Coal Dust Reduce the Rate of Root Growth and Photosynthesis of Five Plant Species in Inner Mongolian Grassland

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ABSTRACT: Dust pollution is one of the major environmental problems in opencast mining, which has a significant impact on the surrounding ecosystem. Little is known about the effect of coal dust deposition on plant growth in grasslands, especially on root growth. In this study, we studied how coal dust deposition affected plant growth, with a focus on root growth. Five plants which commonly can be found in Inner Mongolian grassland were selected and cultured with hydroponics methods in greenhouse. Two kind of coal dust (coal powder and granite powder) were sprayed on the plant for 35 days. Root morphology parameters and photosynthesis parameter were determined. We found that among the six measured root morphological characters, root surface area and volume were negatively affected by coal dust in most species. Both coal powder and gangue powder inhibited root growth of four out of five species. *Lespedeza davurica* was the only species that was not affected by dust pollution. Coal dust can negatively affect the photosynthesis rate. Based on these results, we found that coal dust is harmful for plant growth. The growth of grass with long-term acceptance of coal dust pollution may be threatened, even can not be grow in the contaminated grassland.

INTRODUCTION

Dust pollution is a major environmental problem occurred during the mining process of open-pit coal mines. This problem is common in six countries (USA, China, India, Russia, South Africa, Australia), which hold 84% of world hard coal reserves [1,2]. Dust pollution is serious in the arid areas of Inner Mongolia, China, where many open-pit coal mines have been established in recent years. During 2006–2010, Inner Mongolia was the biggest coal production province in China [3]. Eleven out of the 14 open-pit coal mines in China are located in Inner Mongolia [4]. Most of the open-pit coal mines are located in the Inner Mongolian grasslands. Meanwhile development of animal husbandry and livelihood of local people highly depend on the health of these grasslands. Thus, dust pollution may pose threats to the livelihood of local people via its damage on grassland health. For example, in the city of Xilinhhot at least 106 km² of grasslands were polluted by coal dust, and 6.7 million Chinese Yuan was paid to compensate herdsmen during 2011–2013 [5].

Dust pollution has been documented to have significant effects on the health of ecosystems and plants. Coal dust increases soil surface temperature [6], and pH value and metal ion concentrations of water leaching from coal pits [7,8]. It contains toxic chemicals such as fluoride and sulfur compounds, which negatively affects vegetation growth [9]. Coal dust emission shades off sunlight, adversely affecting photosynthetically active radiation [10] and photosynthesis performance of *Avicennia marina* in South Africa [2]. Dust particles occlude stomata [11,12]. Coal dust from an Indian mine alters leaf morphology and leaf physiology of nearby garden plants [13]. Biomass of annual plants was significantly bigger on the coal dust plume than off the plume in Oregon, USA [14].

All the researches we have found focus on effects of coal dust pollution on plants’ aboveground parts; no study has assessed its effects on plant belowground parts. Besides this, dust of different origin and nature should have a different influence on the plant growth. There are two sources of coal dust in open-pit coal mining in Inner Mongolia, and we suspect the two types of dust have different effects on plant growth, due to their differences in chemical composition. Coal powder, coming from the pit or coal yard, should have...
similar chemical composition as the coal itself. The most common coal in Inner Mongolia is lignite, which contains mainly C (63.73%), H (6.26%), O (28.12%), N (1.43%), and S (0.46%) [15]. Gangue powder, coming from digging, transporting, and heaping of waste soils (the soil covering the coal and need to be removed during mining), contains SiO₂ (76–77%), Na₂O and K₂O (7.75–8.15%), and CaO (0.20–0.22%) [16]. Wong et al. (1984) report that road dust from different sources have different impacts on plants, some inhibiting, while others promoting, plant root growth [17]. Coal dust from different sources may also affect plant root growth differently.

If the effects of coal powder and gangue powder on plant growth differ among species, then in the long-run some species would be threatened and may go extinct, while other species would increase in abundance. In other words, species composition in a grassland under long-term coal dust pollution may change significantly, leading to changes in grassland state and ecosystem services it can provide. This study examined the short-term effects of coal powder and gangue powder on plant growth of different species. Our questions were (1) how coal powder and gangue powder affect root growth, leaf photosynthesis, and plant biomass, (2) if coal powder and gangue powder affect the same species differently, and (3) if the effects differ among plant species.

