*remote sensing*

MDPI

*Technical Note*

# Examining the Influence of Crop Residue Burning on Local $PM_{2.5}$ Concentrations in Heilongjiang Province Using Ground Observation and Remote Sensing Data

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**Abstract:** Although a many studies concerning crop residue burning have been conducted, the influence of crop residue burning on local $PM_{2.5}$ concentrations remains unclear. The number of crop residue burning spots was the highest in Heilongjiang province and we extracted crop residue burning spots for this region using MOD14A1 (Thermal Anomalies & Fire Daily L3 Global 1 km) data and national land cover data. By analyzing the temporal variation of crop residue burning and $PM_{2.5}$ concentrations in Heilongjiang province, we found that the total number of crop residue burning spots was not correlated with the variations of $PM_{2.5}$ concentrations at a provincial (regional) scale. However, crop residue burning exerted notable influence on the variations of $PM_{2.5}$ concentrations at a local scale. We experimented with a set of buffer zone radiuses to examine the influencing area of crop residue burning. The results suggest that the valid influencing area of crop residue burning was between 50 and 80 km. The mean $PM_{2.5}$ concentration measured at stations close to crop residue burning spots was more than 60 $\mu g/m^3$ higher than that measured at stations not close to crop residue burning spots. However, no consistent, significant correlation existed between the existence of crop residue burning spots and local $PM_{2.5}$ concentrations, indicating that local $PM_{2.5}$ concentrations were influenced by a diversity of factors and not solely controlled by crop residue burning. This research also provides suggestions for better understanding the role of crop residue burning in local and regional air pollution.

**Keywords:** crop residue burning; $PM_{2.5}$ concentrations; remote sensing; MOD14A1

## 1. Introduction

Since the outbreak of a severe haze episode in Beijing in December 2012, regional and national haze episodes have been frequently witnessed across China in recent years. Since $PM_{2.5}$ is a major threat to people's health, the government is placing more and more emphasis on the monitoring and improvement of local and regional air quality. One key step for understanding the formation and evolution mechanism of airborne pollutants is to quantify the contribution of different emission sources to local $PM_{2.5}$ concentrations. Hence, many studies [1–4] have been conducted to analyze sources of $PM_{2.5}$ concentrations in different cities and have shown that emission sources such as traffic, coal burning, biomass burning, cooking, dust related emissions, industrial pollution, and secondary inorganic aerosol all contributed significantly to variations of $PM_{2.5}$ concentrations. In addition to these sources, the contribution of crop residue—materials left over from the production of crops—burning to local and regional haze episodes has been widely discussed recently. In November 2016, more than thirty big cities in China experienced a long-lasting haze episode, which caused massive social and economic losses. According to the survey reports provided by the Ministry of Environmental Protection (MEP) [5], crop residue burning, especially in Heilongjiang province, was the major cause for this national haze episode. According to analysis based on remotely sensed data, MEP revealed that during a week's time, the total number of detected crop residue burning spots in Heilongjiang province was up to 580, much larger than that in neighboring provinces. Similarly, within the Beijing-Tianjin-Hebei region, the most polluted region in China, crop residue burning induced air pollution has been reported as well. MEP suggested that crop residue burning was the major contribution to a severe regional haze episode in the Beijing-Tianjin-Hebei region in October 2015 [6]. Recently, with increasing haze episodes caused by crop residue burning, massive studies have been conducted to quantify the total emission of crop residue burning at the regional and national scale [7–9] and evaluate the emission of in-situ crop residue burning [9–15]. These studies mainly focused on quantifying emission factors of crop residue burning and predicting the total emission amount of different pollutants caused by crop residue burning at the local, regional, and national scale. However, compared with traffic, industry emissions, and other major emission sources, few in-depth studies on the quantitative influences of crop residue burning on the variations of local and regional $PM_{2.5}$ concentrations have been conducted. Yin et al. [16] examined the spatial and seasonal distribution of crop residue burning across China and its correlation with regional $PM_{2.5}$ concentrations. This research [16] attempted to establish qualitative correlations between the intensity of crop residue burning and regional $PM_{2.5}$ concentrations by analyzing the total number of crop residue burning spots and the spatio-temporal variations of regional $PM_{2.5}$ concentrations, respectively. Yin et al. [16] provided a feasible solution for linking the temporal variations of regional $PM_{2.5}$ concentrations to the influencing area and intensity of regional crop residue burning activities. However, this research simply revealed that the temporal variation of the total number of crop residue burning spots within a large region was generally consistent with that of regional $PM_{2.5}$ concentrations. Due to the resolution inconsistence between MODIS and $PM_{2.5}$ data, the influence of crop residue burning on the variations of local $PM_{2.5}$ concentrations has yet to be thoroughly investigated.

Currently, the negative influence of crop residue burning on local and regional air quality has been widely accepted, and a set of environmental protection policies will be implemented accordingly. Hence, large-scale crop residue burning activities will be strictly restricted and the number of crop residue burning induced regional haze episodes will be reduced effectively. Meanwhile, scattered crop residue burning activities still exert strong influences on the variation of local $PM_{2.5}$ concentrations. In this case, we employed ground $PM_{2.5}$ observation data and remote sensing data to understand the correlation between crop residue burning and the variation of $PM_{2.5}$ concentrations surrounding crop residue burning spots. The method and findings from this research may provide useful references for scholars and decision makers to better monitor and manage air pollution induced by crop residue burning.

## 2. Materials

### 2.1. Study Sites

Heilongjiang province (43°26′–53°33′N, 121°11′–135°05′E), located in the northeast of China, is adjacent to Jilin province in the south and Inner Mongolia in the west (the location of Heilongjiang province is shown in Figure 1). The west part of Heilongjiang province belongs to the Songnen

Plain and the northeast part belongs to the Sanjiang Plain. The north and southeast part of Heilongjiang province are mainly mountain landscapes. Heilongjiang province is controlled by Temperate Continental Monsoon Climate. Heilongjiang province is one of the most important heavy industry centers in China. Meanwhile, due to its excellent climate and soil conditions, Heilongjiang province is well-known for its high-quality agricultural products, rice in particular. The unique climate and geographical conditions lead to a one-cropping system in Heilongjiang province. Since the crop is mainly harvested in the fall, the burning activities of crop residue are frequently witnessed in October, increasing the potential risk of haze episodes at a local, even regional scale.

