Postprint of Field Observations on Aeolian Sand Flow Characteristics over Two Types of Gobi Surfaces

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Abstract

Analyzing the wind-sand flow structure and the relationship between friction velocity and sand transport rate on Gobi surfaces under vegetation cover and artificial disturbance is of great significance for protecting the ecological environment of Gobi regions. This study investigates Gobi surfaces under vegetation cover and Gobi surfaces after artificial vegetation removal, respectively. The results show that under different surface conditions, the variation trends of wind-sand flow structure are basically the same, which can be roughly divided into three categories: fluctuating decrease, increase followed by decrease, and monotonic decrease. The sand transport rate density of disturbed surfaces is greater than that of original surfaces. Friction velocity is divided into high and low wind speed regimes with 0.50 m · s^(-1) as the boundary. On surfaces under vegetation cover, there is no significant linear correlation between sand transport rate and friction velocity in either high or low wind speed regimes; whereas on surfaces after artificial vegetation removal, sand transport rate and friction velocity satisfy the traditional low-order polynomial relationship in the high wind speed regime, while there is no linear relationship between them in the low wind speed regime.

Full Text

Preamble

Field Observations of Wind-Drift Sand Flow Characteristics Over Two Gobi Surfaces

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Abstract

Analyzing the structure of wind-drift sand flow over Gobi surfaces and the relationship between friction velocity and sediment transport rate under vegetation cover and anthropogenic disturbance is crucial for ecological conservation in Gobi regions. This study investigates both naturally vegetated Gobi surfaces and surfaces where vegetation has been artificially removed. The results demonstrate that under different surface conditions, the variation trends of wind-drift sand flow structure are fundamentally similar and can be broadly categorized into three types: fluctuating decrease, initial increase followed by decrease, and monotonic decrease. The sediment transport rate density on disturbed surfaces exceeds that on pristine surfaces. Using $0.50\ \mathrm{m \cdot s^{-1}}$ as the threshold, friction velocity is divided into high and low wind speed regimes. On vegetated surfaces, no significant linear correlation exists between sediment transport rate and friction velocity in either regime. However, on surfaces where vegetation has been artificially cleared, the relationship in the high wind speed regime conforms to traditional low-order polynomial functions, while no linear relationship exists in the low wind speed regime.

Keywords: Gobi surface; wind-drift sand flow structure; sediment transport rate; friction velocity

Gobi, also known as "gravel desert," refers to a type of desert landscape distributed in arid or extremely arid regions with gravel-covered surfaces. Its natural characteristics include weak soil development, sparse vegetation cover, and highly unstable vesicular crusts on the surface layer [1]. In China, Gobi is concentrated in the Alxa Plateau, Hexi Corridor, Junggar Basin, and Tarim Basin, with a total area of approximately $5.695 \times 10^5\ \mathrm{km}^2$ [2]. Research on Gobi wind-drift sand is relatively limited compared to studies on shifting sand surfaces. The most distinctive feature of Gobi surface wind-drift sand flow structure is the "elephant trunk effect" [3], which occurs because the average saltation angle of sand particles over Gobi surfaces is generally larger than that over shifting sand surfaces. Wind speed, saltation angle, and particle size are all important factors influencing wind-drift sand flow structure [4]. Previous studies have explored core issues in aeolian physics, including Gobi surface wind-drift sand flow structure, wind velocity profiles, and the relationship between sediment transport rate and wind speed, primarily through wind tunnel experiments [2], [5] and field observations [6].

Wind tunnel experiments by Zhang Kecun et al. [7]–[9] indicate that aeolian sand activity is concentrated within 20 cm of the surface, with wind-drift sand flow exhibiting "elephant trunk effect" characteristics, and the height of maximum sand content shifting upward with increasing wind speed. Field observations by Liu Benli et al. [6] on natural Gobi surfaces atop the Mogao Grottoes show that during certain periods, wind-drift sand flow structure displays the same variation trend as shifting sand surfaces, while during other periods it exhibits "elephant trunk effect" characteristics. Comparative studies by Huang Cuihua et al. [10] on sand and gravel Gobi surfaces at Dunhuang Mogao Grottoes reveal significant differences: sand surfaces show exponentially decreasing sediment transport with height, whereas Gobi surfaces reach maximum transport at a certain height that increases with wind speed. Field observations by Wang Zhiqiang et al. [10] in the Lop Nur Gobi region of Xinjiang demonstrate that aeolian sand activity is mainly concentrated within 60 cm of the surface, with vertical distribution varying by particle size, and sediment transport rate following an exponential relationship with wind speed.