MATERIALS AND METHODS

Monitoring the Deposition Rate of Coal Dust

Coal dust deposition rate was monitored at West #2 Coal Mine of Shengli Coal Field, located in west Xilinhot, Inner Mongolia, China. The type of coal is lignite. The dominant wind is west wind. The average annual rainfall was 350 mm [18].

Dust deposition rate was monitored by a gravimetric method during Apr–Sep of 2013. Dust was collected following the Chinese National Standard [19,20] during Apr-Sep of 2013 when local coal mines can only be working in this periods. Two collection sites were set up 500 m away from the coal mine, one to the east and the other, west. At each collection site, three collection cups (15 cm in diameter and 30 cm high) were set up 50 m apart, each placed on a 180 cm-tall cement column. The collection cup was filled with glass balls (1.2 cm in diameter).

The dust in each collection cup was washed with deionized water. The dust solution, filtered through 1 mm-sieve, was poured into a porcelain crucible. The porcelain crucible with dust solution was first heated dry on a hot plate, then baked in a drying oven at 105°C. After it was weighed (W2), the crucible was washed with deionized water and baked in the drying oven at 105°C, and its weight taken (W1). The difference in the two weight measures was the dust weight (W2 – W1).

Laboratory Experiment Design

Five common species in the region were selected for the experiment: Agropyron cristatum, Chenopodium album, Lespedeza davurica, Leymus chinensis, and Melissilus ruthenicus. Seeds were collected from the grassland far from the West #2 Coal Mine in September of 2012. During May–Jul of 2013 seeds were germinated and plants cultured hydroponically in a greenhouse. Seeds were placed in sand for 7 days to allow germination. On the 7th day plants were moved into hydroponic growing systems, each filled with 10 L of Hoagland nutrient solution. Three treatments were set up: control (CK), coal powder treated (CP), and gangue powder treated (GP). The coal powder and gangue powder were collected from West #2 Coal Mine. Each treatment included three replicates, each replicate a hydroponic growing system. Each hydroponic system held 10 plants, with 2 plants from each of the 5 species.

Under the CP or GP treatment, either coal powder or gangue powder was sprayed on the plants and added into the nutrient solution at the same time once every two days. The amount of the sprayed coal powder or gangue powder was equal to the coal dust deposition rate measured at the downwind site (0.59 g/m²/d). A cuboid cap (100 × 50 × 160 cm) was used to cover the plants of the same treatment during dust spraying. Since the aboveground and belowground part of plant were divided by the engraftment plate, dust sprained can not come into the solution. The dust sprayed were added directly into the nutrients solution based on the area of the plate and dust deposition rate. Physical and chemical properties of coal powder and gangue powder from the coal mine were tested. The powder was sieved by a 0.149 mm and the heavy metal determined by Atomic Absorption Spectrometry). The pH value of powder was determined by a pH meter (Leici co., LTD, PHS-3C type) with a powder and water ratio of 1:5. All the determination was three replicates.

Roots of all plants were scanned with an Epson Perfection V700 Photo Scanner (Seiko Epson Corpo-
ration, Nagano, Japan) once every 7 days for 35 days (not includes the 7 days of germination). After the scan the plants were put back to their origin positions in the hydroponic growing systems. The scanned images were analyzed with a WinRHIZO Root Analysis System (Regent Instruments Inc., Canada). Measurements of six root morphological variables (volume, surface area, number of tips, length, numbers of forks, and diameter) were recorded. On the last sampling time (the 35th day), leaf temperature, stomata conductance, and net photosynthetic rate were measured with a portable Photosynthesis System (LI-6400XT, USA). Three measurements were taken on each plant during 9–11:30 A.M. under a LED light source, each on a healthy and fully mature leaf. Finally, all plants were harvested and put into a drying oven at 75°C. Root biomass and total plant biomass were weighed after the plants were dried for 24 hours.

