Local PM$_{10}$ and PM$_{2.5}$ emission inventories from agricultural tillage and harvest in northeastern China

Weiwei Chen$^{1,*}$, Daniel Q Tong$^{2,3}$, Shichun Zhang$^1$, Xuelei Zhang$^1$, Hongmei Zhao$^1$

1. Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 100029, China
2. Cooperative Institute for Climate & Satellites, University of Maryland, College Park, MD 20740, USA
3. Center for Spatial Information Science and Systems, George Mason University, Fairfax, VA 22030, USA

ARTICLE INFO

Article history:
Received 19 October 2015
Revised 12 November 2015
Accepted 2 February 2016
Available online 30 December 2016

Keywords:
PM
Emission factor
Agricultural inventory
Tillage
Harvest
Burning

ABSTRACT

Mineral particles or particulate matters (PMs) emitted during agricultural activities are major recurring sources of atmospheric aerosol loading. However, precise PM inventory from agricultural tillage and harvest in agricultural regions is challenged by infrequent local emission factor (EF) measurements. To understand PM emissions from these practices in northeastern China, we measured EFs of PM$_{10}$ and PM$_{2.5}$ from three field operations (i.e., tilling, planting and harvesting) under relatively dry conditions (i.e., soil moisture <15%), respectively. The EFs of PM from field tillage and planting operations were negatively affected by topsoil moisture. The magnitude of PM$_{10}$ and PM$_{2.5}$ emissions from these three activities were estimated to be 35.1 and 9.8 kilotons/yr in northeastern China, respectively, of which Heilongjiang Province accounted for approximately 45%. Spatiotemporal distribution showed that most PM$_{10}$ emission occurred in April, May and October and were concentrated in the central regions of the northeastern plain, which is dominated by dryland crops. Further work is needed to estimate the contribution of agricultural dust emissions to regional air quality in northeastern China.

© 2016 The Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. Published by Elsevier B.V.

Introduction

Agricultural activity is an important source of atmospheric particulate matter (PM) emission (Hinz and Tamoschat-Depolt, 2002). Studies have shown that the primary PM sources are wind erosion, land tilling, fertilization, chemical substance application, crop harvesting, grain handling, residue burning and animal feeding. Secondary aerosols are formed in homogenous or heterogeneous reactions with gas precursors (e.g., ammonia, chemical substances and volatile organic compounds (VOC)) released from these activities (Pattey and Qiu, 2010). Moreover, other field practices like slurry spraying, pesticide application, unpaved road traffic and fuel combustion by farm machinery may also contribute to PM emission (Aneja et al., 2009; EEA, 2009).

Soil tillage and crop harvest have been identified as the two largest anthropogenic contributors to agricultural PM emissions in Europe and North America (Cassel et al., 2003; Bogman et al., 2005). During mechanical disturbances of
agricultural land, soil particles can be disintegrated and suspended in the air, especially particles of with a diameter less than 10 μm (i.e., PM_{10}). These suspended particles are mainly composed of soil mineral and organic dust generated in the processes of field practices. Although these operations occur over only a few days, the magnitude of particle emissions might be several times greater than that from wind erosion of cropland (Goossens and Riksen, 2004). Previous studies have indicated that intense mechanical disturbance (i.e., disk and plowing) (Hinz and Tamoschat-Depolt, 2002; Holmén et al., 2008), high soil silt percentage (Carvacho et al., 2004), low soil moisture (Wang et al., 2010) and high wind speed (Kasumba et al., 2011) enhance soil particles escaping to the atmosphere. With similar cultivation methods and soil silt percentages, PM emissions associated with soil tillage and crop harvest are generally highest in wheat fields, followed by potato and cotton fields (Wang et al., 2010). Smaller root zone and less crop residue in wheat fields should lead to more particulate escaping.

At present, regional or national inventories of particles emissions from agricultural operations mostly focus on western countries, such as Europe countries, the United States and Canada. Bottom-up estimates, based on emission factor (EF) from these operations, are the main methods for inventory compilation. In addition, data are generally needed on the cultivated areas, crop calendars, EFs from field practices, and the percentage of conservation tillage (EPA, 1992; CARB, 2003; EC, 2007; EEA, 2009). Choosing suitable EF values is the key to regional inventory. However, currently existing values are rare, and these values vary greatly among different agricultural regions (Chen, 2015). Differences in soil texture, water conditions, and crop planting systems increase the uncertainty of EF values, even by several orders of magnitude for the same field operations. European Environment Agency (EEA) guidelines stated that the best way to gather the relevant data is to adopt local EF values for inventory. Therefore, determinations of EF values in the main agricultural regions around the world would be very helpful for improving the accuracy of inventory and estimation methods.

