Emission Inventory and Control Policy for Non-road Construction Machinery in Tianjin

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Emission inventory and control policy for non-road construction machinery in Tianjin

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Abstract

The establishment of a non-road construction machinery emission inventory forms the basis for the analysis of pollutant emission characteristics and for the formulation of control policy. We analysed and investigated data on populations, emission factors and activity levels for the construction machinery in Tianjin to estimate an emission inventory. Finally, a variety of emission reduction scenarios were used to simulate emission reductions and propose the most effective control policy. The results show that total emissions of CO, HC, NOx, PM_{10} and $PM_{2.5}$ from non-road construction machinery in Tianjin of 2018 reached 4180.78, 951.44, 5833.85, 383.92 and 365.70 t, respectively. Forklifts, excavators and loaders were the three most important emission sources in Tianjin. There are clear differences in the emissions of different districts. Large machinery emissions were mainly distributed across the Binhai New Area, which includes high volumes of port machinery and tractors in Tianjin Port. Based on various emission reduction scenarios, the effect of emission reductions is estimated. The IAD affected the reduction of CO and HC emissions with RR values of 17.6% and 17.3%, respectively, while EMO affected the mitigation of PM_{10} and $PM_{2.5}$ emissions and RR values by 18.0% and 18.4%, respectively. The emission reduction control policy for non-road construction machinery is proposed, including the accelerated updating of non-road machinery emission standards; integrating diesel engine research and development institutions to accelerate the development of vehicle after-treatment technology; and establishing a cooperation mechanism for scientific research institutes, government departments and enterprises in the control of non-road mobile machinery emissions.

Keywords: Non-road construction machinery; Emission inventory; Spatial distribution; Scenario analysis; Control policy

1 Introduction

With continuous improvements in the control of motor vehicle emissions, pollution from non-road mobile machinery has become increasingly prominent. The carbon monoxide(CO), hydrocarbon(HC), nitrogen oxides(NOx) and particulate matter(PM) emitted by non-road mobile machinery account for 18%-29% of mobile sources in the world (Yan et al. 2013). Due to the numerous modes of non-road mobile machinery production, the wide range of applications involved, the large number of possessions involved, and uncontrolled pollution emissions, the management and control of those emissions pose significant challenges. According to the China Motor Vehicle Environmental Management Annual Report (2019)(MEE 2019), the NOx emission of construction machinery, agricultural machinery, ships and railway locomotives accounted for 37%, 32%, 26% and 3%, respectively. In 2009, the European Environmental Protection Agency published the emission inventory, which showed that non-road mobile source was an important pollution source in Europe (EEA 2019). In Yan's research, non-road mobile source will become the main source of mobile pollution after 2030 and become the largest source of CO and HC pollutants in Asia after 2050(Yan et al. 2013).

With the acceleration of urbanization and industrialization, the use of non-road construction machinery in China has grown rapidly. With this trend, the population of excavators and loaders increased from 120,000 and 230,000 vehicles in 2001 to 1.6 million and 1.55 million vehicles in 2017, reflecting 13.3- and 6.7-fold increases, respectively(CCMA 2017). As emission standards for Chinese construction machinery are still lax, emissions of NOx and PM are high. Most construction and road construction sites are distributed in densely populated urban living areas, and human health is highly vulnerable to such pollution. Further reducing people's confidence in air quality management directly affects the reputation of major cities in China.

Research on the emission control measures of non-road mobile source and their impacts on air quality must be supported with accurate source emission inventories.

Since 1991, the US EPA has conducted a large number of studies on non-road mobile source emissions. The CO, HC, NOx, and PM emission inventories of non-road construction machinery have been established(Chow et al. 2011; Diazrobles et al. 2009; Lin et al. 2005; Sarwar et al. 2005). At the end of the 20th century, the European Union also developed an air pollution emission inventory of non-road mobile source. The results showed that non-road construction machinery contributions to NOx and PM were only less than those of industrial sources(Desouza et al. 2020; Winther and Nielsen 2011).

In China, the research on emission source inventory of non-road mobile source is still in the initial stage. The Pearl River Delta (PRD), Yangtze River Delta (YRD) and Beijing-Tianjin-Hebei (BTH) regions have begun to research the emission inventory of non-road mobile sources(Hou et al. 2019; Lang et al. 2018; Li et al. 2019; Zheng et al. 2009; Zhong et al. 2018). Zheng Junyu has constructed a data set of non-road mobile machinery based on the activity level, comprehensive emission factors and space-time allocation factors in PRD. A bottom-up calculation method was used to establish the non-road mobile machinery emissions inventory of the PRD in 2014. Construction machinery emissions in the PRD were dominated by those generated by construction vehicles and excavators, which contribute 40.1% and 33.9%, respectively(Bian YH 2018). Huang Cheng has established the emission inventory of air pollution sources for non-road mobile machinery in the YRD based on a field survey of non-road mobile machinery in these cities of the YRD. The results showed that CO and VOCs emitted from agricultural machinery accounted for 88% and 77%, respectively. NOx and $PM_{2.5}$

emissions from construction and municipal engineering machinery contributed 49% and 35%, respectively(HUANG Cheng 2018). Non-road machinery emission test research on BTH was relatively limited and has only started recently. An emission inventory of typical agricultural machinery for Beijing from 2006 to 2016 has been established based on the actual emission factors, population and activity level(Hou et al. 2019). The results showed that CO, NOx, HC and PM from agricultural machinery decreased by 63.11%, 72.07%, 62.93% and 74.67% from 2006 to 2016. In Liang's study, a high temporal-spatial resolution emission inventory for agricultural machinery in China was developed(Lang et al. 2018). Whereas the above non-road mobile source emission studies on BTH focus on agricultural machinery, there have been no evaluations of the effects of construction machinery emissions and control policies in BTH.

To fill this gap, we measured the spatial distribution of non-road construction machinery in Tianjin through surveys and compiled the non-road mobile construction machinery emission inventory of Tianjin in accordance with the methods of the emission inventory guidelines. The Monte Carlo model was used to calculate the uncertainty of the emission inventory. Finally, emission reduction scenarios were tested to assess the effects of different policies and to provide a basis from which government managers can formulate pollution control policies in the future.

2 Data and methodology

2.1 Estimating emissions methods

In this study, the emission of the pollutant from non-road construction machinery sources in Tianjin was estimated for the base year 2018.

Non-road construction machinery emissions were calculated with the method based on population and rated net power from the Non-road Mobile Source Emissions Inventory Compiled Technical Guidelines (Guidelines)(MEE 2014). The calculation formula is as follows:

$$\mathrm{E} = \sum_{x}\sum_{y}\sum_{z}\left(P_{x,y,z} \times G_{x,y,z} \times LF_{x,y,z} \times hr_{x,y,z} \times EF_{x,y,z}\right) \times 10^{-6}$$

where E is annual emissions of CO, NOx, HC, PM_{10} and $PM_{2.5}$ (t); x, y, and z are the type of non-road mobile machinery, emission standard and power segment, respectively; P is machinery population; G is the average rated power level, (kw/unit); LF is load factor; hr is annual used hours of each non-road mobile machinery(h); and EF is emission factor of each pollutant(g/kWh).

2.2 Construction machinery population

The population of non-road construction machinery in Tianjin were obtained from government survey statistics and the China construction machinery industry yearbook. Forklifts, loaders and excavators are the three main types of construction machinery used in Tianjin. In addition, road rollers, bulldozers, and graders are often used in road construction. In this study, construction machinery are classified as follows: forklifts, excavators, loaders, road rollers, bulldozers, tractors, cranes, graders, pavers, milling machines, generators and other construction machinery.