Data Analysis

One-way analysis of variance was used to compare each variable among three treatments at a sampling time (SPSS 13.0 for Windows). The variables were six root morphological characters, leaf temperature, stomatal conductance, net photosynthetic rate, root biomass, and total plant biomass. Statistical significance was defined for \( p = 0.05 \).

RESULTS

Deposition Rate of Coal Dust and Chemical Properties of Coal Powder

Dust deposition rate was 0.26 g/m²/d at the upwind site (\( N = 3, se = 0.06 \)) and 0.59 at the downwind site (\( N = 3, se = 0.10 \)). Concentration of heavy metal in the powder was determined (Table 1). Concentration of chromium (Cr) and lead (Pb) were significantly smaller in coal powder than in gangue powder (\( p = 0.0005 \) and 0.0001, respectively).

### Table 1. Physical and Chemical Properties of the Two Types of Coal Dust.

<table>
<thead>
<tr>
<th>Dust</th>
<th>pH</th>
<th>Cd (means ± se, N = 3, mg/kg)</th>
<th>Cr (means ± se, N = 3, mg/kg)</th>
<th>As (means ± se, N = 3, mg/kg)</th>
<th>Cu (means ± se, N = 3, mg/kg)</th>
<th>Pb (means ± se, N = 3, mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal powder</td>
<td>6.06</td>
<td>0.05 ± 0.01a</td>
<td>22.14 ± 1.56b</td>
<td>4.12 ± 0.16a</td>
<td>13.36 ± 0.74a</td>
<td>11.89 ± 0.15b</td>
</tr>
<tr>
<td>Gangue powder</td>
<td>7.27</td>
<td>0.018 ± 0.01b</td>
<td>51.07 ± 1.07a</td>
<td>3.77 ± 0.08a</td>
<td>15.13 ± 0.45a</td>
<td>30.03 ± 0.71a</td>
</tr>
<tr>
<td>Soil of the original site *</td>
<td>8.22</td>
<td>0.093</td>
<td>38.3</td>
<td>6.85</td>
<td>12.3</td>
<td>15.0</td>
</tr>
</tbody>
</table>

*According to the published data by Guo (2012) [21], the original grassland was the grassland before the coal mine was established.

Plant Root Morphology, Photosynthesis, and Biomass

**Agropyron Cristatum**

Measurements of all six root morphological variables in the dust treatments were smaller than those in the control, but the measurements were statistically the same between the two dust treatments (Figure 1). Between the dust treatments and the control, measurements of five variables in the CP and GP treatments, and root diameter in the GP treatment became significantly smaller than those in the control by the last sampling time (day 35). Root diameter in the CP treatment was statistically the same as that in the control throughout the experiment. Between the CP and GP treatments measurements of all six variables were the same throughout the experiment.

Leaf temperature was the same among the three treatments (Figure 2). Stomatal conductance was significantly smaller in the dust treatments than in the control (\( p = 0.016 \) for coal powder, and 0.011 for gangue powder); net photosynthetic rate in the dust treatments were significantly smaller than (CP) (\( p = 0.018 \)) or the same as (GP) that in the control. Between the two dust treatments both stomatal conductance and net photosynthetic rate were statistically the same.

Both root and total biomass were smaller in the dust treatments than in the control (coal powder: \( p = 0.035 \) and 0.001, respectively; gangue powder: \( p = 0.014 \) and 0.001, respectively, Table 2). Between the two dust treatments there was no difference in both variables.

**Chenopodium Album**

Measurements of three out of six root morphological variables (root volume, surface area, and length) in the dust treatments were smaller than those in the control, while measurements of all six variables were statistically the same between the two dust treatments (Figure 3). Between the dust treatments and the con-
Figure 1. Comparison of temporal trends in six root morphology variables among three treatment groups, control (CK), coal powder (CP), and gangue powder (GP) for Agropyron cristatum. Different letters indicate significantly different means among treatments (●—CK, ▲—GP, ■—CP).

Leaf temperature in the two dust treatments were significantly bigger than that in the control, and it was smaller in the CP than in the GP treatment (Figure 2). However, stomatal conductance and net photosynthetic rate were statistically the same among the three treatment groups.

