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LETTER

The rationality of PM2.5 monitoring sites' locations based on exposure level across eastern China

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Abstract

Due to the heterogeneity of $PM_{2.5}$ and population distribution, the representativeness of existing monitoring sites is questionable when the monitored data were used to assess the population exposure. By comparing the $PM_{2.5}$ concentration from a satellite-based dataset named the China High Air Pollutants (CHAP), population and exposure level in urban areas with monitoring stations (UWS) and without monitoring stations (UNS), we discussed the rationality of the current spatial coverage of monitoring stations in eastern China. Through an analysis of air pollution in all urban areas of 256 prefectural-level municipalities in eastern China, we found that the average $PM_{2.5}$ concentration in UNS in 2015 and 2018 were 52.26 $\mu g\ m^{-3}$ and 41.32 $\mu g\ m^{-3}$, respectively, which were slightly lower than that in UWS (52.98 $\mu g\ m^{-3}$ and 41.48 $\mu g\ m^{-3}$). About 12.1% of the prefectural-level municipalities had higher exposure levels in certain UNS than those in UWS. With the faster growth of UNS population, the gap between exposure levels of UNS and UWS were narrowing. Hence, currently prevalent administration-based principle of site location selection might have higher risk of missing the non-capital urban areas with relatively higher $PM_{2.5}$ exposure level in the future.

1. Introduction

In the past decades, the acceleration of urbanization and industrialization brought severe air pollution problems in China (Li *et al* 2016, Hao *et al* 2020). $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 μm) is one of the major air pollutants, which has serious impacts on human health and global climate change (Cao *et al* 2012, 2016).

To effectively monitor and assess $PM_{2.5}$ pollution, a large amount of monitoring stations managed directly by central government (state-controlled-stations for short) were established. The first batch of cities, including 74 key prefecture-level cities, started monitoring $PM_{2.5}$ routinely and listed the concentration of $PM_{2.5}$ as an elementary index of air quality in 2013. By 2015, the number of these cities expanded to 338. As the $PM_{2.5}$ concentration is closely related to human activities, much attentions were focused on the central downtown area of key cities. The monitoring network greatly enhanced the nationwide monitoring ability and played an important role in the control of $PM_{2.5}$ pollution (You 2014, Chen *et al* 2015, Wang *et al* 2019).

The primary principle of selecting the location of a state-controlled-station was administrative division. The current monitoring network covers the capital urban area of prefectural-level municipalities. And the minimum number of stations in each capital urban area depends on the urban size and population of the downtown area. However, the representativeness of the administration-based stations is questionable because of the heterogeneous distribution of $PM_{2.5}$ and population. For example, the assessment of site locations in Beijing showed that the monitoring stations were mainly located in the city centre. But there were few stations in the suburbs despite a large proportion of the population living there (Li *et al* 2018, Yu *et al* 2018). And during the

