Effect of vegetation coverage on aeolian dust accumulation in a semiarid steppe of northern China

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Wind erosion and sand storms are common phenomena in semiarid steppes of northern China and could have important impact on soil nutrient balances. Vegetation coverage is one of the key factors influencing wind erosion and aeolian dust accumulation. We conducted a field experiment to investigate the effects of vegetation coverage on airborne dust accumulation and evaluated effects of dust input on the contribution of nutrients to vegetation-mulched fields. Five vegetation coverage treatments (15%, 35%, 55%, 75% and 95%) were constructed, with 0% coverage as a control. Vegetation coverage significantly affected dust accumulation in degenerated semiarid grasslands. The amounts of dust trapped by the increasing coverages were 1.7, 1.8, 2.0, 2.1 and 2.1 times of that by the control plot, respectively. The total accumulations reached a maximum of 2.5 g m−2 day−1 at 75% coverage and remained stable with further increasing vegetation coverage. The particles in the dust trapped by treatment without vegetation coverage were significantly coarser than those by treatments with vegetation. In addition, the dust trapped by treatments with vegetation contained more organic carbon, nitrogen and phosphorus content than that by the control plot. This finding indicates that areas with higher vegetation coverage can obtain more nutrients by trapping airborne dust in semiarid steppes.

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1. Introduction

Dust transport pathways can range in scales from local (over a few hundred meters) to global (over thousands of kilometers) distance. This indicates that potential dust impacts upon ecosystems can operate over similar scales (McTainsh and Strong, 2007). On a global scale, a region or one major ecosystem type can be a large “dust collector”; the positive or negative effects of dust collection determine whether an ecosystem is a dust source or sink and can also directly reflect the loss and accumulation of soil resources. Therefore, it has been suggested that dust plays an important role in many biogeochemical processes (Prospero, 1999; Muhs et al., 2008).

In the past several decades, a large number of studies have shown that nutrient input is a function of aeolian dust and an important factor affecting soil nutrients, especially in those regions where winds often occur (Leys and McTainsh, 1999; Lv and Ma, 2003; Stoorvogel et al., 1997; Swap et al., 1996; Thomas and Dougill, 2011). Aeolian dust may often be higher in fertility than the existing soil where it is deposited. There is a net increase in soil nutrients when wind deposition is stronger than wind erosion, otherwise, a net loss of nutrients will occur (Lv and Ma, 2003; Thomas and Dougill, 2011). Stoorvogel et al. (1997) showed that 50% of the nutrients in a humid tropical rainforest along the Ghana coast were derived from the dust carried by dry and hot winds from the Sahara. Swap et al. (1996) drew more startling conclusion in that a particularly strong sandstorm was capable of blowing 4.8 × 105 t dust at one event from the Sahara in Africa to the Amazon Basin in South America, with an annual transport of settled dust of up to 1.3 × 108 t, corresponding to 190 kg·ha−1. Through dust fall, the Amazon Basin has obtained 1–4 kg P·ha−1 yr−1, which is greatly distributed to the nutrient pool of the rainforest ecosystem. Leys and McTainsh (1999) also showed that the filtration effect of vegetation on the dust is a crucial process,
estimating that shelterbelts in Australia can reduce downwind dust sedimentation by more than 50%. A large number of studies have confirmed that dust deposition played an important role in soil formation of semi-arid and semi-humid lands (Cattle et al., 2002; Derry and Chadwick, 2007; Gustavson and Holliday, 1999; Johnston, 2001; McIntosh et al., 2004; Tiller et al., 1987; Wen et al., 2002). Some studies have demonstrated that dust fall can enrich various nutrients (P, K, Mg, Na, Ca, Fe, Cu, Mn and Mo) in surface soil (Reynolds et al., 2001; Wen et al., 2002) and that the increase of certain elements indirectly influences the utility efficiency of other elements. For example, carbonate influences the biological efficiency of Na, P, K and Mg, while both Mo and P are essential to the N-fixation process (Reynolds et al., 2001).

