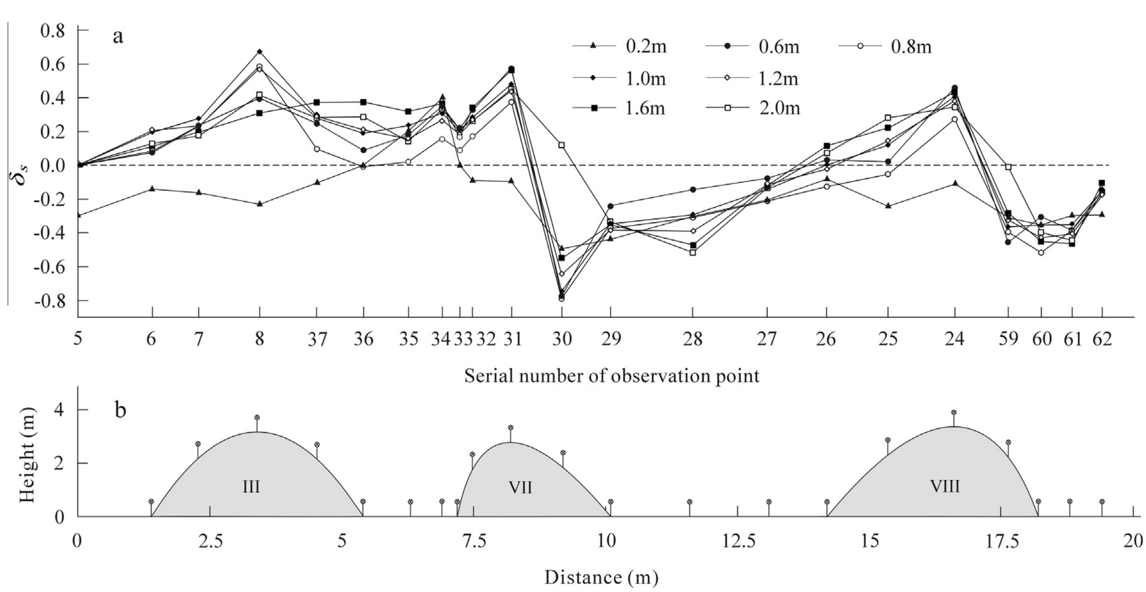

Fig. 7. Variation in the fractional speed-up ratio (δ_s) across the typical nebkha observation area. (a) Variation curves of δ_s; (b) layout of the observation points.

semi-mobile dune sub-belt, and the blown-sand particles intercepted in this sub-belt had been fine.

Sites 8 and 9 were located in the Songory Reaumuria fixed nebkha sub-belt, which was the last barrier in the nebkha belt. The average *VC* in this sub-belt was greater than 84%, and the vegetation had a strong ability to fix dunes (Fig. 3a, Table 2). The maximum z_0 value occurred in this sub-belt and was approximately 192.5 times that of the semi-mobile nebkha sub-belt and 8.75 times that of the semi-fixed nebkha sub-belt. The average δ_s value at each height over 0.6 m was, respectively, −0.632 and −0.630, indicating that this sub-belt had the ability to reduce wind velocity. Compared with the former two nebkha sub-belts, the average particle size of TS8 was even smaller, reducing to as low as 0.046 mm. The silt and clay content further increased to 47.75% and 10.18%, respectively, and the particle sorting capability of the topsoil was the worst (Fig. 6). This indicated that in this sub-belt, vegetation and dunes intercepted almost all near surface particles, drastically reducing the threat of blown-sand from the mobile dune area to the oasis.

4.2. Protective effects reflected by wind profile in the typical nebkha observation area

In the typical nebkha observation area, the soil at the inter-dune region consisted of bare and hard clay, and only sand dunes were covered in vegetation that consisted mostly of Tangut Nitraria 0.3–0.6 m in height. According to wind velocity measurements at 10 m at the 75 observation points, the contour map of δ_s for each height was drawn. The contour maps of δ_s at heights of 0.2, 0.8, 1.6 and 2.5 m were sufficient to show the effect on wind field by nebkhas (Fig. 8), as well as the effects of these changes on the interception of windblown sand.

