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The Spatial Variation of Aerodynamic Parameters and Wind Erosion Potential in Southwestern Tarim Basin from Shifting Desert to Oasis

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Abstract. The southwestern Tarim Basin of China is a primary wind erosion damage and environmental degradation region characterized by shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands. To determine their relative susceptibility to wind erosion under different land cover types, wind velocity profiles were measured and used to determine friction velocity (u_*) and aerodynamic roughness (z_0) of the four land cover types throughout the wind erosion season of 2010–2012. The erodible particles contents of surface soil mass were analyzed. The u_* averaged 0.33 ms^{-1} , 0.44 ms^{-1} , 0.61 ms^{-1} and 0.81 ms^{-1} , while z_0 averaged 0.39 mm, 13.58 mm, 39.51 mm and 310.8 mm for the shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands, respectively. The results showed that u_* and z_0 were both correlated with surface roughness properties of the underlying vegetation condition and z_0 decreases with increasing wind speed due to the near surface plant roughness properties and wind flow. The erodible particles content were 56.92%, 60.17%, 65.80% and 74.56% for the shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands, respectively. These results indicate that though the oasis farmlands have the largest erodible particles content but with the greatest u_* and z_0 , the dynamic wind conditions were not usually able to achieve by causing the dust emission. In contrast, the shifting sand dunes have the greatest potential for wind erosion due to lowest u_* and z_0 .

1. Introduction

Wind erosion is one of the geomorphology processes, also of the major reasons for land degradation, and mainly happens in the arid and semi-arid area [1, 2]. This has a negative impact on air quality, resulting in the detachment, transportation and re-deposition of soil particles. Wind erosion not only affects soil productivity, but also causes crop damage worldwide [3, 4].

Aeolian erosion occurs only when friction velocity (u_*) surpasses the threshold friction velocity. Threshold friction velocity was defined as the minimum u_* which the flow has sufficient energy to initiate particle movement from its resting position on the soil surface [2]. Friction velocity and



aerodynamic roughness (z_0) were affected by surface characteristics of windblown soils. Sharratt and Feng [5] report that u_* and z_0 were influenced by the types of tillage. They found that under cutter tillage has a greater u_* and z_0 than conventional tillage during the fallow phase of a wheat-fallow rotation due to the enhanced roughness of the soil surface created by the under cutting. The aerodynamic parameters were directly affected by the surface vegetation growth status. Vegetation can reduce wind speed and soil erodibility and has been shown to have the capacity to decrease soil loss by wind [6]. Lancaster & Baas [7] found that vegetation increases both aerodynamic roughness length and threshold wind shear velocity. He & Li [8] observed the effects of vegetation on wind breaking and dune fixation in Horqin Sand dunes in northeast China and found that vegetation can efficiently absorb momentum, thereby reducing ground sand activities and preventing sand movement.

Friction velocity is a parameter used to describe the shear stress near the surface. Shear stress, or the stress exerted on the surface by wind shear, is influenced by winds and surface roughness [9]. The flux of windblown dust is dependent on u_* with greater fluxes and u_* would be higher. Zhu and Zhang [10] point out that the dust concentration was low during the pre-emission period of a dust storm event, and the rapid increased of u_* provides favorable dynamic conditions for dust emission.

Aerodynamic roughness can be used as an integrative and fundamental parameter influencing wind erosion, which is critical in calculation of u_* and erosion thresholds [11, 12]. Aerodynamic roughness length was used for scaling the wind momentum consumption caused by surface roughness [13] and can therefore be used as an integrative and fundamental parameter influencing wind erosion which is critical in calculation of u_* and erosion thresholds [11, 12]. Raupach [14] demonstrated that the attenuation effect of roughness on erosion is closely related to momentum absorption by roughness.

Tarim Basin in northwestern China is one of the primary dust sources in arid and semiarid regions of the world. The study area, which is located in the southwestern margin of Tarim Basin at the edge of the Taklimakan Desert, is very susceptible to wind erosion. From the desert to oasis, there were four typical surface covers from shifting sand dunes, semi-sifting sand dunes, fixed sand dunes and oasis farmlands. Few studies have investigated the aerodynamic characteristics of oasis farmland crops in China, and no studies have examined u_* and z_0 of the consecutive desert landscapes in the Tarim Basin. Therefore, this study was conducted to analyze the vegetation parameters changes with time in responding to changes in u_* and z_0 , and the erodible particles contents of surface soil mass. In order to evaluate u_* and z_0 of different surface covers and determine their relative susceptibility to wind erosion. The results of this study will help provide a theoretical basis for reasonable exploitation and management of land in the southwestern margin of Tarim Basin.

