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Characteristics of Wind Erosion and Deposition in Oasis-desert Ecotone in Southern Margin of Tarim Basin, China

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Abstract: The oasis-desert ecotone is a fragile ecological zone that is affected both by oasis and desert conditions. To understand the impact of the differences in wind power, and the influence of wind erosion and deposition on the ecotone, meteorological data and contemporaneous wind erosion and deposition data were collected on the southern margin of Tarim Basin with serious sand-blown hazards. The wind velocity, average wind velocity, sand drift potential (DP), resultant sand drift potential (RDP), and sand transportation rate decrease significantly and successively across four landscape types with increasing vegetation coverage (VC). Flat surfaces and areas of shifting sandy ground experience intense wind erosion with fast movement of mobile sand dunes; semi-fixed sand areas experience extensive wind deposition but only slight wind erosion; and fixed sand areas experience only slight wind erosion and deposition. Volume of wind erosion on bare newly reclaimed farmland is up to 6.96 times that of bare shifting sandy ground. Wind erosion volume per unit area and VC follow an exponential function relationship in natural conditions, while wind deposition volume per unit area does not conform to any functions which has close relationship with vary topography and arrangement patterns of vegetation besides for VC. The results indicate that the volume of wind erosion has a close correlation with VC, and different types and distribution patterns of topography and vegetation also profoundly influence the wind deposition volume in the field, and underground water tables in different landscape types control the plant community distribution.

Keywords: wind erosion; wind deposition; oasis-desert ecotone; vegetation coverage (VC); topography; Cele County

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1 Introduction

The concept of oasis-desert ecotone was promoted by Clements (1905) based on the idea of an ecotone as an ecological classification. The oasis-desert ecotone is an environment that is an ecologically frail zone (Niu, 1989). It lies between desert and oasis zones, being affected by the influences of both oasis and desert eco-systems, and is therefore prone to degeneration. Undoubtedly, desert vegetation in the oasis-desert ecotone plays an important role in preventing desertification and maintaining oases stabilization (Zhao *et al.*,

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2008). Spatial and temporal changes of oasis-desert ecotone are related to variations in the extent of the oasis (Wang and Zhao, 2001).

Wind erosion is a phenomenon that is common in regions where dry winds blow. These regions correspond to dry lands: areas where the soil, generally, is dry and shifting, and lacks vegetation for most of the year (Ekhtesasi and Sepehr, 2009). In the past, there has been some research related to wind energy variations, and the relationship between a wind dynamic environment and dune formation in deserts has been researched worldwide (Bullard *et al*., 1996; Hereher, 2010; Zhang *et al*., 2011). Changes to the aeolian environment of the Lower Mojave Valley reflect complex interactions among the wind regime, river channel morphology and sediment, surface and subsurface hydrology, geology, vegetation, and human influence (Laity, 2003). In several field studies, small-scale wind erosion and deposition processes have been monitored by marking the changing level of the soil surface on steel rods or erosion bridges driven into the ground (Wiggs *et al*., 1995; Hesse and Simpson, 2006; Li *et al*., 2009). Utilizing color sand in wind tunnel experiments to observe spatial patterns in vegetation canopies, different vegetation densities respectively represented wake-interference and isolated roughness flow (Katrin *et al*., 2013). The strongest correlation between vegetation coverage and transport rate was found considering the two miniphones placed on the hummock within the vegetation (Barrineau and Ellis, 2013). Many factors usually influence the effects of wind erosion besides climate (Yang *et al*., 2012). Vegetation density is the most important, but vegetation height and width also have a close relationship with soil erosion (Bressolier and Thomas, 1977; Wolfe and Nickling, 1993). Theoretical derivation and wind tunnel experiments suggest that there is an exponential relationship between vegetation cover (VC) and the wind erosion rate (Wasson and Nanninga, 1986; Dong *et al*., 1996; Burri *et al*., 2011). The wind erosion rates and nutrient loss by dust emission are strongly affected by plant cover (Li *et al*., 2007). The effectiveness of different plant types in increasing soil resistance to wind erosion were: perennial shrubs>perennial pasture>forest>annual pasture>forage crops (Zhao *et al*., 2005). Obtaining measurements of these factors during a windstorm is invaluable to wind erosion research (Lopez, 1998). Different surface cover as an agent reduces the extent of wind erosion on semi-arid landscapes (Hupy, 2004). The wind tunnels that were used provide a controlled environment allowing experiments to be performed repeatedly and under set conditions (Fryrear, 1986). However, wind tunnels do not cover large areas with short testing time, which are uncharacteristic of most wind events. They can not produce natural wind profiles and fluctuations (Stout and Zobeck, 1996), which makes the extrapolation of the results to actual physical field conditions difficult (Lopez, 1998).

However, few researchers have examined the effects of sand-blown movement, wind erosion, and deposition on the surface of oasis-desert ecotone. Oasis-desert ecotones are under threat of disappearance in the future if reclamation activities continue. The vegetative distribution area markedly decreased from 1000 m in 1978 to 30 m in 2008 in the Minqin oasis-desert ecotone in Gansu Province, China. The coverage of *Tamarix* spp. bushes reduced from 25% to 7% (Ma *et al*., 2009). As a typical region, the southern margin of the Taklimakan Desert in Uygur Autonomous Region of Xinjiang in China is experiencing problems of decreasing underground water table and VC, which may increase blown-sand hazards. The relationship between sand transportation rate and VC has been researched mainly in wind tunnel experiments, while the relationship among wind deposition, VC and topography is not very clear. The research on wind erosion and deposition processes on different landscape types in an oasis-desert ecotone can effectively provide a theoretical basis and support against blown-sand damage to vast farmlands in the hyperarid regions. The objectives of this study are: 1) to show the importance of oasis-desert ecotone in decreasing wind velocity, desertification prevention, and ensuring oasis ecological security; 2) to discuss the characteristics of sand blown activities in different landscape types; 3) to analyze the relationship between VC, topography, volume of wind erosion, and wind deposition in field work, and 4) to provide a theoretical basis for the protection and rehabilitation of oasis-desert ecotones in hyperarid areas.

2 Materials and Methods

2.1 Study area

Cele County (35°17′55″–39°30′00″N, 80°03′24″–82°10′34″E) lies between the southern margin of Taklimakan Desert and the northern Kunlun Mountain, which are located in the Hotan Prefecture of Uygur Autonomous Region of Xinjiang in China (Fig. 1a). It belongs to a typical continental warm temperate climate zone, which is a region that is seriously affected by sand-blown hazards. A large area of oasis-desert ecotone is located in the western and northern part of Cele County. Weather that causes sand-blown events occurs continuously, with 20–30 days of gales and dust storms each year. The sand-blowing weather and floating-dust weather aggregate to over 90 and 150 days annually, respectively (Zhang, 1995). The average precipitation is 35.1 mm, and the potential evaporation capacity is 2600 mm annually. A greater difference can occur between day- and night-time temperatures. The annual highest and lowest temperatures were 41.9℃ and –23.9℃, respectively. The annual prevailing wind direction is westerly and northwesterly (Yang, 1990), and the annual average wind velocity at a height of 2 m is 2.36, 1.75, 1.60 and 0.96 m/s at the sites of shifting sandy land, semi-fixed sandy land, fixed sandy land, and oasis. Severe windy and dusty occurrences limited social and economic development in Cele County, which has been forced to relocate elsewhere three times because of frequent imminent drifting sand dunes. The sand grains on the surface of the oasis-desert ecotone are mainly very fine aeolian sands, and the average grain size range is 70–165 μm (2.6–4.0 ϕ). The soil moisture content on the surface of the depth of 0–20 cm was between 0.15% and 0.35%, and which was more than 5% in the oasis. The distribution density of *Tamarix* spp. nebkhas on the surfaces of shifting sandy, semi-fixed sandy, and fixed sandy lands were 1.76, 5.72 and 0.8 per hectare, respectively.