Northeastern China is a major region for crop production and covers approximately 20% of the total arable land area in China (National Bureau of Statistics of China, 2013). This region is one of three black earth terrains in the world. The soil type (i.e., Molisol) and cropping pattern (i.e., single season) are unique in China and bare soils are exposed to atmosphere for up to seven months each year. Thus, agricultural disturbance may increase the potential of PM emissions from soil, especially with decreases in soil organic matter content (Liang et al., 2007; Liu et al., 2011). However, limited research has led to uncertainties about the magnitude and mechanisms of PM originating from field operations in this region.

The objective of this study is to understand the characteristics and magnitudes of PM emissions from tillling and harvesting in northeastern China. We measured the EFs from agricultural operations of tilling, planting and harvesting operations at four agricultural stations in 2012 and 2013. We then estimated the county-level PM_{10} and PM_{2.5} emissions from these activities using determined EFs and statistical information of crop areas and calendars. Finally, the uncertainties of regional PM emissions are discussed.

1. Materials and method

1.1. Study region

The EF measurements were conducted at four sites (Fig. 1), i.e., the black-soil protection agro-technical station in Dehui County (DH, 44°12′29″N, 125°34′04″E), a crop planting demonstration base in Yushu County (YS, 44°51′27″N, 126°24′45″E), the National Observation Station of Hailun Agro-ecology System in Hailun county of Heilongjiang Province (HL, 47°26′00″N, 126°38′00″E) and the Sanjiang Mire-Wetland Experimental Station in Heilongjiang Province (SJ, 47°35′00″N, 133°31′00″E). At these sites, local climate is characterized as temperate continental monsoonal. The mean annual temperature is 4.8°C, with a mean January temperature of −15.1°C and a mean July temperature of 23.1°C. Annual precipitation is 522–615 mm, of which more than 60% falls in June through August. The growing season starts in May and ends in September; the remaining seven months are the non-growing season (from October to April of the following year). Corn and soybean are two predominant upland crops, planted on 66% of the total arable lands in northeastern China. The DH and YS regions are major corn producing areas in Jilin Provinces, and large areas of soybean fields are planted in other two regions. Soil tillage and crop planting starts in late April and ends in mid-June. Crops are harvested and straw is burned in October. The soil type at the investigation sites is black soil, and the related soil information is summarized in Table 1.

1.2. Farmland operations and PM emission factor processing

Considering significance of dryland to agricultural dust emissions and the high proportion of corn and soybean grown in the area, local EFs from major agricultural activities were measured for corn and soybean fields. In northeastern China, field operations for corn and soybean production involve three procedures. The first procedure is land preparation in April or May, including deep plowing, harrowing or diskling and land plane operations. In the past ten years, multiple land preparation processes have gradually been combined into process, with the development of multifunctional field tillling machinery, thus reducing the number of passes. The second procedure is planting or seed sowing for drylands in April or May, which incorporates sowing and fertilizer applications. The third procedure is crop harvesting or reaping in September or October. Mechanical harvesting practices have become popular in the past five years.

At each site (i.e., DH, YS, HL and SJ), the three operations, tilling, planting and crop harvesting, were conducted in experimental fields (i.e., corn or soybean) of 200 – 250 m × 100 m (length × width) in May or October of 2012 and 2013. The dust aerosol sampling during field operations and EF processing followed the method in Wang et al. (2010). Dust aerosol sampling was conducted during each tractor pass of each operation. At the end of each one-way pass, the tractor stopped at the end of the field and turned off its engine until all sampling was completed and the dust plume generated had moved off the sampling area. The return pass back across the field was made and similarly sampled. Four
Fig. 1 – The locations of PM emission factor measurements at farmland sites of Dehui county (DL), Yushu county (YS), Hailun county (HL) and Sanjiang station (SJ). The blue solid lines indicate major rivers; the green coarse solid lines represent large mountains; the green circles are the capitals of three provinces; and the blue triangles are the sampling locations of the emissions factor measurements. PM: particulate matter.