2. Methods and materials

2.1. Study area

The study area was near the Qira National Field Research Station for Desert Steppe Ecosystems, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, and located in southwestern margin of Tarim Basin, Xinjiang Province, China (Figure. 1). The study area is extremely dry, with an annual average precipitation of 35.1 mm and an evaporation rate of 2600 mm [15]. The temperature of the study area ranges from 41.98°C in summer to -23.98°C in winter. The annual average wind speed is 2.8 ms⁻¹, and the prevailing winds are out of the west.

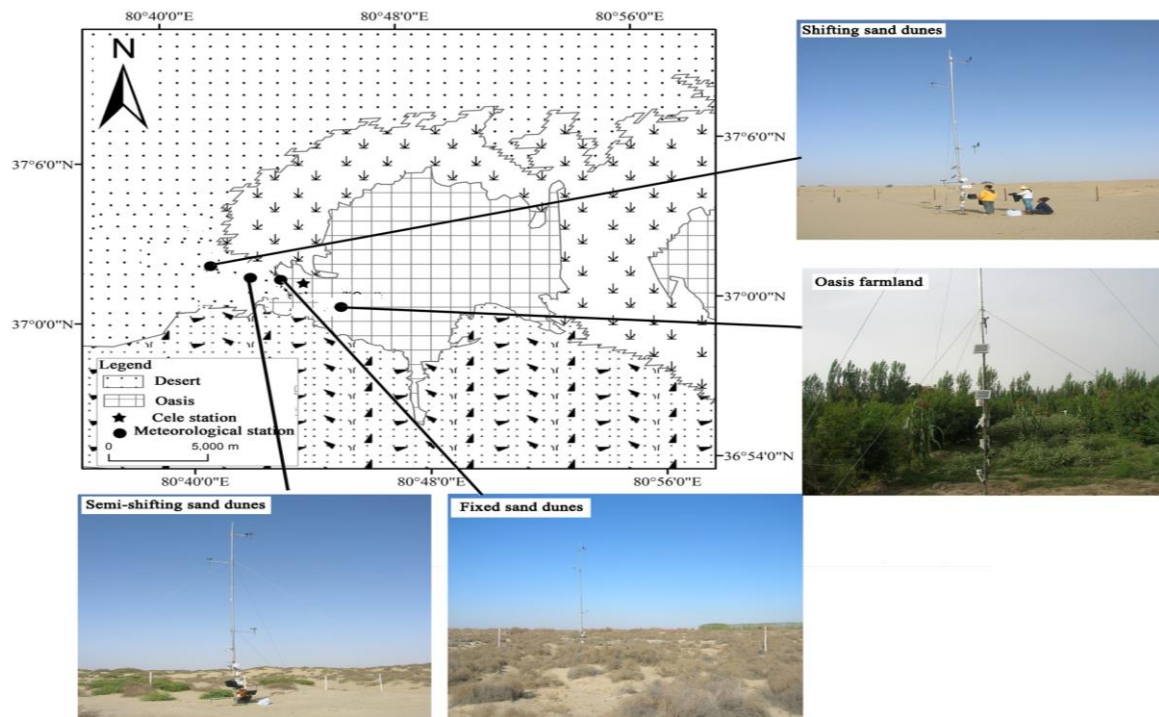


Figure 1. Location of the experimental sites

2.2. Experimental design

The land cover types of the study area, which were assessed by Mu [16] and Mao [17], consisted of shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands. The locations of the four sites are shown in Figure. 1 and a brief description of the four land cover types was provided in Table 1. We examined u^* and z_0 for the four sites from March to October of 2010 to 2012. All sites were equipped with an automatic meteorological station to observe wind speed and air temperature at heights of 1, 2, 4, 8, and 10 m. Wind velocity was measured using three-cup anemometers (S-WSA-M003, ONSET), while air temperature was measured using thermistors (S-TMB-M006, ONSET). The data collection instrument was a datalogger (U30-NRC, ONSET) that recorded data every minute.