Vegetation coverage is a crucial factor affecting wind erosion and airborne dust accumulation in semiarid steppes. Grasslands degraded by human activities have been a major dust source in northern China (Xu et al., 2005; Yan et al., 2010; Zhao et al., 2000). The wind tunnel test has shown that erosion of grassland soil by overgrazing and reclamation amounts to 14 and 4 kg m\(^{-2}\), respectively, corresponding to 45 and 13 times of that of ungrazed grasslands (Xu et al., 2005). At the same time, a large area of grasslands receives and intercepts abundant dust fall. It was reported that the natural dust fall in typical steppe areas reaches 35.2 t km\(^{-2}\) month\(^{-1}\) in the Xilin River Basin of northern China (Wang et al., 2000). However, the balance between wind erosion and dust fall greatly influences steppe soils at the ecosystem level. The soils of restored grasslands in grazing exclosures contained finer particle materials with higher nutrient contents than those of continuously overgrazed grasslands (Yan and Tang, 2008). In degraded grasslands, low vegetation coverage could not trap the dust fall and thus became a source of dust. It is therefore necessary to quantify the trapping effect of different vegetation coverages on the aeolian dust to better understand the role of vegetation in aeolian dust accumulation in arid and semi-arid regions.

Most previous studies have focused on the relationships between vegetation coverage and wind erosion (Dong et al., 1996; Li et al., 2007; Mu and Chen, 2007). However, few studies have been conducted to quantify the function of vegetation in trapping dust. We here hypothesize that an increase in vegetation coverage would improve the efficiency of dust accumulation and add more organic carbon (OC) and nutrients to the degenerated grassland soil. To test this hypothesis, we conducted a field experiment by constructing five vegetation coverage treatments (15%, 35%, 55%, 75% and 95%) with 0% coverage as a control. The specific objectives were (1) to explore the effect of vegetation coverage on trapping aeolian dust and (2) to evaluate the effect of dust nutrient contribution on the vegetation-mulched fields.

2. Methods

2.1. Site description

This study was conducted in the north bank of the middle of the Xilin River, in Inner Mongolia of China (43°26′20″N, 116°04′00″E, Fig. 1). There is a fixed sand belt with 10 km width near the north of study site. The semi-arid region was formed on basalt plateaus and mainly covered with fine-sand loess. Typical soil types are chestnuts and calcic chernozems. It is characterized by semiarid steppe climate: cold and dry in winters but mild and humid in summers, with an annual average rainfall of 285 mm (1961–2004). Precipitation is highly variable, with 75% occurring from June to September. Strong winds occur from March to May with an average monthly speed of up to 4.9 m s\(^{-1}\). The annual average temperature is 2.4 °C. The average temperature was −22.3 °C in the coldest month (January) and 18.8 °C in the hottest month (July). After cold and dry winters, numerous strong storms result from high air pressure gradients between the Siberian mainland and eastern Asia in spring (Hoffmann et al., 2008). The natural dust fall in this area reaches 35.2 t km\(^{-2}\) month\(^{-1}\) (Wang et al., 2000). Wind erosion and dust storms are common phenomena in this area and contribute considerably to matter balances (Hoffmann et al., 2008).

2.2. Experimental design

We bound herbage into small clusters (20 cm height) with thin wires to mimic different vegetation coverage and used the treatment without any vegetation (0%) as the control. These clusters were fixed onto square-opening galvanized iron trays (side length = 90 cm, height = 5 cm). Five cover levels (15%, 35%, 55%, 75% and 95%) using herbage clusters of 10 cm\(^{2}\) in a vertical projection area were simulated with a uniform arrangement. In total, 18 iron trays were mounted into the ground of grasslands which experience degradation because of serious wind erosion. Inter-treatment buffer zones of 1.2 m were left to minimize the interference between treatments. These trays were arranged in a vertical row against the main wind direction, and three replicates were set up for each treatment (Fig. 2). The field site was fence-protected to prevent interference during the experiment time.

2.3. Dust collection and physical and chemical analysis

The experiment started on May 28, 2009. We collected dust from the trays on May 22, 2010. We first removed herbage clusters in iron trays and then cleaned the trapped dust with brushes into plastic

![Fig. 1. Location of the experimental site.](image-url)
bags. The weight of these bags was then documented. Fifteen soil cores (4 cm in diameter) from the top 10 cm were collected before the start of the experiment as the local soil.

The particle size of trapped dust and soil was measured by a Japanese SALD-3001 laser particle size analyzer. Soil OC was measured by digestion with potassium dichromate and back-titration with 0.025 mol L\(^{-1}\) ferrous ammonium sulfate (Kalembsa and Jenkinson, 1973). The measurement of total nitrogen (N) followed the classical Kjeldahl digestion method (Moore and Chapman, 1986). Total phosphorus (P) was determined by the ascorbic acid and ammonium molybdate blue method (Schlichting et al., 1995).

### 2.4. Statistical analyses

Data were statistically analyzed using a 10.0 SPSS software package and the significance level was considered at the level of 0.05. Standard errors of the treatment means were calculated by one-way analysis of variance (ANOVA). Multiple comparisons among means of dust accumulation, particle size and contents of OC, total N and P of the trapped dust for different treatments were performed with Tukey's honestly significant difference (HSD) test.