According to surveys and estimates, the population of non-road construction machinery in Tianjin was approximately 22481 by the end of 2018. The non-road construction machinery population and type distribution in each district were detailed in Figure 1 and Table S1. Forklifts, excavators and loaders constitute the largest proportion of construction machinery, accounting for 47%, 23% and 7%, respectively (Figure 1). Based on the classification of emission standards, the proportion of Pre-China I, China I, China II and China III are 8%, 26%, 51% and 15%, respectively (Figure 2). Table S2 shows that non-road construction machinery met Pre-China I and China I emission standards before 2010. With the extension of use time, older vehicles were scrapped and eliminated. China II emissions continued for nearly 6 years, resulting in the China II population accounting for the largest proportion.

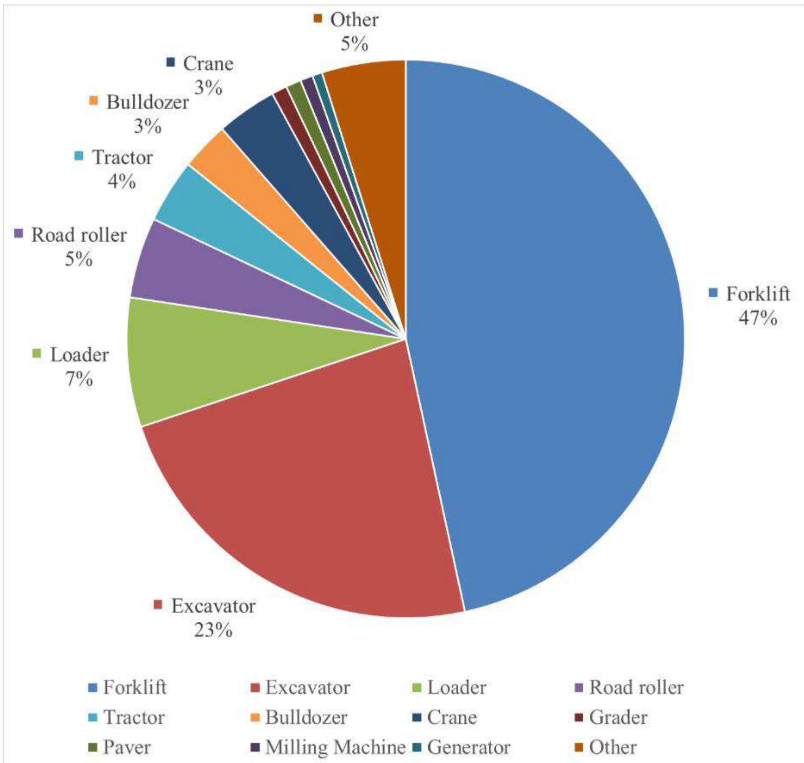

Figure 1 Type distribution of non-road construction machinery

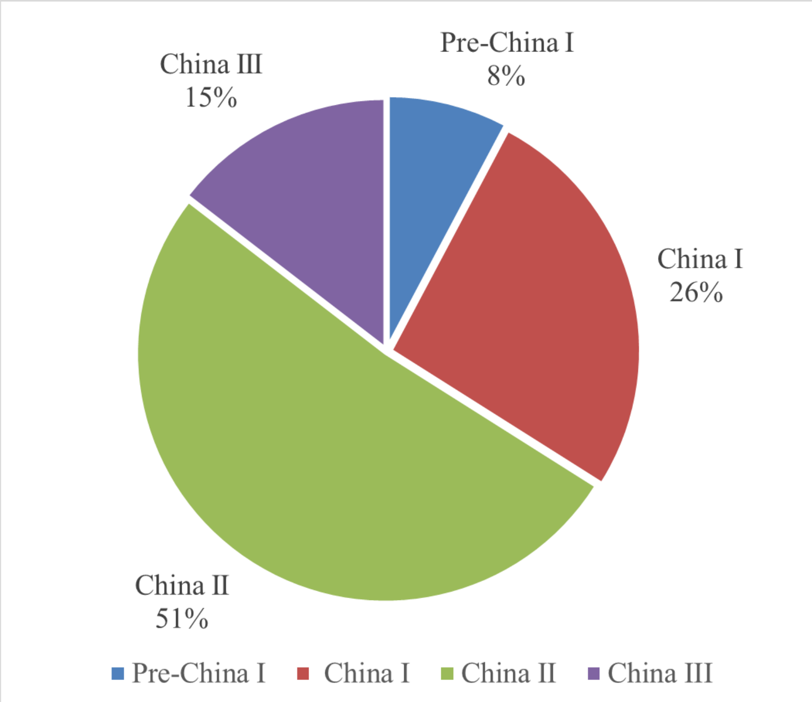

Figure 2 Emission standard distribution of non-road construction machinery

2.3 Emission factors and activity data

Emission factor refers to the number of pollutants emitted per unit of activity level. For non-road construction machinery, the pollutant emission concentration when outputting a unit of power per unit of time was defined as the emission factor. In this study, basic emission factors were obtained according to the Guidelines (Table S3).

The activity levels of non-road construction machinery are closely related to the different operating regions. In this study, we conducted a large number of investigations to make up for the lack of basic data on non-road machinery activity levels, which were including the average rated power, load factor, and average annual operating hours. The average rated power was obtained through dividing the total power by the population in Tianjin. The load factor was 0.65, which was found in the relevant research. The average annual operating hours of non-road construction machinery referred to the values in the Guidelines, and the activity level of each non-road construction machinery type was shown in Table S4.

2.4 Uncertainty calculation

Due to the lack of key data, errors in monitoring results and random errors, certain uncertainties will be caused in establishing the emission inventory and，which including errors resulting from the statistical process of determining activity levels and a lack of localized emission factors. The Monte Carlo simulation model is used to quantify the range of uncertainty(Kelliher et al. 2017; Ramirez et al. 2008; Sun et al. 2019).

Monte Carlo simulation is a commonly used random sampling simulation method. Random sampling and simulation are performed to obtain the approximate solution to a problem that characterizes the probability distribution characteristics of the problem. The Monte Carlo simulation method involves three steps: 1) construct a probability process and determine the distribution probability of each parameter used in a calculation; 2) employ sampling from the known probability distribution and generate random numbers satisfying this distribution by computer for mathematical experiments; and 3) establish various estimators and investigate the estimators of random variables after mathematical experiments to characterize the distribution characteristics of the random distribution(Wu et al. 2009).

Crystal Ball software is used for Monte Carlo simulation in this study. We conduct

10,000 simulations of the uncertainty of the emission inventory of non-road construction machinery at a 95% confidence level.

2.5 Scenario analysis for emission reduction

Several policies have been introduced in many provinces and cities to control non-road construction machinery and include the elimination of old machinery(EOM) and the installation of after-treatment devices(IAD) (Table 1). According to a preliminary investigation, it is more difficult to install exhaust after-treatment equipment onto Pre-China I and China I emission standard construction machinery due to the poor emission conditions of such machinery. It is possible to reduce emissions by eliminating old machinery. The emissions of China II non-road mobile machinery can be significantly reduced by installing after-treatment devices (DOC and DPF). The efficiency of pollutant emission reduction after transformation can reach roughly 70%.

Table 1 Specific definitions of Non-road construction machinery reduction scenarios in Tianjin.

Scenarios	Specific definition
Normal situation (NS)	Take 2018 as the base year, emission control is maintained in 2018
Install after-treatment device (IAD)	50% of the China II emission standard construction machinery were equipped with after-treatment devices
Eliminate old machinery (EOM)	50% of Pre-China I and China I construction machinery were eliminated.