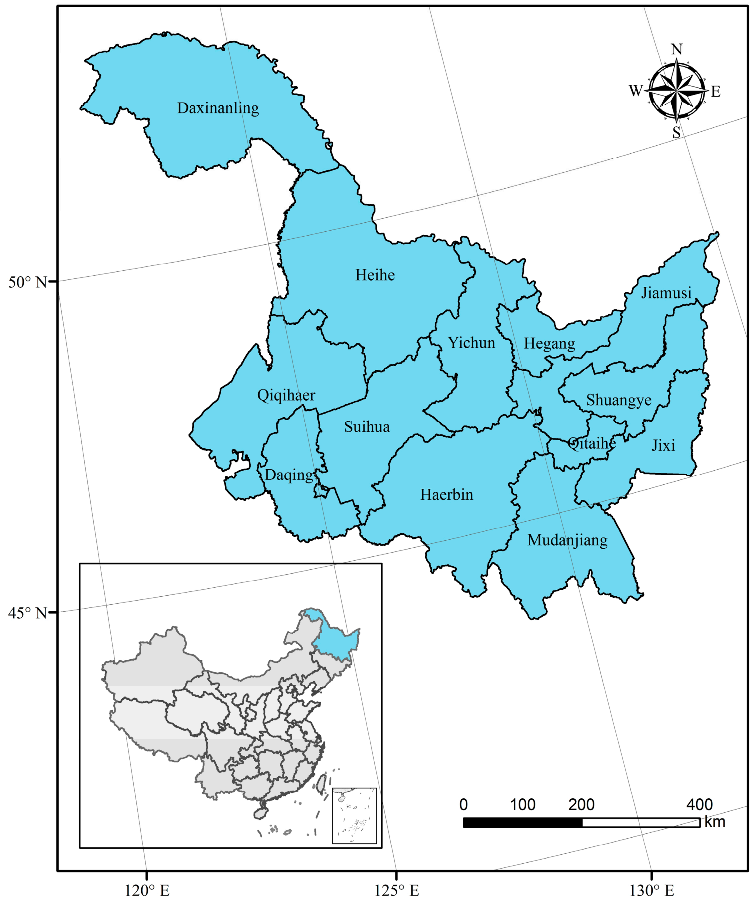



**Figure 1.** Geographical location of Heilongjiang province in China.

As introduced above, MEP suggested that large-scale crop residue burning was the major cause for a national wide haze episode (31 October 2016 to 6 November 2016). Specifically, MEP pointed out that the number of observed crop residue burning spots in Heilongjiang province was up to 580 whilst the total number across China was 756. MEP further revealed that the detected total number of crop residue burning spots in Heilongjiang province was much larger (1072) during the same period (31 October–6 November) in 2015. Meanwhile, the total number of crop residue burning spots for most provinces was on average less than five per day, even during the period with intensive crop residue burning activities. To establish reliable correlations between crop residue burning and the variation of $PM_{2.5}$ concentrations surrounding crop residue burning spots, a large number of ground $PM_{2.5}$ observation stations, which are close enough to crop residue burning spots, is required. Therefore, Heilongjiang province was an ideal study site for this research and the period 31 October 2016 to 6 November 2016, when the crop residue burning activities were the most intense in Heilongjiang province, was selected as the study period.

## *2.2. Data Sources*

### 2.2.1. Ground $PM_{2.5}$ Concentrations Data

Ground $PM_{2.5}$ data were acquired from the website PM25.in. This website collects official $PM_{2.5}$ concentration data as well as data on other airborne pollutants, all provided by the China National Environmental Monitoring Center (CNEMC), and publishes hourly air quality information for all monitoring cities. Since 1 January 2015, the number of monitoring cities has increased to 367 and the total number of observation stations has been increased to 1450. By calling specific API provided by PM25.in, we collected hourly $PM_{2.5}$ data for all observation stations within the Heilongjiang province during the period of 30 October to 6 November 2015. The distribution of 55 ground $PM_{2.5}$ observation stations within Heilongjiang province is demonstrated in Figure 2.