At 0.2 m, δ_s values at a stoss slope and a lee slope were just under 0, but the δ_s value at inter-dunes was often above 0 (Fig. 8a). This is mainly due to vegetation on the dunes; wind velocity sensors at 0.2 m were under vegetation canopy and were sometimes located on the stoss slope. Due to a lack of vegetation, the inter-dunes became airflow paths among randomly distributed dunes, with δ_s values greater than 0. This indicated that the Tangut Nitraria shrub not only played a decisive role in maintaining stable dune morphology but also effectively intercepted windblown sand below canopy height. At 0.8 m, the δ_s value at a stoss slope was generally greater than 0, and the δ_s value at a lee slope was almost less than 0. However, when upwind dunes were densely distributed, the δ_s value at a stoss slope of downwind dunes was also less than 0, similar to those for the Dunes IV, VII, X and XII. δ_s values for inter-dune locations were close to 0 (Fig. 8b). This indicated that 0.8 m above the ground surface exceeded the height of the canopy, and the effect of dune morphology on the δ_s value exceeded the effect of vegetation on the δ_s value. At 1.6 m, the effect of dune morphology on the δ_s value was more significant (Fig. 8c). Among the twelve dunes in the observation area, only the heights of Dunes II, VI and XII were less than 1.6 m. Due to the helical vortex on the lee slope, the overall δ_s value for the whole observation area was mostly less than 0. This indicated that at 1.6 m, dune morphology had a decisive effect on the δ_s value, while vegetation had almost no effect. At 2.5 m, the effect of dune topography on δ_s began to weaken, and only δ_s values at heights above 2.5 m on the lee slopes of Dunes III, IV, VII, VIII and IX were less than −0.2, while δ_s values for others were mostly near 0.0. Wind field change at different heights showed that the effect of vegetation on the δ_s value was limited to heights below the canopy, and the effect of dune morphology on the δ_s value generally reached the height of the dunes, but the wind field above dune height was almost free of the effects of dune morphology.

5. Discussion and conclusions

When the ratio (L/l) of downwind distance (L) to the height (l) of a dune reaches 8–10, wind velocity is gradually restored to that of free wind, and an internal boundary layer begins to form. When L/l reaches 25–30, the internal boundary layer develops stably, and the wind profile is close to that calculated for sites upwind (Walker and Nickling, 2002). Site 10 of the observation section was located in cropland of the Minqin Oasis (Fig. 3), downwind of site 9 in the fixed nebkha sub-belt. The L/l value for site 10 was 13.3, within the range of 10–25, indicating that the wind velocity at this position was gradually returning to that of winds beyond the protective scope of the nebkha belt. However, the nebkha belt protects the oasis not only by reducing wind velocity but also by intercepting highly concentrated windblown sand from mobile dunes in the desert. When sand-laden wind passed through the nebkha belt, almost all of the particles were deposited in the belt. Thus, even though wind velocity was gradually restored within the oasis, the damage caused by windblown sand to the inner ecosystem of the oasis was minimized.

Although the average height of Tangut Nitraria shrubs, *T. ramosissima* shrubs and Songory Reaumuria shrubs was less than 0.6 m, 1.5 m and 2.3 m, respectively, these shrubs played the most important role in the interception of windblown sand. Below the height of 0.6 m, except at site 2 on the mobile dune, δ_s values at the observation sites were negative. With the increase of *VC*, δ_s values showed a decreasing trend, and at the height of 0.2 m, the minimum value of δ_s was below −0.95 (Fig. 3a). In the typical nebkha

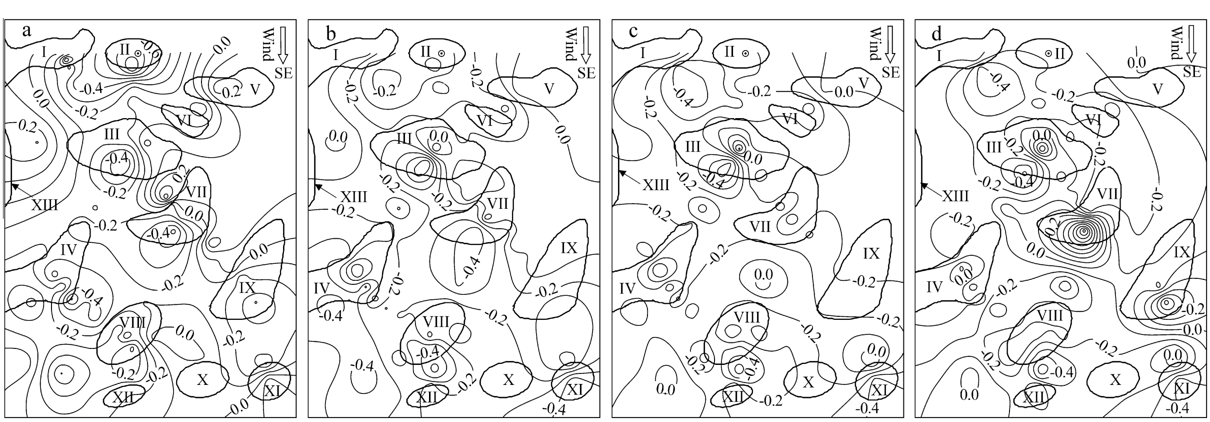

Fig. 8. Variations of wind field at different heights over the typical nebkha area. (a), (b), (c) and (d) Represent the wind field at 0.2 m, 0.8 m, 1.6 m and 2.5 m heights, respectively.

observation area, with the exception of a small number of bare inter-dunes, δ_s values below the height of 0.6 m were negative and generally fell within the range of −0.15 to −0.55; at the height of 0.2 m, the minimum δ_s fell below −0.6 (Figs. 7 and 8a). This result indicated that vegetation has significant effects on reducing wind velocity below canopy height. Previous research has shown that approximately 80% of total windblown sand flux occurs below the height of 0.3 m, and more than 90% of total windblown sand flux occurs below the height of 2.0 m (Wu, 2010). Based on the finding that dunes weaken near surface wind velocity, we conclude that shrub vegetation intercepts the vast majority of windblown sand originating from mobile dunes.