Reduction effects under different control scenarios were estimated by Reduction

Rates (RR) relative to the normal situation (NS) as given by the following equation:

$$RR_{ERS} = \frac{E_{NS} - E_{ERS}}{E_{NS}} \times 100\%$$

Where ERS is the emission reduction scenario (including IAD, EOM); E is the non-road construction machinery emissions.

2.6 Quality Assurance and Quality Control

The quality control of non-road construction machinery inventory data involved the following three steps:

1) Data sources on activity levels were checked and calibrated to ensure the accuracy of records used in the field investigation. 2) The consistency of the survey space and of the time range of non-road construction machinery pollution sources was checked. 3) The integrity of the survey data was checked to ensure that the data covered all types of non-road construction machinery pollution sources.

3 Results and discussion

3.1 Emission inventory of non-road construction machinery

The emission inventory of non-road construction machinery in Tianjin for 2018 was estimated using the methods described in the prior section. Total atmospheric pollutant emissions of CO, HC, NOx, PM_{10} and $PM_{2.5}$ were 4180.78, 951.44, 5833.85, 383.92 and 365.70 t, respectively. These values were several times higher than those of non-road mobile sources estimated in 2015(ZHANG Yi 2017). The average power calculation method was used, as it is more accurate than the fuel calculation methods used in previous similar studies. The population data used in this study were also more reliable and based on actual surveys. As HC and NOx from construction machinery were the important precursors of atmospheric $PM_{2.5}$ in megacities(Guo et al. 2020), emissions of non-road mobile machinery cannot be ignored. The emission control of non-road construction machinery in such cities must be improved.

The contribution rate of emissions from different construction machines was shown in Figure 3. Among the non-road construction machinery, forklifts, excavators and loaders were the most important emission sources in Tianjin. While the emissions of individual forklifts were not significant, they generated the largest proportion of pollutants due to their frequent use. Excavators and loaders accounted for 30.8%, contributing 40-60% of all pollutants. Therefore, control policies on non-road mobile machinery should focus on large populations of construction machines. The spatial distribution of pollutants from non-road construction machinery in Tianjin is illustrated in Figure 4. There are obvious differences in the emissions of different districts. Large machinery emissions were mainly distributed across the Binhai New Area, Wuqing District, Xiqing District, Dongli District, Jinghai District and Beichen District. Especially for the Binhai New Area, the proportion of total emissions reached 43% for all pollutants. The Heping, Hongqiao, Hebei, Hedong and Nankai District were the regions with the lowest emissions, which was due to the high rates of urbanization and less building construction in these five regions. Emissions of non-road construction machinery were significantly negatively correlated with the level of urbanization. The contributions of non-road construction machinery emission sources in different districts were shown in Figure 5. The results showed that forklifts, excavators, loaders and road rollers are construction machines with the greatest contributions in each district. Among them, the contributions of emission sources in Heping District and Binhai New Area were different from those of other districts. As Heping District has the highest level of urbanization and there are no large factories in the area, emission sources here mainly included excavators, loaders and road rollers. The Binhai New Area is the largest district in Tianjin with a large number of factories and the Tianjin Port(Chen et al. 2016; Na et al. 2017). On port terminals, a large number of tractors were operated. Therefore, in the Binhai New Area, forklifts, excavators, loaders, road rollers and tractors generated the most emissions.

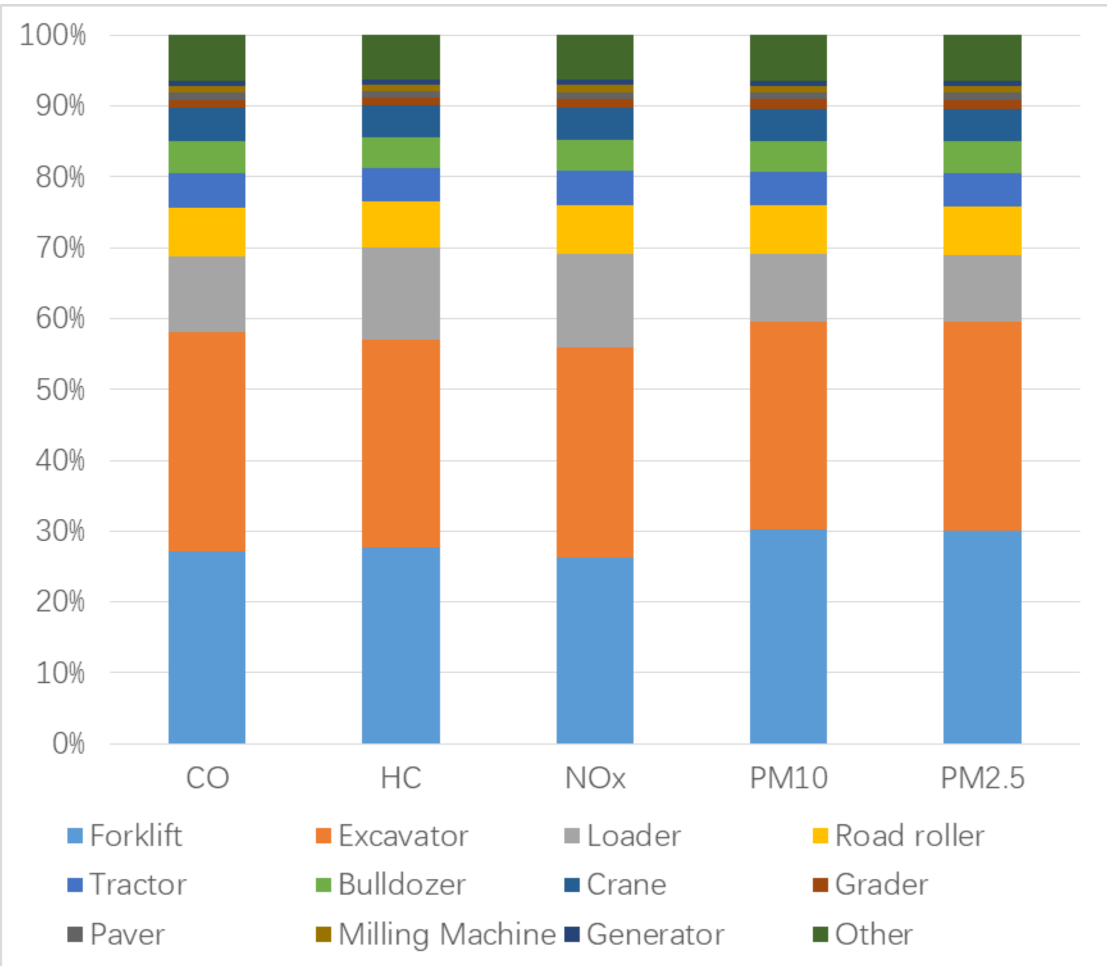

Figure 3 the contribution rates of emissions from different construction machines