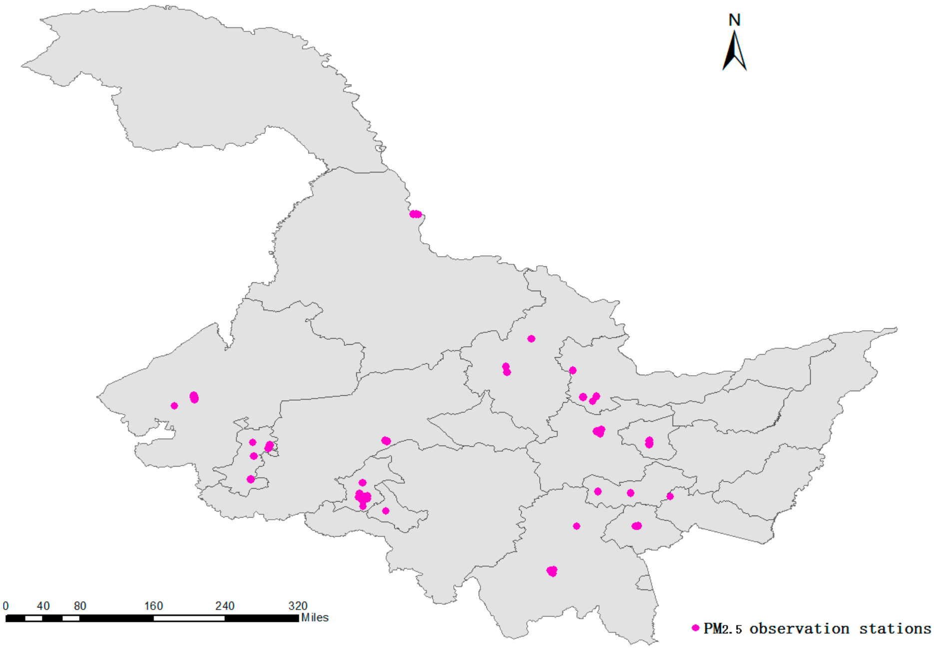



**Figure 2.** Distribution of ground $PM_{2.5}$ observations within Heilongjiang Province.

### 2.2.2. Remote Sensing Data

Similar to previous studies [7–9], this research employed MODIS Thermal Anomalies/Fire products (MOD14A1) for extracting crop residue burning spots. MODIS Thermal Anomalies/Fire products are mainly produced based on MODIS bands at 4 and 11 mm radiances [17]. The fire detection strategy is based on absolute detection of a fire (when the fire strength is sufficient to detect) and on relative detection of a fire according to the difference between its Digital Number (DN) and the DN from the background, which considers the variability of the surface temperature and reflection by sunlight. Several experiments have been conducted to reject typical false alarm sources, such as sun glint or an unmasked coastline [18]. MOD14A1 data with a spatial resolution of 1 km are produced every 8 days as a level-3 raster product in the Sinusoidal projection. This product is of three dimensions: fire-mask (1D) and a maximum fire-radioactive-power (2D) are provided for each day (3D) in the 8-day period. The fire-mask contains an eight band-sequential (day), representing eight consecutive days of data collection. By separating the eight fire-masks, we can extract daily Thermal Anomalies/Fire images. For Heilongjiang province (43°26′–53°33′ N, 121°11′–135°05′ E), four tiles of MOD14A1 data, h25v03, h26v03, h26v04, and h27v04, were downloaded to cover the entire study area. We extracted daily fire maps from 31 October to 6 November 2015. The MOD14A1 data were downloaded from NASA's LAADS Data Center [19].

2.2.3. Land Cover Data

Although daily fire maps effectively reflect the distribution of fire spots across the study areas, these fire spots are not necessarily crop residue burning spots. The burning of urban rubbish and wild fires that occur in the forests may also be detected in the daily fire maps. As a result, land cover data that categorizes the cropland can be employed to assist the extraction of crop burning spots from fire maps. In this case, we obtained a 2015 land cover product with 30 m resolution from Resources and Environmental Science Data Center, Chinese Academy of Science (http://www.resdc.cn/). This dataset is the latest, high-resolution national land cover data set and has been widely used in a diversity of studies. There are six major land cover types: cropland, forest, grassland, water, urban, industrial and residential areas, and unused land. By identifying fires that occurred in the cropland areas, we can extract reliable crop residue burning spots for the following analysis.

## 3. Methods

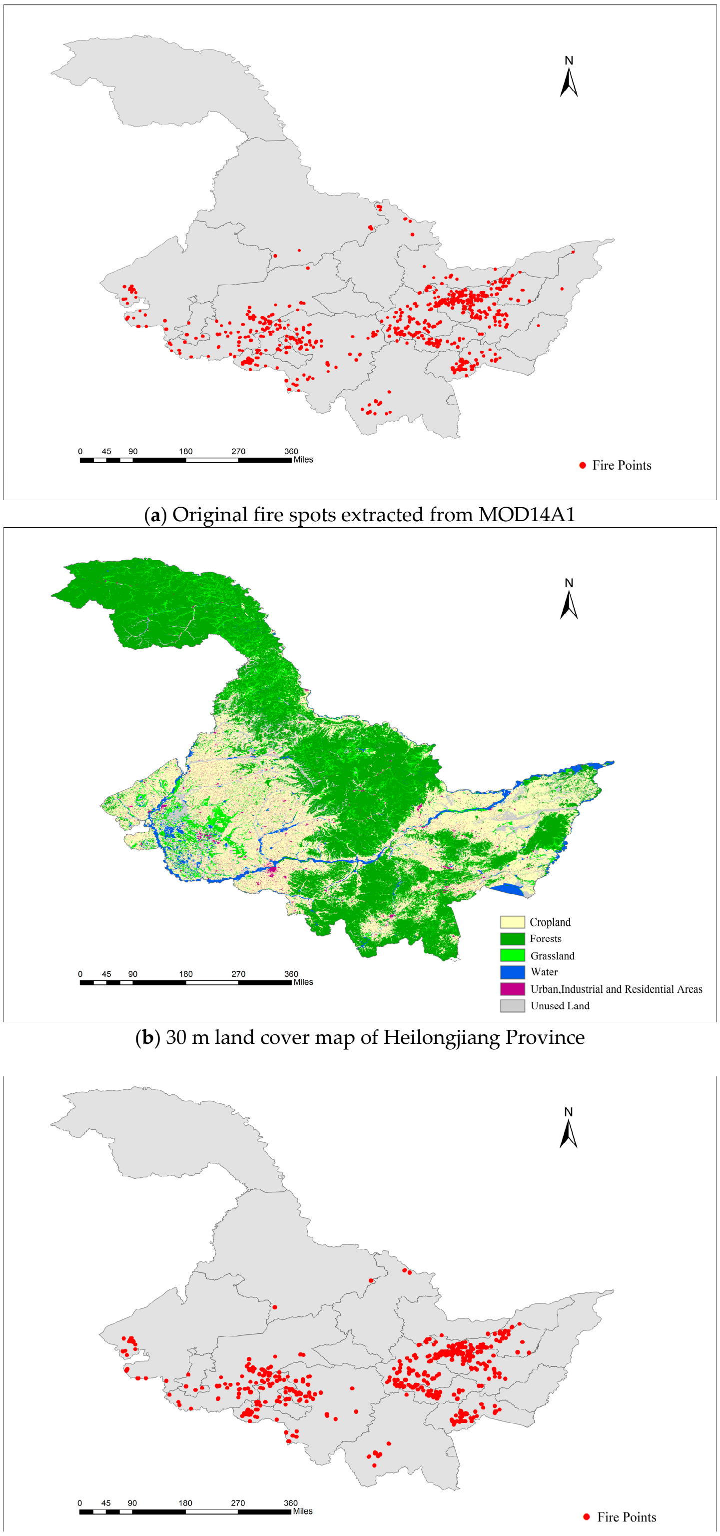
First, MOD14A1 data were preprocessed using the MODIS Reprojection Tool for the following analysis. The preprocessing tasks included: re-projection of raw images, format conversion, image mosaic, and the separation of fire-masks. Then, by setting proper DN thresholds, daily fire maps for Heilongjiang province during this study period were produced. Secondly, overlay analysis was conducted using the land cover data and daily fire maps and fire spots detected on the land cover type identified as cropland were extracted as crop residue burning spots. Following this, buffer zone analysis was conducted to find ground $PM_{2.5}$ observation stations that were close to the crop residue burning spots. To examine the influence of crop residue burning on local $PM_{2.5}$ concentrations, buffer zones with different radii were tested to find the valid influence area of crop residue burning. For each day during the study period, the buffer zone analysis divided all observation stations into two groups: stations that were close to crop residue burning spots and stations that were not influenced by nearby crop residue burning spots. Statistical and correlation analysis were conducted for each group of stations to reveal the influence of crop residue burning on local $PM_{2.5}$ concentrations.