<table>
<thead>
<tr>
<th>Site code</th>
<th>Plant type</th>
<th>Soil silt (%)</th>
<th>Soil moisture (%, V/V)</th>
<th>Mean wind (m/sec)</th>
<th>Agricultural operations</th>
<th>EF (mg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PM₁₀</td>
<td>PM₂.₅</td>
</tr>
<tr>
<td>DH</td>
<td>Corn</td>
<td>24.0</td>
<td>7.3 ± 1.3</td>
<td>6.7 ± 1.5</td>
<td>Tilling</td>
<td>119 ± 23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.3 ± 1.3</td>
<td>5.1 ± 1.0</td>
<td>Planting</td>
<td>17 ± 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>–</td>
<td>–</td>
<td>Harvesting</td>
<td>–</td>
</tr>
<tr>
<td>YS</td>
<td>Corn</td>
<td>–</td>
<td>10.2 ± 1.7</td>
<td>5.5 ± 1.3</td>
<td>Tilling</td>
<td>96 ± 29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10.2 ± 1.7</td>
<td>4.2 ± 1.4</td>
<td>Planting</td>
<td>17 ± 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15.7 ± 2.1</td>
<td>4.4 ± 0.9</td>
<td>Harvesting</td>
<td>18 ± 7</td>
</tr>
<tr>
<td>HL</td>
<td>Soybean</td>
<td>20.0</td>
<td>18.7 ± 2.0</td>
<td>5.4 ± 1.5</td>
<td>Tilling</td>
<td>31 ± 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18.7 ± 2.0</td>
<td>4.3 ± 1.6</td>
<td>Planting</td>
<td>10 ± 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13.5 ± 1.5</td>
<td>5.7 ± 0.9</td>
<td>Harvesting</td>
<td>33 ± 9</td>
</tr>
<tr>
<td>SJ</td>
<td>Soybean</td>
<td>19.5</td>
<td>25.0 ± 2.1</td>
<td>6.2 ± 1.1</td>
<td>Tilling</td>
<td>9 ± 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25.0 ± 2.1</td>
<td>6.8 ± 1.8</td>
<td>Planting</td>
<td>4 ± 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>–</td>
<td>–</td>
<td>Harvesting</td>
<td>–</td>
</tr>
</tbody>
</table>

The emission factors are the means of 10–20 replicates and the standard error. “-” indicates no value for the item.
PM$_{10}$ or PM$_{2.5}$ samplers (Dustrack 8520, TSI Incorporated, Shoreview, MN) were used to determine the 1-sec PM$_{10}$ or PM$_{2.5}$ concentrations (mg/m$^3$) at four heights (0.5, 1.6, 2.2 and 4.3 m) in the downwind direction of tractor travel. The PM$_{10}$ samplers were kept approximately 3 m from the tractor. PM$_{10}$ and PM$_{2.5}$ samplers were set in the upwind direction (ca. 50 m away) to record background concentrations during operations. Samplers were set at four heights to simulate the dust plume height induced by each type of mechanical operation (tilling, planting and harvesting). A total of 15 to 20 passes were made across the field during each separate agricultural operation. The PM samplers can record 1-sec PM$_{10}$ or PM$_{2.5}$ concentrations (milligrams per cubic meter), based on the cutoff inlet conditions (Chen, 2015):

$$E = \frac{H}{z_0} \frac{U(h) C(h) t \cos \theta}{w} dh$$

where, $h$ (m) is the height aboveground, $z_0$ (m) is the surface roughness length, $U(h)$ (m/sec) is the average wind speed at height $h$ during the pass, $dh$ (m) is the 10 equally spaced height intervals between $z_0$ to the top of plume, $C(h)$ (mg/m$^3$) is the mean concentration at height $h$ during the pass, $\theta$ (degree) is the angle between the measured wind direction and the tractor path, $w$ (m) is the upwind width of soil worked during the test period, $dh$. Vertical concentration profiles were fitted to logarithmic functions. Based on the profiles, $H$ (m) was defined as the height at which the dust concentration was extrapolated to 0.0. The background PM concentration was first removed from the field operation PM concentration before using Eq. (1) to calculate the emission factors.