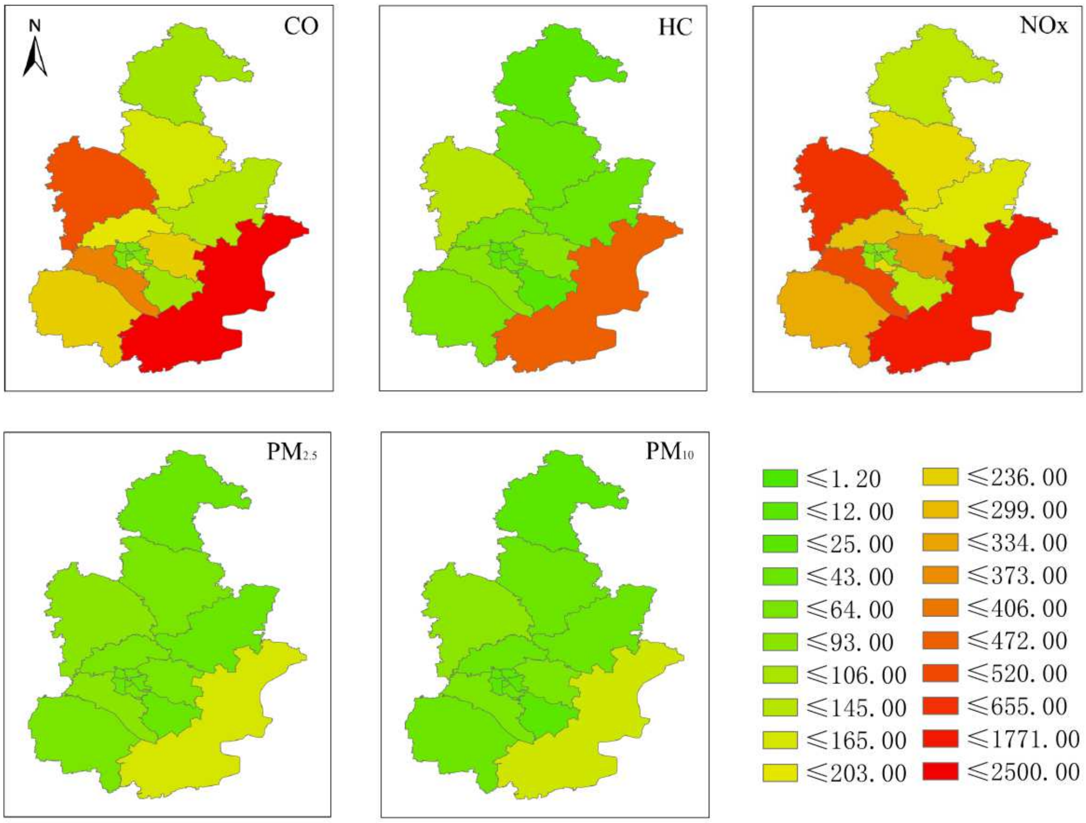

Figure 4 Spatial distribution of total emissions from construction machinery (t)

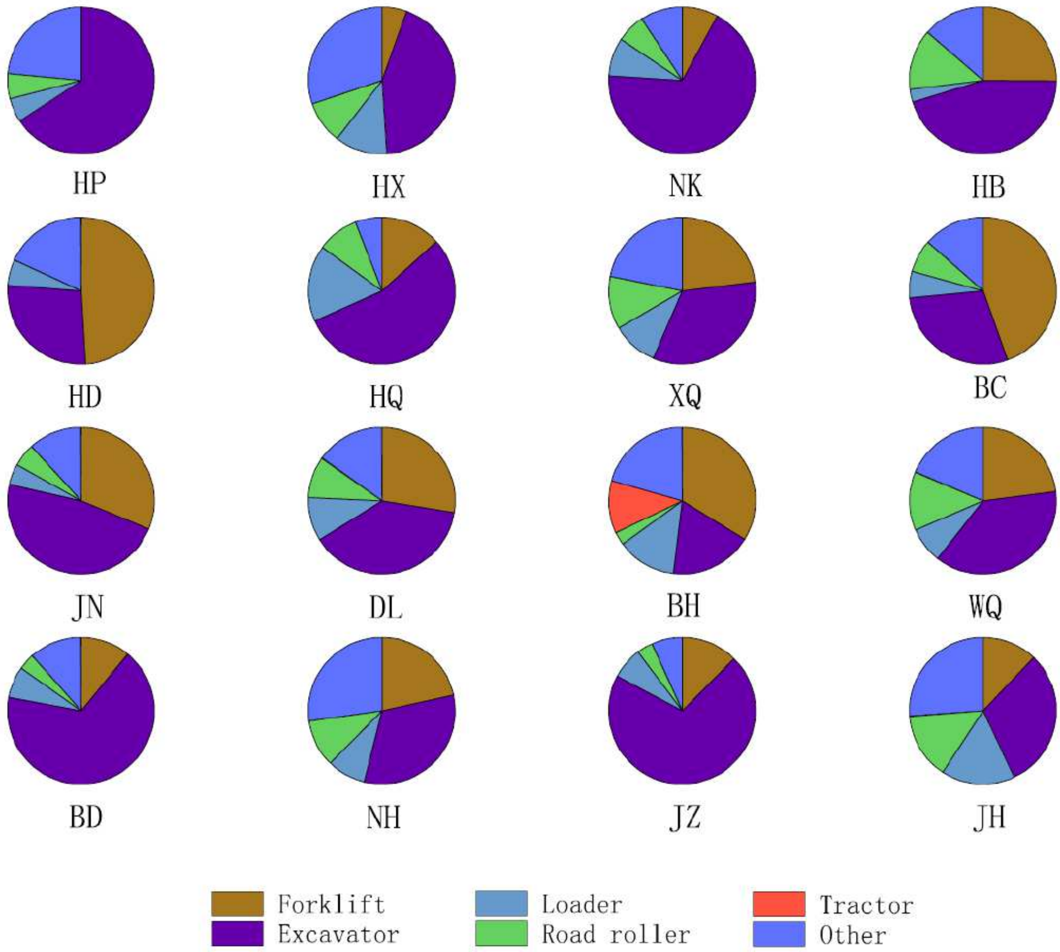

Figure 5 The contributions of non-road construction machinery emission sources in different districts (%)

3.2 Emissions under different reduction scenarios

Emissions from non-road construction machinery and reduction rates under different reduction scenarios were shown in Figure 6 and Table 2. The emission will be controlled to different levels under different emission reduction scenarios. The IAD has an overwhelming effect on reductions of CO and HC emissions with RR values of 17.6% and 17.3%, respectively, while EOM has limited effects on the reduction of CO and

HC emissions with RR values of 3.7% and 6.9%, respectively. The results indicate that the IAD and EOM have similar effects on NOx emissions control. RR values are 16.4% and 16.0% for the IAD and EOM, respectively. For PM_{10} and $PM_{2.5}$, the RR of EOM is higher than the IAD, indicating that the elevation of emission standards has a more obvious effect on PM emission reduction. At present, research on the emissions of non-road mobile machinery is in its infancy, and there are gaps in relevant non-road construction machinery policy measures. The simulation results of the emission reduction scenarios in this study can thus guide future control policy development.

