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Effects of aeolian processes on nutrient loss from surface soils and their significance for sandy desertification in Mu Us Desert, China: a wind tunnel approach

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Abstract: Mu Us Desert, a region with high aeolian activity, is at extremely high risk of sandy desertification. Using surface soil samples collected from Mu Us Desert of northern China, we evaluated the effects of aeolian processes on nutrient loss from surface soils by employing wind tunnel experiments. The experiments were conducted using free-stream wind velocities of 14, 16, 18 and 22 m/s. Our results showed that the fine particles (<50 μm in diameter; 12.28% of all transported materials) carrying large nutrient loadings were exported outside the study area by aeolian processes. After the erodible fine particles were transported away from the soil surfaces at low wind velocity (i.e. 14 m/s), the following relatively high wind velocity (i.e. 22 m/s) did not have any significant effect on nutrient export, because the coefficients of variation for soil organic matter, total phosphorus, total nitrogen and available potassium were usually <5%. Our experimental results confirmed that aeolian processes result in a large amount of nutrient export, and consequently increase the risk of sandy desertification in arid and semi-arid ecosystems.

Keywords: sandy desertification; aeolian activity; soil nutrients; Mu Us Desert

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In China, 'aeolian desertification' or 'sandy desertification' (Wang, 2013a), a type of vegetation loss that is characterized by the appearance of degraded land, mainly occurs at the margins of mobile sandy deserts, sandy lands, cultivated grasslands, steppes and gobi deserts (Huang et al., 2001; Li et al., 2005; Wang et al., 2005a, 2007, 2008a; Hoffmann et al., 2011). In these areas, aeolian processes erode surface sediments (Shao, 2008) and result in spatial heterogeneity of surface soils (Okin and Gillette, 2001), and are also the key abiotic mechanism for soil nutrient export (Schlesinger et al., 1990; Schlesinger and Pilmanis, 1998; Okin et al., 2009). Along with aeolian processes, the risk of sandy desertification also increases in mobile sandy deserts and sandy lands of various arid, semi-arid and some semi-humid regions (Zhang et al., 2003; Wang et al., 2008b; Shao et al., 2011). During aeolian processes, the coarse particles (>50 μm in diameter) travel short distances and may increase the heterogeneity of soil resources at landscape scale, producing 'islands of fertility' (Garner and Steinberger, 1989; Field et al., 2012); however, large quantities of fine particles (<50 μm in diameter) with abundant nutrients are exported (Zobeck et al., 1989; Leys and McTainsh, 1994). Over recent decades, simulations and field experiments have indicated a close relationship

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between the spatial heterogeneity of soil resources and aeolian processes (Schlesinger and Pilmanis, 1998; Ravi et al., 2009). Although the ecological effects of aeolian inputs on steppe and fynbos ecosystems in Africa have been evaluated (Reynolds et al., 2001; Soderberg and Compton, 2007; Okin et al., 2008), the loss of nutrients from surface soils in arid and semi-arid regions of China remains poorly understood.

In arid and semi-arid regions of China, sandy desertification is closely associated with aeolian processes (Wang et al., 2005a, 2007). At the landscape scale, there has been a decrease in the area of steppe vegetation, which included high-grade forage has been replaced by low-grade grassland vegetation and anchored dunes have become semi-anchored or mobile dunes (Wang et al., 2006). Although nutrient loss resulting from surface sediment export is the key mechanism of land degradation during the sandy desertification process (Schlesinger et al., 1990; Dong et al., 1995; Li et al., 2010; Field et al., 2012), its quantification and contribution to sandy desertification in arid, semi-arid and some semi-humid regions of China remains poorly understood. In addition, studies on nutrient loss associated with land degradation have been widely conducted at the landscape scale using field observations (e.g. Larney et al., 1998; Hobbs and Harris, 2001; Li et al., 2007, 2008; Okin et al., 2009), but few studies have attempted to employ a wind tunnel to investigate soil nutrient loss under different soil and wind regimes. Therefore, in this study we employed wind tunnel experiments to analyze nutrient loss from collected soil samples in the Mu Us Desert and the redistribution of nutrients under various stresses caused by aeolian processes.