2.2 Data and processing

There were six sampling sites in the study area, of which four were located near meteorological stations, one at Grassland station, and one at Rewake (Fig. 1b). In July 2010, four meteorological stations were installed at different sites on the oasis-desert ecotone and the inner oasis to monitor wind velocity at heights of 0.5, 1, 2, 4, 8 and 10 m (including wind direction) (Fig. 1b). The meteorological stations had HOBO U30 meteorological surveying instruments, which automatically log changing meteorological data every second. The logging interval time was usually 1 minute. The wind velocity resolution was 0.19 m/s and the wind direction resolution was 1.4°. No. 1 meteorological station (No. 1 MS) was representative of a surface of flat shifting sandy ground. No. 2 meteorological station (No. 2 MS) and No. 3 meteorological station (No. 3 MS) represent semi-fixed sandy ground and fixed sandy ground, respectively. No. 4 meteorological station (No. 4 MS) was representative of the oasis, in which cotton and pomegranate were planted with VC of more than 80%. At the foot of three weather stations, ten vegetation quadrats were chosen (except for the site in the oasis), on which wind erosion iron rods were inserted to observe changes of wind erosion and deposition. There were two, four, and four vegetation quadrats on shifting sandy, semi-fixed sandy and fixed sandy ground, respectively. In

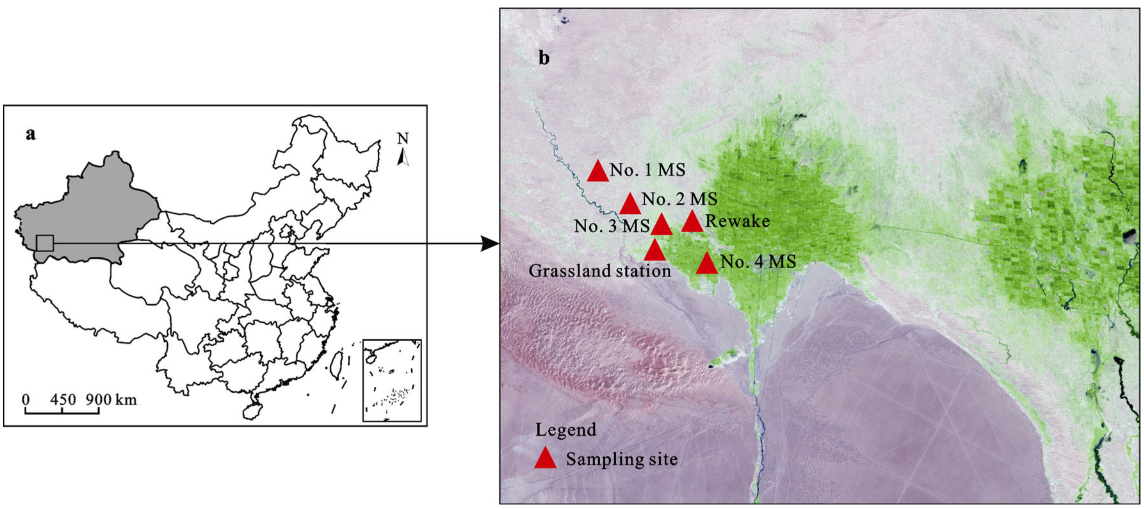

Fig. 1 Location of study area in China (a) and landscape types of study area (b). MS is meteorological station

May 2010, wind erosion rods were plugged into the experimental plots with horizontal interval distances between 30 cm and 80 cm in key geomorphologic positions. Some data were lost in the area of semi-fixed sandy ground. The experiment was divided into four or five observation periods from 13 May to 20 October in 2012. The VC was 3%, 27%, and 67%, respectively, from the sites of shifting sandy, semi-fixed sandy, and fixed sandy ground. The calculation method for the VC rate applied the following formula:

$$VC = (\sum_{i=1}^{n} CD_i) / A \quad (1)$$

where VC represents vegetation cover rate (%); CD_i represents the canopy diameter of plant i in the quadrat; and A represents the total area of vegetation in the quadrat.

In 2011, five Big Spring Number Eight (BSNE) traps were installed on the surfaces at five sites: No. 1 MS, No. 2 MS, No. 3 MS, Grassland station, and Rewake. BSNE samplers were installed at heights of 10, 20, 30, 50, 100, and 200 cm above ground, and the sand transportation entrance was 5 cm high and 2 cm wide with an area of 10 cm^2. The land at Rewake had been reclaimed for two years and the land of Grassland station had been reclaimed for more than 15 years.

On the surface of the shifting sandy ground, the vegetation comprised mainly of sparse *Tamarix* spp. shrubs, *Hexinia polydichotoma*, and *Halogeton glomeratus*. At the site of No. 2 MS, the surface vegetation mainly comprised tall *Tamarix* spp. shrubs, *Alhagi sparsifolia*, and *Karelinia caspia*. At No. 3 MS, the surface vegetation included comparatively flourishing *A. sparsifolia* and numerous *H. glomeratus* (Table 1). The cross section of the terrain along the line of four meteorological stations was measured by base station instruments, and the elevation is 1349, 1359, 1355, and 1367 m at sites of No. 1 MS, No. 2 MS, No. 3 MS and No. 4 MS, respectively. The length of exposed erosion rods was measured at regular intervals during sand blowing events. Because the vegetation was patchy in distribution, different vegetation quadrats were chosen on the three landscape types. The area of every vegetation quadrat was approximately 100 m^2. The sites of the wind erosion rods, vegetation roots, and vacant land were measured by a total station instrument, with a fixed error of 2 mm and a proportional error of 2 mm/km. The VC of two quadrats was zero located in shifting sandy ground and newly reclaimed bare farmland.

The sand transportation flux at the height of 202.5 cm was calculated by consecutive integration for each sand transportation phase. We applied the Kriging interpolation method by Surfer 8.0 software and topographic data to produce wind erosion and wind deposition DEM graphs. Based on the analyzed outcome of the meteorological and wind erosion data with different VC and topography, we determined the characteristics of wind erosion and wind deposition on the oasis-desert ecotone. All data and graphs were created with Excel 2003, Origin 9.0, and Surfer 8.0 software.

2.3 Methods

Sand drift potential denotes regional sand-blown movement intensity over a long period time. Variations in the wind strength, mainly influenced by different VC and landscape type conditions, can affect the surface processes of wind erosion and deposition. Thus, different wind strengths and landscape types can shape various small-scale surface landforms. Several studies (Fryberger and Dean, 1979; Bullard *et al.*, 1996) have shown that sand drift potential (DP) is proportional to the potential sand flux. DP can be calculated using following formula (Lettau and Lettau, 1978; Fryberger and Dean, 1979):

Table 1 General conditions at six sampling sites

Site	Latitude	Longitude	Elevation (m)	Vegetation type	VC (%)	Landscape type
No. 1 MS	37°02′37″	80°40′53″	1349	*Tamarix* spp., *Halogeton glomeratus*, *Hexinia polydichotoma*	3	Shifting sandy ground
No. 2 MS	37°01′47″	80°42′32″	1359	*Tamarix* spp., *Karelinia caspia*, *Alhagi sparsifolia*	27	Semi-fixed sandy ground
No. 3 MS	37°01′21.0″	80°43′25.7″	1355	*Alhagi sparsifolia*, *Halogeton glomeratus*	67	Fixed sandy ground
No. 4 MS	37°00′11.7″	80°45′23.4″	1367	Cotton, Pomegranate	>80	Farmland
Grassland station	37°00′21.9″	80°43′14.5″	1360	Cotton	>50	Farmland
Rewake	37°01′34.9″	80°45′07.3″	1366	Jujube tree	>30	Farmland

Note: MS is meteorological station

$$DP = V^2 (V - V_t)t \quad (2)$$

where *DP* represents the sand drift potential denoted by a vector unit (VU); *V* represents the wind velocity, which is greater than the sand driving threshold velocity; V_t represents sand driving threshold velocity, and *t* represents the percentage time that the wind velocity exceeds the sand driving threshold velocity.

The values for total horizontal mass flux *Q* were calculated by integrating the horizontal flux $q(z)$ from the ground to 202.5 cm.

$$Q = \int_0^{202.5} q(z)\mathrm{d}z \quad (3)$$

z represents the sand transportation flux at different heights from ground surface to 202.5 cm height.