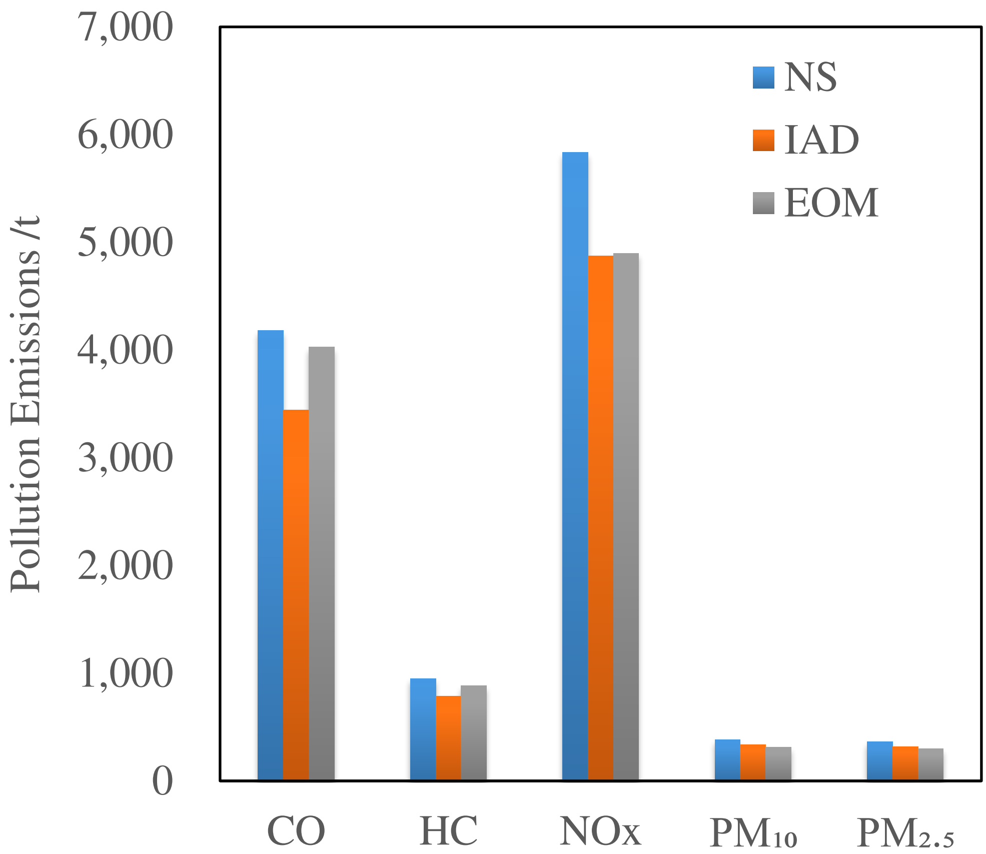

Figure 6 the emissions from non-road construction machinery under different reduction scenarios

Table 2 Reduction rates of emissions under different scenarios

reduction rate	CO	HC	NOx	PM_{10}	$PM_{2.5}$
IAD	17.6%	17.3%	16.4%	12.4%	12.5%
EOM	3.7%	6.9%	16.0%	18.0%	18.4%

3.3 Uncertainty analysis

In this study, non-road mobile construction machinery population, activity level and emission factor were the three forms of emission inventory uncertainty considered.

At present, several cities in China have not established a registration and filing system for non-road mobile construction machinery. Non-road mobile construction machinery is widely used, and its working environments tend to be very harsh. It is difficult to determine the population, power level and age of construction machinery. To mitigate uncertainty as much as possible, we have done our best to carry out detailed and accurate survey classifications. However, the types of sites surveyed, construction stages considered and the representativeness of mechanical samples may introduce uncertainty.

The activity level of construction machinery was obtained through a large sample survey of more than 20,000 machines. However, some uncertainty and large relative deviations in activity level information for some machinery may remain due to the variety of machinery considered.

Emission factors are the weakest facet of research on the emission inventory of non-road construction machinery. The research results of non-road construction machinery emission factors are still very limited. It is impossible to accurately assess the emission levels of various machinery types, engine power and emission standards. It is thus necessary to supplement actual measurement research on the localized emission factors of various non-road mobile construction machinery to mitigate emission inventory uncertainty.

According to the Monte Carlo model, the uncertainty of the emission inventory is calculated based on the logarithm distribution with parameters such as emission factor, activity level, and population with an error level of 10%. The average uncertainty ranges (at a 95% confidence level) for CO, HC, NOx, PM_{10} and $PM_{2.5}$ were measured as −13.64%~18.12%, −15.22%~15.79%, −13.32%~15.13%, −13.58%~15.37%, and −13.27%~15.58%, respectively. While the uncertainty of the emission inventory is inevitable, the comprehensive prediction of the emissions of non-road mobile machinery can still guide the formulation of environmental policies.

3.4 Control policy

The emission standard of non-road mobile machinery must be improved. In China, most non-road mobile machinery only adheres to China II emission standard. Many vehicles can meet the China II emission standard by installing DOC, EGR and other after-treatment devices, which has hindered the development of advanced control technologies such as DPF and SCR. Many companies cannot afford to make significant technology and capital investments to adopt advanced control technology, hindering technological research and development.

Therefore, the short-term goal of pollution control can be achieved by improving emissions management and accelerating the installation of DPF and SCR advanced exhaust treatment devices for non-road mobile machinery. The ultimate goal of the long-term control of non-road mobile machinery exhaust pollution can be achieved by providing preferential policies for research and development enterprises, accelerating the development of DPF and SCR advanced technology, and reducing costs of transformation.

In terms of the integration and development of non-road diesel engine manufacturers, due to the small scale and insufficient technical reserves of many diesel engine manufacturers in China, their manufacturing levels are limited, and the precision of key components of developed engines is low. As a result, the combustion of domestic engines cannot achieve the best efficiency or the requirements of higher emission standards. It is necessary to integrate decentralized capital, introduce technology, improve the production of non-road engines, and ultimately achieve emission reduction and quality improvements to non-road mobile machinery.

Pollution problems related to non-road mobile machinery have been attracted to the attention of the Chinese government. It is necessary to establish a cooperative mechanism for scientific research institutes, government departments, enterprises and other relevant parties in the control of non-road mobile machinery emissions. First, scientific research institutes must establish preliminary emission standards based on the data, and the government must then promulgate a detailed plan of action according to these standards. Enterprises must provide prompt feedback on the implementation of such standards and finally achieve the precise control of non-road machinery emissions.

Conclusion

This study provides comprehensive estimations of non-road construction machinery emissions of CO, HC, NOx, PM_{10}, and $PM_{2.5}$ for Tianjin. Total atmospheric pollutant emissions of CO, HC, NOx, PM_{10} and $PM_{2.5}$ were measured at 4180.78, 951.44, 5833.85, 383.92 and 365.70 t, respectively. Among non-road construction machinery, forklifts, excavators and loaders were found to be the three most important sources of emissions in Tianjin, contributing 70% of all pollutants. Regarding spatial distributions, there are clear differences in the emissions of different districts. The contribution of emission sources in Heping District and the Binhai New Area is different from those of other districts.

Analysis results of emission reduction scenarios show that the IAD has an overwhelming effect on the reduction of CO and HC emissions with RR values of 17.6% and 17.3%, respectively. The EMO has a more obvious effect on the reduction of PM emissions. For NOx, the IAD and EMO have similar effects on NOx emissions control with RR values of 16.4% and 16.0% for IAD and EMO, respectively.

Finally, the emission reduction control policy for non-road construction machinery is proposed to provide basic support for the future management of non-road mobile machinery. The emission standard for non-road mobile machinery must be improved. The development of vehicle after-treatment technology should be accelerated to reach international standards, and cooperation between scientific research institutes, government departments and enterprises in the control of non-road mobile machinery emissions must be established.

Ethics approval and consent to participate

Not applicable

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.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Qijun Zhang：Conceptualization, Methodology, Writing-Original draft preparation, Writing-Reviewing and Editing.
Ning Wei：Data curation, Software.
Lei Yang: Data curation.
Xi Feng: Data curation.
Yanjie Zhang: Validation.
Lin Wu: Supervision.
Hongjun Mao: Funding acquisition, Methodology, Writing-Reviewing and Editing.

