

Emission Inventory and Spatial Distribution of Particulate Matter from Dust Sources in Zhengzhou City, China

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Abstract

Background: With the rapid development of society and economy, Zhengzhou city, a new first-tier city in central China, is facing high levels of particulate matter (PM) pollution. Dust source has been generally recognized as one of the major source of PM emission that cannot be ignored. In this study, we aimed to establish an emission inventory of PM from dust source and characterize its spatial pattern in Zhengzhou, China.

Methods: A GIS/RS based approach was proposed to establish the emission inventory of total suspended particles (TSP), particulate matter 10 (PM₁₀) and particulate matter 2.5 (PM_{2.5}) from dust source. Bare ground, construction sites and paved roads in 2016 was recognized with high resolution remote sensing data. Technical Guidelines for Emissions Inventory of Particulate Matter Emitted from Dust Source recommended by the Ministry of Ecological Environment (MEP) was used to estimate PM emission, and a spatial grid of 3km×3km resolution was established to display the distribution of PM emission from different dust sources.

Results: The total emission of TSP, PM₁₀ and PM_{2.5} in Zhengzhou was 237.5 kt·a⁻¹, 103.7 kt·a⁻¹ and 22.4 kt·a⁻¹, respectively in 2016. Compared to other cities in China, the PM emission in Zhengzhou was at a relatively high level. Construction dust source was the main emission source in Zhengzhou, the TSP, PM₁₀ and PM_{2.5} emission of which account for 76.42%, 89.68% and 88.39%, respectively of the total emissions, followed by road dust source and soil dust source. Spatially, total TSP, PM₁₀, PM_{2.5} emission were larger in main urban areas including Jinshui, Zhongyuan, Erqi, Jingkai and other urban districts. Zhongmou, Xingyang and Xinzheng, which bordering with the main urban area, were also the area with high PM emission, while Dengfeng, Gongyi and other remote areas had relatively small emission of PM.

Conclusions: The GIS/RS based approach has good applicability for identifying the emission characteristics in urban area, and it is urgent for Zhengzhou city to take specific measures for the prevention and control of atmospheric pollution under the severe situation of high-level PM emission.

1. Background

With the rapid industrialization and urbanization of Chinese cities, air pollution has become one of the most serious environmental problem. Haze weather frequently occurs in autumn and winter, and the air quality becomes even worse in many developed cities[1–3]. Serious air pollution issue not only restricts the sustainable development of regional economy, but also brings great negative influence on human health[4]. As the major components of atmospheric pollutants, particulate matter (PM) has received much attention in the field of atmospheric environment research[5–7]. There are various sources of PM emission, of which dust source is the most common source in urban areas. Dust source refers to a certain range of atmospheric particulates that generated from loose surface and entered to the ambient air by natural and human factors, which can be divided into soil dust, construction dust, road dust and the field

dust [8]. Studies have shown that the contribution rate of $PM_{2.5}$ and PM_{10} emission from dust source account for 41.8% and 60.0%, respectively in Nanchong [9], 16.7% and 23.6% in Haikou, respectively [10], 22.1% and 28.7% in Qingdao [11], and 30% and 42% in Tianjin[12], dust source has been generally recognized as one of the major source of PM emission that cannot be ignored.

Previous studies have made great efforts on the estimation of PM emission, nevertheless, most of these studies were carried out in big cities in developing countries such as Beijing, Shanghai in China[13–14], New Delhi in India[15], and focus more on the industrial and vehicle source of PM emissions[16–19], while few studies have been conducted to investigate the PM emission from dust source in medium-sized cities with rapid growth and severe air pollution problems. Zhengzhou, a fast-growing megacity city in the central area of China, is facing serious air pollution issue along with the rapid economic development and expansion of urban area. According to the investigation conducted by MEP in 2016, the air quality of Zhengzhou city was the seventh from the bottom among 74 major cities of China, and the number of days exceeding the national air quality standard of PM_{10} and $PM_{2.5}$ accounted for about 70%[20]. For better implementation of the action plan for the prevention and control of atmospheric pollution that issued by the State Council of China, it is urgent for Zhengzhou city to get more information about PM emission characteristics to enhance the pertinence and effectiveness of the prevention and control of atmospheric pollution.

Based on the high resolution image of ZY-3 satellite, the distribution of dust sources (bare ground, construction sites and paved roads) of Zhengzhou in 2016 was identified. The emission of TSP, PM_{10} and $PM_{2.5}$ from different types of dust sources were estimated according to the Technical Guidelines for Emissions Inventory of Particulate Matter Emitted from Dust Source[21], and a grid model of 3 km × 3 km resolution was established to demonstrate the spatial distribution of PM emission under the support of ArcGIS 10.2. It is expected that the results of this study could provide scientific reference for atmospheric pollution prevention and control.