### 1.3. Development of county-level PM emission inventory

National or regional PM emission inventories in Occident countries were universally compiled using EF-based methods (EPA, 1992; Hinz and Tamoschat-Depolt, 2002; CARB, 2003; Bogman et al., 2005; EEA, 2009). These methods mainly require three types of data, i.e., crop areas, crop calendars and EFs induced by different field operations as well as the number of times the emitting practice is carried out. The algorithm of agricultural PM emissions according to EEA guidelines is briefly described in Eq. (2). Previous studies, using similar calculation methods, have shown that the EF of specified field operations varies considerably under different climate or soil conditions (Chen, 2015):

$$E_{PM} = \sum_{i=1}^{I} \sum_{n=0}^{N} \frac{EF_{PM,i,k} \cdot A_i \cdot n}{V}$$

where, $E_{PM}$ (kg/ha) is the emission of PM$_{10}$ or PM$_{2.5}$ from the ith crop, $I$ is the number of crops grown, $A_i$ (ha)is the annual cropped area of the ith crop, $N_i,k$ is the number of times the kth operation is performed on the ith crop per year (yr$^{-1}$), $EF_{PM,i,k}$ is the EF for the kth operation of the ith crop (kg/ha).

In this study, we also used the EF-based method to develop county-level PM emission inventories for northeastern China. In each county, twelve crop areas (i.e., corn, soybean, rice, wheat, sorghum, cotton, oil crops, sugar beet, fiber crops, tube crops, vegetables and melons) were obtained from national and provincial statistical yearbooks (i.e., China, Jilin, Liaoning, Heilongjiang and Inner Mongolia) and the agricultural statistical yearbook in 2013. For each crop, conventional field activities (i.e., tilling, planting and harvesting) and crop calendar information (i.e., month) are collected from local agriculture-related websites and questionnaires. For corn and soybean fields, local measured EFs and also EFs provided by California Agriculture Resource Board (CARB) and EEA were used to calculate PM$_{10}$ emissions (ton/yr) from different field activities. For other crop fields, we choose the EFs from CARB and EEA. The PM$_{2.5}$ emissions from field activities were estimated by measured coefficients of PM$_{2.5}$ and PM$_{10}$ during field activities (Fig. 2). For each county, the emission intensity (ton / (yr·ha)) was calculated by dividing emissions by geographic area.

### 1.4. Data analysis

Non-linear correlations between PM$_{10}$ EFs and soil moisture were determined. All of the statistical and plotting procedures were performed using SigmaPlot 10.0 (SPSS Inc., Chicago, USA) and R-packages (https://www.r-project.org/).

### 2. Results

#### 2.1. Emission factors for field tilling, planting and crop harvesting

Field measurements showed that fugitive PM$_{10}$ and PM$_{2.5}$ concentrations followed the order: tilling $>$ harvesting $\geq$ planting (Fig. 2). The ratios of PM$_{2.5}$ and PM$_{10}$ concentrations induced by field activities, planting and crop harvesting were $(28 \pm 19)%$, $(26 \pm 15)%$ and $(32 \pm 12)%$, with no significant differences among the three percentages. The PM$_{10}$ EFs ranged from 31 to 119 mg/m$^2$ for tilling, from 4 to 17 mg/m$^2$ for planting, and from 18 to 33 mg/m$^2$ for crop mechanical harvesting (Table 1). The PM$_{10}$ released from tilling was significantly higher than that released from planting and crop harvesting with same meteorological conditions. The PM$_{10}$ EFs of tilling and planting displayed an exponentially decreasing trend with increasing soil moisture (Fig. 3), similar to that found in Wang et al. (2010). Based on the empirical equations, PM$_{10}$ emissions from tilling and planting were estimated to be 92 and 15 mg/m$^2$ for dry soil (i.e., 10%, V/V) and 28 and 7 mg/m$^2$ for wet soil (i.e., 20%, V/V).

#### 2.2. Magnitude of agricultural dust emissions

Using measured local EFs, total emissions of PM$_{10}$ and PM$_{2.5}$ in northeastern China in 2013 were calculated to be 35.1 and
9.8 kilotons, respectively (Table 2). However, PM\(_{10}\) emissions based on the methods of CARB and EEA were estimated to be 196.4 and 8.5 kilotons, indicating large differences among the three calculation methods. Field tilling, planting and crop harvesting accounted for 61%, 11% and 28% of total emissions, respectively. On the provincial scale, Heilongjiang was the biggest contributor, with 46% of the total agricultural emissions from all crops, and Liaoning had the smallest contribution.