These findings reveal substantial discrepancies among existing Gobi surface wind-drift sand movement studies. Ideal wind tunnel simulations generally yield the "elephant trunk effect" [2]-[3], [8]-[9], with the height of maximum transport increasing with wind speed. Field observations have captured this pattern under certain wind speeds [3], [10], but under other conditions show trends identical to shifting sand surfaces [12]. In natural environments, complex and variable wind regimes, wide-ranging surface material compositions, and varying coverage of gravel and vegetation all represent important factors affecting Gobi wind-drift sand movement. This may explain why quantitative comparison among these results remains challenging. To deepen understanding of Gobi wind-drift sand movement patterns, strengthened field observations of various typical surfaces are necessary.

Unlike shifting sand surfaces, Gobi is a product of long-term wind erosion [13]. Recent field observations, wind tunnel experiments, and wind regime analyses indicate that extensive Gobi regions serve as important sediment sources for the Badain Jaran Desert and the Chinese Loess Plateau [14]. Therefore, wind erosion remains a crucial component of Gobi research. Current Gobi surface studies also focus on wind erosion, with different surface conditions producing varying erosion amounts. Meng Xiaonan et al. [15] analyzed surface dust emission concentrations based on vehicle compaction frequency, finding that more compaction leads to higher dust concentrations, demonstrating significant human impacts on Gobi surfaces and the need for protective measures to reduce wind erosion. Yin Daiying et al. [16] conducted wind tunnel experiments with varying degrees of Gobi surface disturbance, showing that greater disturbance leads to higher wind erosion. Gravel can reduce wind speed [17] and thus decrease erosion. Compared with bare surfaces, gravel-covered surfaces significantly reduce wind erosion, with gravel size also affecting erosion amounts [18]. However, research by Wang Xunming et al. [19] in the Gobi region of China and Mongolia contradicts traditional understanding, showing that in low gravel coverage areas, increased gravel coverage enhances wind erosion capacity. Vegetation also reduces wind erosion, with sediment transport rate decreasing significantly with height as vegetation coverage increases [20]. Clearly, research on fundamental Gobi wind-drift sand movement patterns will help determine wind erosion amounts and the roles of gravel and vegetation in erosion processes.

This study compares wind-drift sand flow structures through observations of vegetated and artificially de-vegetated Gobi surfaces, and explores the relationship between sediment transport rate and friction velocity, aiming to provide fundamental data support for soil erosion prevention in Gobi regions, enrich Gobi wind-drift sand research, and offer scientific basis for Gobi ecological conservation.

1.1 Study Area Overview

The study area is located at the westernmost end of the Hexi Corridor, at the intersection of Gansu, Qinghai, and Xinjiang provinces, bounded by the Dangjin Pass, adjacent to the Altun Mountains to the west and the Qilian Mountains to the east. The observation site belongs to Aksai County, Jiuquan City, Gansu Province, approximately 50 km southwest of Dunhuang City (Figure 1 [Figure 1: see original paper]). The region has a temperate continental arid climate with distinct variations in temperature and moisture, an average annual precipitation of approximately 40 mm concentrated in summer with large interannual variability, annual evaporation exceeding 2000 mm (far greater than precipitation), frequent strong winds, and recurrent dust storms. Prevailing winds are northwesterly [21]. In 2017, observations were conducted on two surface types: a naturally vegetated Gobi surface (Figure 1a) with surface materials primarily composed of coarse sand, fine sand, and minor silt (Table 1), sparsely covered with low vegetation; and an artificially de-vegetated surface in the same area (Figure 1b) where gravel content decreased, coarse sand content increased, fine sand content decreased, and silt and clay content increased due to anthropogenic disturbance, though the surface remained dominated by coarse and fine sand. Upwind of the prevailing wind direction, chemical materials were used for sand fixation, with sediment collectors and three-dimensional ultrasonic anemometers deployed for observations.

