Fine particle emission from agriculture soil erosion based on wind-tunnel experiment

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Abstract. PM$_{2.5}$ generated from soil can cause air pollution problem in China. Therefore, controlling soil dust is important to improve air quality. The study investigated the physical and chemical properties of the soil (moisture content, CaCO$_3$, OC, EF) in a city of China and used a wind tunnel for simulating wind erosion process to explore the PM$_{2.5}$ emission properties from soil surface. Experimental conditions include three sampling heights (20, 40 and 70 cm above the ground) and five wind speeds (from 4 to 12 m/s with the increment of 2 m/s). The studies showed that PM$_{2.5}$ emission rate from soils obeyed exponential function increment. Emission rate ranged from 0.3 to 233μg/m$^2$·s. Sandy loam cinnamon with lowest moisture content and CaCO$_3$ had the largest emission rate. Soil type, wind speed and sampling height from soil surface all had significant impact on emissions rate.

1.Introduction

China is one of the countries which is most affected by soil erosion problem in the world (Liu et al., 2013). The total area of bare soil having the potential for wind erosion in China is 1.957 million km$^2$, accounting for 20.6% of the total land area (Nan et al., 2016). The phenomenon of wind erosion is commonly happened in spring in northern China due to the greater wind speed and relatively longer duration (Dong et al., 1996). The emitted dust from soil suspends into the ambient air, and is bombarded and abraded by the surrounding particles. Fine particulate matters with average aerodynamic diameters of $\leq$ 2.5 μm (PM$_{2.5}$) are thus generated. Soil erosion by wind is an important source of ambient PM$_{2.5}$. It can cause serious air pollution problem, such as haze in China. A large amount of PM$_{2.5}$ generated from the agricultural fields by wind erosion can cause ambient concentration exceeds the National Air Quality Standard of China for PM$_{2.5}$. Besides, exposure to PM$_{2.5}$ can cause various diseases in respiratory and cardiovascular systems (Chen et al., 2019). Thus, it is important to evaluate fine particle emission from soils and find the potential factors affecting the emission.

In this research, the emission process was simulated in a wind tunnel using five tray soil samples collected in a northern city of China. The emitted PM$_{2.5}$ was monitored for calculating emission rate of soil. Factors such as soil type, height from the soil surface and wind speed were evaluated to find their effects on emission rate. The study has theoretical and practical significance for preventing and controlling air pollution problem in China.
2. Materials and Methods

2.1. Study area
This study was conducted in Tianjin, Northern China. Tianjin (38°34′–40°15′N, 116°43′–118°19′E) has a typical monsoon climate with highest wind speed in spring. The annual average wind speed was 2.1 m/s in 2016 with the maximum reached at 11.6 m/s in spring. Five sampling sites, which were located in four suburb areas including Jinghai, Ninghe, Baodi and Jizhou, were determined based on the soil type. The soil samples were collected in spring due to the contribution of soil erosion on ambient air was the highest compared with other seasons.

2.2. Soil samples collection and property analysis of soils
The undisturbed soil samples were collected in a tray with specific size (L×W×H: 0.8×0.3×0.1 m) and transported to wind tunnel for erosion study. Disturbed top soils were also collected to analyze physical and chemical properties of soils, which includes soil moisture content, calcium carbonate (CaCO$_3$) content, organic carbon (OC) and erodible fraction (EF).

Soil moisture content was measured at six points located evenly in each soil sample by a moisture probe (Trime-pico64, IMKO company, Germany) connected with a handhold device (HD2, IMKO Company, Germany). Capacity method was used to determine the content of CaCO$_3$ in soil by a CaCO$_3$ tester (Model 08.53, Eijkelkamp company, Netherlands). The organic carbon of the soil was measured using elemental analyzer (2400 SeriesII CHNS/O, PE American company, U.S.A.). Aggregate size distribution of the soil sample was measured by a laser diffraction particle size analyzer (BT-9300S, Dandong Company, China) with size range of 0.1 to 340 μm, to calculate erodible fraction (EF). Erodible fraction is commonly used to evaluate the rate of soil erodibility. It can be calculated by the following equation:

$$EF = \frac{W < 0.84}{TW} \times 100$$  \hspace{1cm} (1)

Where, EF is erosion rate (%); W <0.84 represents the weight of soils with size less than 0.84 mm; TW is the total weight of soil sample.