1 Study area

The study area (37°49'–38°05'N, 106°59'–107°35'E; 1,320–1,470 m asl; Fig. 1) is located in the Mu Us Desert, which has been identified as a region with high aeolian activity and is at extremely high risk of sandy desertification (Middleton and Thomas, 1992; Wang et al., 2005b). Details of the regional environment have been described by Wang et al. (2013b). The

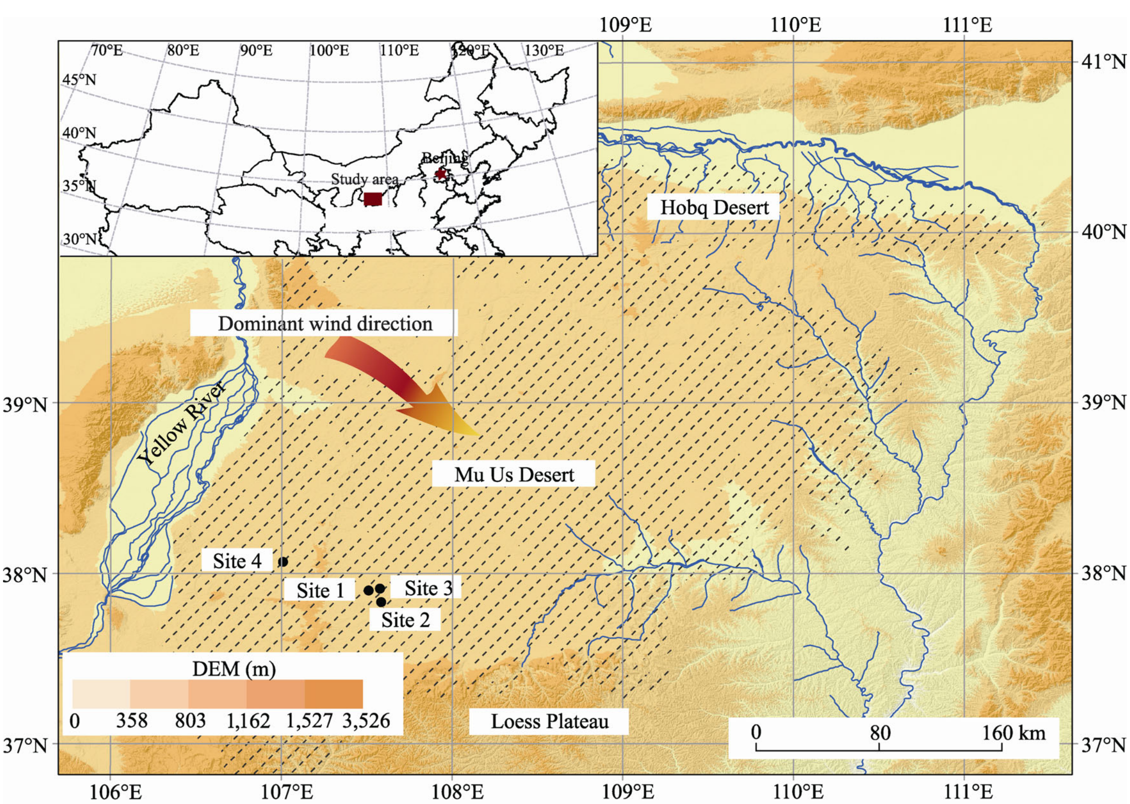

Fig. 1 Location of the Mu Us Desert and the sampling sites in this study

study area has a semi-arid climate with a mean annual precipitation of 294 mm, an actual annual evaporation of 2,060 mm (1954–2002) and an annual mean wind velocity of 2.7 m/s. The average frequency of dust storms is 123 days per year with standard visibility of <10 km. The landscape is a desert steppe with some anchored, semi-anchored and mobile dunes. Dominant plant species, which are mostly annual herbaceous plants, include *Salix psammophila*, *Caragana microphylla*, *Stipa grandis*, *Stipa bungeana*, *Agropyron cristatum*, *Thymus serpyllum* var. *mongolicus*, *Caragana tibetica*, *Oxytropis aciphylla*, *Nitraria sibirica* and *Kalidium foliatum*.