## 4. Results

### *4.1. Extraction of Crop Residue Burning Spots*

With processed MOD14A1 data, we firstly produced daily fire maps for Heilongjiang province. MOD14A1 data are level 3 products, and only one parameter is required. The DN value for MOD14A1 represents the category of different reflection types, such as water, cloud, and non-fire. Specifically, DN value 7 stood for fire with low confidence, 8 for fire with nominal confidence, and 9 for fire with high confidence. Generally, sacrificing a small proportion of fire spots will not influence the following statistical and correlation analysis whilst the inclusion of false fire spots may influence the accuracy of the following overlay and buffer zone analyses. Therefore, we discarded potential fire spots with low confidence, and selected DN 8 and DN 9 as the thresholds to extract daily fire maps.

As introduced, the daily fire maps include fire spots detected in urban areas and forests, so the 30 m-resolution land cover map of Heilongjiang province was employed for the overlay analysis. The extracted daily fire spots were mainly point-based vector data whilst the land cover data was raster data. For most GIS tools, overlay analysis can only be executed between two sets of vector data. So, we employed the Extraction tool in ArcGIS for obtaining information from raster images and assigning the attribute to a corresponding vector object. Through the overlay analysis, fire spots located on the cropland type were extracted as crop residue burning spots (Figure 3). The extraction results of crop residue burning are listed in Table 1. It is worth mentioning that the total number of crop residue burning spots extracted using the MOD14A1 data and the 30 m land cover map was 3362, whilst the number of extracted crop residue burning spots reported by MEP was 1072. The difference may be attributed to the processing of the extracted crop residue burning spots. We did not merge crop residue burning spots that were located nearby, whilst MEP may treat several crop residue burning spots located close together as one large residue burning spot. The difference in processing methods exerts slight influences on the following analysis, as the calculated number of crop residue burning spots for each day generally changed proportionally.




(**a**) Original fire spots extracted from MOD14A1

(**b**) 30 m land cover map of Heilongjiang Province

(**c**) Extracted crop residue burning spots

**Figure 3.** The extraction of crop residue burning spots within Heilongjiang province on 31 October 2015.

**Table 1.** Detected number of crop residue burning spots and mean $PM_{2.5}$ concentrations within Heilongjiang province during 31 October to 6 November 2015.

| Date | Total Number of Crop Residue Burning Spots | Mean $PM_{2.5}$ Concentrations (μg/m$^3$) |
|---|---|---|
| 2015/10/31 | 597 | 67.84 |
| 2015/11/01 | 469 | 132.06 |
| 2015/11/02 | 373 | 182.79 |
| 2015/11/03 | 899 | 136.15 |
| 2015/11/04 | 397 | 105.55 |
| 2015/11/05 | 466 | 52.49 |
| 2015/11/06 | 161 | 123.64 |

## *4.2. The Influence of Crop Residue Burning on Local $PM_{2.5}$ Concentrations*

### 4.2.1. Total Number of Crop Residue Burning Spots and Mean $PM_{2.5}$ Concentrations within Heilongjiang Province

Yin et al. [16] attempted to establish a qualitative linkage between the number of crop residue burning spots and the temporal variation of $PM_{2.5}$ concentrations at a regional scale. The result suggested that a long-term variation of the total number of crop residue burning spots was generally consistent with the average $PM_{2.5}$ concentrations within specific regions. For this research, we also attempted to examine whether there was a correlation between the total number of crop residue burning spots and $PM_{2.5}$ concentrations within Heilongjiang province during episodes with intense crop residue burning. The simultaneous variations of the total number of crop residue burning spots and mean $PM_{2.5}$ concentrations within Heilongjiang province are shown in Figure 4. According to Figure 4, it is noted that there is no clear linear correlation between the number of crop residue burning spots and mean $PM_{2.5}$ concentrations at the provincial level. Different from Yin et al.'s findings [16], this research suggests that crop residue burning, even with the largest intensity (the number of crop residue burning spots in Heilongjiang province was the most in China during this period) exerted limited influence on the variations of $PM_{2.5}$ concentrations at a large scale, which was also influenced significantly by a diversity of emission sources and meteorological factors. Therefore, we would suggest further examination of the influence of crop residue burning on local $PM_{2.5}$ concentrations.