Table 1. Description of the four experimental sites

Land types	Location	Elevation	Details
Shifting sand dunes	37°02'37"N 80°40'53"E	1339 m	The experiment site was located at the southern edge of the Taklimakan Desert and had sparse vegetation cover. The major type of vegetation was branchy tamarisk
Semi-shifting sand dunes	37°01'47"N, 80°42'32"E	1352 m	The semi-shifting sand dunes had sparse vegetation cover. The major type of vegetation was branchy tamarisk
Fixed sand dunes	37°01'20"N 80°43'25"E	1356 m	The fixed sand dunes is dominated by shrub and sub-shrub
Oasis farmland	37°00'12.55"N 80°45'23.65"E	1371 m	The Oasis farmland site is covered by perennial herb and bush

2.3. Evaluation of u^* and z_0

Friction velocity (u^*) and aerodynamic roughness (z_0) were assessed from the wind speed profile measured during high wind events. Assessments were made at a height of 3 m when wind speeds were

greater than 6.0 ms^{-1} and the winds were from the prevailing wind direction [5, 18]. Fetch was unlimited in the shifting sand dune and semi-shifting sand dunes, while it varied from 3 to 5 km in fixed sand dunes and from 5 to 10 km in oasis farmlands under prevailing winds.

Campbell & Norman [1] pointed out that airflow within the internal boundary layer was considered to be entirely in accordance with the new surface and can be described by a log wind velocity profile:

$$u_z = \frac{u_*}{k} \ln\left(\frac{z-d}{z_0}\right) \quad (1)$$

Where u_z is the wind speed (ms^{-1}) at height z (m), k is von Karman's constant (0.4), z_0 is the roughness parameter of the underlying surface (m), and d is the zero plane displacement (m). U_* and z_0 were calculated by linear regressions of log linear plots of $(z-d)$ versus u_z according to Eq. (1). Wind speed measured at five heights (1, 2, 4, 8 and 10 m) above the soil surface provided a goodness of fit ($R^2 > 0.95$), which made the measurements within the boundary layer.

Zero plane displacement d is a major parameter that indicates the absorption of momentum at the mean level of individual roughness elements [19]. The d was originally estimated by a function of roughness element height (h) according to Stanhill [20]:

$$\log_{10} d = 0.979 \log_{10} h - 0.154 \quad (2)$$

Where h is the roughness element height (m). Roughness element height was estimated as the average vegetation height. Final estimation of d was obtained by adjusting the value of d to reach the best fit of the relationship between $\ln(z-d)$ and u_z ; d corresponded to the value that maximized R^2 of the relationship. The z_0 was then achieved as the intercept of the $\ln(z-d)$ versus $u(z)$ relationship [1].

To estimate u_* and z_0 in Eq. (1), neutral atmospheric stability was required. Oke [33] indicated that neutral stability only existed during high winds. In the present study, neutral atmospheric stability was verified using Richardson's number [1]:

$$Ri = \left(\frac{(g/T)(\partial T / \partial z)}{(\partial u / \partial z)^2} \right) \quad (3)$$

Where Ri is Richardson's number, g is the gravitational constant (9.8 ms^{-2}), and T is air temperature (K). ∂T And ∂u are the variations in temperature (K) and wind speed (ms^{-1}), respectively, with height ∂z (m). Neutral stability was determined based on Thom [21] as the Ri was between -0.01 and 0.01 .

3. Result and discussion

3.1. Zero plane displacement

Zero plane displacement is an important aerodynamic parameter that defines the height at which momentum is absorbed by tall vegetation. Thom [19] proposed that d is the mean level of momentum absorption by a rough surface. Molion & Moore [22] demonstrated that the value of d may have a significant impact on flux-profile relations and stability functions. When compared with other sites, little or no roughness elements were available to absorb momentum of shifting sand dunes and semi-shifting sand dunes. Thus, d was estimated to be 0 m from our best fit analysis of $\ln(z-d)$ versus $u(z)$. The average zero plane displacements of fixed sand dunes and oasis farmlands were 0.300 (SD=0.0453) and 0.535m (SD= 0.0721) in 2011, while they were 0.325 (SD= 0.0933) and 0.519 m