2 Methods

2.1 Field sampling

In November 2012, we collected 20 undisturbed soil samples from the steppe surface of four sampling sites (five samples per site; Fig. 1) using 30 cm×30 cm×30 cm sample boxes. Details of the sampling process have been described by Wang et al. (2012a). In summary, the criteria for the samples collected at each site were that they were intact (sealed with no cracks) and free from anthropogenic impacts. The surface and underlying sediments of all the samples were anchored aeolian sands. The vegetation cover in the study sites was more than 90%. To extract an undisturbed sample, we placed a sample box on the surface and carefully removed the soil from around the box to a depth of approximately 60 cm, taking care to avoid disturbing the sides of the sample, until the box could be pressed downwards to enclose the surface material. A rigid wooden sheet was then inserted horizontally to form the base of the box, enabling the sample to be withdrawn intact. The box was covered to protect the sample surface, and steel wires were used to wrap the box and to ensure that its contents were not disturbed during the process of transport.

2.2 Wind tunnel experiments

Wind tunnel experiments were conducted at the Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou of China. The blow-type and non-circulating wind tunnel had a total length of 37.8 m with a 16.2-m-long test section. The cross-sectional area of the test section was 0.6 m×1.0 m. The free-stream wind velocity in the wind tunnel could be adjusted from 1 to 40 m/s, as described in detail by Dong et al. (2004) and Wang et al. (2012a, 2013b). We fixed each sample in place in the working section of the wind tunnel with the sample surface at the same level as the bottom of the tunnel. To collect the windblown materials, we installed a sand trap of 30-cm width (the same width as the surface sample) and 30-cm height (Fig. 2), which can collect more than 95% of the transported materials (Wang et al., 2012b) at a distance of 10 cm downwind from the sample.

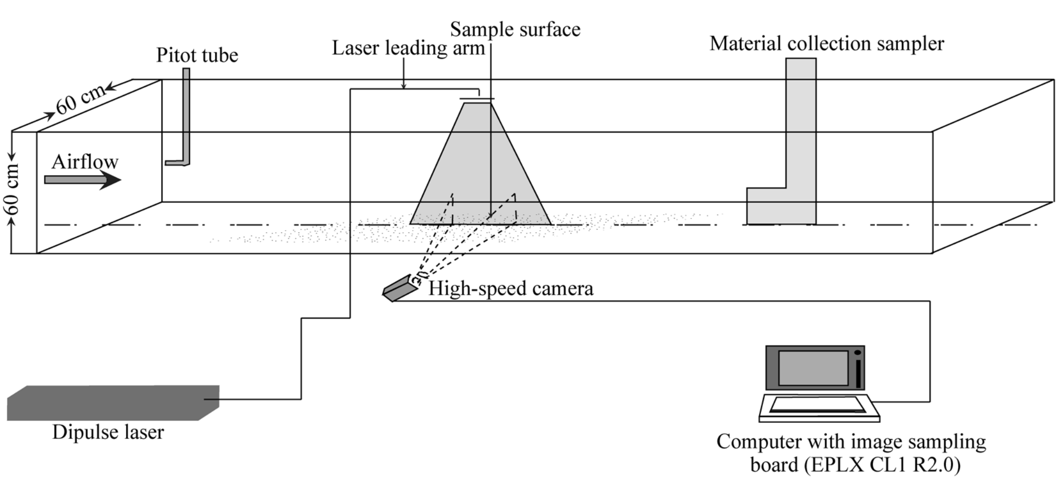

Fig. 2 The wind tunnel and arrangement of samples used in the wind tunnel experiments (modified after Wang et al. (2012a, b) and Wang (2013a))