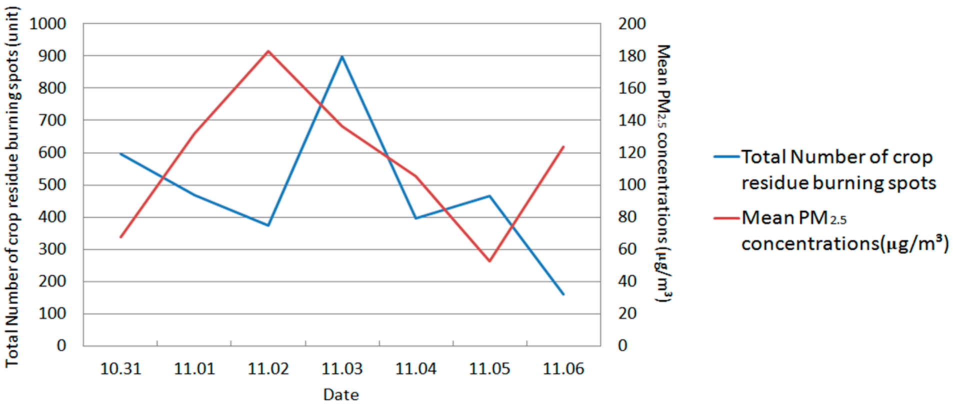



**Figure 4.** The simultaneous variations of the total number of crop residue burning spots and mean $PM_{2.5}$ concentrations within Heilongjiang province.

### 4.2.2. The Influence of Crop Residue Burning on Local $PM_{2.5}$ Concentrations

Since the influencing area of crop residue burning has rarely been investigated by previous studies, we attempted to test different radiuses for buffer zones surrounding the crop residue burning spots.

Through preliminary analysis, we found that 10 km should be a minimum threshold for a valid radius of the buffer zones. For this research, we tested the radiuses of 10, 20, 50, 80, and 100 km. As can be seen from Figure 5, for each scenario, if the distance between one $PM_{2.5}$ observation station and any crop residue burning spot was less than the radius of the buffer zones, then this station was marked as a station that was close to crop residue burning spots; in contrast, if the distance between one $PM_{2.5}$ observation station and any crop residue burning spot was more than the radius of the buffer zones, it was marked as a station that was not close to crop residue burning spots.

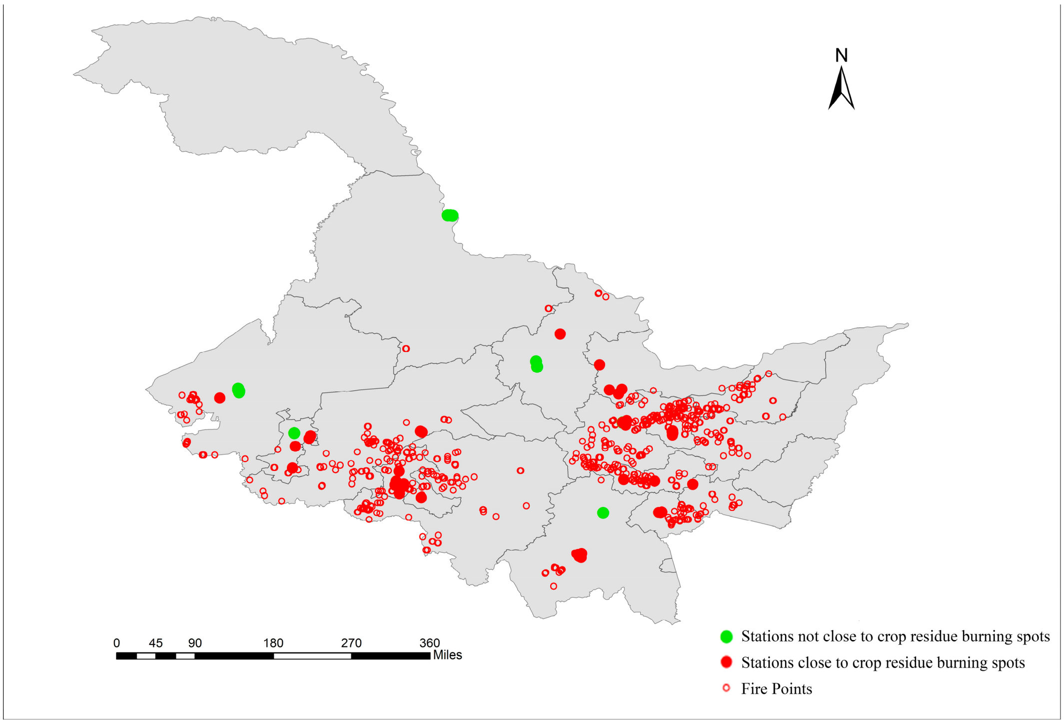



**Figure 5.** Classification of observation stations that were close or not close to crop residue burning spots on 31 October 2015 (The buffer zone radius was 50 km).

For each radius, we calculated and compared the daily mean $PM_{2.5}$ concentration of stations that were close to crop residue burning spots with that of stations that were not close to crop residue burning spots. The comparison results are shown in Figure 6. According to Figure 6, it is noticed that for scenarios 10 km and 20 km, the daily mean $PM_{2.5}$ concentration of stations that were not close to crop residue burning spots was even higher than that of stations that were close to crop residue burning spots for some days, which is not realistic. This phenomenon indicated that the influencing area of crop residue burning was notably larger than 20 km, and, thus, those stations marked as not close to burning spots were also influenced significantly by crop residue burning. Meanwhile, we can see that the difference between mean $PM_{2.5}$ concentrations of stations that were and stations that were not close to burning spots was highly notable for radiuses of 50 km, 80 km, and 100 km (Table 2). According to Table 2, the mean $PM_{2.5}$ concentrations from stations close to crop residue burning spots was more than 60 μg/m$^3$ higher than that from stations not close to crop residue burning spots. Meanwhile, the curve for 80 km and 100 km was very similar. These results indicate that the valid influencing area of crop residue burning on local $PM_{2.5}$ concentrations was between 50 and 80 km. The comparisons between the mean $PM_{2.5}$ concentrations from stations close to crop residue burning spots and those from stations not close to crop residue burning spots are listed in Table 2.