Figure 1 Study area overview

Table 1 Particle size distributions of two typical Gobi surfaces

Particle size	Mass percentage (%)
Vegetated surface (>2 mm) (0.2–2 mm) (0.02–0.2 mm) (0.002–0.02 mm) (<0.002 mm)	Non-vegetated surface

From March to May 2017, we completed site selection, clearing, instrument deployment, and systematic fieldwork for the Gobi observation field. To investigate variations in wind-drift sand flow structure and sediment transport rate with friction velocity, aeolian sand movement observations were conducted on the two Gobi surfaces from March 26 to April 16 and April 5 to May 2. The first observation period began at 18:00 on March 26 on the artificially de-vegetated Gobi surface, lasting 30 minutes with a corresponding friction velocity of 0.25 $\mathrm{m \cdot s^{-1}}$. The second period was conducted on the vegetated surface in the same area, beginning at 17:00 on April 5 with a duration of 37 minutes and a friction velocity of 0.40 $\mathrm{m \cdot s^{-1}}$. During each observation, wind direction remained relatively stable. Synchronous observations were conducted on both surfaces from April 5 to April 16 with approximately identical timing and duration. By May 2, a total of 89 observations had been completed, yielding 36 usable datasets due to natural conditions and human factors. Among these, 43 observations were conducted on the natural surface, producing 17 usable datasets, while 46 observations were conducted on the de-vegetated surface, producing 19 usable datasets.

Wind-drift sand flow structure refers to the distribution of transported sand particles with height within the transport layer. Following the concept of streamwise saltation flux density [22], sediment transport rate density is defined as the amount of sand passing through a unit area perpendicular to wind direction per unit time at a given height, with its height distribution representing wind-drift sand flow structure. Sediment transport rate is the mass of sand transported per unit time per unit width, representing surface transport capacity under specific wind and sand source conditions [5].

The novel flat-opening sediment collector used in the field maintains a vertical inlet relative to the ground. The collector has a total height of 0.85 m and a collection height of 0.6 m, consisting of a fixed base, front cover box, and sand collection boxes [23]. Each collector has 10 inlets with corresponding sand collection boxes at heights of 0.02, 0.12, 0.22, 0.32, 0.38, 0.44, 0.49, 0.53, 0.57, and 0.60 m [24]. The sand collection boxes are made of iron sheet, measuring 0.03 m in length and 0.015 m in width, with an area of 0.00045 $\mathrm{m^2}$.

Assuming a sand collection box at a certain height collects sand mass m during time period T, the sediment transport rate density q is calculated as:

$$q = \frac{m}{S \cdot T}$$

where S is the inlet area of the collection box. The resulting sediment transport rate density has units of $\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$. Ignoring sediment transport outside the observation range of the collector and assuming linear variation of transport rate density q with height between adjacent boxes, integration yields the sediment transport rate Q, with integration limits set at the minimum and maximum heights of the collection boxes. In practice, coefficients for the piecewise linear function are determined by endpoint transport rate densities. This method was applied to raw data to obtain sediment transport rates corresponding to different friction velocities under the two surface conditions. For convenience, sediment transport rate is expressed in units of $\mathrm{g \cdot m^{-1} \cdot s^{-1}}$.

Friction velocity was calculated from instantaneous velocity measurements recorded at 20 Hz by two ultrasonic anemometers at heights of 0.50 m and 1 m. Let the wind velocity components measured by the first anemometer be u_1, v_1, w_1; then instantaneous horizontal velocity is $U_1 = \surd(u_1{}^2 + v_1{}^2)$ and vertical velocity is $W_1 = w_1$. Fluctuating velocities are expressed as:

$$u' = u_1 - \overline{U_1}$$

$$w' = w_1 - \overline{W_1}$$

where $\overline{U_1}$ and $\overline{W_1}$ are mean horizontal and vertical velocities. In turbulent mixing length theory, friction velocity does not vary with height and can be expressed through fluctuating velocities as:

$$u_* = \sqrt{|\overline{u'w'}|}$$

The same method was used to calculate friction velocity from the second anemometer, with the two values averaged to obtain the friction velocity $U*$ for each observation period.

2.1.1 Wind-Drift Sand Flow Structure on Vegetated Surfaces

Given substantial differences in observed sediment transport rate densities, data were normalized to facilitate more intuitive representation of wind-drift sand flow structure, constraining dimensionless transport rate density values between 0 and 1 for each observation. Compared with raw data, this normalization did not substantially alter the variation trends of the structure curves. After normalization, collection box heights became 0.03, 0.20, 0.37, 0.53, 0.63, 0.73, 0.82, 0.88, 0.95, and 1. Based on curve variation trends, wind-drift sand flow structure can be divided into three categories: fluctuating decrease, initial increase followed by decrease, and monotonic decrease. Three typical structure curves were selected from each category for analysis.