During the wind tunnel experiments, the relative humidity of the atmosphere was 35%–42%, which was similar to the humidity during the period when the soil samples were collected. We used clean wind (without saltating clouds) to assess the direct aeolian transport. We conducted the experiments using free-stream wind velocities of 14, 16, 18 and 22 m/s which were determined by a Pitot tube (Fig. 2). The experimental duration for each wind velocity was 360 s. Following the cessation of aeolian transport for each wind velocity, we emptied the sediment sampler and weighed the total amount of sediment collected. In addition, each sample was tested under three sets of conditions designed to simulate different levels of human impact (no impact, moderate impact and severe impact) at the various experimental wind velocities. For moderate and severe impact, samples were first half-crushed and completely crushed to simulate states of moderate and severe human impact, respectively.

2.3 Sample treatment and analysis

Following completion of the wind tunnel experiments, the collected aeolian materials were weighed (balance precision 0.001 g) and subjected to particle size analysis (Mastersizer 2000; Malvern Co. Ltd., Malvern, UK). The sample diameters ranged from 0.02 to 2,000 μm. Nutrient analyses included measurements of soil organic matter (SOM), total nitrogen (total N), total phosphorus (total P), total potassium (total K), available N (N_{avail}), available P (P_{avail}) and available K (K_{avail}). SOM was determined from the soil organic carbon content, which was measured by dichromate oxidation using the Walkley Black procedure (Nelson and Sommers, 1982). Total N was measured using the micro-Kjeldahl procedure; total P was measured colorimetrically using a spectrophotometer following H_2SO_4–$HClO_4$ digestion; and total K was measured using flame photometry following HF–$HClO_4$ digestion. N_{avail} was determined using the alkaline diffusion method; P_{avail} was measured using the Olsen method; and K_{avail} was assessed using the colorimetric method with NH_4OAc extraction. As a consequence of the limited quantities of collected aeolian material available, only the surface soil of samples was used for detailed nutrient analyses. Therefore, we used correlation analysis for discussing the nutrient content of the transported materials (see Bosatta and Ågren, 1997; Dexter, 2004).

3 Results and discussion

3.1 Nutrient content of surface soils

The mean nutrient contents of the surface soils in this region were 8.80 g/kg for SOM, 0.60 g/kg for total N, 0.82 g/kg for total P, 11.00 g/kg for total K, 39.98 mg/kg for N_{avail}, 15.95 mg/kg for P_{avail} and 209.50 mg/kg for K_{avail} (Table 1). We found the differences in the nutrient contents among different sites with the coefficients of variation (CVs) among the surface sediments ranging from 19% to 37% except for total K, which showed almost no variation in nutrient concentrations among the surface sediment samples.

3.2 Particle size composition and its relationship with the nutrient content

The silt and clay fractions (<50 μm in diameter; PM_{50}) in the surface soils occupied 11.13%–44.36% of the total particles, with a mean value of 24.74%. In the transported materials, the proportion of PM_{50} varied between 0.88% and 33.96%, with a mean value of 12.28%. Some nutrients were correlated with the particle size composition of the surface sediments (Tables 2 and 3). For instance, there were significant positive correlations between the fine particles (<50 μm in diameter) and SOM, total N, total P and K_{avail}. The Pearson correlation coefficients of these nutrient components with PM_{50} were 0.506, 0.560, 0.895 and 0.742, respectively, which suggested that most of these nutrients existed in the fine fractions.