(SD= 0.0524) in 2012, respectively. As vegetation condition changes, the variation of d could be described as a unimodal curve that first increased, then decreased. In fixed sand dunes, the d reached the maximum values on 18 June (day 170) in 2011 and 22 July (day 193) in 2012 while the average vegetation height and coverage was 1.5 m and 1.6 m and 26% and 25% on 29 June (day 179) in 2011 and 27 July (day 191) in 2012). In oasis farm land, the maximum d values were observed on 25 June (day 177) in 2011 and 25 July (day 193) in 2012, while the average vegetation height and coverage were 2.5 m and 2.7 m and 68% and 70% on 29 June (day 179) in 2011 and 27 July (day 191) in 2012, respectively. After peaking, d decreased; however, in fixed sand dunes the vegetation height and coverage decreased to 1.3 m and 1.2 m and 22% and 20%, while they decreased to 2.1 m and 2.3m and 62% and 64% in oasis farmlands on 25 September (day 268) in 2011 and 20 September (day 263) in 2012, respectively (Table. 2).

Table 2. Vegetation characteristics at four sites

Surface cover types	Vegetation types	Vegetation composition	Vegetation height (m)		Vegetation coverage (%)		
			2011	2012	2011	2012	
			Day 79 164 268	79 164 268	83 171 263	83 171 263	
Shifting sand dunes	Tamarix ramosissima	Shrub	0.9 1.1 1.2	1.2 1.1 1.1	0.41 0.51 0.44	0.35 0.55 0.51	
Semi-shifting sand dunes	Tamarix ramosissima		1.1 1.2 1.1	1.1 1.1 1.2	3.2 4.1 3.8	4.1 5.6 4.8	
Fixed sand dunes	Tamarix ramosissima Alhagi sparsifolia Karelinia caspica			1.2 1.6 1.2	20 26 22	19 25 20	
Oasis farmlands	Pomegranate Crops Jujube	Perennials Herb bush	Shrub sub-shrubs	2.4 2.7 2.3	53 68 62	55 70 64	

The results show that there was an obvious variation between vegetation status (e.g., vegetation height and coverage) and d in the fixed sand dunes and oasis farmlands. That is, high vegetation or coverage has a larger zero plane displacement. These findings indicated that vegetation height and coverage critically affects d . Dong [23] reported that there was a positive correlation between displacement height, with both height and density of standing vegetation. However, for very short (height < 0.05 m) and sparse vegetation (density < 800 stems m⁻²), there was no displacement height. Within withered shrubs (such as Alhagi sparsifolia and Tamarix ramosissima) in the fixed sand dunes prior to the vegetation turning green likely influenced d , causing the minimum value of 0.24 m in March rather than 0 m. For the oasis farmlands, the d value ranged from 0.41 to 0.58 m with a mean value of 0.56 m (Figure. 2). The d value showed similar variation as that of the fixed sand dune, but zero plane displacement was higher than for the fixed sand dune. One explanation for the higher d value is that the oasis farmlands have high roughness elements, while the fixed sand dune only has low roughness elements (Table. 2). Crawley [24] indicated that vegetation at the surface increases the total drag and provides a degree of shelter that results in reduced surface shear stress, and Morris [25] pointed out that, as the roughness elements tightly packed the flow resistance in skimming flow will be enhanced.