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Figures

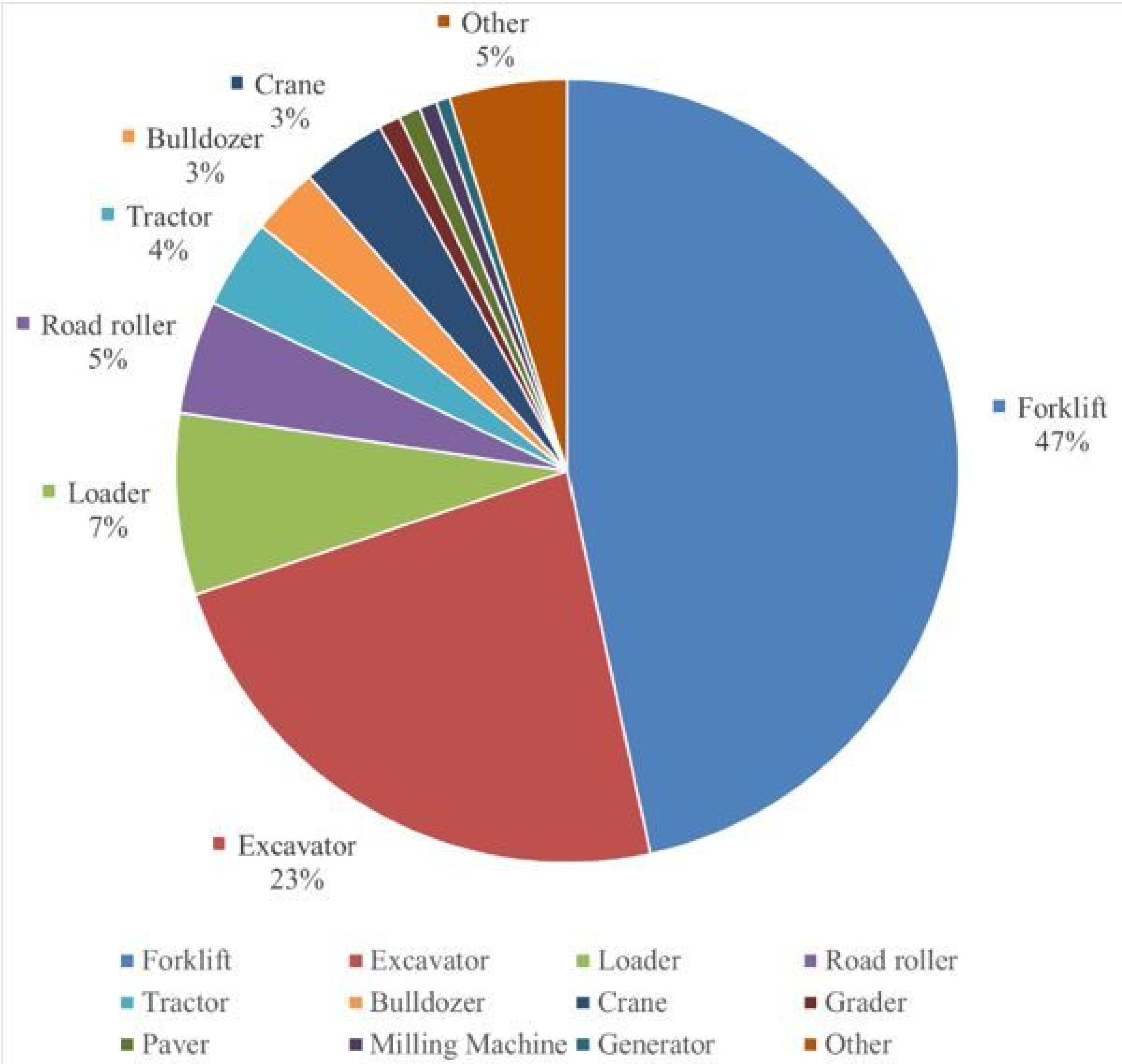

Figure 1

Type distribution of non-road construction machinery

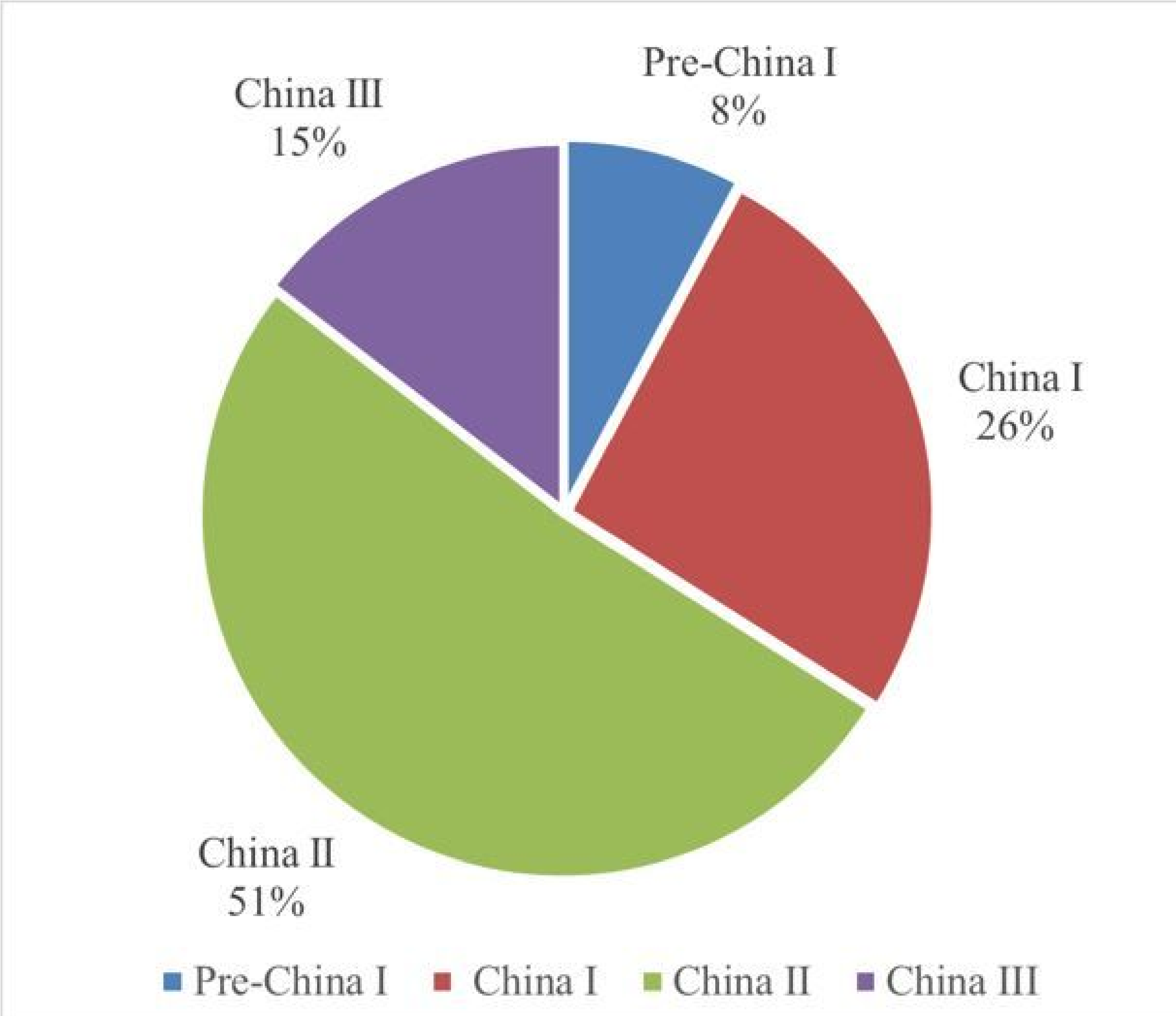

Figure 2

Emission standard distribution of non-road construction machinery