2. Materials And Methods

2.1 Study area

Zhengzhou City, the capital of Henan Province, is a new first-tier city with an area of 7446 km². The geographic location is between 112°42'~114°14'E and 34°16'~34°58' N (Fig. 1). There are 10 municipal districts (Jinshui District, Zhongyuan District, Erqi District, Guancheng District, Huiji District, New high-tech Zone, Economic Development Zone, Airport Economy Zone, Shangjie District, Zhengdong New District), 5 county-level cities (Gongyi City, Dengfeng City, Xinzheng City, Xinmi City, Xingyang City), and one county (Zhongmou County) in Zhengzhou. Zhengzhou City is characterized by the north temperate continental monsoon climate with an annual mean temperature of 13.9 °C, the annual average precipitation is 640 mm, which concentrated in June, July and August. The average wind speed is 2.8 ~ 3.2 m/s, the maximum wind speed is 18 ~ 22 m/s, which mostly occurs in April or September. The soil

types mainly include Cinnamon soil (62.5% of the total area), fluvo-aquic soil (26.9%), sandy soil (5.1%), stony soil(2.6%), coarse soil (1.9%) and a small amount of red clay (0.8%) and purple soil (0.2%).

2.2 Data processing and spatial mapping

Remote sensing data used in this study was acquired from the Chinese Resource Satellite ZY-3. ZY-3 is China's first three linear array stereo mapping satellite, the maximum spatial resolution of which is 2.1 m. Since the launch of the satellite in January of 2012, images from ZY-3 have been widely used in land surveying, territorial mapping, and ground information extraction[22–24]. Before identifying the distribution of emission source, ENVI 5.3 was used for the preprocessing of images, including radiometric calibration, geometric correction, image enhancement and splicing and clipping, the 1:50,000-scale topographic map was used for geometric correction, and the error was less than 0.5 pixels after correction.

The spatial distribution of bare ground, construction sites and different types of roads (national road, provincial road, county road and township road) were identified by visual interpretation in ArcGIS 10.2. Every piece of emission source was extracted as a shapefile, the attribute data of each shapefile included name, location, length, area and other association attributes. After the manual extraction, all the shapefiles were overlaid together and a new thematic layer was formed to calculate the emission of TSP, PM₁₀ and PM_{2.5} with method recommended by the MEP, then a grid of 3km × 3 km resolution was established to display the spatial distribution of TSP, PM₁₀ and PM_{2.5} emission from different dust sources.

2.3 Methodology

2.3.1 Soil Dust

Soil dust is generated from bare ground such as bare farmland, exposed mountains, tidal flats, dry river valleys, unhardened spaces. The influence factor of emission from soil dust include particle size distribution of surface soil, surface roughness, vegetation coverage, surrounding shielding conditions and meteorological conditions. Bare ground in this study mainly focuses on the farmland in the surrounding urban areas and the open land without hardening or greening.

The formulas for calculating emission of PM from soil dust sources are as follows:

$$W_{Si} = E_{Si} \times A_s \quad (1)$$

$$E_{Si} = D_i \times C \times (1 - \eta) \times 10^{-4} \quad (2)$$

Where W_{Si} is the total PM_i emission, t/a; E_{Si} is the PM_i emission coefficient, t/(m²·a); A_s is the area of soil dust source, m²; D_i is the dust emission factor of PM_i, t/(10⁴ m²·a); η is the dust removal efficiency by

pollution control technology, %. Since only the dust emission of the exposed ground was considered in this study, the removal efficiency of the exposed ground control efficiency was set to zero.

$$D_i = k_i \times I_{we} \times f \times L \times V \quad (3)$$

$$C = 0.504 \times u^3 / PE^2 \quad (4)$$

Where k_i is the percentage of PM_i in soil dust. The recommended values of TSP, PM_{10} and $PM_{2.5}$ are 1, 0.30 and 0.05, respectively; I_{we} is the soil wind erosion index, which is 331 for TSP, 99 for PM_{10} and 17 for $PM_{2.5}$ according to the soil texture of Zhengzhou. f is the ground roughness factor, the value of which is 0.5; L is the unshielded width factor, and the value is 1.0; V is the vegetation coverage factor, and the value is 0.9. C is the climatic factor, u is the annual average wind speed, m/s; PE is the Thomthwaite Precipitation Index (evaporation index), and the PE formula is as follows:

$$PE = 1.099 \times p / [0.5949 + (0.1189 \times T_a)] \quad (5)$$

Where p is the annual precipitation, mm; T_a is the annual average temperature, °C.

The average wind speed of Zhengzhou is 1.984 m/s, the annual precipitation value is 833.1 mm and the annual average temperature is 16.5 °C in 2016.

2.3.2 Construction dust

Construction dust is the dust generated during the construction process, such as urban municipal infrastructure, the construction and demolition of building, the engineering of the equipment installation and building decoration. The influence factors of emission from construction dust source including construction area, construction time and PM emission coefficient. In this study, area of main building construction and decoration construction was considered as the construction area for the calculation of construction dust emission.

The calculation formulas for the emission from construction dust are as follows:

$$W_{Ci} = E_{Ci} \times A_C \times T \quad (6)$$

$$E_{Ci} = 2.69 \times 10^{-4} \times (1-\eta) \quad (7)$$

Where W_{Ci} is the total PM_i emission of the construction dust, t/a; E_{Ci} is the average PM_i emission coefficient of the entire construction zone, t/(m²·month); A_C is the area of construction zone, m²; T is the period of construction activities, which is generally calculated by the number of construction days/30 (according to the survey, the average construction days in Zhengzhou was 179 d in 2016); η is the removal efficiency by pollution control technology, %.