3 Results and Analyses

3.1 Topography and wind velocity change

The general topography becomes higher from shifting sandy ground to the oasis (Fig. 2). The greatest elevation difference was approximately 33 m on the section line. This revealed that the resistance ability against drifting sand became greater with increased VC and topography along the section line. The highest point was a tall *Tamarix* spp. nebkhas. The shape of the topography was a wave curve because bare sandy ground usually shows intense wind erosion and the sites with vegetation show higher topography because of the accumulation of drifting sand by dense shrubs.

Annual average wind velocity at different levels decreased from shifting sandy ground to the oasis (Fig. 3). The annual average wind velocity at the heights of 0.5 and 1.0 m on semi-fixed sandy and fixed sandy ground decreased by 39.81% and 63.25%; and 43.9% and 47.54%, respectively, compared with that on shifting sandy ground. The average wind velocity at the heights of 2 and 10 m on semi-fixed sandy, fixed sandy ground, and oasis decreased by 26.83% and 8.65%; 31.67% and 14.53%; and 59.76% and 45.27%, respectively, compared with that on shifting sandy ground, which accounted for the fact that wind velocity decreases more close to the ground. Furthermore, on approaching or entering the oasis, natural vegetation and shelterbelts have a sheltering effect in decreasing the wind velocity and fixing drifting sands. The average wind velocity difference between the height of 0.5 and 1 m on semi-fixed sandy ground was small because there were many higher nebkhas in the upwind direction, which effectively reduced the wind velocity near the ground surface.

3.2 Analysis of sand drift potential (DP) on four landscape types

The adopted threshold wind velocity for sand-driving was 5 m/s and 6 m/s at the height of 2 m and 10 m, respectively (Chen *et al.*, 1995; Dong *et al.*, 1996). The frequency of sand-blowing wind at site No. 1 MS was 4.73 and 4.35 times greater than that at the height of 2 m, and 1.44 and 1.74 times greater than that at a height of 10 m at sites No. 2 MS and No. 3 MS in one year, respectively (Table 2). Influenced by artificial

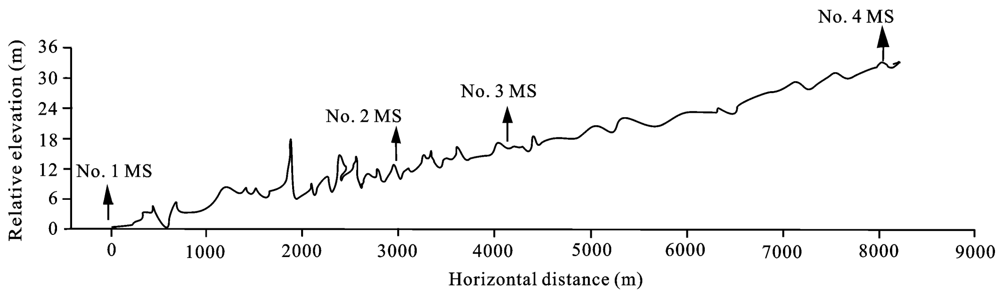

Fig. 2 Topography along section line

Table 2 Time and frequency of sand blowing wind in one year on four landscape types

Site	Landscape type	Time of blowing wind at height of 2 m (min)	Frequency (%)	Time of blowing wind at height of 10 m (min)	Frequency (%)
No. 1 MS	Shifting sandy ground	28 569	5.440	37 751	7.18
No. 2 MS	Semi-fixed sandy ground	6020	1.150	26 125	4.97
No. 3 MS	Fixed sandy ground	6569	1.250	21 650	4.12
No. 4 MS	Oasis	31	0.006	3488	0.66

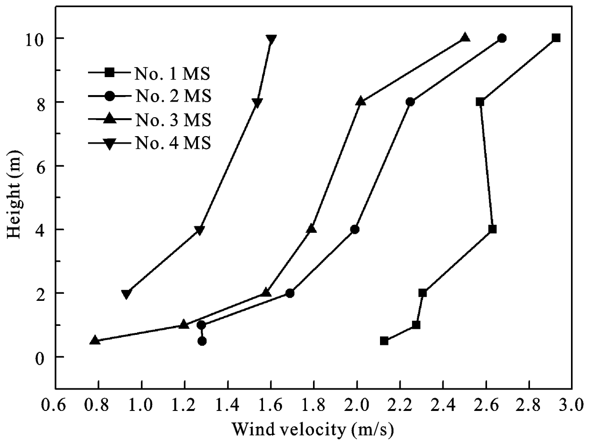

Fig. 3 Wind profiles over four landscape types. Meanings of No. 1 MS to No. 4 MS are listed in the Table 1

shelterbelts and crops, the occurrence of sand-blowing wind at site No. 4 MS in the oasis was very small.

The DP and resultant sand drift potential (RDP) in the area of shifting sandy ground were significantly greater than that at sites No. 2 MS and No. 3 MS (Fig. 4). The DP and RDP at sites No. 2 MS, No. 3 MS, and No. 4 MS were decreased by 47.91%, 53.39%, 96.46%, and 42.01%, 47.31%, 95.59% compared with that at site No.1 MS, respectively. The DP and RDP in the oasis were so small as to be negligible compared with the other three sites. The value of DP and RDP for the area of shifting sandy ground was 70.89 VU and 54.37 VU, respectively (Fig. 4). According to Fryberger and Dean (1979) (Table 3), this is based on an RDP, which belongs to a high wind energy environment, whereas the sites of semi-fixed sandy ground and fixed sandy ground belong to a middle wind-energy environment, and the inner oasis belongs to a low wind-energy environment.

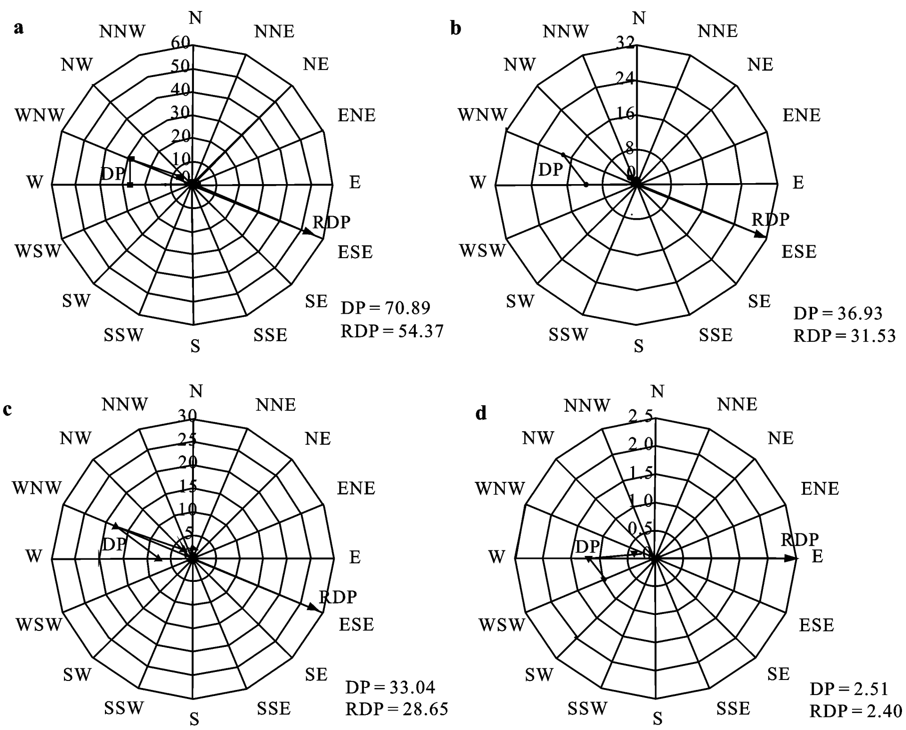

Fig. 4 Sand drift potential (DP) and resultant sand drift potential (RDP) change on four landscape types over a year. a. No. 1 MS; b. No. 2 MS; c. No. 3 MS; d. No. 4 MS (unit: VU)

Table 3 Classification of wind energy environment and direction variability index