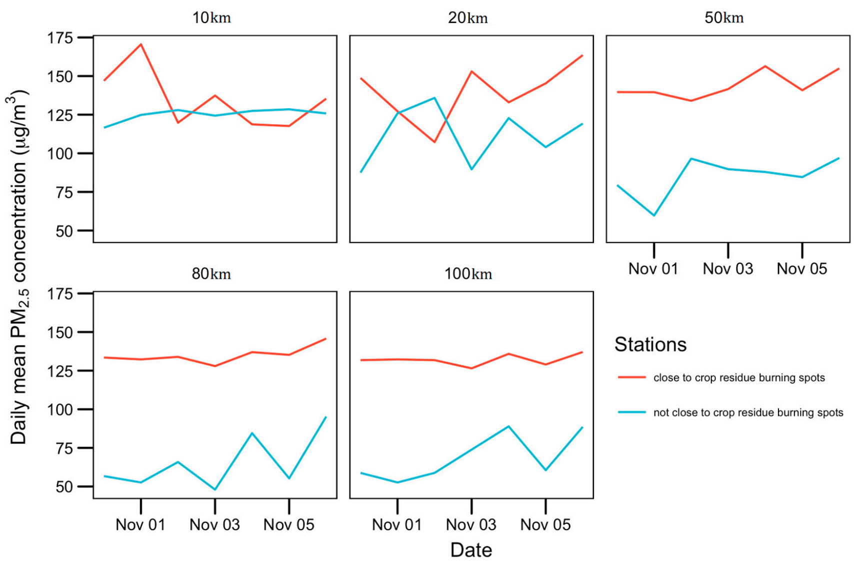



**Figure 6.** Comparison of daily mean $PM_{2.5}$ concentrations of stations that were close to crop residue burning spots and stations that were not close to crop residue burning spots (where the red line represents stations close to crop residue the blue line represents stations not close to crop residue burning spots) during 31 October–6 November 2015.

**Table 2.** The comparison between the mean $PM_{2.5}$ concentrations from stations close to and those from stations not close to crop residue burning spots ($\mu g/m^3$).

| Day | Buffer: 50 km | | Buffer: 80 km | | Buffer: 100 km | |
|---|---|---|---|---|---|---|
| | Not Close | Close | Not Close | Close | Not Close | Close |
| 2015/10/31 | 79.44 | 139.63 | 56.74 | 133.47 | 58.82 | 131.81 |
| 2015/11/01 | 59.71 | 139.57 | 52.64 | 132.29 | 52.64 | 132.29 |
| 2015/11/02 | 96.55 | 133.99 | 65.85 | 133.93 | 58.82 | 131.81 |
| 2015/11/03 | 89.71 | 141.59 | 48 | 127.95 | 75.99 | 126.50 |
| 2015/11/04 | 87.91 | 156.37 | 84.55 | 136.99 | 88.95 | 135.89 |
| 2015/11/05 | 84.58 | 140.81 | 55.28 | 135.22 | 60.57 | 128.99 |
| 2015/11/06 | 96.97 | 154.97 | 95.28 | 145.78 | 88.61 | 137.07 |
| overall | 84.98 | 143.85 | 65.48 | 135.09 | 69.20 | 132.05 |
| difference | 58.86 | | 69.61 | | 62.85 | |

Meanwhile, for each scenario, we examined the correlation between the existence of crop residue burning and $PM_{2.5}$ concentrations, and the results are shown in Table 3. According to Table 3, it is noted that there was no consistent, significant correlation between the existence of crop residue burning spots and local $PM_{2.5}$ concentrations. This result suggests that local $PM_{2.5}$ concentrations were influenced by a diversity of emission sources, geographical conditions, and meteorological factors [20,21] and was not solely controlled by crop residue burning, even during specific haze episodes.

**Table 3.** The correlation between the existence of crop residue burning and local $PM_{2.5}$ concentrations.

| | | Existence of Nearby Crop Residue Burning Spots | | | | |
|---|---|---|---|---|---|---|
| | | 10 km | 20 km | 50 km | 80 km | 100 km |
| $PM_{2.5}$ concentrations | 2015/10/31 | 0.190 | 0.078 | 0.154 | 0.216 | 0.210 |
| | 2015/11/01 | 0.008 | 0.120 | 0.352 ** | 0.213 | 0.213 |
| | 2015/11/02 | 0.065 | −0.170 | 0.191 | 0.157 | 0.152 |
| | 2015/11/03 | −0.094 | 0.088 | 0.199 | 0.037 | 0.124 |
| | 2015/11/04 | −0.084 | 0.214 | 0.270 * | 0.067 | 0.038 |
| | 2015/11/05 | −0.100 | 0.191 | 0.229 | 0.426 ** | 0.230 |
| | 2015/11/06 | 0.050 | 0.146 | 0.434 ** | 0.368 ** | 0.257 |

Pearson Correlation Coefficient: * Correlation is significant at the 0.05 level (2-tailed), ** Correlation is significant at the 0.01 level (2-tailed).

## 5. Discussion

### *5.1. More Field Experiments are Required for Validating Fire Products*

Although the MODIS Thermal Anomalies/Fire products have been widely employed to detect fires, crop residue burning spots may still be influenced by other scattered false fires or fires from other burning activities. Currently, most studies directly employed existing remote sensing products, such as MOD14A1 data and the fourth generation of the Global Fire Emissions Database (GFED4), for extracting crop residue burning spots. Meanwhile, few field experiments were conducted to valid the suitability of these international remote sensing data sources in detecting burning activities of crop residue in China, which may lead to potential biases. For instance, the DN values of MOD14A1 data ranging from 7–9, suggest the possibility of a fire spot. The MOD14A1 data instructions suggest that 7 stands for fire with low confidence, 8 for fire with nominal confidence, and 9 for fire with high confidence. In practice, the number of extracted fire spots using DN 7–9, 8–9, and 9 for Heilongjiang province during 31 October to 6 November 2015 was 5160, 4589, and 504. As one can see, the selection of different parameters leads to completely different extraction results, and there is no feasible solution to decide what parameter is more suitable for fire detection, especially the detection of crop residue burning in China. As a result, in future research, more field experiments should be conducted to examine the reliability and suitability of different fire products for crop residue burning.