2.3.3 Paved road dust

Road dust refers to the dust that generated from paved roads and entering the ambient air under dynamic conditions (wind power, motor vehicle rolling, crowd activities, etc.). The paved roads of Zhengzhou can be divided into four categories including national roads, provincial roads, township roads and county roads.

The calculation formulas of PM emission from each category of paved roads are as follows:

[Due to technical limitations, these formulas could not be displayed here. Please see the supplementary files section to access these formulas.]

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Where W_{Ri} is the total emission of PM_i from road dust, t/a; E_{Ri} is the average emission coefficient of PM_i from different categories of paved roads, g/(km·vehicle); L_R is the length of road, km; N_R is the average traffic flow on the road during a certain period of time, the vehicle/a; n_f is the number of dust-free days; k_i is the particle size multiplier of PM_i , the recommended value is 3.23 g/ km (TSP), 0.62 g/km (PM_{10}) and 0.15 g/km ($PM_{2.5}$); sL is road dust load, g/m²; W is the average vehicle weight, t; η is the removal efficiency by pollution control technology, %, when multiple measures are implemented simultaneously, the maximum removal efficiency should be taken as the final value.

In this study, days with precipitation exceed 0.25 mm/d was taken as the number of dust-free days. In order to obtain the traffic flow data, a 10-day-long monitoring experiment was carried out on each category of paved roads to obtain traffic flow (N_R) and the road dust load of different types of road. The average vehicle weight and other traffic information were estimated based on the observation data, the emission parameters of different levels of roads in Zhengzhou are shown in Table 1.

Table 1
Emission parameters of different levels of roads

Road type	National road	Provincial road	County road	Township road
Traffic flow (vehicles/day)	7579	6432	1500	850
Dust load (g/m ²)	0.27	0.33	0.52	1.57
Average weight (t)	8.80	6.90	4.70	2.80
TSP emission coefficient (g/VKT)	9.02	8.45	8.64	13.92
PM10 emission coefficient (g/VKT)	1.73	1.62	1.66	2.67
PM2.5 emission coefficient (g/VKT)	0.42	0.39	0.40	0.65

3. Results And Discussion

3.1. Emission Inventory and Spatial Distribution of PM from soil dust

1259 piece of bare grounds were identified in Zhengzhou in 2016 with a total area of 68.97 km², which were mainly distributed in Zhongmou and Xinzheng. Zhongmou has the largest exposed area, which accouts for 52.50% of the total area of bare ground in Zhengzhou, followed by Xinzheng, Dengfeng and Xinmi. (Fig. 2(a)). Figure 2(b), 2(c) and 2(d) display the spatial distribution of PM emission from soil dust source with a grid of 3km × 3 km resolution. Results show that the emission of TSP, PM₁₀ and PM_{2.5} from soil dust source were 507.40 t·a⁻¹, 45.53 t·a⁻¹ and 1.30 t·a⁻¹, respectively in Zhengzhou. The maximum PM emission from soil dust source concentrated in Zhongmou and Xinzheng, which is consistent with the distribution characteristic of bare grounds. The Airport Economy Zone also has high PM emission, the main reason is that the soil type is mainly silt soil, which can be easily raised into air by wind and human activities, therefore lead to high emission coefficient. Dengfeng has a complex terrain that decreases from north to south, Xinmi is surrounded with mountains, although the area of bare ground are not small in the two regions, the limitation of topography reduced the effects of wind and human farming activities and lead to low PM emission. Xingyang, Gongyi and the urban area of Zhengzhou have the minimum PM emission, and it is mainly due to the small area of bare grounds.

3.2. Emission Inventory and Spatial Distribution of PM from construction dust

The number of construction sites was 1,793 in Zhengzhou with a total area of 145.25 km² in 2016, which was mainly distributed in the urban area (Fig. 3(a)). The emission of TSP, PM₁₀ and PM_{2.5} from construction dust source was calculated to be 181.5 kt·a⁻¹, 93.0 kt·a⁻¹ and 19.8 kt·a⁻¹, respectively. Figure 3 showed the spatial distribution of PM emission from construction dust sources in Zhengzhou City in 2016. The result suggests that PM emission from construction dust is closely related to regional development degree. The emission of TSP, PM₁₀ and PM_{2.5} from construction dust sources are centered in 4 districts with high developed culture and economics, including Zhongyuan, Huiji, Jinshui and Zhengdong New District, the four regions formed a urban area-centered high emission circle. Zhongmou, Xingyang and Xinzheng, bordering the main urban area, also have high PM emission under the influence of regional conditions and urban economic radiation. Low PM emission area located in Gongyi and Dengfeng, which is far away from the main urban zone of Zhengzhou and lack of leading industries for economic development.