3.3 Nutrient loss with the transported materials

During aeolian processes, particles in the 50–500 μm fraction lead to the heterogeneity of topsoil nutrients and contribute to 'islands of fertility'. Larger particles also induce succession and changes in community organization in grasslands (Ravi et al., 2010; Alvarez et al., 2012) and increase the likelihood of dust production (Munson et al., 2011). However, most of the particles with the diameter <50 μm were transported by suspension and deposited at greater distances from the source region, resulting in important effects on marine and terrestrial ecosystems (Chadwick et al., 1999; Jickells et al., 2005; Duncan et al., 2008; Neff et al., 2008; Field et al., 2012). In the present study

Table 1 Nutrient content of the surface soils for each sample, along with the standard deviation (SD), mean and coefficient of variation (CV) for each nutrient component

Site/Sample code		SOM	Total N	Total P	Total K	N_{avail}	P_{avail}	K_{avail}
		(g/kg)				(mg/kg)		
Site 1	YC01	6.58	0.40	0.66	11.00	23.90	13.17	200.00
	YC02	12.18	0.84	0.84	11.00	60.40	23.14	250.00
	YC03	13.30	0.75	0.87	11.00	54.00	25.55	250.00
	YC04	8.68	0.65	0.85	11.00	48.40	12.72	230.00
	YC05	10.63	0.59	0.78	11.00	46.00	14.09	220.00
Site 2	YC06	7.04	0.53	0.74	11.00	33.70	18.67	170.00
	YC07	8.67	0.66	0.93	11.00	54.90	24.52	200.00
	YC08	9.43	0.56	0.90	11.00	39.90	13.75	190.00
	YC09	9.04	0.57	0.85	11.00	40.00	12.60	160.00
	YC10	9.74	0.70	0.87	11.00	62.80	12.14	170.00
Site 3	YC11	9.57	0.72	0.97	11.00	24.80	21.31	260.00
	YC12	14.42	1.01	1.14	11.00	70.90	24.40	240.00
	YC13	10.60	0.66	0.94	11.00	40.00	16.38	280.00
	YC14	8.46	0.49	1.00	11.00	36.50	15.92	270.00
	YC15	7.92	0.62	1.00	11.00	24.70	16.50	300.00
Site 4	YC16	6.28	0.54	0.69	11.00	18.50	8.71	160.00
	YC17	6.45	0.48	0.58	11.00	26.90	13.75	170.00
	YC18	5.24	0.44	0.66	11.00	41.70	13.75	170.00
	YC19	6.39	0.37	0.65	11.00	23.90	9.39	170.00
	YC20	5.43	0.34	0.59	11.00	27.80	8.59	130.00
SD		2.54	0.16	0.15	0.00	14.94	5.32	47.96
Mean		8.80	0.60	0.82	11.00	39.98	15.95	209.50
CV		0.29	0.27	0.19	0.00	0.37	0.33	0.23

Note: SOM, soil organic matter; total N, total nitrogen; total P, total phosphorus; total K, total potassium; N_{avail}, available N; P_{avail}, available P; K_{avail}, available K.

Table 2 Pearson correlation coefficients between the particle size fractions and nutrient components of all surface samples

Particle size	SOM	Total P	Total N	N_{avail}	P_{avail}	K_{avail}
<2 μm	0.402	0.846**	0.521*	0.195	0.405	0.597**
<5 μm	0.399	0.833**	0.516*	0.140	0.393	0.629**
<10 μm	0.374	0.808**	0.490*	0.083	0.353	0.614**
<15 μm	0.342	0.782**	0.455*	0.048	0.328	0.592**
<20 μm	0.355	0.787**	0.454*	0.050	0.337	0.620**
<50 μm	0.506*	0.895**	0.560*	0.197	0.442	0.742**
<100 μm	0.293	0.814**	0.403	0.107	0.359	0.509*
<150 μm	0.016	0.582**	0.141	–0.099	0.222	0.294
<200 μm	–0.152	0.396	–0.043	–0.257	0.135	0.198
<250 μm	–0.239	0.275	–0.149	–0.352	0.085	0.159
>250 μm	0.239	–0.275	0.149	0.352	–0.085	–0.159
Median	–0.100	–0.641**	–0.184	0.051	–0.161	–0.326
Mean	0.171	–0.340	0.081	0.322	–0.140	–0.258

Note: * and ** mean significance at the 0.05 level and 0.01 level (2-tailed), respectively.