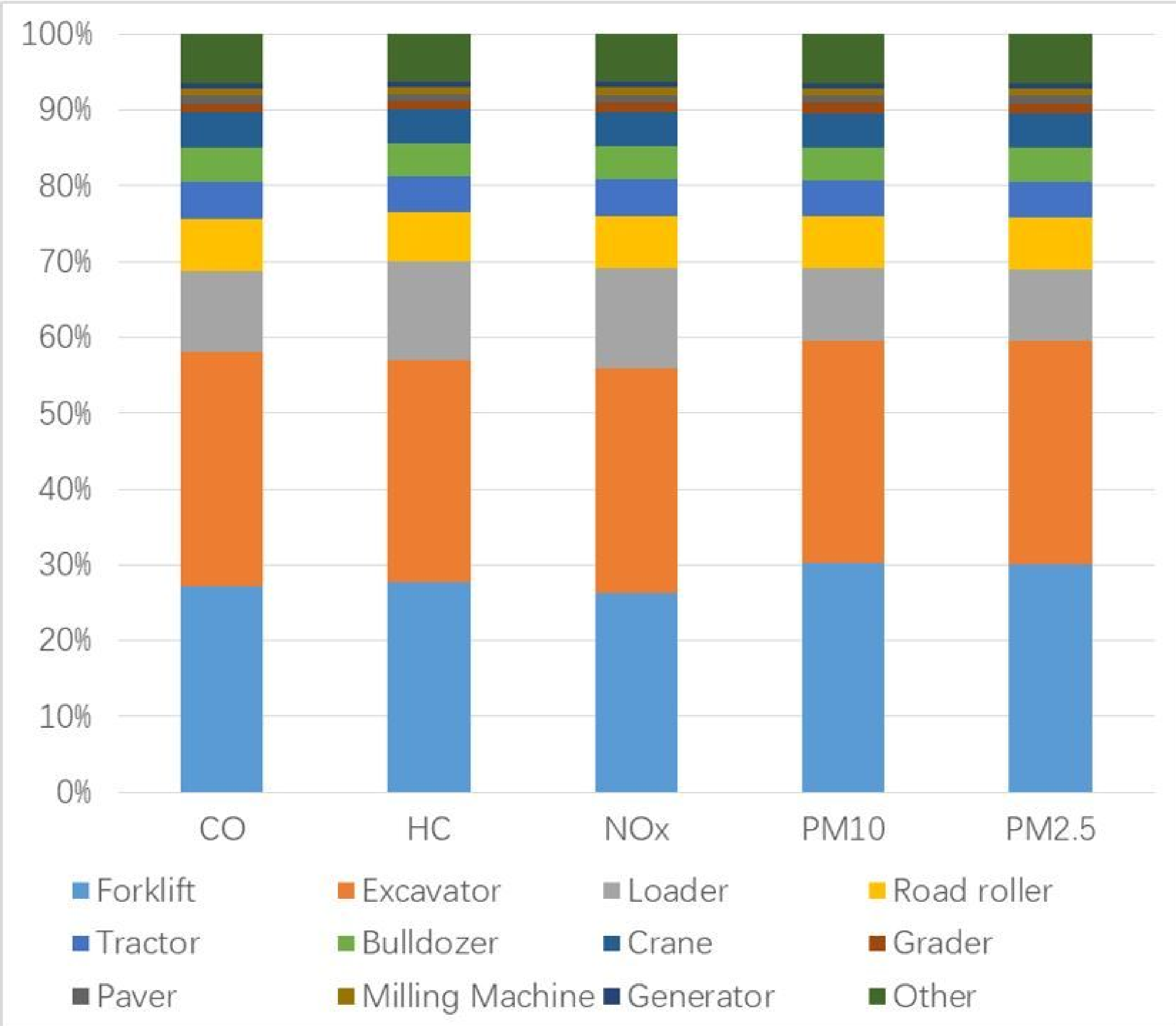

Figure 3

the contribution rates of emissions from different construction machines

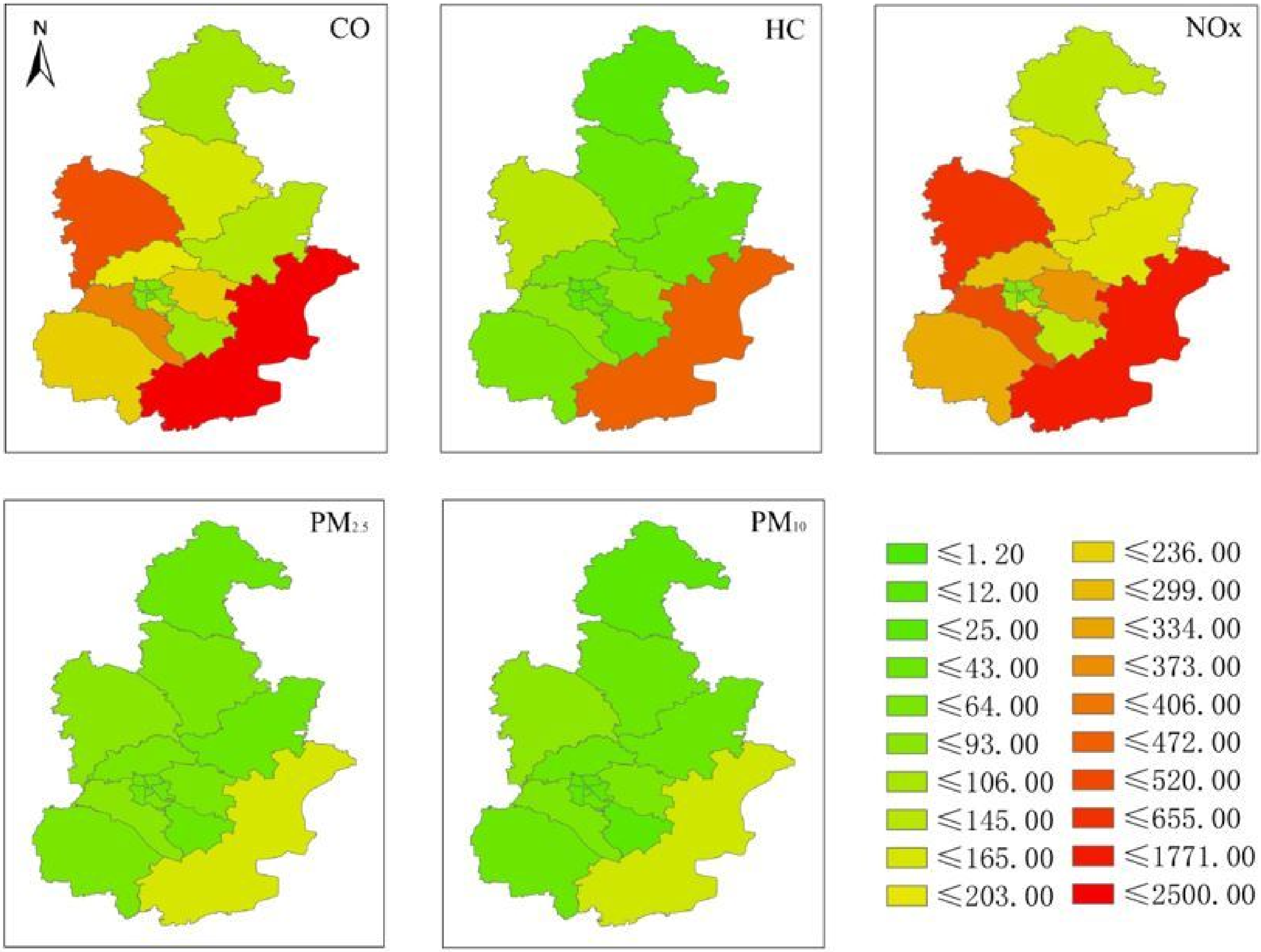

Figure 4

Spatial distribution of total emissions from construction machinery (t) 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.