Compared with other cities in China, TSP emission from construction dust sources in Zhengzhou is 1.26 times of Beijing and 1.89 times of Wuhan, PM₁₀ emission is 1.32 times of Beijing and 0.98 times of Wuhan, and PM_{2.5} emisson is 0.35 times of Beijing and 1.06 times of Wuhan[24–25]. It is assumed that the reason resulting in high PM emisson in Zhengzhou was the reconstruction of the urban village. The

Government of Zhengzhou demand that all the urban villages within the fourth ring road of Zhengzhou should be demolished by the end of 2016. To complete the target on schedule, large number of construction work has been conducted in the main urban area in the year of 2016, which result in a substantial increase of PM emission from construction sources.

3.3. Emission Inventory and Spatial Distribution of PM from Road dust

The total length of paved roads in Zhengzhou in 2016 was 10,601.50 km, and the length of national road, provincial road, county road and township road were 396.30 km, 901.40 km, 2,439.88 km and 6,863.92 km, respectively. It has been calculated that the total emission of TSP, PM₁₀ and PM_{2.5} from paved roads were 55.5 kt·a⁻¹, 10.7 kt·a⁻¹ and 2.6 kt·a⁻¹, respectively (Table 2). Among different levels of roads, township road has the largest PM emission, followed by provincial road, county road and national road. This is because the length of township road is far more than other types of roads, and the road dust load of township road is relatively large. Although the dust load of provincial road is small, the heavy traffic volume lead to high PM emissions. It can be seen that the TSP, PM₁₀ and PM_{2.5} emission from road dust is large in Zhengzhou, but compared with other cities of similar size in China, PM emission from road dust in Zhengzhou are still at low level[26–27].

The spatial characteristics of TSP, PM₁₀ and PM_{2.5} emission from road dust source in Zhengzhou was shown in Fig. 4b, c, d. For different levels of roads, high PM emission mainly concentrated in the main urban areas such as Zhongyuan, Huiji, Jinshui and Zhengdong New District, it is because the main urban region is the intersection of the Longhai Railway and the Beijing-Guangzhou Railway, besides, the 107 National Highway, the 310 National Highway, the Beijing-Hongkong-Macao Expressway and the Lianhuo Expressway all pass through the area. PM emission from roads is also higher in the junction of Zhongmou, Xingyang, Xinzheng and the main city in the area, and the emission of the area which are far from the urban area such as Shangjie and Dengfeng is small.

Table 2
Emission of TSP, PM₁₀ and PM_{2.5} from paved roads

Type	Length(km)	TSP(t/a)	PM ₁₀ (t/a)	PM _{2.5} (t/a)
State road	396.30	7958.07	1527.56	369.57
Provincial road	901.40	14387.84	2761.75	668.17
County road	2439.88	9285.82	1782.42	431.23
Township road	6863.92	23857.19	4579.40	1107.92
Total	10601.50	55488.93	10651.13	2576.89

3.4. Total PM emissions from dust source

The calculation results showed that the emission of TSP, PM₁₀ and PM_{2.5} of Zhengzhou in 2016 were 237.5kt·a⁻¹, 103.7kt·a⁻¹ and 22.4 kt·a⁻¹, respectively. By analyzing the source of PM, it can be found that the construction dust was the main dust sources of PM emission in Zhengzhou, TSP, PM₁₀ and PM_{2.5} emission from construction dust accounted for 76.43%, 89.69% and 88.50%, respectively of total dust sources (Table 3).

The spatial distribution of total PM emission was shown in Fig. 5b, 5c and 5d, it can be seen that the emission of TSP, PM₁₀ and PM_{2.5} were mainly concentrated in the Zhongyuan, Huiji, Jinshui, Zhengdong New District and other main urban areas. Zhongmou, Xingyang and Xinzheng, which bordering with the main urban area, were also the high PM emission area. While the areas that far away from the main urban area had low emission intensity such as Shangjie and Dengfeng. Three aspects of reasons of the emission characteristics was concluded. Firstly, the majority of construction sites are distributed in the main urban area, secondly, the dense road network and heavy traffic flow of the main urban area increases the PM emission, moreover, although soil dust is more prevalent in the suburbs than in the urban area, but due to the small PM emission from soil dust, it doesn't make much difference to the general characteristic of total emissions.

Results from the analysis revealed that the key zones for PM emission control from dust sources are mainly distributed in the main urban area of zhengzhou, which is consist of Zhongyuan, Huiji, Jinshui, Zhengdong New District. Furthermore, areas such as Zhongmou, Airport Economy Zone and Xinzheng are more likely to face increasing serious PM emission problems due to the acceleration of urbanization under policy orientation, so it is necessary to conduct early prevention of PM emission in these potential PM emission areas.