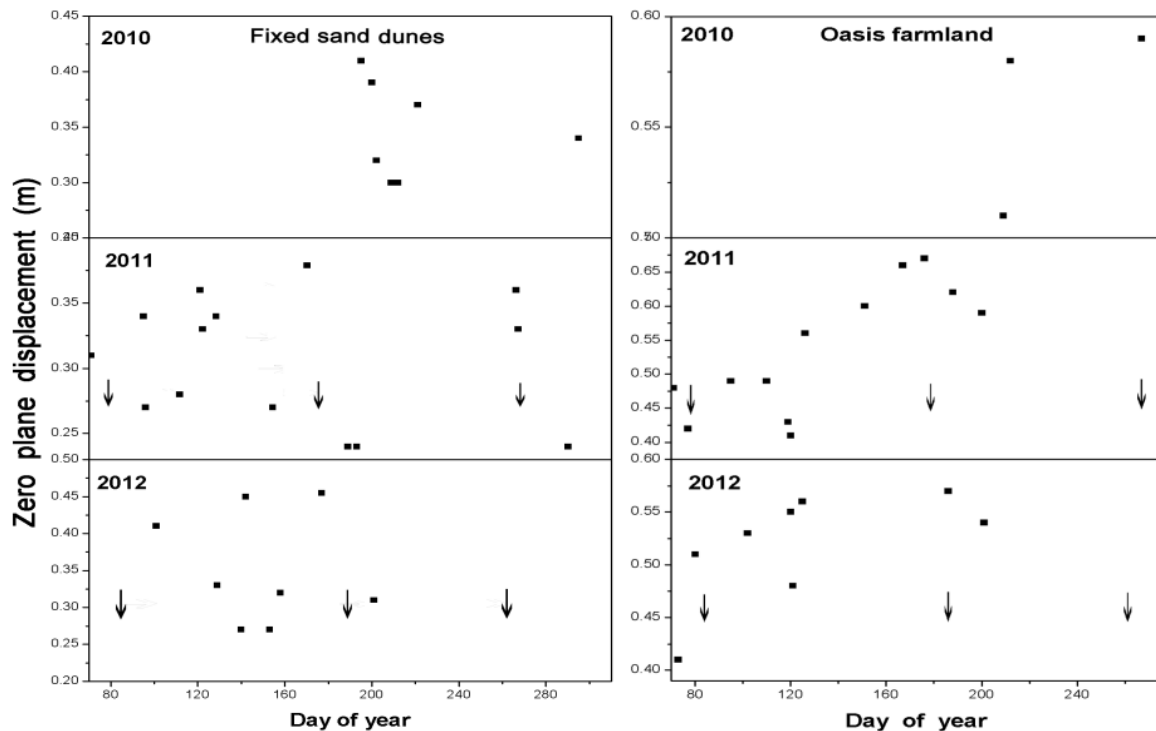


Figure 2. Zero plane displacement for fixed sand dunes and oasis farmlands sites during high wind events from 2010 to 2012. The arrows indicate dates of measuring vegetation parameters.

3.2. Friction velocity

Friction velocity ranged from 0.23 to 0.43 ms^{-1} for the shifting sand dune, from 0.33 to 0.64 ms^{-1} for the semi-shifting sand dune, from 0.43 to 0.78 ms^{-1} for the fixed sand dune and from 0.63 to 0.98 ms^{-1} for the oasis farmlands across all high wind events observed in this study (Figure. 3). The oasis farmlands had the highest u_* , while the shifting sand dune had the lowest. These values, which were significantly different at $P < 0.05$, which likely reflects differences in the roughness characteristics of the two sites, with the oasis farmlands having relatively tall vegetation oriented in wide rows, while the shifting sand dunes have sparse and short vegetation (Table. 2).

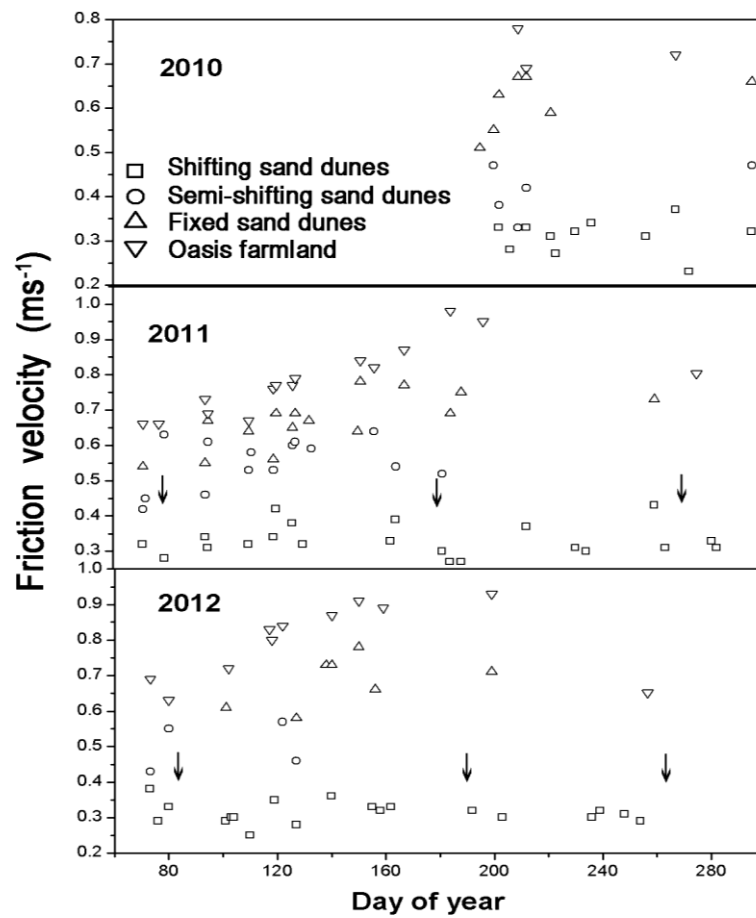


Figure 3. Friction velocity for the shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands sites during high wind events in 2010 to 2012. The arrows indicate dates of measuring vegetation parameters.