DP (VU)	RDP (VU)	Wind-energy environment	RDP/DP	Direction variability index
>400	>54	High wind-energy environment	>0.8	High ratio
200–400	27–54	Middle wind-energy environment	0.3–0.8	Middle ratio
<200	<27	Low wind-energy environment	<0.3	Low ratio

The annual DP of sites No. 1 MS to 4 MS was 70.89, 36.93, 33.04, and 2.51 VU, respectively. The DP and RDP at a height of 10 m for the area of shifting sandy land were 1.92, 2.15, and 28.24 times greater, and 1.72, 1.9, 22.65 times greater than those at sites No. 2 MS, 3 MS, and 4 MS, respectively. The maximum DP occurred in June and then decreased through July, May, and April. The DP of these four months accounted for about 50% of the annual DP. The DP in January for all four landscape types was zero (Fig. 5). The DP in the WNW and W directions was the maximum for the year (Fig. 4) and accounted for 75% of 16 directions. We estimated that the wind regime was of a unimodal pattern, which agrees with the conclusions of Zu (2003), and Li *et al.* (2004). An exception was the direction variability index of RDP/DP at site No. 2, with an index of 0.52, which belongs to an obtuse bimodal wind pattern regime; the remainder of the direction variability index influenced by topography ranged from 0.77 to 0.96. The direction variability index at site No. 3 MS was 0.96, which belongs to a high ratio unimodal pattern; the remainder had mainly a high direction variability index.

The resultant sand drift direction (RDD) on the ecotone was approximately 108°, which was identical to the annual distribution frequency of sand-blowing wind. The DP at site No. 2 MS was greater than that at site No. 3 MS; however, the RDP was the reverse. This revealed that the general intensity of sand blown activity on semi-fixed sandy ground was stronger than that on fixed sandy ground. The resistance ability of the high *Tamarix* spp. nebkhas to sand-blowing wind resulted in a wavy surface and a varied direction of the sand-blowing wind on semi-fixed sandy land.

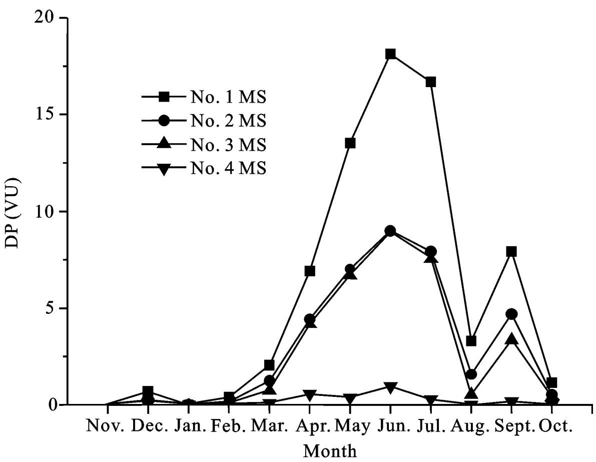

Fig. 5 Sand drift potential (DP) distribution in different months over a year

3.3 Differences in sand transportation flux between oasis-desert ecotone and oasis

The sand transportation flux at different heights, and the total sand flux at the height of 202.5 cm decreased significantly from shifting sandy ground to oasis, the sand transportation flux in the oasis was very small (Fig. 6). Horizontal sand transport flux of the semi-fixed sandy, fixed sandy, Grassland station and Rewake ground decreased by 46.36%, 92.85%, 98.98% and 92.11%, respectively, compared with the area of shifting sandy ground (No. 1 MS) during the period 12–15 July, 56.18%, 90.99%, 95.91% and 93.17% during 15–19 July, and 56.49%, 94.08%, 98.2% and 95.39% during 19–23 July, respectively. The decreased degree during 23–31 July and 31 July–16 September was similar to that during the first three periods compared with shifting sandy ground. Because the farmland at Rewake was plowed, with loose sand and low VC, the horizontal sand transport flux was similar to, or greater than that of the area of fixed sandy ground (No. 3 MS) during the same observation period. During the weakest wind velocity period between 16 September and 22 October, the horizontal sand transportation flux at the sites of semi-fixed sandy, fixed sandy, Grassland station and Rewake ground decreased by 56.18%, 90.99%, 95.91% and 93.17%, respectively, compared with the area of shifting sandy ground. The average sand transportation flux between 12 July and 22 October at site of shifting sandy ground were up to 2.25, 16.14, 65.16, 15.75 times greater than that at sites of semi-fixed sandy ground, fixed sandy ground, Grassland station, and Rewake, respectively (Fig. 6).

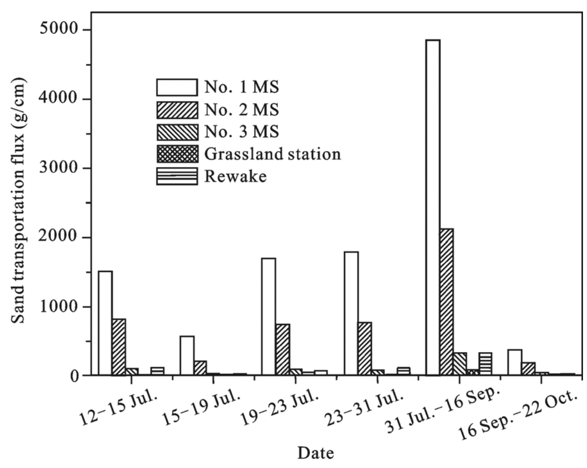

Fig. 6 Horizontal sand transportation flux of Big Spring Number Eight (BSNE) traps from ground surface to 202.5 cm

The sand transportation rate decreased with increased height above the ground on the sites of shifting sandy ground and semi-fixed sandy ground (Figs. 7a to 7f). However, in several observation periods, the sand transportation rate in the higher layer above 50 cm was more than that in the lower layer near the ground on the fixed sandy ground, Grassland station or Rewake (Figs. 7g to 7l), because of nebkhas with high VC on the fixed sandy ground, and high shelterbelts and higher soil moisture in the farmland at the Grassland station. This accounts for the movement of sand in the higher layer, which was transported by some distance instead of originating at the sites of sand traps, where little sand was moved by the wind or subjected to surface erosion in areas of farmland that had been reclaimed several years previously.

3.4 Characteristics of wind erosion and deposition in oasis-desert ecotone

3.4.1 Characteristics of wind erosion and deposition from November 2010 to October 2011

The shifting sand surface experienced intense wind erosion, even though a mobile sand dune moved into the stick experiment quadrat from November 2010 to October 2011 (Table 4). The maximum depth of wind erosion was 25.7 cm and the shallowest depth was 0.6 cm during the year. Wind erosion was the dominant process with a net erosion volume of 0.0342 m^3/m^2, and wind deposition activity occurred in only a small area because of movement by shifting sand dunes. The total net wind deposition was 0.0082 m^3/m^2 during more than four months on the semi-fixed sandy ground. This unusual phenomenon occurred because the front of the area containing wind erosion rods had several large *Tamarix* spp. nebkhas, and the wind erosion rod experiment was located in a comparatively low-lying area. Net volume per unit area in the area of fixed sandy ground was 0.0018 m^3/m^2 during the same year. The common characteristics of wind erosion and deposition indicate that the wind velocity and volume of wind erosion decreased abruptly with increasing VC on the oasis-desert ecotone. Nebkhas inhibit the movement of sand from around their roots; however, upwind of and to the sides of the nebkhas, wind erosion and sand loss occurs on the surface, if the ground is bare sand. Generally, the degree of wind erosion on the surface decreases with increasing VC, which is mainly caused by the distance to the oasis and topography. Near the oasis, partial bare land experiences slight