Our results showed that county-level PM\(_{10}\) emissions were significantly correlated to planting areas of corn and soybean (\(n = 214, r^2 = 0.62, p < 0.0001\)), which were major dry farmlands in northeastern China. The ratio of PM\(_{10}\) emission to crop area in each county varied from 1.37 to 8.69 kg/ha, with an average of (2.10 ± 1.14) kg/ha.

2.3. Spatio-temporal distribution of agricultural dust emissions

The characteristics of spatial distribution showed that agricultural PM\(_{10}\) emissions substantially covered most areas except two forest regions, i.e., the greater and smaller Hinggan Mountains and the Changbai Mountains (Fig. 4). The total magnitude of PM\(_{10}\) emissions depended on the area of dryland farming in each county, and the largest administrative county is Neijiang located in western Heilongjiang Province. Although the differences in the agricultural PM\(_{10}\) emissions according to the three calculation methods were determined, the high emission intensity (i.e., county-area-based PM\(_{10}\) emissions) was clearly shown to be concentrated in the Songnei Plain, the western part of the Sanjiang Plain and small parts of the Liaohhe Plain (Fig. 4).

The PM\(_{10}\) emissions from agricultural tilling and harvesting mainly occurred in April, May, September, October and November (Fig. 5). The two highest emission months were May and April, which accounted for 56% and 19% of total annual emissions, respectively. This level indicates that spring tilling and planting accounts for three-fourth of annual emissions. The period of crop harvest and fall tilling from September to November accounts for only 20% of PM\(_{10}\) emissions in northeastern China. The emission ratios of field operations from corn, soybean and rice farmland to all croplands were 60%, 19% and 5%, respectively.

3. Discussion

Among various agricultural sources of PM emissions, previous studies have focused on crop residue burning contributions to regional extreme smog and haze events (Zhang et al., 2007, 2010). Agricultural anthropogenic or wind-blown dust emissions from farmlands are overlooked in regional air quality modeling. However, these emissions may play an important role in northern China, an area with widespread dryland farming. For example, current study of northeastern China first discussed the systematic procedures of developing regional emission inventory (EI) compliance, thereby serving to further national emission inventory from agriculture in China.

In this study, calculated PM\(_{10}\) EF values (4–119 mg/m\(^2\)) in northeastern China fell within the range previously reported around the world. Holmén et al. (2001) reported that the PM\(_{10}\) EF
values of various field activities ranged from 0 to 800 mg/m²; Bogman et al. (2005) estimated a PM₁₀ EF range of 150–230 mg/m² from crop tilling and harvesting in Belgium; Qiu and Pattey (2008) measured a PM₁₀ EF of 74 mg/m² for wheat harvest in Canada; Wang et al. (2010) reported PM₁₀ EF values from different operations in cotton, wheat and tomato fields, ranging from 8 to 488 mg/m²; and Moore et al. (2014) determined the PM₁₀ EF for conventional operations and combined management practices to have a range of 41–168 mg/m² in fall tilling operations. Our results showed that the PM emissions from tilling were approximately six and three times those from planting and harvesting for corn and soybean fields, respectively. In California, land preparation practices (e.g., ripping, plowing, disking and tilling) account for more than 65% of the total agricultural PM₁₀ emissions, whereas planting and harvesting account for the remainder of the emissions (Clausnitzer and Singer, 1996, 1997). The reasons for more dust production from land preparation or tilling operations include the greater soil disturbance and drier soil conditions than in other operations. Moreover, combining practices of land preparation could significantly reduce PM₁₀ and PM₂.₅ by 60% and 29%, compared to conventional practices (Moore et al., 2014). Therefore, promoting and popularizing combined conservation management methods is an efficient approach to decrease agricultural PM emissions, especially for vast farmland in northeastern China.

Most studies have suggested that the main controlling EF was soil moisture, followed by wind speed, and soil silt content for similar farming operations. The exponentially decreasing relationships between PM EFs from tilling and soil

### Table 2 – Magnitude of agricultural PM₁₀ and PM₂.₅ emissions from all crop fields and the two main crops of corn and soybean, all crop areas and corn and soybean areas in each province and eastern Inner Mongolia.