Table 3 Linear regression equations between the particle size fractions (x) and nutrient components (y) of the surface soils

Particle size	SOM	Total N	Total P	K_{avail}
<2 μm	/	y=0.1054x+0.3811 (R^2=0.27)	y=0.1604x+0.4960 (R^2=0.72)	y=35.4820x+136.7500 (R^2=0.36)
<5 μm	/	y=0.0481x+0.3895 (R^2=0.27)	y=0.0728x+0.5106 (R^2=0.69)	y=17.2180x+135.1000 (R^2=0.40)
<10 μm	/	y=0.0272x+0.3993 (R^2=0.24)	y=0.0421x+0.5190 (R^2=0.65)	y=10.0080x+136.7000 (R^2=0.38)
<15 μm	/	y=0.0196x+0.4126 (R^2=0.21)	y=0.0315x+0.5274 (R^2=0.61)	y=7.4753x+138.9400 (R^2=0.35)
<20 μm	/	y=0.0160x+0.4156 (R^2=0.21)	y=0.0260x+0.5301 (R^2=0.62)	y=6.4357x+136.6300 (R^2=0.39)
<50 μm	y=0.1310x+5.5633 (R^2=0.26)	y=0.0093x+0.3665 (R^2=0.31)	y=0.0140x+0.4798 (R^2=0.80)	y=3.6280x+119.7400 (R^2=0.55)

Note: / means no significant correlation between the particle size fractions and SOM at the 0.05 level (2-tailed).

region, the proportion of PM_{50} in all transported materials was approximately 12.28%, which contained abundant nutrients. For instance, at the wind velocity of 22 m/s, the concentrations of SOM, total N, total P and K_{avail} of the PM_{50} fraction were 18.70 g/kg, 1.30 g/kg, 1.90 g/kg and 482.50 mg/kg, respectively (Table 4). In the absence of human disturbance, the loss of SOM, total N, total P and K_{avail} from the surface soils of the study region averaged 5.70, 0.50, 0.40 and 0.12 mg/m^2, respectively for the combined PM_{50} emission rates (Table 5). Therefore, our results further verified aeolian processes play an important role in nutrient loss and have a substantial impact on sandy desertification in arid and semi-arid regions (Okin et al., 2004; Soderberg and Compton, 2007; Farsang et al., 2012). At the wind velocities of 14–22 m/s in the wind tunnel, the coefficients of variation (CVs) for SOM, total P, total N and K_{avail} in the transported materials were usually <5%, which suggested that after the erodible fine particles were transported away from the soil surfaces at low wind velocities, the following relatively high wind velocities may not result in significant change in nutrient loss.

Table 4 Results from the regressions (using the equations listed in Table 3) of nutrient content of the fine particle fractions in the transported soil materials at the wind velocity of 22 m/s

Particle size	SOM (g/kg)	Total N (g/kg)	Total P (g/kg)	K_{avail} (mg/kg)
<2 μm	N/A	10.90	16.50	3,685.00
<5 μm	N/A	5.20	7.80	1,856.90
<10 μm	N/A	3.10	4.70	1,137.50
<15 μm	N/A	2.40	3.70	886.50
<20 μm	N/A	2.00	3.10	780.20
<50 μm	18.70	1.30	1.90	482.50

Note: N/A means data were not included because of weak correlations between the particle size fractions and SOM.

Table 5 Nutrient content of PM_{50} (particle size <50 μm in diameter) in the transported soil materials and the mean nutrient content of the surface soils for each sample at the wind velocity of 22 m/s for intact (A), half-crushed (B) and completely crushed (C) treatments