### 3. Results

#### 3.1. Effect of vegetation coverage on dust accumulation

With increasing vegetation coverage, dust accumulation also increased and reached a maximum at 75% vegetation coverage, remaining stable with higher proportions. This can be well described by an exponential function (Fig. 3). Compared to the control (without vegetation coverage), the five treatments with vegetation trapped significantly more dust \((p<0.05)\). The treatments with vegetation coverage of 15%, 35%, 55%, 75% and 95% trapped dust at a rate of 2.0, 2.2, 2.4, 2.5 and 2.5 g m\(^{-2}\) day\(^{-1}\), respectively, corresponding to 1.7, 1.8, 2.0, 2.1 and 2.1 times of the control. In addition, the dust accumulation at 75% and 95% vegetation coverage was significantly higher than that of 15% \((p<0.05)\). However, there was no significant difference between the other treatments with different vegetation coverages \((p>0.05)\).

The amount of dust trapped by different treatments demonstrated three change phases: the first phase is from 0% to 15% coverage, the amount of dust trapped rapidly increased from 1.2 g m\(^{-2}\) day\(^{-1}\) to 2.0 g m\(^{-2}\) day\(^{-1}\); the second phase is from 15% to 75% coverage, where the amount of dust trapped slowly increased from 2.0 g m\(^{-2}\) day\(^{-1}\) to 2.5 g m\(^{-2}\) day\(^{-1}\); and the third phase is from 75% to 95%, where the amount of dust remained steady with further increase of vegetation coverage. In the third phase, the grassland with 75% vegetation coverage level may have prevented re-suspension of the dust in the tray and completely trapped the aeolian dust in this area (Fig. 3).

#### 3.2. Characteristics of particle size of the trapped dust under different vegetation coverage

The sand content in the trapped dust under different vegetation coverage levels was significantly lower than the control (without vegetation coverage) and local soil \((p<0.05)\) (Table 1). As the vegetation curbs the re-suspension of dust, treatments with vegetation coverage had more fine particles trapped in the dust. For example, the treatments with different vegetation coverage levels trapped dust in which clay and silt particles account for 12.1–20.4% of the total particles (Table 1), but the trapped dust from these treatments with different vegetation coverages did not significantly differ in particle size.

#### 3.3. The nutrient input effect of the dust

Dust trapped by the five treatments with vegetation contained significantly higher concentrations of OC, total N and total P than the control treatment without vegetation (Table 2). The respective concentrations of OC, total N and total P at 75% of vegetation coverage were 20.8 g kg\(^{-1}\), 1.7 g kg\(^{-1}\) and 1.0 g kg\(^{-1}\), respectively, or 4.0, 2.6 and 5.7 times of the control. The concentration of OC and total N of the dust trapped by the 15% vegetation coverage treatment were significantly lower than that of the other four higher vegetation coverage treatments \((p<0.05)\). There was no significant difference between four treatments of 35%, 55%, 75% and 95% in the concentration of OC and total N. In the concentration of total P of dust, there was no significant difference between three treatments of 55%, 75%, and 95%, but all of them were significantly higher than that of treatments of 35% and 15%. The treatment of 15% was significantly lower than the 35% vegetation coverage treatment \((p<0.05)\).

The C/N ratio in the dust trapped by the four treatments of 35%, 55%, 75% and 95% was significantly higher than in the control treatment and in the local soil, e.g., the C/N ratio in the dust trapped by 75% vegetation coverage treatment was 12.3, which is 1.5 and 1.3 times of the control treatment and local soil (Table 2), respectively.

OC, total N and total P accumulations from experimental treatments also increased with the vegetation cover (Fig. 4). The treatment with 75% of vegetation coverage trapped OC, total N and total P at rates up to 52.4 mg C m\(^{-2}\) day\(^{-1}\), 4.3 mg N m\(^{-2}\) day\(^{-1}\) and 2.4 mg P m\(^{-2}\) day\(^{-1}\);
respectively, corresponding to 8.5, 5.5 and 12.0 times than that of the control. The pattern of nutrient accumulation from our experimental treatments is different from that observed in dust accumulation. Dust accumulation exhibited a critical point at around 15% of vegetation coverage (Fig. 3), whereas nutrient accumulation appears to exhibit a critical point at 35% vegetation coverage for total OC and total N and between 35% and 55% for total P.