<table>
<thead>
<tr>
<th>Province/region</th>
<th>Crop area (×10⁶ ha)</th>
<th>Corn and soybean area (×10⁶ ha)</th>
<th>Total PM₁₀ emissions (kiloton)</th>
<th>Total PM₂.₅ emissions (kiloton)</th>
<th>PM₁₀ emissions from corn and soybean fields (kiloton)</th>
<th>PM₂.₅ emissions from corn and soybean fields (kiloton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liaoning</td>
<td>5.8</td>
<td>4.0</td>
<td>5.1</td>
<td>0.56</td>
<td>3.3</td>
<td>0.36</td>
</tr>
<tr>
<td>Jilin</td>
<td>4.3</td>
<td>2.5</td>
<td>6.2</td>
<td>0.68</td>
<td>5.3</td>
<td>0.58</td>
</tr>
<tr>
<td>Heilongjiang</td>
<td>11.9</td>
<td>9.0</td>
<td>16.3</td>
<td>1.80</td>
<td>12.2</td>
<td>1.34</td>
</tr>
<tr>
<td>Inner Mongolia</td>
<td>4.7</td>
<td>2.9</td>
<td>7.5</td>
<td>0.83</td>
<td>3.8</td>
<td>0.42</td>
</tr>
<tr>
<td>All</td>
<td>26.6</td>
<td>17.6</td>
<td>35.1</td>
<td>3.86</td>
<td>24.6</td>
<td>2.71</td>
</tr>
</tbody>
</table>

Fig. 4 – County-level total PM₁₀ emission estimates (i.e., magnitude and density) for agricultural tillage, planting and harvest operations in northeastern China, based on three sets of emissions factors from local-measurement (a, d), CARB (b, e) and EEA methods (c, f). EFL Inner Mongolia: Eastern Four Leagues of Inner Mongolia; CARB: California Agriculture Resource Board; EEA: European Environment Agency.
moisture illustrated that PM emissions greatly increased when soil moisture was less than 10% and rapidly decreased when soil moisture was greater than 20%–25% (Fig. 3). Generally, soil moisture in wet climates is significantly greater due to more precipitation. In the published standards, CARB EFs represent a Mediterranean arid climate, with original measurements in California (CARB, 2003). The EEA guidelines provide two sets of EFs, for wet climates and dry climates, and the values for dry climates are tenfold for wet climates (EEA, 2009). Our studies showed that the EFs from tilling (i.e., 9–119 mg/m²) were significantly lower than those in dry climates as reported by CARB (i.e., 517 mg/m²) and EEA (i.e., 225 mg/m²), but higher than those in wet climates as reported by EEA (i.e., 25 mg/m²). Similarly, the EFs from soybean and corn harvesting (18–33 mg/m²) in this study are far below the CARB guidelines (188 mg/m²) and EEA guidelines (110 mg/m²) for dry climate conditions and are comparable to EEA guidelines (11 mg/m²) for wet climates. The levels of EFs are reasonable for the Northeastern Plain, which is mainly characterized by a semi-wet climate with a total precipitation of 500–750 mm. Conversely, the higher soil organic content in blackland was conductive to more soil-to-atmosphere transfer than other soil types under similar field operations. Thus, the local-EF-based PM₁₀ emissions (i.e., 35.1 kilotons) estimated in this study were approximately one-fifth and quadruple those measured with CARB and EEA methods, respectively, indicating the importance of measuring local EFs to obtain accurate estimates. The study also implies that greater agricultural dust emissions occurred in regions in northern China and northwestern China due to the drier climate and lower soil organic matter contents.

Temporal, spatial and chemical profiles are important information inputs for air quality modeling. The diurnal profile and chemical profile induced by field tilling have been estimated in a previous study (Chen et al., 2015). Spatiality showed that agricultural dust emissions are mainly concentrated in the center of northeastern China (Fig. 4), where widespread dry and farming occurs. The topography of northeastern China is characterized by so-called “three mountains with plains”. The west, north and east borders of this area are delimited by the Greater Hinggan Mountains, the lesser Hinggan Mountains and the Changbai Mountains, respectively, whereas the south is a flat area adjacent to the “Beijing-Tianjin-Hebei” region. The agricultural dust emissions in the west, north and east could be neglected due to less farmland in the mountainous areas. In addition, the southwestern part of northeastern China comprises primarily grassland areas under the administration of Hulunbeir League, Tongliao City and Chifeng City. Although dust could also be released from grass mowing in September and October, previous studies have generally considered mowing to be a natural wind-blown dust source (Shinoda et al., 2011). We did not include grassland in the agriculture sources, resulting in lower emission intensities in the three leagues or cities of Inner Mongolia. With the exception of the mountains and grasslands, other regions considered are the general Northeast Plain, involving the Sanjiang Plain (i.e., northeastern corner), the Songnen Plain (i.e., center part) and the Liaohe Plain (i.e., southern part and southeastern corner). In the past few decades, a large number of natural wetlands in the Sanjiang Plain have been reclaimed as farmland, and field rice is the main crop now (Zhang et al., 2011). Little dust is emitted during rice reaping; therefore, most areas in the Sanjiang Plain are limited emission sources of agricultural dust. A similar status can be seen in the lower Liaohe Plain, where much rice planting occurs.