2.3. Wind tunnel and experiment procedures
The experiment was performed in wind tunnel (see Figure 1) located in Tianjin Research Institute for Water Transport Engineering. The tunnel encompasses six sections. Major parameters of wind tunnel are listed below:

1) Continuously adjustable wind speed: 0-30 m/s
2) Drive power: 400kw
3) Dimension of experiment section ((L×W×H):15.0 m×4.4 m×2.5 m

![Fig.1 Configuration of wind tunnel](image)

The collected undisturbed soil sample was placed in the centre of experimental section of the wind tunnel to measure the PM$_{2.5}$ emission. During the experiment, five wind speeds from 4 to 12 m/s with the increment of 2 m/s were set for each soil sample. The erosion time under each wind speed was determined to be 10 min based on the results of literature review (Panebianco et al., 2016). Three dust...
monitors (8530, TSI Inc, MN, USA) placed at the heights of 20, 40 and 70 cm above the soil sample were used to measure the PM$_{2.5}$ concentration due to wind erosion. The dust monitors can measure the real-time dust mass concentration ranged from 0.1 to 10 µm at the time interval of 1 s in this study. The sampling flow was set as 3 L/min. According to the concentration data collected by the dust monitor and the wind speed at each sampling height, the emission rate (ER, amount of PM$_{2.5}$ released from the surface of a given area per unit time, µg/m$^2$·s) was calculated by the following equation:

\[
E = \frac{1}{L} \int CudZ
\]  

(2)

Where, L is the length of soil sample (m); C represents the mass concentration of PM$_{2.5}$ at height z (µg/m$^3$); u denotes the wind speed at height z (m).

3. Results and Discussion

3.1 Physical and chemical properties of the soils

The results of physical and chemical properties of the soil sample are presented in Table 1, which include moisture content, CaCO$_3$, OC and EF. Heavy loam wet fluvo-aquic soil had the maximum values of moisture content and OC. The variations of moisture content and OC among soil samples were small with range from 9.6 to 14 g/kg and 10.11 to 16.47%, respectively. The difference of CaCO$_3$ content among soils was large with range from 1.14 to 114.83 g/kg. EF ranged from 94.07 to 99.92%. Sandy loam cinnamon soil had the highest EF and heavy loam wet fluvo-aquic soil had the lowest value.

| Properties           | Medium loam fluvo-aquic soil | Heavy loam fluvo-aquic soil | Clay fluvo-aquic soil | Heavy loam wet fluvo-aquic soil | Sandy loam cinnamon soil |
|----------------------|------------------------------|----------------------------|-----------------------|---------------------------------|--------------------------|
| Moisture content (%) | 12.56                        | 15.49                      | 11.50                 | 16.47                           | 10.11                    |
| CaCO$_3$(g/kg)       | 114.83                       | 59.21                      | 9.00                  | 1.14                            | 4.09                     |
| OC(g/kg)             | 10.50                        | 14.00                      | 9.60                  | 16.47                           | 10.11                    |
| EF (%)               | 96.35                        | 99.64                      | 99.32                 | 99.92                           | 94.07                    |