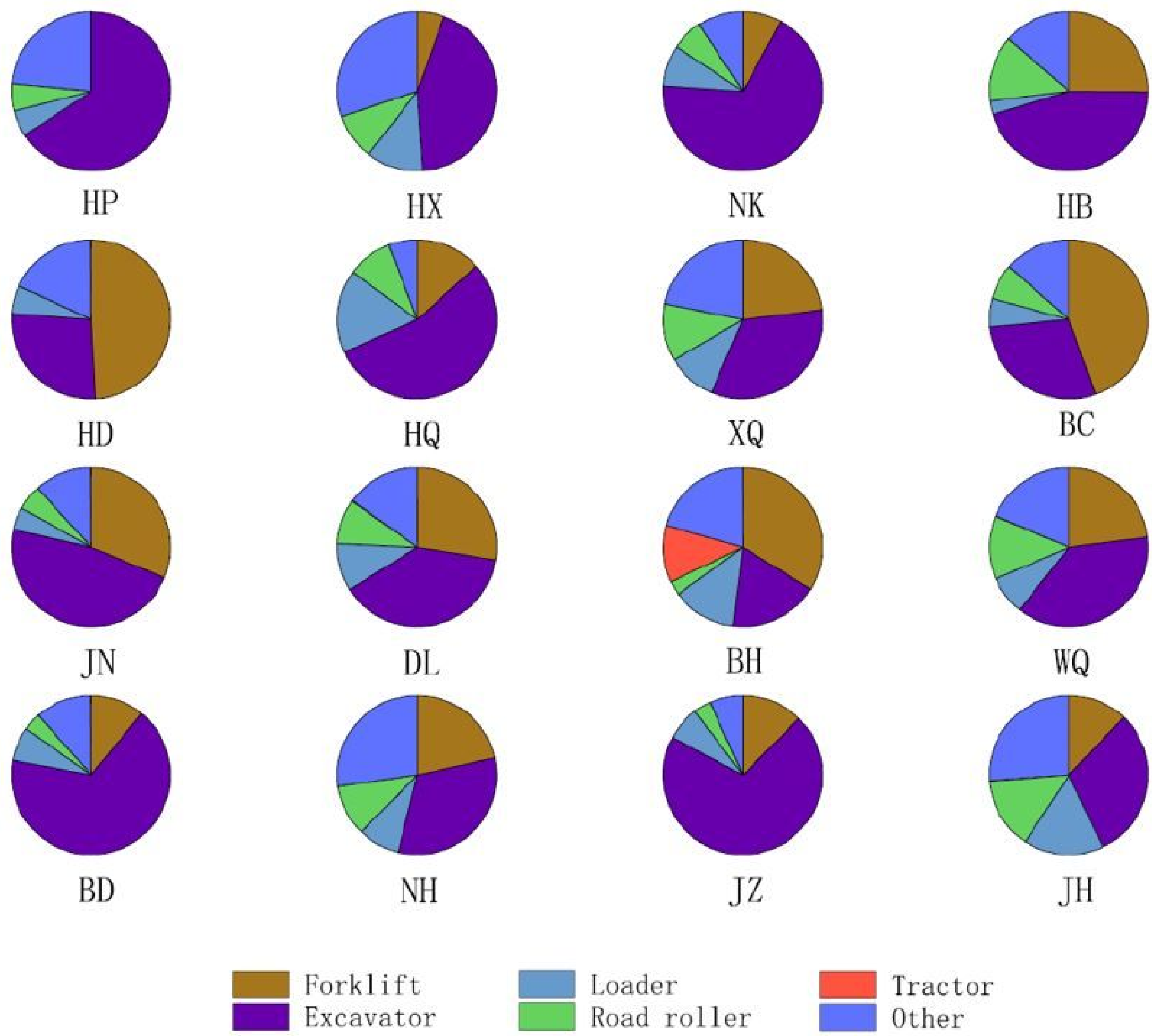

Figure 5

The contributions of non-road construction machinery emission sources in different districts (%)

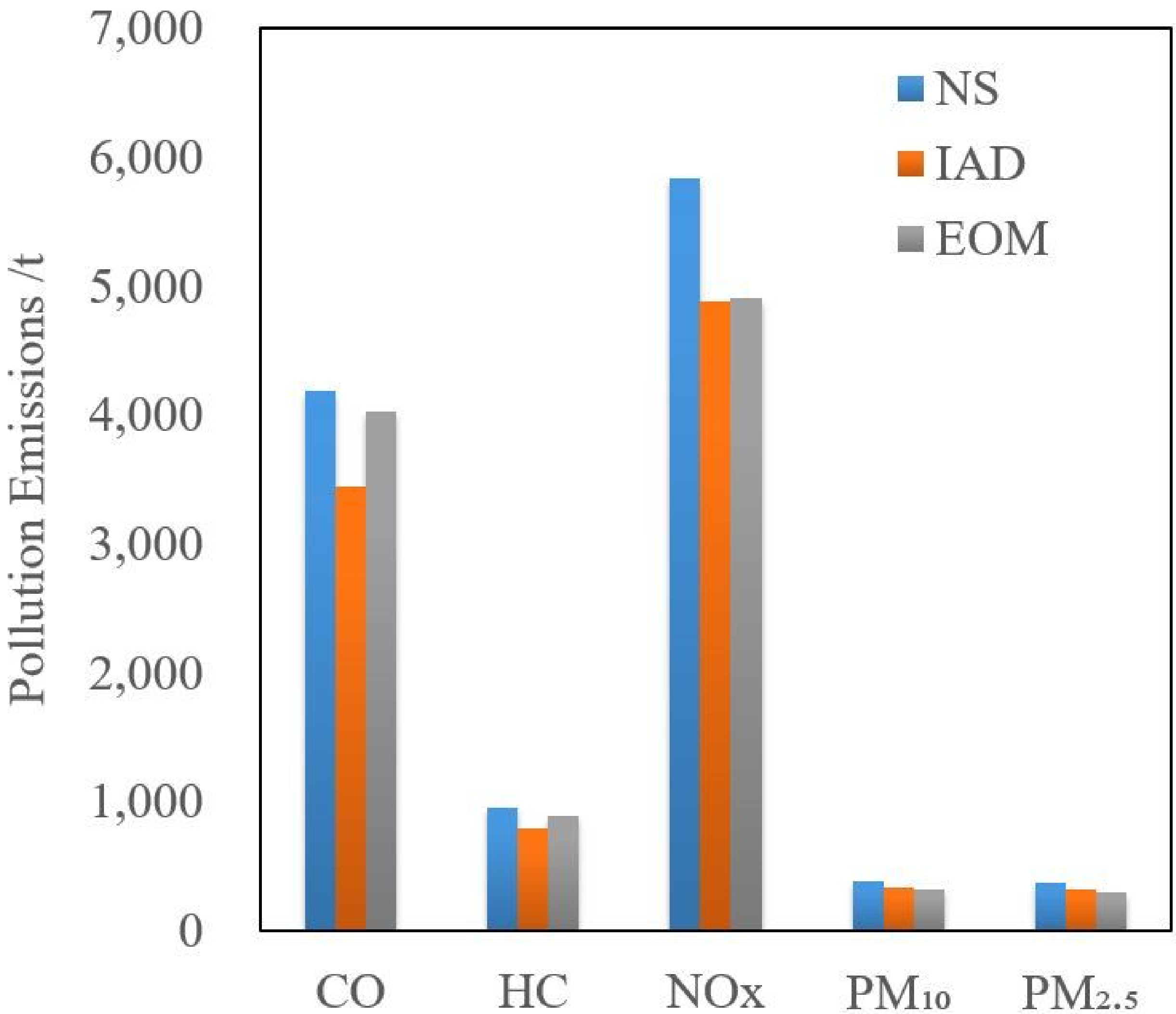

Figure 6

the emissions from non-road construction machinery under different reduction scenarios

Supplementary Files

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- SupplementaryMaterials1.docx