Root biomass was statistically the same among the three treatments (Table 2). Total biomass was significantly smaller in the dust treatments than in the control; while it was the same between the two dust treatments.

Lespedeza Davurica

The values of all six root morphological variables...
were statistically the same among the three treatments by the last sampling time (day 35) (Figure 4). Although number of root tips on the 3rd and 4th sampling times, and root length on the 3rd sampling time were different among treatments, the differences disappeared by the last sampling time.

Leaf temperature in the dust treatments was the same as (CP) or bigger than (GP) that in the control; and it was smaller in the CP than in the GP treatment (Figure 2). However, stomatal conductance and net photosynthetic rate were statistically the same among the three treatments.

Both root and total biomass were the same among the three treatments (Table 2).

![Graphs showing leaf temperature, stomatal conductance, and net photosynthetic rate](image)

**Figure 2.** Comparison of three photosynthesis variables on the last sampling day (day 35) among three treatment groups: (a) control (CK); (b) coal powder (CP); and (c) gangue powder (GP) for all five species. Different letters indicate significantly different means among treatments within a species.
Measurements of four out of six root morphological variables were statistically the same between the dust treatments and the control, while measurements of five variables were statistically the same between the two dust treatments (Figure 5). Between the dust treatments and the control, the two variables with different values were root surface area (CP = GP > control) and root diameter (GP > CP = control) on the last sampling time. Between the CP and GP treatments, the one variable with different value was root diameter (CP < GP) on the last sampling time.

Leaf temperature was significantly bigger, stomatal conductance was either significantly smaller (CP) or the same (GP), and net photosynthetic rate was signifi-
Coal Dust Reduce the Rate of Root Growth and Photosynthesis of Five Plant Species

Significantly smaller in the dust treatments, compared to that in the control (Figure 2). Between the two dust treatments there was no difference in all three variables.

Root biomass in the dust treatments was the same as (CP) or significantly smaller (GP) than that in the control (Table 2). Total biomass was significantly smaller in the dust treatments than in the control (Table 2). Between the two dust treatments there was no difference in the two variables.

**Melissilus Ruthenicus**

Measurements of four out of six root morphological variables were significantly smaller in the dust treat-

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**Figure 5.** Comparison of temporal trends in six root morphology variables among three treatment groups, control (CK), coal powder (CP), and gangue powder (GP) for Leymus chinensis. Different letters indicate significantly different means among treatments (●—CK, ▲—GP, ■—CP).

**Figure 6.** Comparison of temporal trends in six root morphology variables among three treatment groups, control (CK), coal powder (CP), and gangue powder (GP) for Melissilus ruthenicus. Different letters indicate significantly different means among treatments (●—CK, ▲—GP, ■—CP).
Comparison of Coal Dust Effects Among Species

After spraying coal powder or gangue powder on the plant, different plants have different reaction (Table 3 and 4). Effects of dust addition (CP and GP) on Chenopodium album, Agropyron cristatum and Melisilus ruthenicus contributed equally. Both dust have an strongest impact on Agropyron cristatum and Melissilus ruthenicus, while have no effect on Lespedeza davurica among the five plant species. Leymus chinensis was more affected by coal powder compared it to the gangue powder.

DISCUSSION

On the effects of coal dust, we have found studies on plant species composition [14,22] and plant photosynthesis [23,2], but we have found no study on plant root growth. This study examined the effects of coal dust on plant growth of five species. Lespedeza davurica was the only species whose root morphology was not affected by coal dust; the other four species were negative affected to a varying degree.

Five out of six root morphological characters were negatively affected by coal dust, and one appeared to be positively affected. Among the negatively affected, root surface area were reduced by coal dust in most species (4 species), followed by root volume (3), root length (2 or 3), number of root forks (2), and number of root tips (1). The one positively affected, root diameter, was increased by coal powder in Melisilus ruthenicus, and by gangue powder in Leymus chinensis.

The negative effects of coal dust on root morphology was likely caused by the reduced supply of carbohydrates to root, resulting from reduced photosynthetic efficiency by coal dust. Other people also found that coal dust can reduce photosynthetic performance of the mangrove, Avicennia marina [2]. In addition, the effects of gangue powder on root morphology may be caused by the high concentrations of toxic heavy metals, chromium and lead, in the powder. Root diameter is found to be increased in plants under chromium stress [24]. The soil in the coal mining region could be polluted by heavy metals [25,26].