Site/Sample code		Nutrient content of PM_{50} (g/m^2)			SOM (mg/m^2)			Total P (mg/m^2)			Total N (mg/m^2)			K_{avail} (mg/m^2)		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Site 1	YC01	0.02	/	0.13	5.60	/	5.60	0.50	/	0.50	0.40	/	0.40	0.12	/	0.12
	YC02	0.46	0.01	19.32	5.60	5.60	8.10	0.50	0.50	0.80	0.40	0.40	0.50	0.12	0.12	0.19
	YC03	0.69	0.46	20.65	5.70	5.60	8.30	0.50	0.50	0.80	0.40	0.40	0.60	0.12	0.12	0.19
	YC04	0.84	0.16	21.12	5.70	5.60	8.30	0.50	0.50	0.80	0.40	0.40	0.60	0.12	0.12	0.2
	YC05	0.56	0.20	11.19	5.60	5.60	7.00	0.50	0.50	0.60	0.40	0.40	0.50	0.12	0.12	0.16
Site 2	YC06	0.54	0.19	18.10	5.60	5.60	7.90	0.50	0.50	0.70	0.40	0.40	0.50	0.12	0.12	0.19
	YC07	0.93	1.64	18.08	5.70	5.80	7.90	0.50	0.50	0.70	0.40	0.40	0.50	0.12	0.13	0.19
	YC08	1.14	0.25	14.11	5.70	5.60	7.40	0.50	0.50	0.70	0.40	0.40	0.50	0.12	0.12	0.17
	YC09	0.71	0.19	12.94	5.70	5.60	7.30	0.50	0.50	0.70	0.40	0.40	0.50	0.12	0.12	0.17
	YC10	0.36	0.20	9.48	5.60	5.60	6.80	0.50	0.50	0.60	0.40	0.40	0.50	0.12	0.12	0.15
Site 3	YC11	1.46	0.59	29.28	5.80	5.60	9.40	0.50	0.50	0.90	0.40	0.40	0.60	0.13	0.12	0.23
	YC12	1.59	0.61	71.21	5.80	5.60	14.90	0.50	0.50	1.50	0.40	0.40	1.00	0.13	0.12	0.38
	YC13	1.30	0.59	26.54	5.70	5.60	9.00	0.50	0.50	0.90	0.40	0.40	0.60	0.12	0.12	0.22
	YC14	6.42	0.60	30.01	6.40	5.60	9.50	0.60	0.50	0.90	0.40	0.40	0.60	0.14	0.12	0.23
	YC15	1.05	1.20	16.10	5.70	5.70	7.70	0.50	0.50	0.70	0.40	0.40	0.50	0.12	0.12	0.18
Site 4	YC16	0.78	1.05	7.42	5.70	5.70	6.50	0.50	0.50	0.60	0.40	0.40	0.40	0.12	0.12	0.15
	YC17	0.14	0.09	5.44	5.60	5.60	6.30	0.50	0.50	0.60	0.40	0.40	0.40	0.12	0.12	0.14
	YC18	0.42	0.94	1.99	5.60	5.70	5.80	0.50	0.50	0.50	0.40	0.40	0.40	0.12	0.12	0.13
	YC19	0.63	0.79	6.00	5.60	5.70	6.30	0.50	0.50	0.60	0.40	0.40	0.40	0.12	0.12	0.14
	YC20	0.50	0.37	6.57	5.60	5.60	6.40	0.50	0.50	0.60	0.40	0.40	0.40	0.12	0.12	0.14
Mean		1.03	0.53	17.28	5.70	5.60	7.80	0.50	0.50	0.70	0.40	0.40	0.50	0.12	0.12	0.18

Note: / means data were unavailable.

4 Conclusions

Aeolian processes caused nutrient loss through the export of fine particles (<50 μm in diameter), highlighting the importance of these processes for sandy desertification in the Mu Us Desert. Our experiments showed that the fine particles (12.28% of all transported materials) carrying substantial nutrient loadings were exported during aeolian processes at the sampling sites. Under high-intensity aeolian processes, after the erodible fine particles were transported away from the soil surfaces at low wind velocity (i.e. 14 m/s), the following relatively high wind velocity (i.e. 22 m/s) may have no significant effect on nutrient transport as the CVs for the losses of SOM, total P, total N and K_{avail} were usually <5%. Our experiments confirmed that in addition to the important role of 'islands of fertility' in sandy desertification, aeolian processes causing nutrient loss through the export of fine particles also play a key role in sandy desertification in this region.

Acknowledgments

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