Table 3
Emission of TSP, PM₁₀ and PM_{2.5} from dust sources

Dust type		Soil dust	Construction dust	Road dust	Total
TSP	Total annual emission t·a ⁻¹	507.40	181547.25	55488.93	237543.58
	percentage %	0.21	76.43	23.36	100
PM ₁₀	Total annual emission t·a ⁻¹	45.53	93047.65	10651.13	103744.31
	percentage %	0.044	89.69	10.27	100
PM _{2.5}	Total annual emission t·a ⁻¹	1.30	19842.70	2576.89	22420.89
	percentage %	0.006	88.50	11.49	100

4. Conclusions

Based on the remote sensing data and method recommended by Technical Guidelines for Emissions Inventory of Particulate Matter Emitted from Dust Source, total emission of TSP, PM₁₀ and PM_{2.5} from soil dust, construction dust and road dust in 2016 were estimated, and the spatial distribution of PM emission was mapped in a grid of 3km × 3 km resolution based on RS-GIS approach. The total emission of TSP, PM₁₀ and PM_{2.5} in Zhengzhou was 237.5 kt·a⁻¹, 103.7 kt·a⁻¹ and 22.4 kt·a⁻¹, respectively in 2016. Construction dust source was

the main emission source in Zhengzhou, the TSP, PM₁₀ and PM_{2.5} emission of which account for 76.42%, 89.68% and 88.39%, respectively of the total emissions. The TSP, PM₁₀, PM_{2.5} emission are larger in main urban areas including Jinshui, Zhongyuan, Erqi, Jingkai and other urban districts, while Zhongmou, Xingyang, Dengfeng, Gongyi and other remote areas had small PM emission. The GIS-RS based approach provides an efficient way for identifying the emission characteristics in urban area, the emission inventory and the spatial distribution of PM emission from different dust sources in this study could be a practical guidance for the prevention and control of urban atmospheric pollution.

Abbreviations

PM: Particulate matter; TSP: Total suspended particles; PM₁₀: Particulate Matter less than 10 µm in diameter; PM_{2.5}: Particulate Matter less than 2.5 µm in diameter; MEP: the Ministry of Ecological Environment; GIS: Geographic Information System; RS: Remote Sensing.

Declarations

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Declarations

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Consent for publication: Not applicable.

Availability of data and materials: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author Contributions: HY performed the data analyses and wrote the manuscript; XS and SY proposed ideas of the study; QZ has been involved in data analyses. JS has been involved in revising the manuscript. JC have made substantial contributions in data acquisition. All authors read and approved the final manuscript.

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Figures

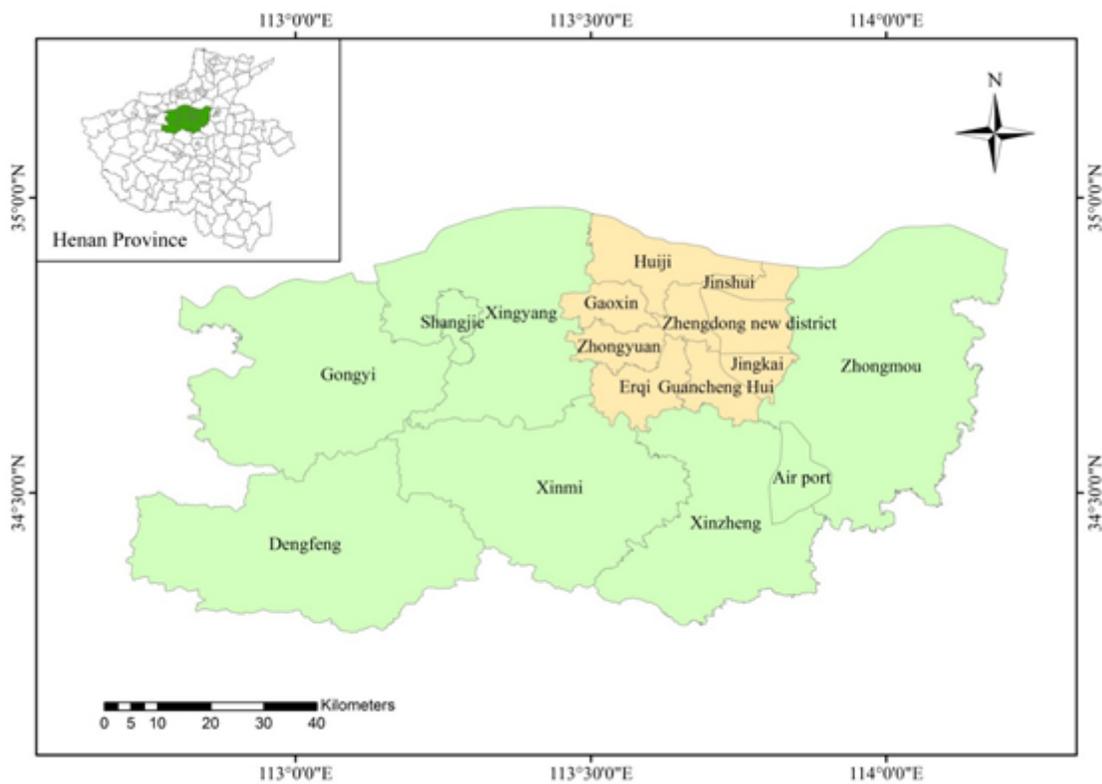


Figure 2

Geographic location and administrative district of Zhengzhou. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the