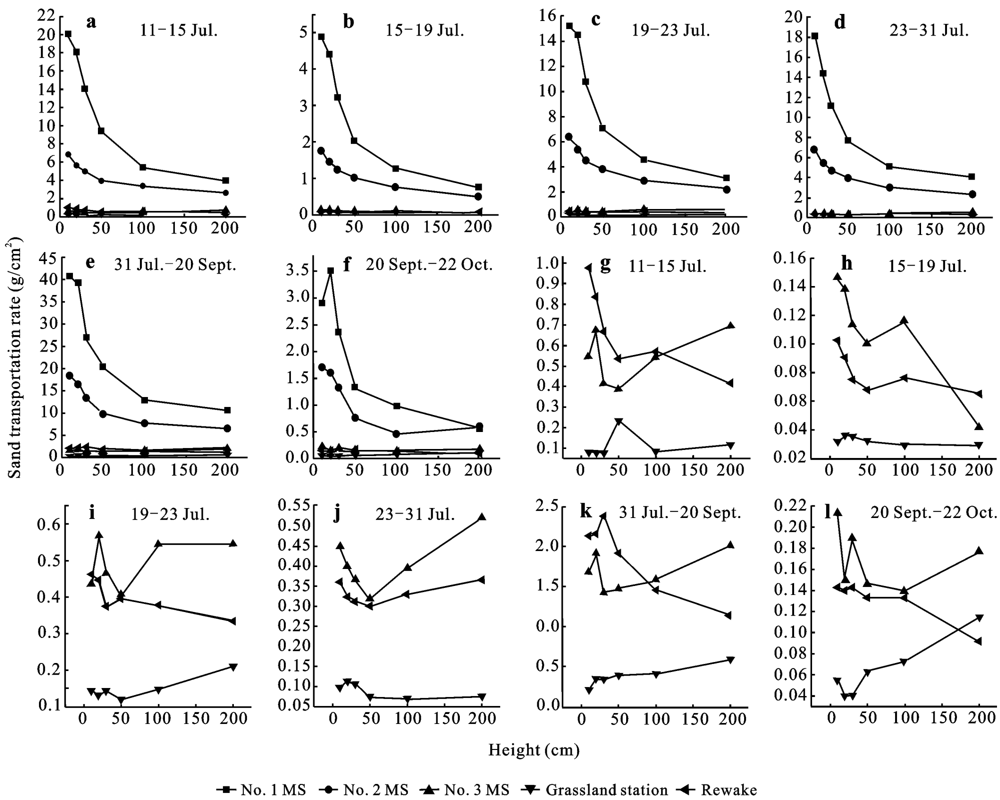

Fig. 7 Comparison of sand transportation rates on five landscape types

Table 4 Volume of wind erosion and deposition on three landscape types

Site	Observation period	Volume of wind erosion (m^3)	Volume of wind deposition (m^3)	Volume of net total wind erosion and deposition (m^3)	Area (m^2)	Net volume per unit area (m^3/m^2)
No. 1 MS	Nov. 2010–Oct. 2011	–9.0190	1.856	–7.1630	209.23	–0.0342
No. 2 MS	Jul. 2011–Oct. 2011	–0.0810	0.760	0.679	82.91	0.0082
No. 3 MS	Nov. 2010–Oct. 2011	–0.3650	0.486	0.121	67.73	0.0018

Note: negative numbers represent wind erosion and positive numbers represent wind deposition

wind erosion, whereas most of the land receives slight wind deposition because of the high VC, which protects the oasis from severe wind-blown damage.

We estimated the relationship between the average wind velocity above the threshold wind velocity at the height of 2 m, and the corresponding volume of wind erosion and deposition and sand blown time under meteorological stations No. 1 and 3. There are specific relationships among average wind velocity above the threshold wind velocity, the duration of the sand-blowing wind, and volume of wind erosion and deposition on shifting sandy land, but not significant (Figs. 8a, 8b, 8d). However, there was a certain degree of correlation between sand blown time and volume of wind erosion, which was better than other correlations (Fig. 8c). The relationship between the average wind velocity above the threshold wind velocity and the volume of wind deposition, had a significant polynomial relationship (Fig. 9b), whereas the duration of the sand-blowing wind and the volume of wind deposition in the area of fixed sandy ground had a linear relationship (Fig. 9d). This showed that there was a clear relationship between the average wind velocity above the threshold wind velocity, and the duration and volume of wind deposition on bare sandy ground, while there was a significant positive relationship between average wind velocity above the threshold wind velocity and the sand blown time with the volume of wind deposition on fixed-sandy ground. The relationships among average wind velocity above the threshold velocity, sand blown time and volume of wind erosion were not significant (Figs. 9a, 9c). At No. 1 MS, there were several mobile sand dunes and a large source of sand available from the bare ground surface. Conversely, at No. 3 MS near the oasis, there was vegetation to block and intercept drifting sand, and a relative little amount of sand available from the surface.

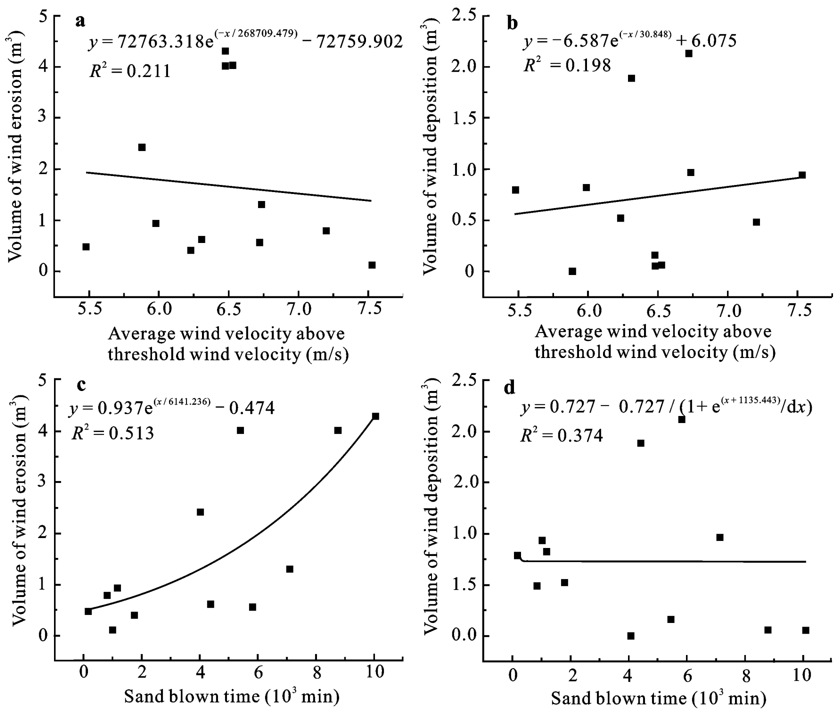

Fig. 8 Relationship among average wind velocity above threshold wind velocity, sand blown time, volume of wind erosion, and deposition on shifting sandy ground (No. 1 MS)

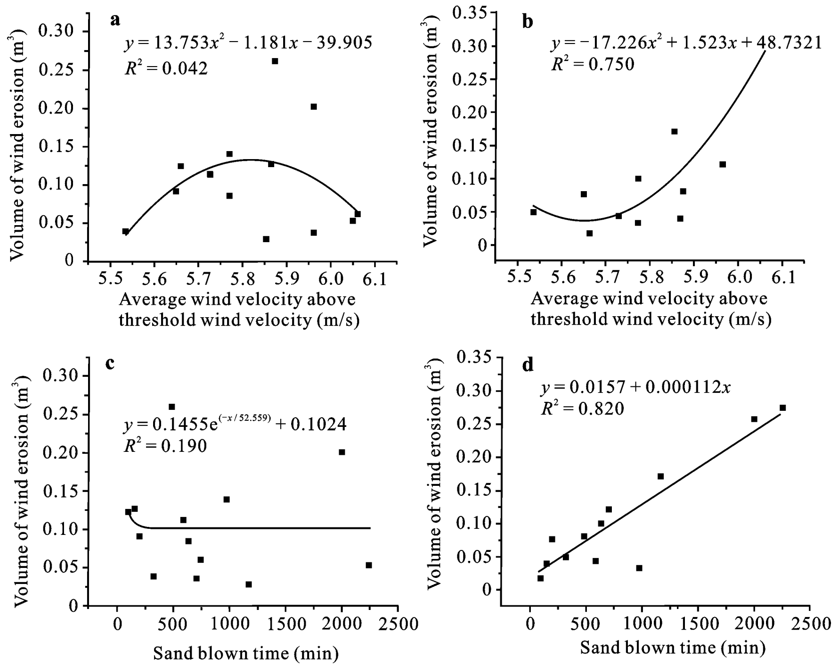

Fig. 9 Relationship among average wind velocity above threshold wind velocity, sand blown time, volume of wind erosion, and deposition on fixed sandy ground (No. 3 MS)

3.4.2 Characteristics of wind erosion and wind deposition from 13 May to 20 October 2012

In 2012, these observation periods had different average wind velocity. The average wind velocity at different heights decreased from shifting sandy land to fixed sandy land, and which was at its lowest from 11 June to 14 August and was strongest from 3 to 11 June, 2012 (Figs. 10a, 10b, 10c), when the corresponding wind erosion was the highest and wind deposition was comparatively small (Figs. 11a, 11b). Generally, the volume of wind erosion per unit area in the same observation period decreased with increased VC (Fig. 11a). Most wind erosion occurred on the surface of newly reclaimed sandy ground near No. 2 MS, and the least on fixed sandy ground with 41.28% VC. The maximum volume of wind deposition occurred on natural reservation land surrounded by newly reclaimed sandy ground and the least occurred on newly reclaimed farmland (Fig. 11b).