As shown in Figure 2a [Figure 2: see original paper], on the vegetated surface at friction velocities of 0.31, 0.39, and 0.43 $\mathrm{m \cdot s^{-1}}$ with observation durations of 75, 12, and 18 minutes respectively, wind-drift sand flow structure exhibited a fluctuating decreasing trend. Maximum values occurred near the surface at 0.02 m, with overall decreasing transport rate density as height increased, though not monotonically. For example, at 0.43 $\mathrm{m \cdot s^{-1}}$, transport rate density decreased from 0.03–0.73, increased from 0.73–0.82, then decreased again, demonstrating fluctuating variation. Overall, at heights below 0.20, transport rate density at 0.31 $\mathrm{m \cdot s^{-1}}$ exceeded that at 0.39 $\mathrm{m \cdot s^{-1}}$, while from 0.20–0.53, the opposite occurred, with both velocities showing lower densities than at 0.43 $\mathrm{m \cdot s^{-1}}$. Above 0.63, transport rate density at 0.39 $\mathrm{m \cdot s^{-1}}$ exceeded the other two velocities, though generally, transport rate density correlated positively with wind speed.

At friction velocities of 0.52, 0.56, and 0.59 $\mathrm{m \cdot s^{-1}}$ with corresponding observation durations of 60, 13, and 5 minutes, wind-drift sand flow structure showed an initial increase followed by decrease, with maximum values at 0.20 (0.12 m height), followed by fluctuating decrease with height. At height 0.03, transport rate density ranked as $0.59 > 0.52 > 0.56$ $\mathrm{m \cdot s^{-1}}$, while at 0.20, densities were similar across the three velocities. At 0.37, density was highest at 0.56 $\mathrm{m \cdot s^{-1}}$ and lowest at 0.52 $\mathrm{m \cdot s^{-1}}$. Above 0.37, density was lowest at 0.59 $\mathrm{m \cdot s^{-1}}$. The short observation duration at this high velocity produced gust-like effects, preventing sand particles from ejecting additional grains to higher levels through impact, resulting in lower transport rate density at higher elevations.

At friction velocities of 0.38, 0.55, and 0.58 $\mathrm{m \cdot s^{-1}}$ with observation times of 20, 13, and 10 minutes, wind-drift sand flow structure showed monotonic decrease. At 0.38 $\mathrm{m \cdot s^{-1}}$, transport rate density was low with maximum values near the surface, decreasing with height though showing a slight bulge at 0.73, generally maintaining a monotonic decreasing trend. At 0.55 $\mathrm{m \cdot s^{1}}$, overall density exceeded that at 0.58 $\mathrm{m \cdot s^{-1}}$. Friction velocity is influenced by both instantaneous and mean velocities, which are affected not only by observation duration but also by field conditions. Within the 13-minute erosion period, increased instantaneous velocity mobilized more sand particles, increasing transport rate density.

2.1.2 Wind-Drift Sand Flow Structure on Non-Vegetated Surfaces

On artificially de-vegetated surfaces, wind-drift sand flow structure variation mirrors that of vegetated surfaces, also categorized into fluctuating decrease, initial increase followed by decrease, and monotonic decrease. As shown in Figure 2b, at friction velocities of 0.31, 0.40, and 0.56 $\mathrm{m \cdot s^{-1}}$ with observation durations of 75, 37, and 4 minutes, structure showed fluctuating decrease—overall decreasing transport rate density with height but increasing at certain levels. For instance, at 0.40 $\mathrm{m \cdot s^{-1}}$, density decreased from 0.03-0.20, increased from 0.20-0.53, decreased from 0.53-0.73, increased from 0.73-0.88, then decreased again, demonstrating a decrease-increase-decrease-increase-decrease pattern. At 0.40 $\mathrm{m \cdot s^{-1}}$, transport rate density only exceeded that at 0.31 $\mathrm{m \cdot s^{-1}}$ at height 0.37, being lower at other heights, while density at 0.56 $\mathrm{m \cdot s^{-1}}$ was generally higher.