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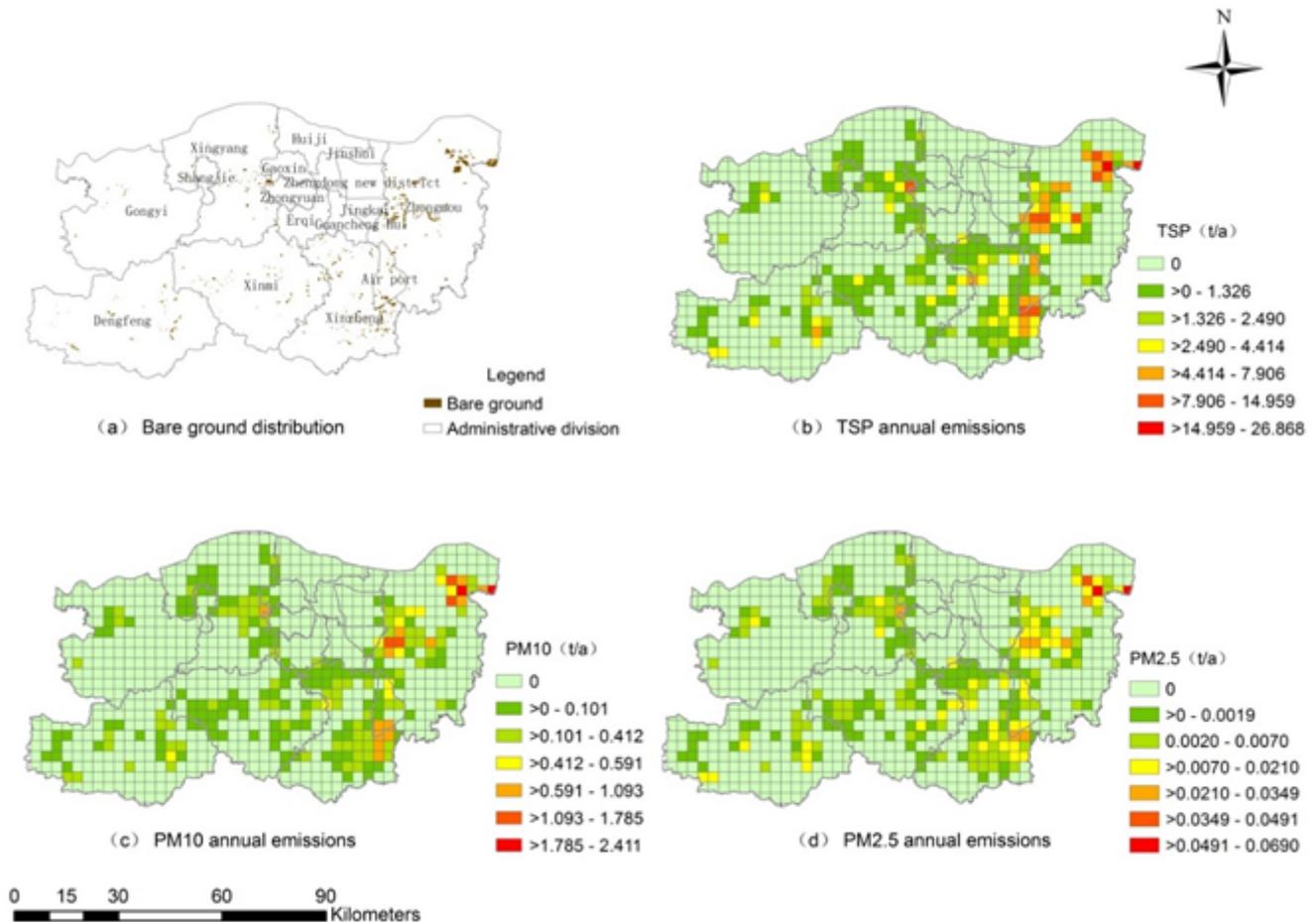


Figure 4

Spatial distribution of PM emission from bare ground. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