4. Discussion

4.1. Effect of vegetation coverage on dust accumulation

Vegetation has been suggested to play an important role in trapping dust, because it can produce surface roughness that reduces wind speed near the soil surface and thus reduces re-suspension of deposited dust. Zhao et al. (2007) also showed that the aeolian erosion of soil decreases by exponential law with the increase of aerodynamic roughness, which curbs the re-suspension of the settled dust. This in turn reduced net dust accumulation (deposition minus re-suspension). It is also possible, though not discussed here, that the vegetation also increases the deposition rate, on the one hand, the vegetation reduces wind speed and reduces its ability of carrying dust (Hoffmann et al., 2007; Zhang et al., 2005); on the other hand, the direct intercept of stems or leaves on dust also increase the deposition rate (Wang, 2004). Therefore, the large net dust accumulation of high vegetation coverage is contributed by the increase of deposition rate as well as the decrease of re-suspension.

We observed two critical points for dust accumulation. One is for the efficiency of trapping dust at close 15% vegetation coverage treatment, above which dust accumulation increases slowly while below, dust accumulation dramatically declines. This indicates that a vegetation cover of at least 15% can efficiently trap dust in this semi-arid region. The second is the maximal capacity to trap, vegetation coverage ranging from 55% to 75%. Actually, however, this vegetation coverage is difficult to reach except in the long-term enclosure grassland in this area.

4.2. Characteristic of particle size of the dust

Numerous studies have suggested that with the continuous transport of soil particles by wind, fine materials are winnowed from the surface, causing the soil texture to become coarser and less fertile (Table 3) (Larney et al., 1998; Lv, 2005; Su et al., 2002; Su and Zhao, 2003; Yan, 2008; Yan and Tang, 2008). Our results confirm the above conclusion, showing that dust trapped by vegetation contained more clay and silt particles than the control. This is due to two major reasons: (1) fine particles of the surface soil layer of the continuously overgrazed grasslands suffered from constant wind erosion, while the enclosed grassland could prevent the soil from wind erosion because of increasing vegetative coverage; (2) the increase of the vegetation coverage enables the enclosed grassland to trap the dust fall, and the dust fall played an important role in the increase of fine particles and nutrients in the soil (Su and Zhao, 2003). In degraded grasslands, low vegetation coverage could not trap the dust fall and thus became a source of dust (Yan et al., 2010).

4.3. The nutrient input effect of the dust

Numerous studies have assessed the effect of nutrient enrichment from dust input (Larney et al., 1998; Leys and McTainsh, 1999). They suggested that finer particles with higher nutrient contents tend to be transported at greater heights, with the enrichment ratio being a site-specific factor that relates the intensity of wind erosion, soil texture and the height at which the airborne sediment was collected. In addition, the enrichment ratio may also be related to the depth of surface soils being sampled, as nutrient contents can decline rapidly with soil depth (Li et al., 2007). In our study, the trapped dust added nutrients to the soil, as the contents of OC, total N and P are 2–4 times higher than in the local soil. This is consistent with a similar experiment in the semiarid region of northwest China, where Li and Liu (2003) found total N and OC content in the dust trapped by gravel mulch plot was 2–3 times that of the local soil. This indicates that dust can be an important nutrient input to arid ecosystems. In the temperate steppe, total N and P accumulations in the aboveground biomass and living roots are estimated to be about 8.8 g N m$^{-2}$ and 0.7 g P m$^{-2}$ (Huang et al., 1996). These values can be regarded as the conservative seasonal N and P demands by grasses. According to our study, 1.6 g N m$^{-2}$ and 0.9 g P m$^{-2}$ can be gained by trapping windblown dust each year. Available N and available P contribute 10% of total N and 3% of total P (Su et al., 2002). Therefore, available N and P input through dust is estimated to be about 0.16 g N m$^{-2}$ yr$^{-1}$ and

**Table 1**

Characteristics of particle size of the trapped dust under different vegetation coverage. Different letters in a row indicate significant differences between particle sizes at 5% level (Tukey’s test).