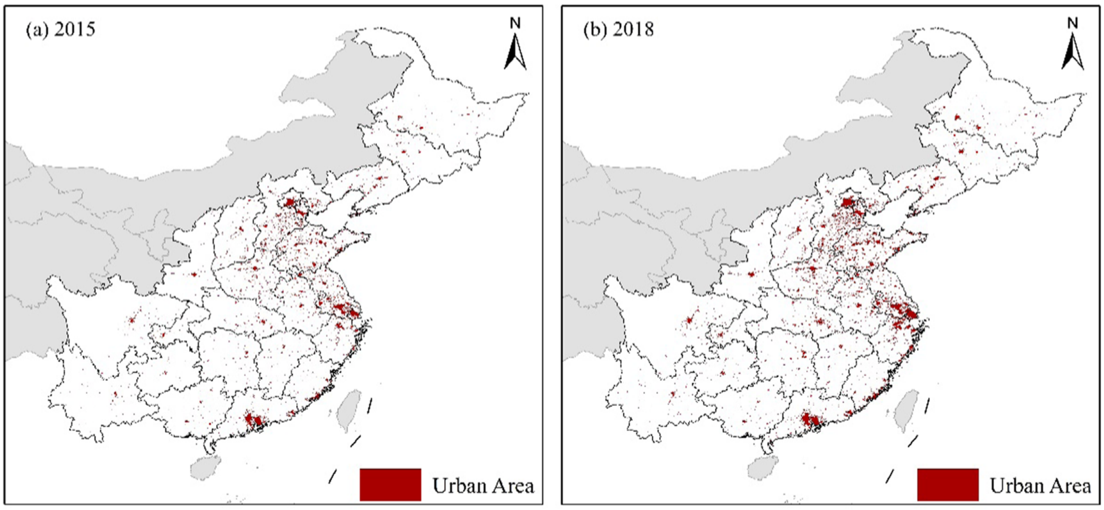

Figure 1. The identified urban areas in eastern China in 2015 (a) and 2018 (b).

rapid urbanization process, the urban environment had a more and more negative impact on the surrounding areas (Han *et al* 2015b). On the other hand, the polycentric urban development, accompanied by consistent growth of population, caused tight environmental stress in the outskirts of the city centres (Sun *et al* 2012, Han *et al* 2015a, Wu *et al* 2018, Sun and Lv 2020). Lin *et al* found that the decline rate of $PM_{2.5}$ in most urban areas was higher than that in other areas (Lin *et al* 2018).

Although massive monitoring stations managed by lower level governments, such as provincial and prefectural-level governments, have been established and are routinely operating, the state-controlled stations were the main data source for most studies on $PM_{2.5}$ concentration distribution and health risk assessment on national scale (Huang *et al* 2018, Ye *et al* 2018, Fan *et al* 2020). Hence, it is worth evaluating whether the administration-based state-controlled-stations have appropriate representativeness. The purpose of this study is to explore the rationality of the spatial coverage of current administration-based $PM_{2.5}$ monitoring stations by comparing the $PM_{2.5}$ concentration from a gridded satellite-based dataset, population and exposure level between urban areas with and without monitoring stations. This information has implications for further improving the air quality surveillance network in the future.

2. Data and methods

2.1. Study region and urban identification

This study covered 256 prefectural-level municipalities in eastern China as shown in figure 1. The urban areas, representing the residential areas scattered in a certain prefecture-level municipality, were identified using Global Urban Boundaries (GUB) dataset generated based on Global Artificial Impervious Area (GAIA) data (Li *et al* 2020). The spatial resolution of GUB dataset is 30 meters and the year of GAIA data collection are 2015 and 2018. In total, 2210 urban areas were identified and the belonging prefectural-level municipalities of these urban areas were also labelled. To simplify the expressions, the four direct-administrated municipalities, including Beijing, Shanghai, Tianjin and Chongqing, were also presented as prefectural-level municipalities.

Among the identified urban areas in each prefectural-level municipality, the one where the administration is located was named 'capital downtown' and the remaining ones consist of county-level downtown and other lower administrative level settlements. These urban areas were categorized into two groups according to the existence of state-controlled-station within the identified urban areas, noted as UWS for urban areas with station(s) and UNS for those without station, respectively. Most capital downtowns (578 out of 858) were in UWS group, while only 41 out of 1352 other urban areas were in UWS group.

2.2. $PM_{2.5}$ and population data

Annually average $PM_{2.5}$ mass concentrations data from China High Air Pollutants (CHAP) dataset (https://weijing-rs.github.io/product.html) with the grid resolution of 1 km × 1 km in 2015 and 2018 were used to analyze the $PM_{2.5}$ concentration distribution and its variation trend in the identified urban areas. The $PM_{2.5}$ concentrations in this dataset were predicted by a space-time extremely randomized trees (STET) model using revised MAIAC AOD product combining meteorological parameters, land coverage, surface topography, and population distribution data (Lyapustin *et al* 2011, Wei *et al* 2020). Evaluation results showed high correlation between the predicted concentrations and the ground-level observations (Wei *et al* 2021).