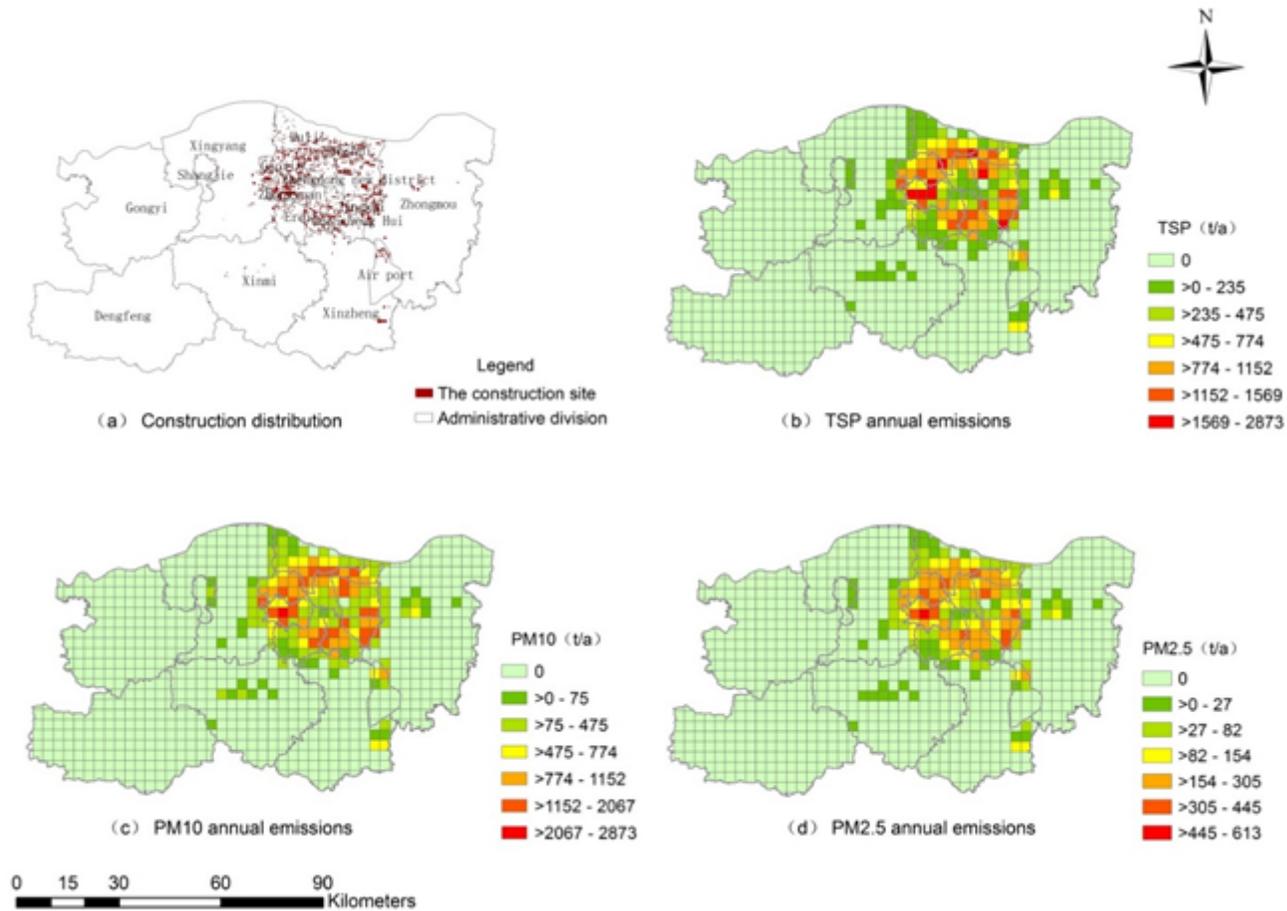


Figure 6

Spatial distribution of PM emission from construction sites. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