Mobile sand dunes moved forward by approximately 13 m (Fig. 12a) on bare shifting sandy ground during five months, the maximum wind erosion depth was 40 cm, and medium wind erosion occurred on the surface with a VC of 3%, the ground surface was mainly dominated by wind erosion process with the maximum wind erosion depth of 2.4 cm (Fig. 12b). Strong wind erosion occurred on the surface of bare newly reclaimed

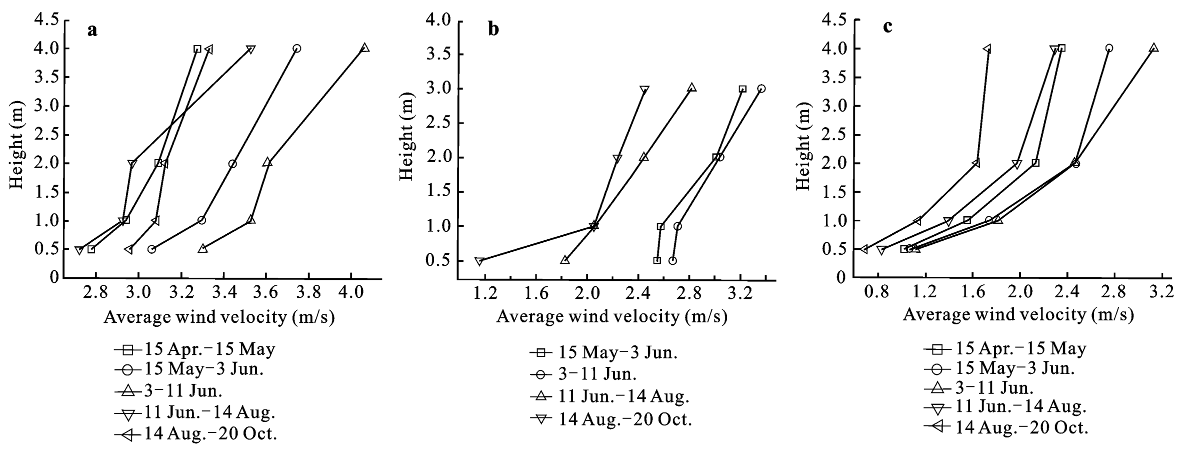

Fig. 10 Average wind profiles on shifting sandy ground (a), semi-fixed sandy ground (b), fixed sandy ground (c) of oasis-desert ecotone

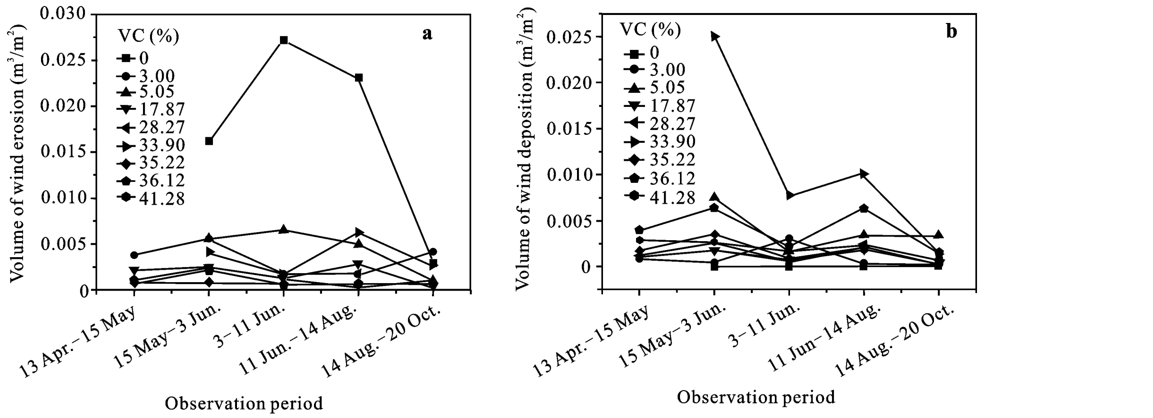

Fig. 11 Volumes of wind erosion (a) and wind deposition (b) during five observation periods under different vegetation coverage (VC)

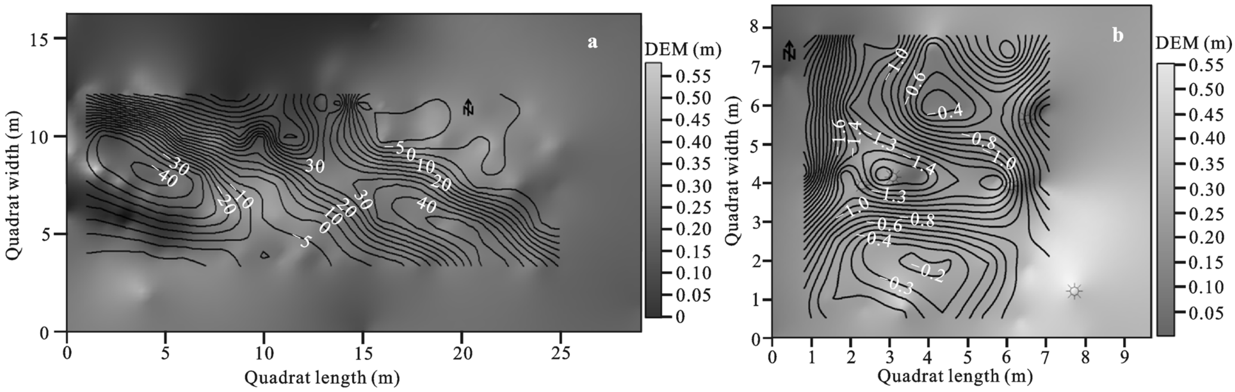

Fig. 12 Equal wind erosion lines based on digital elevation model (DEM) maps on shifting sandy ground with different VC of 0 (a) and 3% (b). ☼ symbol represents sites of vegetation roots. Curve lines represent equal wind erosion and deposition lines, unit: cm

farmland with a maximum recorded wind erosion depth of 9.2 cm (Fig. 13a). Slight wind erosion or wind deposition occurred on bare sandy ground and around shrubs with 5.05% VC on the semi-fixed sandy ground (Fig. 13b). The volume of wind deposition on the surface of natural reservation land surrounded by newly reclaimed farmland was greater than that on the surface with a VC of 36.12% (Figs. 13c, 13d). On the surfaces of fixed sandy ground, there occurred moderate wind erosion on surface of 17.87% VC on bare flat sand ground upward nebkhas and at two lateral flanks beside nebkhas (Fig. 14a), and the maximum wind erosion depth was 4 cm. It was mainly dominated by slight wind deposition on the surface with 28.26% VC, only wind erosion occurred on the bare surface of lower interspaces (Fig. 14b). The topography was comparatively lower and plants were evenly distributed in space on the surface of quadrat with 35.22% VC (Fig. 14c), the amount of wind deposition was maximum on four quadrats, the maximum wind deposition depth was 2.2 cm, though the VC was less than the 41.28% VC (Fig. 14d). On the surface with the highest VC with 41.28%, there occurred mainly wind deposition and only little wind erosion occurred on a lower bare terrain between nebkhas.