### *5.2. Source Apportionment Methods Should Be Employed to Quantify the Relative Contribution of Crop Residue Burning to Local $PM_{2.5}$ Concentrations*

Crop residue burning, especially large scale crop residue burning, exerts strong negative influences on local air quality and even leads to local and regional haze episode. This research also proved that $PM_{2.5}$ concentrations measured at observation stations that were close to crop residue burning spots were notably higher than those that were away from crop residue burning spots. However, local $PM_{2.5}$ concentrations are influenced by a diversity of factors and emission sources. As introduced above, many previous studies have calculated the emission amount of pollutants caused by crop residue burning according to statistical and field-experimented data. However, compared with other sources, the relative contribution of crop residue burning to the variation of local and regional $PM_{2.5}$ concentrations remained unclear. Previous studies [1–4] have quantified the contribution of different sources to $PM_{2.5}$ concentrations in different cities and some major sources (e.g., traffic and coal burning) have been widely acknowledged. For this study, we found that although the $PM_{2.5}$ concentrations measured at stations close to crop residue burning spots were notably higher than those stations not close to crop residue burning spots, the correlations between the existence of crop residue burning spots and local $PM_{2.5}$ concentrations were not significant. In other words, crop residue burning, even during specific haze episodes, is not the only influencing emission source whilst other emission sources (industry and traffic emission) also contribute a lot to the variation of local $PM_{2.5}$ concentrations. Therefore, to comprehensively understand the influences of crop residue burning, source apportionment methods should be employed to quantify the relative contribution of crop residue burning, compared with other sources, to local $PM_{2.5}$ concentrations, especially the variation of $PM_{2.5}$ concentrations during specific haze episodes induced by crop residue burning.

### *5.3. Accumulation and Dispersion of $PM_{2.5}$ Concentrations Should Be Considered to Understand the Influence of Crop Residue Burning on Simultaneous Variations of $PM_{2.5}$ Concentrations*

This research suggested that the existence of crop residue burning spots and the variation of local $PM_{2.5}$ concentrations was not significantly linearly correlated. Firstly, as introduced above, local $PM_{2.5}$ concentrations were also influenced by other major emission sources. In addition, $PM_{2.5}$ produced during crop residue burning can either accumulate at a certain place or disperse to a large region. During this study period, a large number of crop residue burning spots were detected in Heilongjiang province, and $PM_{2.5}$ concentrations for one day is influenced by the accumulation of $PM_{2.5}$ pollutants emitted from crop residue burning in the previous day. Wind direction is an important meteorological factor that influences the accumulation and dispersion of $PM_{2.5}$ concentrations. To examine the influence of individual meteorological influences on the variation of $PM_{2.5}$ concentrations during the period with intense crop residue burning, we analyzed the simultaneous variations between wind direction and $PM_{2.5}$ concentrations during the research period (Figure 7). According to Figure 7, it is noted that there is no clear correlation between $PM_{2.5}$ concentrations and wind directions. This may be attributed to meteorological factors influencing $PM_{2.5}$ concentrations caused by crop residue burning through complicated mechanisms and the variation of $PM_{2.5}$ concentrations was influenced by many other emission sources than just crop residue burning.