Figure. 4 shows that high vegetation has larger u_* and the difference between the four land cover types are significant and reaching a stable order of magnitude. According to Monin-Obukhov similarity theory [26]:

$$z_0 = (z-d) \cdot e^{\frac{-ku}{u_*}} \quad (4)$$

$$\frac{u}{u_*} = C_D^{1/2} \quad (5)$$

Where, C_D is the drag coefficient. Eq (4) and Eq (5) indicated that, as the drag coefficient increased, z_0 increased, and the increase of z_0 indicates an increase of resistance and therefore increased friction and u_* .

Copeland [27] reported that intensive roughness caused by non-erodible elements lying on the soil surface resulted in a higher u_* relative to bare soil. Lyles [28] pointed out that non-erodible elements played a protective role in the soil erosion process, because of the assimilation of segmental overall wind drag and reducing drag on erodible particles. The shifting sand dunes generally had little or no vegetation cover, which contributed to the lowest u_* . In contrast, the oasis farmlands had the highest u_* , which may have been due to enhanced surface friction caused by the porous structure of the vegetation

canopy and the semi-shifting sand dunes and fixed sand dunes had a low u_* , which was likely caused by relatively sparse and low vegetation at the soil surface (Table. 2).

In the southwestern margin of the Tarim Basin, the first high wind event often occurs in mid-March. The u_* values of shifting, semi-shifting and fixed sand dunes in 2011 (Figure. 3) appeared anomalous for 20 March (day 79). These extreme u_* values (0.36 ms^{-1} for shifting sand dunes; 0.53 ms^{-1} for semi-shifting sand dunes and 0.62 ms^{-1} for fixed sand dunes) determined by the wind velocity profile data including the highest velocities (mean velocity at 10 m height = 9.52 ms^{-1} , 7.61 ms^{-1} and 7.23 ms^{-1} during the event, respectively) of all events in 2011. After the anomalous variation (days 72) in 2011, the u_* values of the semi-shifting sand dunes, fixed sand dunes and oasis farmlands appeared to increase with time, but that of the shifting sand dunes remained about the same.

Friction velocity of shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands in 2012 was high for 14 March (day 73) during the first high wind event. The anomalous u_* (0.38 ms^{-1} , 0.53 ms^{-1} , 0.62 ms^{-1} and 0.69 ms^{-1} for shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands, respectively), which was in accordance with high wind speeds (mean wind speed at 10 m = 9.72 ms^{-1} , 9.47 ms^{-1} , 8.2 ms^{-1} and 7.01 ms^{-1} , respectively) observed across the first high wind event in 2012. After the first high wind event, u_* seemed to increase with time, and the increase in u_* with time after the first high wind event was probably because of sustained growth of the vegetation and variations in mean wind velocity across high wind events.