Wind profiling and topsoil particle differentiation along the observation section showed that the nebkha belt plays a crucial role in protecting the agro-ecological system in the Minqin Oasis. When sand-laden wind from mobile dunes in the Badan Jaran Desert passes through each nebkha sub-belt, dune morphology and vegetation weaken the wind velocity and filter blown sand into coarse and fine particulates, successively. In the semi-mobile nebkha sub-belt, wind velocity above the height of 0.6 m is weakened by 5–27%; in the semi-fixed and fixed nebkha sub-belts, with increases in *VC* and vegetation height, wind velocity is maximally reduced by approximately 65%. Protection of the nebkha ecosystem plays a decisive role in maintaining the existence of an oasis. However, nebkhas are located in the transitional zone between desert and oasis; thus, the nebkha ecosystem is unstable and has a low anti-interference ability and is easily degraded by human activity and groundwater recession and aeolian sediments (Jia and Yan, 1995; Zhao et al., 2001).

The nebkha belt at the fringe of the Minqin Oasis has long been designated as a nature reserve and rarely been interfered by human activities. The impact of aeolian sediments and groundwater recession on nebkha belt was strong (Gao, 2003). As we stated above, the aeolian flux from deserts was mainly deposited in semi-mobile and semi-fixed sub-belts due to existence of dunes and vegetation, and led to complicated vegetation/geomorphology process (Barchyn and Hugenholtz, 2015; Durán and Herrmann, 2006; Reitz et al., 2010; Baas and Nield, 2007), including changes in shape and stability of the dunes, and vegetation coverage even plant species (Werner et al., 2011; Barchyn and Hugenholtz, 2015). The semi-mobile dunes and semi-fixed dunes had developed with aeolian deposition over time, some plants on dunes was buried, then semi-fixed dunes might change to semi-mobile or mobile dunes, and semi-mobile dunes might change to mobile dunes. Dunes were easy to be eroded by wind when plants became sparse and under favorable weather condition (Barchyn and Hugenholtz, 2015). The height of dunes is lowered, and the distance between the dune surface and the groundwater table would be shortened. Desert plants began to grow, and some of mobile dunes and semi-mobile dunes began to evolve in a reverse direction. Such a process renders the semi-mobile dunes and semi-fixed dunes tend to be small and dense, while the fixed dunes remain relatively larger (Fig. 3).

Annual aeolian flux from the upwind edge of nebkha belt was 8700 $kg \cdot m^{-1}$ according to the field investigation (Dong et al., 2010), the mean deposition rate in nebkha belt was about 3.2 mm a^{-1}, the result implies that land surface of the nebkha belt was raised by 6.4 m on average during 2000 years. The estimated value of deposition thickness is confirmed by field investigation (Zhang et al., 2015). Over long timescales, groundwater table has been dropping due to aeolian deposition and excessive exploitation (Gao, 2003); this causes the vegetation further away from the water table, and lead to de-vegetation (Laity, 2003). However, desert plants have strong root system. According to the field observation for decades, the most suitable groundwater table for growth of Tangut Nitraria is 1–5 m, and that of *T. ramosissima* is 1–4 m. Tangut Nitraria had a severe recession only when the groundwater table is more than 15 m, and *T. ramosissima* had a severe recession only when the groundwater table is more than 10 m (Xu, 2008). The fixed and semi-fixed dunes covered by Tangut Nitraria and *T. ramosissima* become active when groundwater table exceeding the threshold. The Minqin Oasis originates from alluvial plain and wetland in the tail area of Shiyang River, the topographical features of the Minqin Oasis were lower intermediate and higher around, the groundwater table was generally high (Feng, 1963). Therefore, the increase of land surface elevation has not led to obvious shrinking of the Minqin Oasis. In the case of unchanged aeolian flux and groundwater exploitation, the nebkha belt might move to the Minqin Oasis direction, but the Minqin Oasis might still exist for a long time.

Changes in the wind field at different heights in the typical nebkha observation area indicated that vegetation only significantly reduced wind velocity below canopy height, while dune morphology significantly reduced the near surface wind velocity below dune height. The cooperation of vegetation and dune morphology is a key factor in reducing wind velocity and intercepting windblown sand (Fig. 8). We noted that in semi-fixed and fixed nebkha sub-belts, the vast majority of inter-dunes are bare and hard clay soil. These inter-dunes are often a route for high velocity wind, which negatively affects the deposition of windblown sand from mobile dunes. Therefore, the enhancement of vegetation coverage on inter-dunes is an important measure that can be taken to improve the protective effect of nebkhas.

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