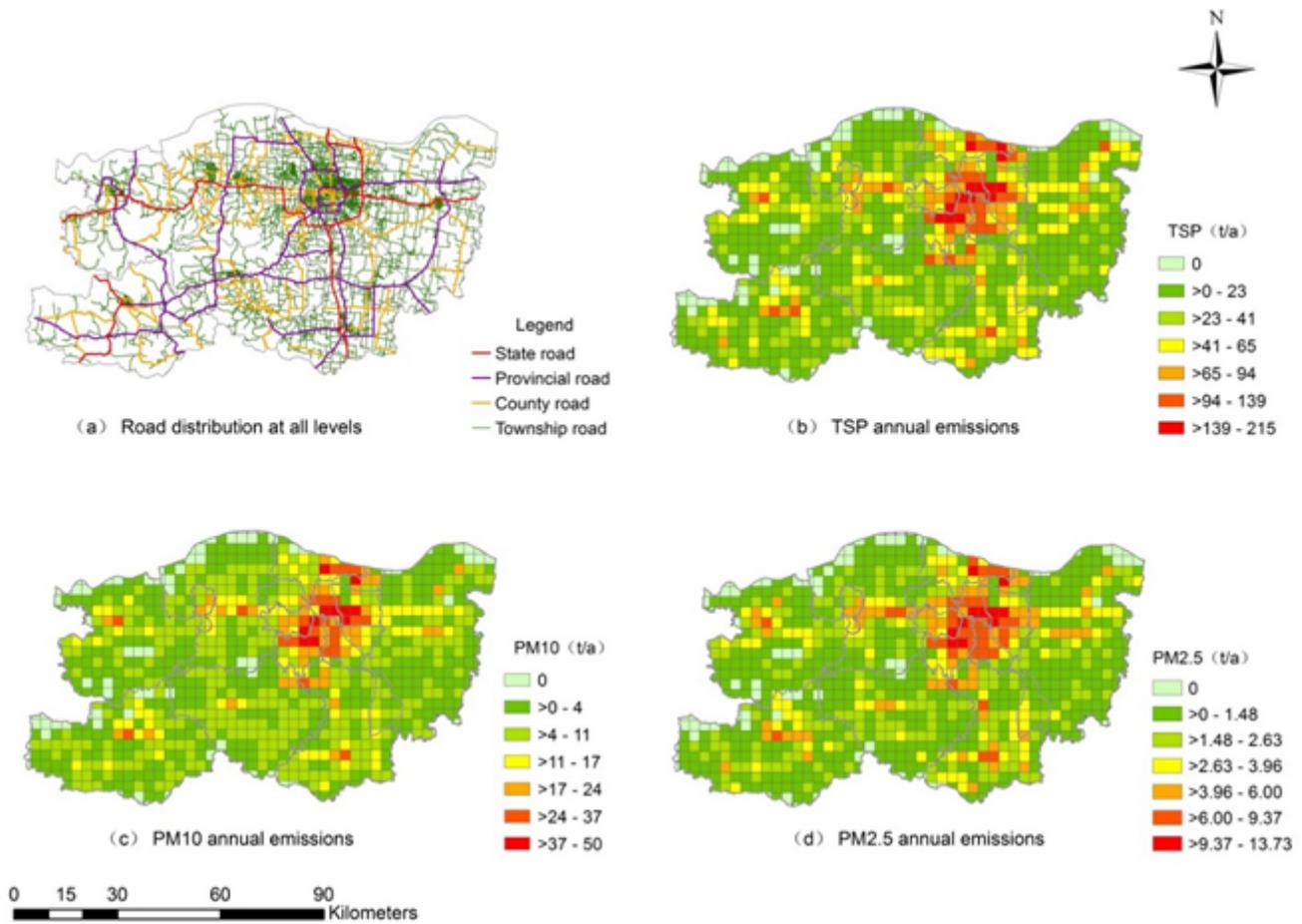


Figure 8

Spatial distribution of PM emission from paved roads. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

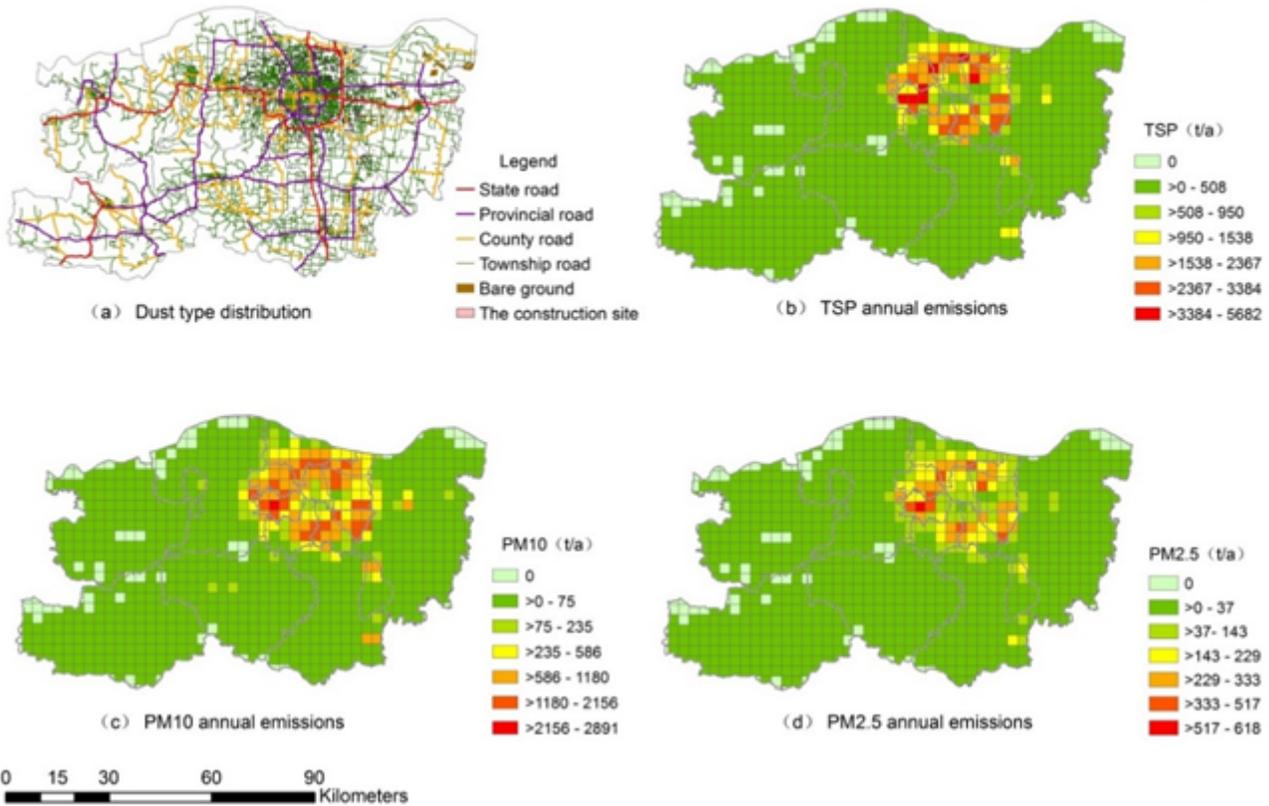


Figure 9

Spatial distribution of total PM emission from dust sources. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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