Agricultural dust emissions occur from March to November in northeastern China based on the crop calendars (Fig. 5). A single planting pattern is used for the main grain crops in the region. Little dust emissions in March originate from wheat because the ground has vegetative cover. April and May are major periods of dust emissions as a result of conventional land preparation and planting corn and soybean. Furthermore, winds during this period enhance both dust emissions from field activities and wind-blown dust emissions, which easily cause regional fugitive dust weather, especially during the continuously clear days of May, when intensive field operations occur. Wheat harvesting, vegetable planting and crop mechanical weeding or spraying pesticides are generally carried out from June to August, generating smaller emissions due to less soil disturbance. September to November is the harvest period of major crops, with two field activities, including crop reaping and fall tillage; with the biggest share occurring in October. Compared with spring tilling, fall tilling has gradually been promoted as a government policy because of its multifunctional effects such as improving soil properties, deepening topsoil, killing pests and conserving water and soil moisture. Thus, the spatio-temporal characteristics of agricultural dust emissions will be affected with the change in crop planting patterns and improvement of field operations. In addition, soil moisture and wind speed are generally lower in the fall than that in the spring, which could reduce soil dust emissions during the mechanical disturbance.

Another important parameter for developing a PM₂.₅ emission inventory is the ratio of PM₂.₅ and PM₁₀ induced by agricultural activities (CARB, 2003; EEA, 2009). The CARB reported the value of 15% for all activities and EEA reported 4% and 6% in wheat and grass production, respectively. In this study, the ratios for tilling, planting and harvesting (i.e., 28, 26% and 32%, respectively) were greater than the CARB and EEA values, possibly because more organic dusts are released with straw and residue ash during tilling and the particle size

Fig. 5 – Monthly variations in agricultural PM₁₀ emissions and the contribution of different crop fields to total PM₁₀ emissions in northeastern China.
of organic dust is smaller than that of mineral particles from field activities (Chen et al., 2015).

As a large agricultural nation, field operations could disturb surface soil and release mineral particles into atmosphere, especially for upland crops, which may affect local and regional air quality or aggravate haze pollutions. Presently, there is no national or regional emission inventory of agricultural dust emissions to support air quality modeling in China (Zhang et al., 2009; Cao et al., 2011; Hu et al., 2011). In future agricultural dust emission research, we recommended that local EFs of PM$_{10}$ and PM$_{2.5}$ from major field operations are measured in major agricultural regions in northern China. The EF values will be useful for generating a set of EFs for a national inventory that could be amended by characteristics of agricultural production, climate, soil and environmental variables. In addition, work is needed to verify the inventory and application of the inventory data to regional air quality modeling to estimate the role of agricultural dust emissions in regional air quality.

4. Conclusions

Agricultural dust emission inventories (i.e., PM$_{10}$ and PM$_{2.5}$) have been developed for northeastern China. The major contributor, field tilling (or land preparations), accounted for approximately three-fifths of the total emissions. Local magnitude, factors-based PM emission calculations presented obvious differences from CARB and EEA guidelines, reflecting the regional climate and soil characteristics of EFs. The regions with high emission intensity are mainly distributed in the center of the Northeast Plain, covering the middle of the Heilongjiang Provinces and the western areas of the Jilin Provinces. These regions are the major corn and soybean planting belts. May is the largest emission month (i.e., 56% of the total annual emissions), due to concentrated land preparation activities. This inventory information, including local emission factors, PM$_{2.5}$/PM$_{10}$ ratios, and temporality, might be useful for national agricultural PM emission inventories and regional air quality modeling. Further research should focus on other dryland regions in China (i.e., the Northern Plain and the Loess Plateau) and more key parameters, especially chemical profiles of agricultural dust emissions.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Nos. 41205106, 41205107 and 41275158). We also thank the staff of the sampling sites for their support in the field experiments and for preparing agricultural information.

References