3.2 Emission rate (ER) of soil

The vertical PM$_{2.5}$ concentrations and emission rates for different soil samples are shown in Figure 2. Concentration decreased with the increasing height, indicated the erosion was mainly occurred at surface of the soil, which was also noted by Feng et al. (2011). It was found that the emission rate increased exponentially with the increasing wind speed with the correlation coefficients all above 0.9 (see Table 2). Emission rates of PM$_{2.5}$ varied among five soil samples from 0.3 to 233 µg/m$^3$·s. Compared to the results reported by Panebianco et al. (2016) in Argentine steppe region, our results of emission rates were lower because of the different ground conditions and wind speeds. Sandy loam cinnamon featured the largest emission amount, followed by heavy loam fluvo-aquic soil and heavy loam wet fluvo-aquic soil, emission from medium loam fluvo-aquic soil was lowest. This is probably due to the low moisture content and CaCO$_3$ in sandy loam cinnamon soil sample, which could decrease the cohesiveness of soil and result in loose easily by wind force. Moisture content has important effect on wind erosion, especially for the small particle. The greater the soil moisture content is, the stronger the resistance to the wind erosion (Sun et al., 2014). The present of CaCO$_3$ can increase the size of clay and agglomerates content, thereby increasing the ability of soil to resist wind erosion (Dong et al., 2018).
Fig. 2 Concentration and emission rate of PM$_{2.5}$ at different vertical heights and wind speeds (bars represent PM$_{2.5}$ concentration and points represent emission rate).

**Table 2 Regression equation of wind speed and PM emission rate.**

| Soil samples                          | PM$_{2.5}$ emission rate                   |
|---------------------------------------|--------------------------------------------|
| Medium loam fluvo-aquic soil          | 20cm: $y = 0.1064x^2 + 1.3604x - 0.212, R^2 = 0.9809$  |
|                                       | 40cm: $y = 0.4486x^2 + 0.5046x - 0.754, R^2 = 0.9919$  |
|                                       | 70cm: $y = 0.0529x^2 + 3.2109x - 3.502, R^2 = 0.9778$  |
| Heavy loam fluvo-aquic soil           | 20cm: $y = 3.9886x^2 - 5.7714x + 2.78, R^2 = 0.9905$  |
|                                       | 40cm: $y = 7.5629x^2 - 20.187x + 14.76, R^2 = 0.9995$ |
|                                       | 70cm: $y = 8.9936x^2 - 25.932x + 20.32, R^2 = 0.993$  |
3.3 Factors affecting ER
Paired T-test analysis was used to determine the effects of soil type, sampling height and wind speed on PM$_{2.5}$ emission rates. Only the statistic result of sampling height was shown here as an example (see Table 3). The emission rates of each paired sampling heights were all significant (p<0.05), which indicated the significant influence of height on soil erosion. Wind speed and soil type were shown to be other significant factors on PM$_{2.5}$ emission rate with p value all below 0.05. Zhao et al. (2019) also reported that dust emission was closely related to the soil type due to the factors such as clay content of different soil types were different.

Table.3 Significant analysis of height, wind speed and soil type.

| Paired Differences | Mean    | Std. Deviation | Std. Error of Mean | 95% Confidence Interval of the Difference | t     | df    | Sig. (2-tailed) |
|--------------------|---------|----------------|--------------------|------------------------------------------|-------|-------|----------------|
| Pair1 20cm – 40cm  | -9.47600| 17.73000       | 3.54600            | -16.79459 - 2.15741                      | -2.672| 24    | .013           |
| Pair2 20cm - 70cm  | -17.96480| 35.11871      | 7.02374            | -32.46109 - 3.46851                      | -2.558| 24    | .017           |
| Pair3 40cm - 70cm  | -8.48880| 18.56839       | 3.71368            | -16.15346 - 2.286                        | -2.826| 24    | .031           |

4. Conclusion
Five representative soils were collected in Tianjin, a northern city in China, for evaluating their emission potentials of PM$_{2.5}$ in a wind tunnel. Results indicated that the emission rate of PM$_{2.5}$ varied among soils with a range from 0.3 to 233μg/m$^2$·s. Emission rate increased exponentially with the increasing wind speed. Soil type, wind speed and vertical height all have significant effects on emission rates.

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