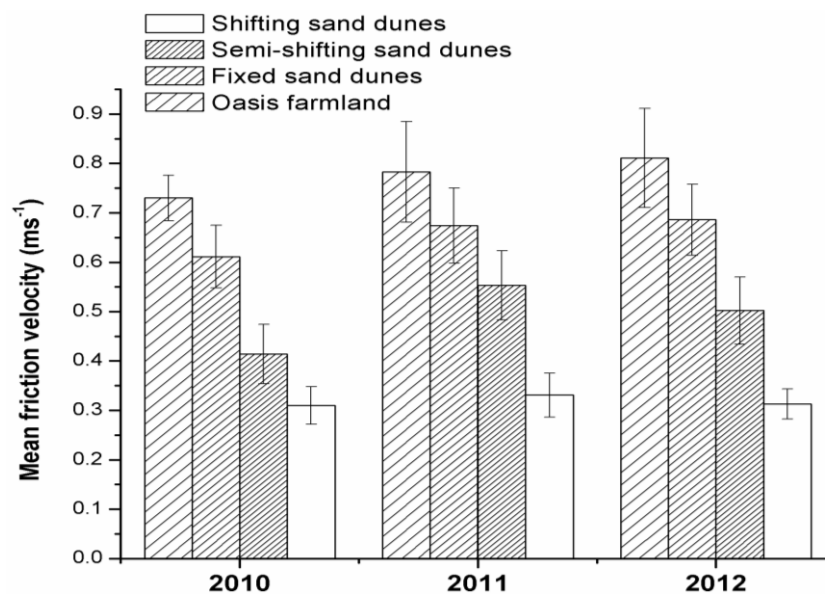


Figure 4. Comparison of mean friction velocity u_* and their standard deviations for shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmland.

3.3. Aerodynamic roughness

The z_0 ranged from 0.12 to 1.37 mm for the shifting sand dune, from 6.92 to 23.72 mm for the semi-shifting sand dune, from 14.8 to 106.8 mm for the fixed sand dune and from 189.6 to 633.8 mm for the oasis farmlands (Figure. 5).

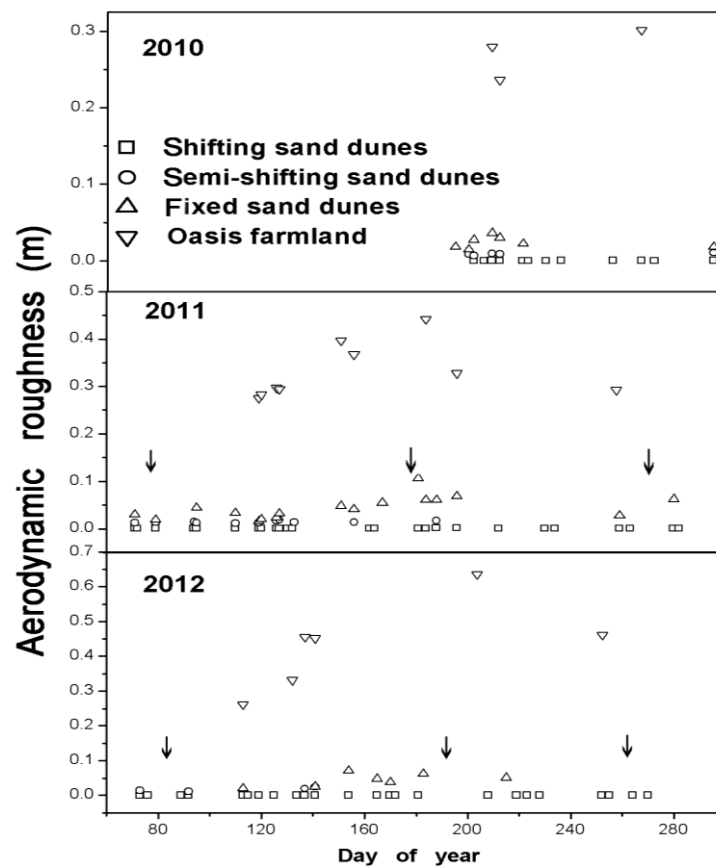


Figure 5. The value of z_0 for the shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands sites during high wind events in 2010 to 2012. The arrows indicate dates of measuring vegetation parameters.

Previous studies have shown that vegetation canopy height and vegetation coverage play important roles in aerodynamic roughness. Counihan [29] reported that z_0 was related to both canopy height and vegetation coverage, with $z_0 = (1.08V_c - 0.08)h$, where V_c is vegetation coverage and h is canopy height in m. In this study, the oasis farmlands had the highest z_0 , while the shifting sand dunes had the lowest. As shown in Fig. 5 and Table 2, the maximum z_0 in oasis farmlands was attained on 9 July (day 188) in 2011 and 20 July (day 199) in 2012, at which time the average vegetation height and coverage was 2.5 m and 2.7 m and 68% and 70% (29 June (day 179) in 2011 and 27 July (day 191) in 2012, respectively. As z_0 decreased, the vegetation height and coverage was 2.1 m and 2.3 m and 62% and 64% on 25 September (day 268) in 2011 and 20 September (day 263) in 2012, respectively.