The greater the plant height and crown width, the more wind deposition would occur around shrubs, especially on the leeward slopes. This is because VC plays a main role in influencing the volume of wind erosion, with a determination coefficient of 0.92 (Fig. 15). The volume of wind erosion decreased according to the exponential function relationship with increasing VC. This finding is in agreement with Wasson and Nanninga (1986) and Dong *et al.* (1996). The volume of wind deposition increased at first, and then decreased with increasing VC, and the volume of wind deposition was highest on the surface of semi-fixed sandy ground. Apart from VC, the topography, type and height of shrubs and the arrangement of plants can also influence wind deposition, and topography was the most significant factor influencing the volume of wind deposition. The volume of wind erosion would be greater if it occurred on lower terrains or on the bare interspaces

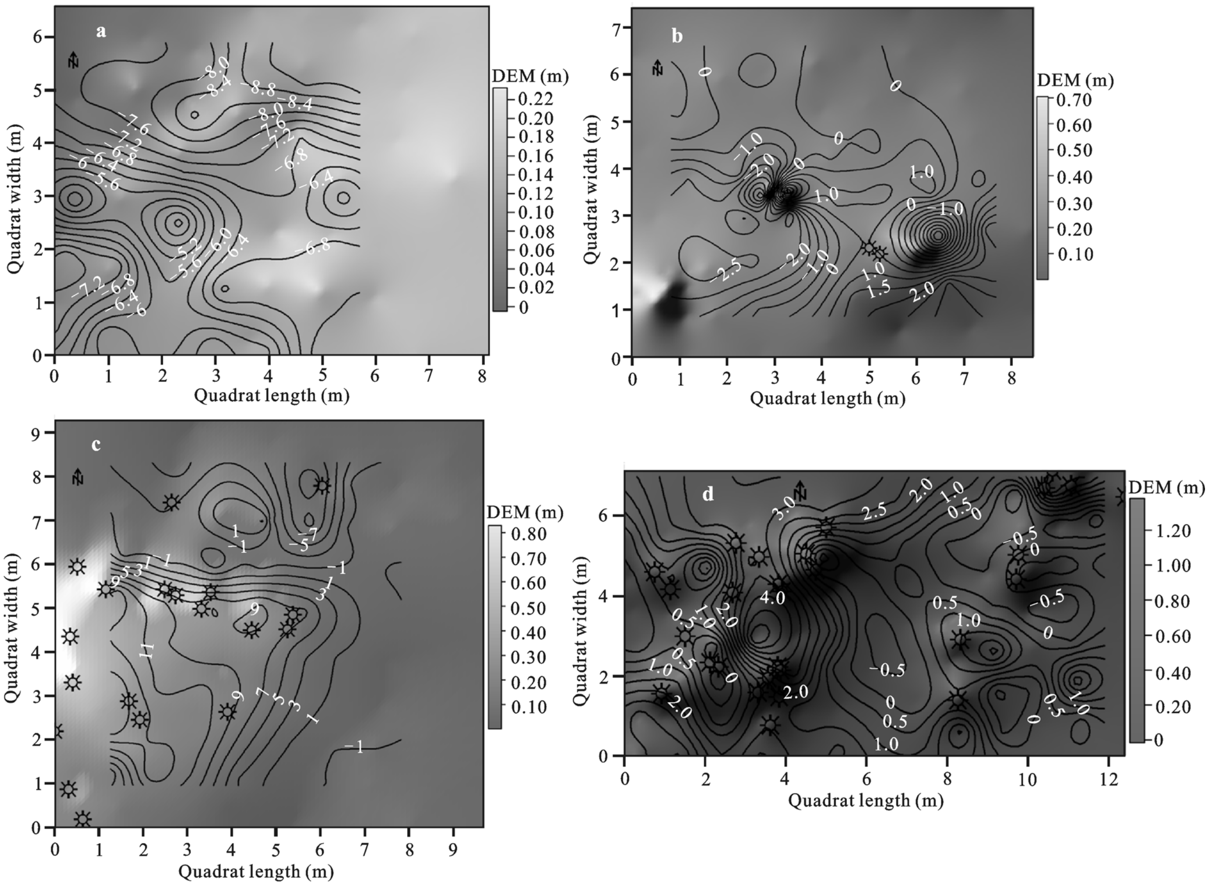

Fig. 13 Equal wind erosion lines based on digital elevation model maps on semi-fixed sandy ground with different VC of 0 (a), 5.05% (b), 33.9% (c), 36.12% (d). ☼ symbol represents sites of vegetation roots. Curve lines represent equal wind erosion and deposition lines, unit: cm

between nebkhas. The newly reclaimed farmland was susceptible to wind erosion because of loose soil on the surface. The volume of wind erosion on newly reclaimed bare ground was up to 6.96 and 10.08, and 74.85 and 6.66 times greater than that on the surfaces with VC of 3%, 5.05%, 33.9% and 36.12%, respectively, over the same period. The volume of wind deposition on natural surfaces with a VC of 33.9%, where the surrounding land was reclaimed, was greater than that on surfaces with 36.12% VC. The higher amount of sand on reclaimed land was easily subjected to deposition within and around plants, and the deposition in wake areas was clear compared to upwind areas for the nebkhas.

4 Discussion

Based on the RDP, shifting sandy ground belongs to a high wind-energy environment, and semi-fixed and fixed sandy ground belong to a medium wind-energy environment, and the inner oasis belongs to a low wind-energy environment, while all DP were less than the category criteria (Table 3). This is because RDP/DP belongs to a high ratio unimodal pattern on the southern margin of Taklimakan Desert.

The daily wind erosion rate in the fixed sandy ground was, on average, only about 1/5 of the rate in the semi-fixed sandy ground, and 1/47 of the rate in the shifting sandy ground in Horqin sandy ground (Li *et al.*, 2005). The lower degree of average sand transportation flux at semi-fixed sandy and fixed sandy ground were 1/2.25 and 1/16 of that on shifting sandy ground in the Cele oasis-desert ecotone, and less than that in Horqin sandy ground, in China. This was caused by the plant type, the soil texture, and soil moisture differences between the two regions. The land surface of the oasis-desert ecotone on the margin of Taklimakan Desert had loose soil texture, and the soil moisture on different surfaces was very small and similar, and the vegetation was distributed in a patchy pattern with lower VC, compared with that on grasslands in the Horqin sandy land.