<table>
<thead>
<tr>
<th>Vegetation coverage</th>
<th>0%</th>
<th>15%</th>
<th>35%</th>
<th>55%</th>
<th>75%</th>
<th>95%</th>
<th>Local soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay (~0.002 mm)</td>
<td>0.6b</td>
<td>1.9ab</td>
<td>2.5ab</td>
<td>2.8ab</td>
<td>3.5a</td>
<td>3.1ab</td>
<td>0.8b</td>
</tr>
<tr>
<td>Silt (0.002–0.05 mm)</td>
<td>3.2c</td>
<td>10.2ab</td>
<td>11.7ab</td>
<td>12.8ab</td>
<td>16.8a</td>
<td>15.1ab</td>
<td>3.5c</td>
</tr>
<tr>
<td>Sand (~0.05 mm)</td>
<td>96.2a</td>
<td>87.9bc</td>
<td>85.9bc</td>
<td>84.4bc</td>
<td>79.7c</td>
<td>81.8bc</td>
<td>95.7a</td>
</tr>
</tbody>
</table>

**Table 2**

Concentrations of carbon (OC), total nitrogen (TN) and total phosphorous (TP) of dust trapped in different vegetation coverage treatments. Different letters in a row indicate significant differences between particle sizes at 5% level (Tukey’s test).

<table>
<thead>
<tr>
<th>Vegetation coverage</th>
<th>OC (g kg$^{-1}$)</th>
<th>TN (g kg$^{-1}$)</th>
<th>TP (g kg$^{-1}$)</th>
<th>C/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>5.2c</td>
<td>0.7c</td>
<td>0.2d</td>
<td>8.0c</td>
</tr>
<tr>
<td>15%</td>
<td>12.3b</td>
<td>1.3b</td>
<td>0.5c</td>
<td>9.4bc</td>
</tr>
<tr>
<td>35%</td>
<td>18.6a</td>
<td>1.6a</td>
<td>0.8b</td>
<td>11.6a</td>
</tr>
<tr>
<td>55%</td>
<td>19.2a</td>
<td>1.7a</td>
<td>0.9a</td>
<td>11.2ab</td>
</tr>
<tr>
<td>75%</td>
<td>20.8a</td>
<td>1.8a</td>
<td>1.0a</td>
<td>12.3a</td>
</tr>
<tr>
<td>95%</td>
<td>21.0a</td>
<td>0.9a</td>
<td>0.9a</td>
<td>11.5a</td>
</tr>
<tr>
<td>Local soil</td>
<td>5.1c</td>
<td>0.6c</td>
<td>0.2d</td>
<td>9.2c</td>
</tr>
</tbody>
</table>

**Fig. 4.** Organic carbon (OC), total nitrogen (TN) and total phosphorous (TP) accumulations by vegetation mulch for different coverage levels. The points are mean values of OC, TN and TP accumulation of three replicates, and bars are standard errors.
increases dust accumulation from 1.2 to 2.0 g m$^{-2}$ yr$^{-1}$, accounting for 2% and 4% of seasonal N and P demand by grasses. Although their accumulation by trapping aeolian dust makes a small contribution over an annual scale, it still plays an important role in the N and P cycles in semiarid grasslands because more nutrients can be retained in this area for a long period. This validates that N and P accumulation through trapping aeolian dust is a significant pathway of N and P input to terrestrial ecosystems on the decadal and centennial scale.

In terms of ecosystem function, aeolian transport of soil nutrients may be of greater importance than transport of surface soil (Li et al., 2007). Fig. 3 shows that the critical point for stable nutrient accumulation occurs at higher coverage than that for dust accumulation, probably close to 35% vegetation coverage in OC and total N, or between 35% and 55% vegetation coverage treatment in total P. Though there is no significant difference in dust accumulation between 35% and 15% vegetation coverage treatment, the concentrations of OC, total N, and total P in the dust trapped by the 35% vegetation coverage treatment were significantly higher than by 15%. This results in a shift of the critical point for nutrient accumulation to a higher plant cover level.

5. Conclusions

Our experiments demonstrate that vegetation coverage has a major impact on both aeolian dust accumulation and nutrient accumulation in the semiarid steppe of northern China. Our research presents two distinct accumulation critical value of coverage. A moderately increased vegetation cover from 0% to 15% considerably increases dust accumulation from 1.2 to 2.0 g m$^{-2}$ day$^{-1}$, while a vegetation cover of 55–75% has the potential to accumulate 2.4–2.5 g m$^{-2}$ day$^{-1}$. The critical point for nutrient accumulation is close to 35% in OC and total N, or between 35% and 55% vegetation coverage treatment in total P. The texture of dust trapped in the tray without vegetation coverage is obviously coarser than in treatments with vegetation and local soil. This finding suggests that land managers wishing to manage aeolian dust may need to adjust their management plans for different targets. If, for instance, a land manager simply wishes to control and trap the aeolian dust, a vegetation cover of about 15% may be sufficient over the short term as a simple trap. To protect and improve the soil in the long-term, our data suggest that at least 35% vegetation coverage is necessary to trap nutrients efficiently.

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References