In the initial-increase-then-decrease category, friction velocities of 0.39, 0.43, and 0.59 $\mathrm{m \cdot s^{-1}}$ corresponded to observation durations of 12, 18, and 5 minutes, showing initial increase followed by decrease. Near the surface, transport rate density was highest at 0.43 $\mathrm{m \cdot s^{-1}}$ and lowest at 0.59 $\mathrm{m \cdot s^{-1}}$, with peak values at 0.20 (0.12 m height), consistent with the "elephant trunk effect" characteristic of Gobi wind-drift sand flow. Above 0.20, density was highest at 0.59 $\mathrm{m \cdot s^{-1}}$ and lowest at 0.43 $\mathrm{m \cdot s^{-1}}$.

At friction velocities of 0.32, 0.35, and 0.49 $\mathrm{m \cdot s^{-1}}$ with observation times of 32, 36, and 34 minutes, structure showed monotonic decrease, with maximum transport rate density near the surface decreasing with height. Overall, in this category, density was highest at 0.32 $\mathrm{m \cdot s^{-1}}$, followed by 0.49 $\mathrm{m \cdot s^{-1}}$, and lowest at 0.35 $\mathrm{m \cdot s^{-1}}$. The described wind-drift sand flow structures show no clear relationship with wind speed. In fluctuating decrease and initial-increase-then-decrease categories, higher wind speeds produce greater transport rate densities, while in the monotonic decrease category, the lowest wind speed yields the highest density. Sediment transport rate density is influenced by both wind speed and sand supply availability. Gobi wind-drift sand flow characteristic values far exceeding 1 indicate that regardless of wind speed, the flow remains in an unsaturated transport state [3].

In summary, wind-drift sand flow structures under both surface conditions are complex, with generally similar variation trends that differ from the traditional “elephant trunk effect” characteristic of Gobi wind-drift sand flow. Structure variation at higher elevations is more pronounced on vegetated surfaces, likely due to higher particle rebound heights after being lofted. Gravel and vegetation coverage significantly increase surface roughness, enhance erosion resistance, reduce soil wind erosion, and can suppress dust events to some extent [25]. Given the complexity of field conditions, this description only outlines the basic characteristics of wind-drift sand flow structure in the study area; specific formation mechanisms require further investigation.

Figure 2 Aeolian sand structure on different surfaces

2.2 Relationship Between Friction Velocity and Sediment Transport Rate

Bagnold [26] proposed that sediment transport rate is proportional to the cube of wind speed exceeding the threshold velocity for particle entrainment. Numerous scholars have since modified Bagnold’ s theoretical formula while maintaining the cubic relationship with friction velocity. However, empirical relationships proposed by Qu Jianjun et al. [2] and Wang Zhiqiang et al. [10] for Gobi surfaces do not follow the cubic law. Field observations by Tan et al. [27] atop the Mogao Grottoes show that sediment transport rate and friction velocity can be described by Owen’ s (1964) saltation formula.

Figure 3 [Figure 3: see original paper] presents our field observation results. Under both surface conditions, sediment transport rate generally increases with friction velocity. As friction velocity increases, airflow transport capacity strengthens and surface erosion intensifies. On vegetated Gobi surfaces, particle movement is minimal at low friction velocities, while higher friction velocities enhance airflow transport capacity and mobilize more sand particles. After surface disturbance, sediment transport rate increases more rapidly with friction velocity than on pristine surfaces. Figure 3 shows that differences in transport rates between the two surfaces increase with friction velocity. The presence of low vegetation on the pristine surface increases aerodynamic roughness, altering wind intensity and suppressing wind erosion [28], resulting in generally lower transport rates than on disturbed surfaces.

Due to complex field conditions and relatively coarse measurement techniques, measured data show considerable scatter. Therefore, using 0.50 $\mathrm{m \cdot s^{-1}}$ as the boundary, low and high wind speed regimes were delineated for separate fitting analysis of friction velocity and sediment transport rate. Linear functions were used for low wind speed regimes, while traditional low-order polynomials were applied to high wind speed regimes. As shown in Figure 3a, on vegetated surfaces, overall fitting performance is poor with low correlation coefficients, though transport rate generally increases with wind speed, reaching a maximum of 4.637 $\mathrm{g \cdot m^{-1} \cdot s^{-1}}$ at 0.59 $\mathrm{m \cdot s^{-1}}$ and a minimum of 0.003 $\mathrm{g \cdot m^{-1} \cdot s^{-1}}$ at 0.15 $\mathrm{m \cdot s^{-1}}$, with an average of 0.47 $\mathrm{g \cdot m^{-1} \cdot s^{-1}}$. In Figure 3b, on disturbed surfaces, friction velocity and sediment transport rate in the high wind speed regime follow the traditional low-order polynomial relationship:

$$Q = a \cdot U_*^b$$

where Q is sediment transport rate, $U*$ is friction velocity, and a and b are fitting parameters (Figure 3). The correlation coefficient between friction velocity and sediment transport rate is relatively high, consistent with traditional low-order polynomial patterns. In the low wind speed regime, linear fitting shows low correlation but an overall increasing trend. The maximum value occurs at 0.45 $\mathrm{m \cdot s^{-1}}$ with a transport rate of 3.993 $\mathrm{g \cdot m^{-1} \cdot s^{-1}}$, while the minimum occurs at 0.31 $\mathrm{m \cdot s^{-1}}$ with 0.016 $\mathrm{g \cdot m^{-1} \cdot s^{-1}}$, averaging 0.75 $\mathrm{g \cdot m^{-1} \cdot s^{-1}}$. Intermittency is an inherent attribute of aeolian sand movement [29], particularly pronounced when sand supply is insufficient. Friction velocity and sediment transport rate measured by collectors represent time-averaged descriptions of aeolian sand movement, which may explain the poor correspondence in the low wind speed regime. At higher wind speeds, airflow energy is more readily transferred to surface particles through saltation, facilitating equilibrium between airborne and surface material exchange, thus making transport patterns more consistent with theoretically grounded low-order polynomial relationships.

Figure 3 The relationship between sediment transport rate and friction velocity

3.1 Wind-Drift Sand Flow Structure

Based on variation trends in wind-drift sand flow structure curves, three categories can be identified: fluctuating decrease, initial increase followed by decrease, and monotonic decrease. Only in the fluctuating decrease category on vegetated surfaces does sediment transport rate density show positive correlation with wind speed; under all other conditions, no direct relationship exists.

3.2 Relationship Between Friction Velocity and Sediment Transport Rate

Under different surface conditions, sediment transport rate generally increases with friction velocity. On vegetated surfaces, the relationship between friction velocity and sediment transport rate does not conform to traditional low-order polynomial patterns. After surface disturbance, no significant correlation exists in the low wind speed regime, while the high wind speed regime follows traditional low-order polynomial patterns with strong correlation.

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References

[1] Shen Yuanchun, Wang Xiuhong, Cheng Weiming, et al. Integrated physical regionalization of stony deserts in China[J]. Progress in Geography, 2016, 35(1): 57-66.

[2] Qu Jianjun, Zhang Kecun, Zhang Weimin, et al. Characteristics of sand-blown flow over simulated Gobi surfaces[J]. Journal of Desert Research, 2012, 32(2): 285-290.

[3] Qu Jianjun, Huang Ning, Tuo Wanquan, et al. Structural characteristics of Gobi sand-drift and its significance[J]. Advances in Earth Science, 2005, 20(1): 19-23.

[4] Zou Xueyong, Dong Guangrong, Wang Zhoulong. A study on some characteristics of drifting sand flux over Gobi[J]. Journal of Desert Research, 1995, 15(4): 368-373.

[5] Zhang Weimin, Wang Wanfu, Zhang Kecun, et al. Wind tunnel experiments on sand-laden wind structure and sand erosion-deposit budget over gravel bed under abundant and deficient sand supplies[J]. Journal of Desert Research, 2009, 29(6): 1015-1020.

[6] Liu Benli, Zhang Weimin, Liu Xiaoning, et al. Field measurements of sand transport rate change under easterly wind condition over Gobi land atop Mogao Grottoes[J]. Journal of Desert Research, 2010, 30(3): 516-521.

[7] Zhang Kecun, Qu Jianjun, Zu Ruiping, et al. Wind tunnel simulation about the effects of the different underlying surfaces on the features of drifting sand current[J]. Arid Land Geography, 2004, 27(3): 352-355.

[8] Zhang Kecun, Qu Jianjun, Zu Ruiping, et al. Research on the characteristics of structure of drifting sand flux and wind velocity profile over Gobi[J]. Research of Soil and Water Conservation, 2005, 12(1): 54-58.

[9] Zhang Kecun, Qu Jianjun, Zu Ruiping, et al. Research on the characteristics of sand-driving wind over Gobi/Mobile sand surface[J]. Journal of Arid Land Resources and Environment, 2008, 22(10): 55-59.