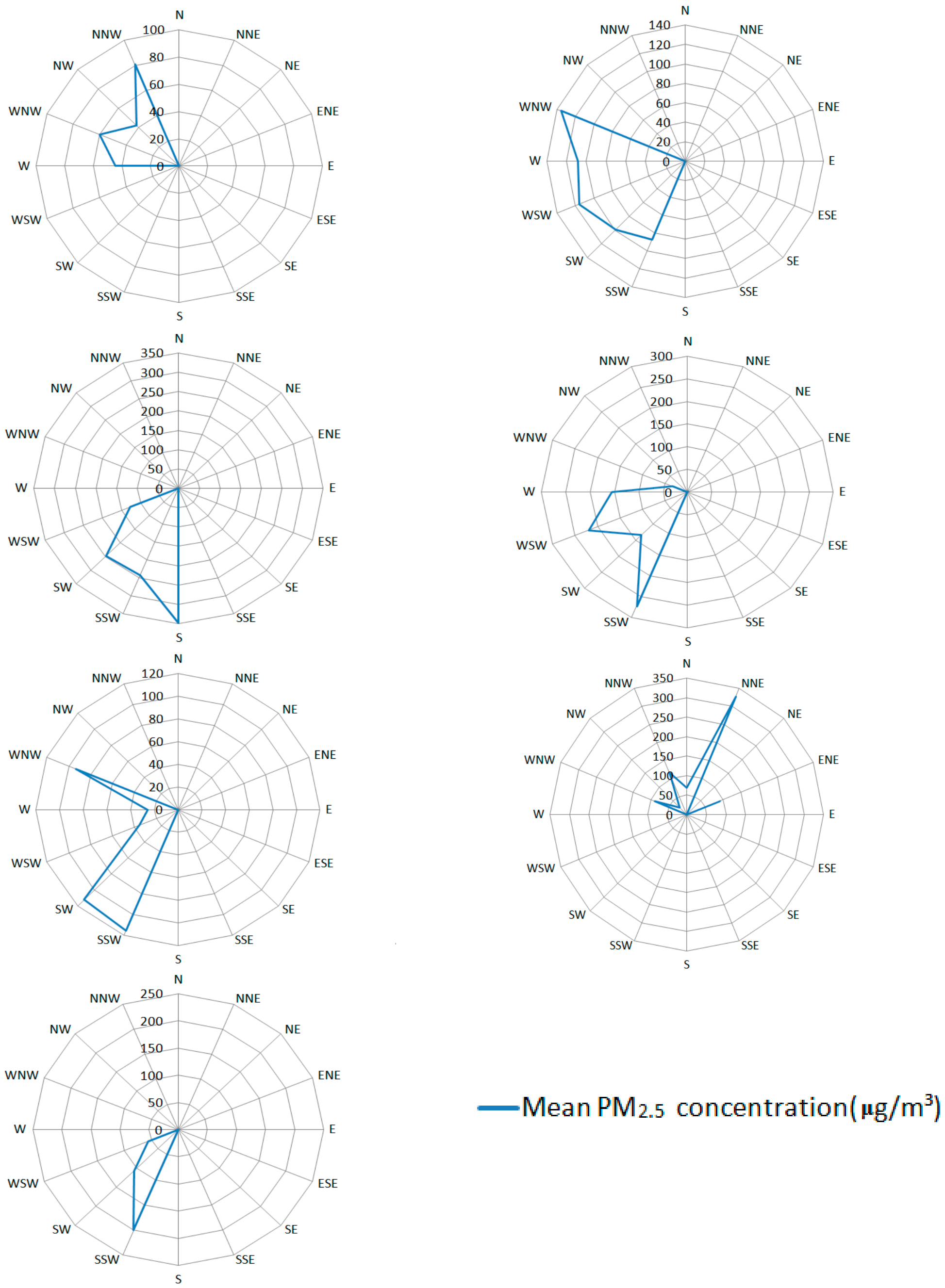



**Figure 7.** Simultaneous variations of wind direction and $PM_{2.5}$ concentrations in Heilongjiang Province during 31 October to 6 November 2015.

To solve this issue, two solutions may be employed. On one hand, a previous study [13] suggests that field-burning experiments can be conducted to simulate the dispersion patterns of airborne pollutants emitted from crop residue burning using comprehensive models that consider the influence of a diversity of meteorological factors. On the other hand, remote sensing data with higher temporal resolutions (at hourly, even minutely scale) can be employed to better monitor the process of crop residue burning. The burning activity of crop residues usually lasts for a short period whilst the influences of crop residue burning on local and regional $PM_{2.5}$ concentrations vary significantly during the burning process. So the daily fire maps from MODIS data cannot reveal the correlation analysis between real-time crop residue burning and the simultaneous variations of $PM_{2.5}$ concentrations. Meanwhile, some advanced remote sensing data offset the disadvantage. Herein we take the Himawari satellites as an example. The Advanced Himawari Imager (AHI) onboard the newly launched Japanese geostationary meteorological satellites, Hamawari-8/9, represents a state-of-the-art optical sensor with significant higher radiometric, spectral, and spatial resolution than those previously available in geostationary orbits [22]. This satellite provided fire information with a spatial resolution 1 km (similar to the MOD14A1 data) and temporal resolution of 10 min, which is highly suitable for establishing the correlating between the real-time process of crop residue burning and simultaneous variations of $PM_{2.5}$ concentrations.

### *5.4. More $PM_{2.5}$ Observation Stations Are Required to Better Understand the Correlations between Crop Residue Burning and Local $PM_{2.5}$ Concentrations*

For this research, we extracted crop residue burning spots for Heilongjiang province during the period of 31 October to 6 November 2015. During this period, the daily average number of crop residue burning spots was more than 450 whilst the number of ground $PM_{2.5}$ observation stations was only 55 within the Heilongjiang province. Due to the limitation of available data sources, the extracted number of stations that were close to crop residue burning spots was also very small, even during the period with the most intense crop residue burning activities. In this case, more detailed and in-depth statistics cannot be supported. Meanwhile, for regions within which $PM_{2.5}$ concentrations varied significantly, the statistics and comparison of average $PM_{2.5}$ concentrations calculated using stations across the study areas, may even lead to some biased conclusions. This issue may be solved using $PM_{2.5}$ concentration data with a finer resolution. Nowadays, in addition to the national network, provincial air quality monitoring networks have been established gradually. The provincial monitoring network (the data has been available to some specific research institutions) included many more observation stations than the national network. In addition to national and provincial monitoring networks, rapid development of local networks for air quality monitoring has been witnessed. For some cities (e.g., Beijing and Shijiazhuang) within the Beijing-Tianjin-Hebei region, the number of local air quality monitoring stations, which are mainly operated by companies and research institutions, has exceeded 1000, and the data may be available in the future. With a much denser network of air quality monitoring, it is possible to find multiple observation stations surrounding one crop residue burning spot, and then we can further examine how the influence of crop residue burning varies along with different distances to the burning spots. In this case, we can establish regression models for estimating local $PM_{2.5}$ concentrations with the influence of crop residue burning. With growing availability, fine-scale local $PM_{2.5}$ data can become an ideal source for investigating the quantitative influences of crop residue burning on local $PM_{2.5}$ concentrations.

## 6. Conclusions

Based on MOD14A1 data and national land cover data, we extracted crop residue burning spots for Heilongjiang province, where crop residue burning activities were most intense. By analyzing the temporal variation of crop residue burning and $PM_{2.5}$ concentrations, we found that the total number of crop residue burning spots, even during the period with the most burning spots, was not correlated with variations of $PM_{2.5}$ concentrations at the provincial (regional) scale. At the local scale, we experimented with a set of buffer zone radiuses to examine the influencing area of crop residue burning. The results suggested that the valid influencing area of crop residue burning was between 50 and 80 km. The mean $PM_{2.5}$ concentration measured at stations close to crop residue burning spots was more than 60 μg/m$^3$ higher than that measured at stations not close to crop residue burning spots. In spite of strong influences of crop residue burning on nearby $PM_{2.5}$ concentrations, no consistent, significant correlation existed between the existence of crop residue burning spots and local $PM_{2.5}$ concentrations. This phenomenon suggests that $PM_{2.5}$ concentrations are influenced by a diversity of factors and not solely controlled by crop residue burning, even during specific haze episodes induced by crop residue burning. This research also provides suggestions for better understanding the role of crop residue burning in local and regional air pollution.

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