Raupach [30] reported that the roughness function is equal to zero for a smooth wall and increases with aerodynamic wall roughness. Xue [31] calculated z_0 for three Gobi desert surfaces in northern China and found that it ranged from 0.3 to 1.9 mm, which was similar to the results observed for the shifting sand dunes in the present study. Kenneth [32] reported that the z_0 values for three semi-desert shrub communities ranged from 0.01 to 0.07 m in south-central Wyoming, USA, which was comparable to the fixed sand dunes in the present study. Oke [33] found that z_0 ranged between 1 and 10 mm for areas in which the soil is level and bare, which were concordant with the values observed for shifting sand dunes in the present study. Zhou [34] indicated that, with the increase of drag coefficient, the resistance increased, leading to an increase of z_0 . Lv & Dong [35] reported that a higher wind velocity was associated with greater turbulence and lower z_0 . The results of our study are consistent with those of previous investigations. Schmid & Bunzli [36] and Zilitinkevich [37] found

that wind flow also had an obvious influence on the magnitude of z_0 for the vegetation surface. Because the surface downward momentum transmission processes play an important role in controlling the ability of surface roughness elements to absorb momentum [19]. Zhang [38] indicated that this ability is related to air pressure and influenced by the interaction between near-surface wind flow and roughness elements. Toure [39] pointed out that the potential for wind erosion decreases for aerodynamically-rougher surfaces. The results of the present study indicate that z_0 is correlated with the surface roughness properties of the underlying vegetation conditions (e.g., vegetation height), and decrease with increases in wind speed.

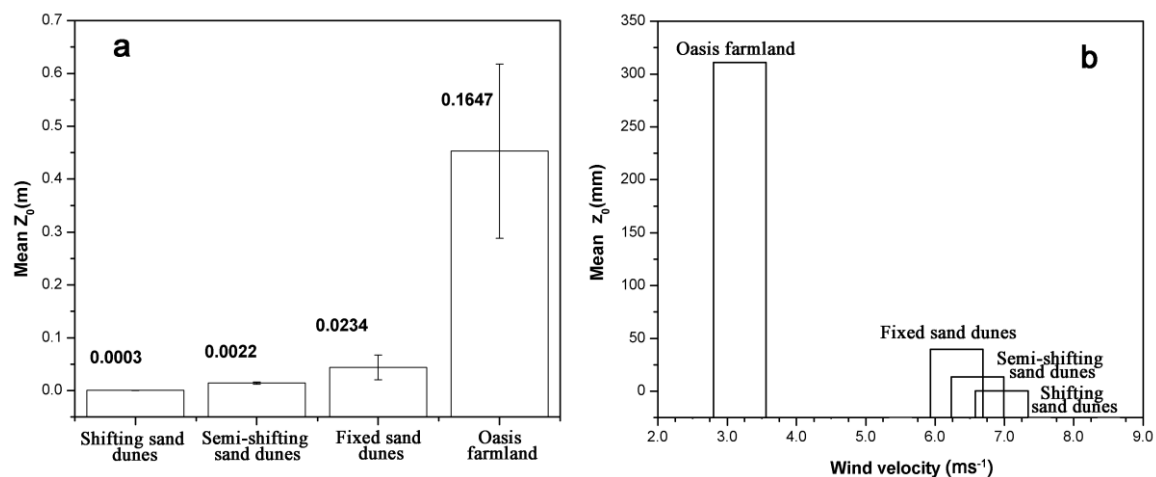


Figure 6. Comparison of mean z_0 and their SD values (a); the mean z_0 at different wind velocity for shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands (b).

4. Conclusion

Tarim Basin in northwestern China is a primary site of wind erosion damage and environmental degradation that is mainly underlain by shifting sand dunes, semi-shifting sand dunes, fixed sand dunes and oasis farmlands. This study is the first to quantify the effects of the consecutive desert landscapes in the Tarim Basin on aerodynamic parameters. Friction velocity and z_0 are both correlated with surface roughness properties of the underlying vegetation condition (e.g., vegetation height and vegetation coverage), while z_0 decreases with increasing wind speed. Moreover, the value of u^* and z_0 during high wind events was lower in early vegetation growth stages and higher in later vegetation growth stages. The u^* and z_0 were always highest in the oasis farmlands and lowest in shifting sand dunes. Since dust emission is related to the percentage of erodible particles content, the oasis farmlands are expected to have the lowest potential, while the shifting sand dunes are expected to have the highest potential for wind erosion among the four investigated land cover types.

Acknowledgments

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