[10] Huang Cuihua, Wang Tao, Zhang Weimin, et al. Contrastive study on sand drift movement over sandland and gravel Gobi desert in extremely arid regions[J]. Arid Zone Research, 2007, 24(4): 556-562.

[11] Wang Zhiqiang, Huang Shengmin, Yu Tao, et al. Research on the characteristics of blowing sand drift over Gobi surface by field experiment[J]. Environment Protection of Xinjiang, 2010, 32(3): 10-13.

[12] Jiang Fuqiang, Li Ying, Li Kaichong, et al. Study on structural characteristics of Gobi wind sand flow in 100km wind area along Lan-Xin Railway[J]. Journal of the China Railway Society, 2010, 32(3): 105-110.

[13] Thomas David. Arid Zone Geomorphology: Process, Form and Change in Drylands (third edition)[M]. Oxford: A John Wiley & Sons, Ltd., Publication, 2011.

[14] Wang Xunming, Cai Diwen, Sun Jimin, et al. Contributions of modern Gobi desert to the Badain Jaran Desert and the Chinese Loess plateau[J]. Scientific Report, 2019, 9(1): 1-4.

[15] Meng Xiaonan, Yan Ping, Wang Zhenting, et al. Dust emission by vehicle crushing: Experiments on Gobi, Gansu, China[J]. Journal of Desert Research, 2019, 39(1): 80-87.

[16] Yin Daiying, Qu Jianjun, Zu Ruiping, et al. Impact of disturbing modes on amount of wind erosion of sandy Gobi[J]. Journal of Desert Research, 2014, 34(1): 1-8.

[17] Tan Lihai, Zhang Weimin, Liu Benli, et al. Simulation of wind velocity reduction effect of gravel beds in a mobile wind tunnel atop the Mogao Grottoes of Dunhuang, China[J]. Engineering Geology, 2013, 159: 67-75.

[18] Tan Lihai, Zhang Weimin, Qu Jianjun, et al. Aeolian sand transport over Gobi with different gravel coverages under limited sand supply: A mobile wind tunnel investigation[J]. Aeolian Research, 2013, 11: 67-74.

[19] Wang Xunming, Lang Lili, Hua Ting, et al. Gravel cover of Gobi desert and its significance for wind erosion: An experimental study[J]. Journal of Desert Research, 2013, 33(2): 313-319.

[20] Yu Peidong, Chen Yinping, Li Yuqiang, et al. Influence of vegetation coverage on sand flow structure and wind erosion yield with wind tunnel experiment as a case[J]. Journal of Desert Research, 2019, 39(5): 29-36.

[21] Ning Wenxiao, Huang Xiaoqi, Wang Xuesong, et al. Abrasion rates of ventifacts[J]. SN Applied Sciences, 2019, 1(8): 855.

[22] Shao Yaping. Physics and modeling of wind erosion (second edition)[M]. Dordrecht: Springer, 2008.

[23] Wang Rende, Li Qing, Chang Chunping, et al. Sampling efficiency of a new flat opening collector for particles with various sizes[J]. Journal of Desert Research, 2018, 38(4): 1-5.

[24] Liu Xuyang, Ning Wenxiao, Wang Zhenting. Aeolian sand structure at the brink of Barchans[J]. Journal of Desert Research, 2019, 39(6): 76-82.

[25] Li Kuan, Xiong Xin, Wang Haibing, et al. Spatial distribution and formation causes of frequent dust weather in West Inner Mongolia[J]. Arid Zone Research, 2019, 36(3): 657-663.

[26] Bagnold R. A. The Physics of Blown Sand and Desert Dunes[M]. New York: Dover Publications, INC., 1941.

[27] Tan Lihai, Zhang Weimin, Qu Jianjun, et al. Aeolian sediment transport over Gobi: Field studies atop the Mogao Grottoes, China[J]. Aeolian Research, 2016, 21: 53-60.

[28] Zhang Chunlai, Zou Xueyong, Dong Guangrong, et al. Wind tunnel studies on influences of vegetation on soil wind erosion[J]. Journal of Soil and Water Conservation, 2003, 17(3): 31-33.

[29] Wang Zhenting, Zhang Chunlai, Wang Hongtao. Intermittency of aeolian saltation[J]. The European Physical Journal E, 2014, 37(12): 126.

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