Among the five species, L. davurica was the only species whose root morphology, photosynthesis, and biomass were not affected by coal powder or gangue powder. Our result is consistent with other findings that L. davurica or Lespedeza species is/are resistant to disturbances such as drought [27,28] and heavy metal contamination [29,30]. Coal dust pollution is likely to reduce light availability to plants, but L. davurica is known to have strong adaptation to different light intensities and can be cultivated widely across geographical regions [31].

Effect of coal dust pollution on photosynthetic efficiency varied by species: net photosynthetic rate was reduced by coal dust in three of the five species, but not affected in the other two species. The species-specific response is likely related to the capacity of leaf trapping dust particles. Naidoo and Naidoo (2005) observe that dust particles are trapped in between leaf hairs on pubescent leaves and species affected least by dust are the ones with glabrous leaves [32]. The three species whose photosynthesis were negatively affected were either with pubescent leaves (A. cristatum and L. chinensis) or with leaflets clustered together (M. ruthenicus). The two species whose photosynthesis were not affected were with glabrous leaves (L. davurica and C. album).

Leaf temperature was increased by coal dust in four of five species. We believe the cause for the increased leaf temperature is the same as that reported by Hirano et al. (1995) for cucumber and kidney bean plants: coal dust particles on the leaf surface absorb solar energy, leading to increase in leaf temperature [12].

In this study, we found that coal dust inhibited plant root growth and reduced photosynthetic rate of some species, but did not affect other species. The species with less resistance to coal dust pollution would gradu-
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### Table 3. Summary the Effects of Coal Powder on Plant Growth Based on the Results from the Last Sampling Time.

<table>
<thead>
<tr>
<th>Plant Species</th>
<th>Root Morphology</th>
<th>Photosynthesis¹</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume</td>
<td>Fork</td>
<td>Length</td>
</tr>
<tr>
<td>Agropyron cristatum</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Chenopodium album</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Lespedeza davurica</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Leymus chinensis</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Melissilus ruthenicus</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

¹LT: leaf temperature; SC: stomatal conductance; NPR: net photosynthetic rate.

- Value of the coal powder group was significantly smaller than that of the control group.
- Value of the coal powder group was significantly bigger than that of the control group.
Blank: Values of the coal powder group and the control group were statistically the same.

### Table 4. Summary the Effect of Gangue Powder on Plant Growth Based on the Results from the Last Sampling Time.

<table>
<thead>
<tr>
<th>Plant Species</th>
<th>Root Morphology</th>
<th>Photosynthesis¹</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume</td>
<td>Fork</td>
<td>Length</td>
</tr>
<tr>
<td>Agropyron cristatum</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Chenopodium album</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Lespedeza davurica</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Leymus chinensis</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Melissilus ruthenicus</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

¹LT: leaf temperature; SC: stomatal conductance; NPR: net photosynthetic rate.

- Value of the coal powder group was significantly smaller than that of the control group.
+ Value of the coal powder group was significantly bigger than that of the control group.
Blank: Values of the coal powder group and the control group were statistically the same.
ally decrease in abundance and may even disappear from the grasslands under long-term coal dust pollution, while the species with strong resistance to coal dust pollution are likely to stay and become dominant. Long-term field observations and experiments on the responses of grassland ecosystems to coal dust pollution are needed, so we can gain knowledge on the patterns and processes related to coal dust pollution, and apply the knowledge to manage the grasslands better so the ecosystem services can be optimized to meet the needs of multiple land users.

CONCLUSIONS

In this study five common plant species in an Inner Mongolian grassland were treated with coal dust to simulate the effects of coal dust deposition on plant growth. Our results showed that *L. davurica* was most resistant to coal dust deposition among the five species. Coal dust inhibited plant root growth. Among the six root morphological characters, root volume and surface area were reduced by coal dust in most species. More observations and experiments should be carried out to study the responses of grassland ecosystems to coal dust pollution.

ACKNOWLEDGEMENTS

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