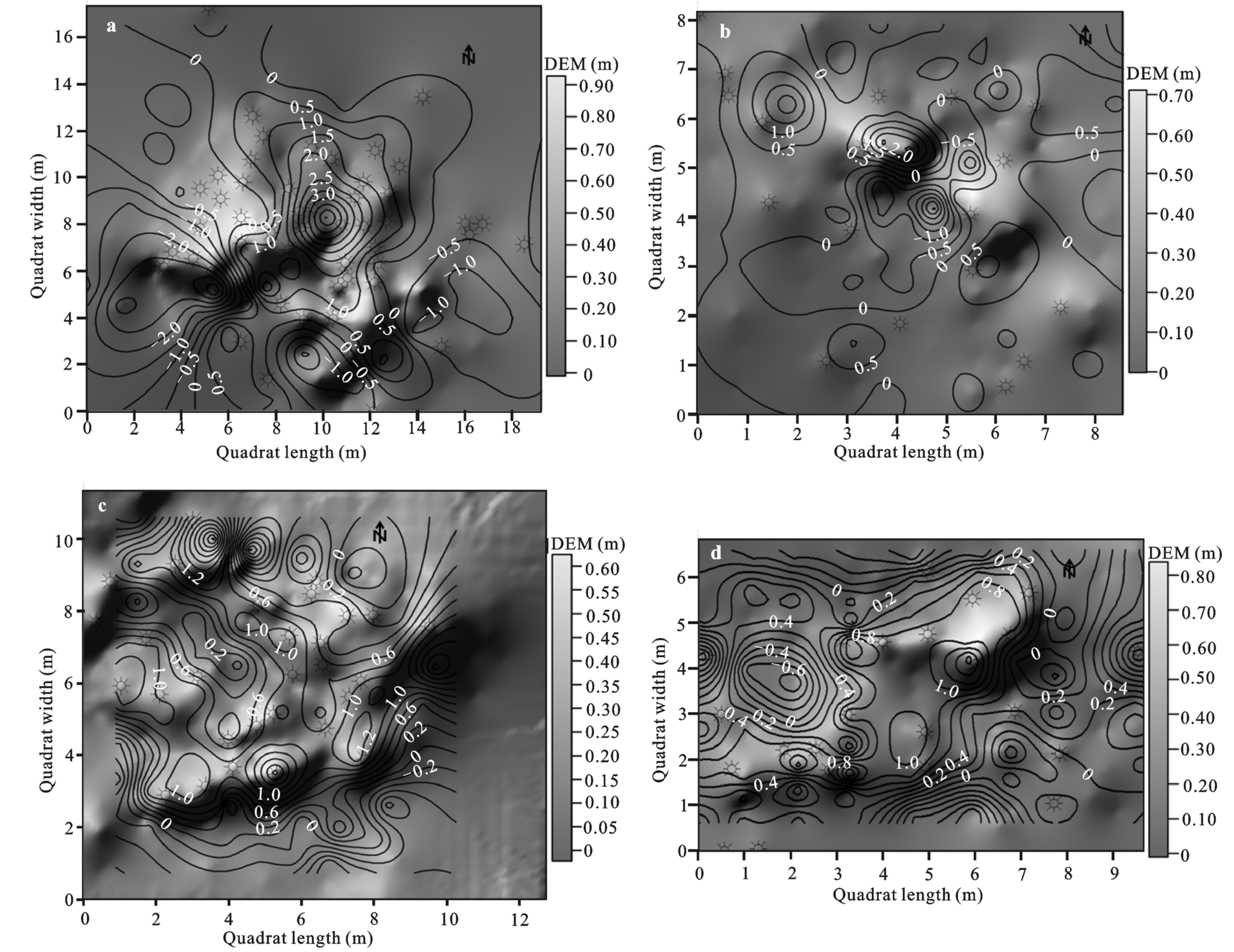

Fig. 14 Equal wind erosion lines based on digital elevation model maps on fixed sandy ground with different VC of 17.87% (a), 28.26% (b), 35.22% (c), 41.28% (d). ☼ symbol represents sites of vegetation roots. Curve lines represent equal wind erosion and deposition lines, unit: cm

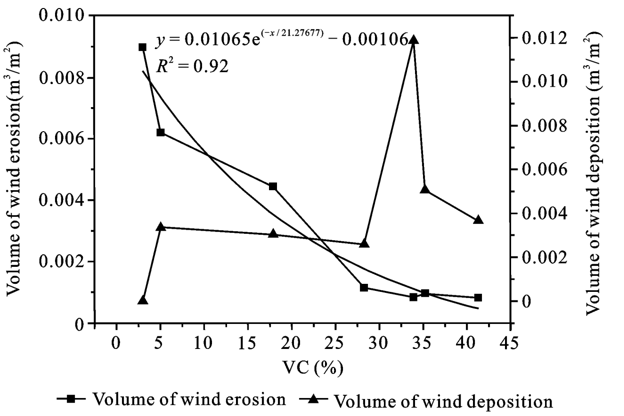

Fig. 15 Fitting functions between vegetation cover (VC) and volume of wind erosion and deposition per unit area

In previous work, the leeward slopes were found to have 29%–33% higher deposition rates than the windward slopes, the summits or plane positions on grazed and ungrazed ground on the Xilin Gol grassland, in Inner Mongolia (Hoffmann *et al.*, 2008), which is in agreement with this study. The ability to resist burial by sand of the dense *Tamarix* spp. shrubs on semi-fixed sandy ground was greater than other topography units, and therefore it revealed extensive wind deposition on the leeward slopes or lower levels of the *Tamarix* spp. nebkhas.

The underground water tables mainly control the plant community distribution on the Cele oasis-desert ecotone (Dai *et al.*, 2009). The distribution density of *Tamarix* spp. nebkhas on the semi-fixed sandy ground was greater than that on shifting sandy or fixed sandy ground. The efficiency of sand resistance of the *Tamarix* spp. was higher than that of the *Alhagi sparsifolia* and *Karelinia caspia* communities. *Tamarix* spp. can deposit more fine sand from the air flow, and the higher elevation created by the high *Tamarix* spp. nebkhas chains can deposit more blowing sand, in particular, on the leeward slope. Keiko and Satoshi (2007) concluded that a vegetation canopy with a low height, high density, and vegetation flexibility was effective in reducing the sand-transport rate. The branch flexibility of the *Tamarix* spp. shrubs is better than that of *Alhagi sparsifolia* and *Karelinia caspia* vegetation, and it can therefore accumulate more wind-blown sand within and around the canopy, which can change the surface topography of the semi-fixed sandy ground.

Katrin *et al*. (2013) concluded that in the low and medium-density canopies, sediment deposits were primarily found in the wake areas downstream of the tussocks. They overlapped with the adjacent downstream tussocks in the medium-density canopy, but not in the low-density canopy. In the high-density canopy, very few sand grains were entrained by the wind, and the deposited grains were evenly distributed within the disturbed zones surrounding the grass tussocks. The distribution density of plants is the most important factor influencing wind erosion, followed by plant height and width (Bressolier and Thomas, 1977). The conclusion of our field work concurs with the above views. However, the vegetation distribution patterns in the field were irregular compared with the designed orderly distribution patterns in the wind tunnel experiments. Wind erosion occurred mainly upwind or in lateral flanks of nebkhas, and bare sandy ground on the interdunes. Conversely, the dynamic annual change in total VC was inversely related to the amount of soil wind erosion (Zhao *et al*., 2005). Therefore, data on the vegetation flexibility and VC changes in different seasons for different plants in hyperarid lands are important to improve the research into sand fixation effects in the future. Further research is therefore needed on the topic of field-based wind power, and wind erosion and deposition, to understand this complex geomorphic component of the environment. Our findings suggest that better management practices to restore vegetation in the oasis-desert ecotone are required to reduce soil erosion and maintain the fragile sandy ground ecosystem of the oasis on margin of the Taklimakan Desert.

5 Conclusions

During one year of monitoring, the DP and RDP decreased significantly with increasing VC from an area of shifting sandy, to semi-fixed sandy, to fixed sandy ground. The sand transportation rate at the lower layer was less than that at the higher layer in sand-driving wind at the sites of fixed sandy ground or the oasis. Intense wind erosion is accompanied by fast movement of drifting sand dunes on the shifting sandy ground, and large blowing sand accumulates on and behind higher nebkhas slopes on semi-fixed sandy ground, slight wind erosion and deposition occurs on fixed sandy ground near the oasis. Furthermore, farmland reclamation can significantly accelerate the wind erosion process. There were no significant correlations among the average wind velocity above the threshold wind velocity and the volume of wind erosion and deposition and sand blown time on the surface of bare shifting sandy ground, however, there occurred significantly positive correlations among the average wind velocity above the threshold wind velocity and the volume of wind deposition, sand blown time and volume of wind deposition on the surface of fixed sandy ground. The wind erosion volume per unit area and VC follow a significant exponential function trend, while the wind deposition volume per area is closely linked with topographic changes, plant types, plant heights and arrangement patterns of vegetation apart from the VC in the field. Distribution density of *Tamarix* spp. shrubs should be enhanced near oasis, nets of shelter-forest system should be improved by utilizing different trees, shrubs and grasses.

Natural vegetation of the oasis-desert ecotone is very important, which is a matter of urgency to protect the ecotone land against excessive reclamation and abusive levels of grazing. VC should be increased using artificial (i.e., plants were irrigated by flood in summer or cultivated in evenly distribution in space) or natural measures mainly including improving soil moisture conditions in the oasis-desert ecotone to strengthen its ability to resist sand blowing, and ensure that the oasis on the southern margin of Tarim Basin is preserved.

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