The population data from LandScan dataset (https://landscan.ornl.gov/) with the grid resolution of 1 km $\times$ 1 km in 2015 and 2018 were used to analyze the distribution of population density and $PM_{2.5}$ exposure (Bhaduri *et al* 2007, Graesser *et al* 2012). The LandScan dataset was generated by a Global Population Distribution Model using the sub-national census data, land cover, road density, urban distribution, settlements locations, etc.

The gridded $PM_{2.5}$ concentrations and population were collocated with the GUB dataset by Nearest resampling algorithm. For each identified urban area, the annually mean $PM_{2.5}$ concentration and total population were determined by calculating the average of $PM_{2.5}$ concentrations and summations of population in all the grids located in this urban area. In a certain prefectural-level municipality, the average $PM_{2.5}$ concentrations (total population) of UWS and UNS were calculated by averaging (summing) the mean $PM_{2.5}$ concentrations and total population of all urban areas categorized as UWS and UNS, respectively.

2.3. Exposure level

The method of calculating the population's $PM_{2.5}$ exposure level (PPME) was similar to the model used in Kousa *et al* (2002). In each identified urban area, the PPME was calculated by multiplying mean $PM_{2.5}$ concentration and total population with unit of persons$\cdot\mu$g m^{-3}. Both larger population and higher $PM_{2.5}$ concentration could lead to higher PPME in an urban area.

3. Results

3.1. $PM_{2.5}$ in UWS and UNS urban areas

The average $PM_{2.5}$ concentrations of each prefectural-level municipalities in UWS and UNS were shown in figure 2. Similar spatial distribution characteristics were observed between concentrations in UWS and UNS. Heavily polluted areas were mainly concentrated in Beijing-Tianjin-Hebei, Yangtze River Delta and Sichuan Basin, which were consistent with the ground-level observations (Shen *et al* 2020). The variation trends of $PM_{2.5}$ concentrations in UWS were similar to those in UNS from 2015 to 2018. Average $PM_{2.5}$ concentrations across eastern China decreased from 53.0 μg m^{-3} and 52.3 μg m^{-3} to 41.5 μg m^{-3} and 41.3 μg m^{-3} in UWS and UNS, respectively. But the reduction amount showed large regional disparity. The reduction of $PM_{2.5}$ concentration in Beijing-Tianjin-Hebei was the largest among the city agglomerations, about 17.7 μg m^{-3} and 18.9 μg m^{-3} in UNS and UWS, respectively. The $PM_{2.5}$ concentration in Sichuan Basin decreased in a relatively slighter degree, only 6.9 μg m^{-3} and 7.9 μg m^{-3} in UNS and UWS, respectively. The reduction amount of $PM_{2.5}$ concentration in Yangtze River Delta was close to the average value across eastern China, about 11.5 μg m^{-3} and 12.3 μg m^{-3} in UNS and UWS, respectively.

Figure 3 presented the differences between average $PM_{2.5}$ concentrations of UWS and UNS in the same prefectural-level municipalities (DPM) and a positive DPM value means higher $PM_{2.5}$ concentration in UWS. On average, the $PM_{2.5}$ concentrations of UWS were slightly higher than those of UNS. And the discrepancies narrowed significantly from 2015 to 2018. The average DPM in all the prefectural-level municipalities was 0.72 μg m^{-3} in 2015 and decreased to 0.16 μg m^{-3} in 2018. The DPM concentrated between -2 μg m^{-3} and 4 μg m^{-3} and the distribution of municipality numbers peaked at DPM range of 0–2 μg m^{-3}. The comparison between DPMs in 2015 and 2018 showed that the gaps in $PM_{2.5}$ concentrations between UWS and UNS were narrowing rapidly. As a result, the municipalities with absolute DPMs less than 2 μg m^{-3} increased significantly and the municipalities with absolute DPMs larger than 10 μg m^{-3} almost disappeared. Specifically, the number of prefectural-level municipalities where $PM_{2.5}$ concentrations in UNS were higher than those in UWS (DPM < 0) increased from 92 in 2015 to 98 in 2018.

3.2. Population in UWS and UNS urban areas

Like $PM_{2.5}$ concentrations, the differences of population between UWS and UNS were also decreasing. In total, the population in all UNS increased by 16.7% (from 156 million to 182 million) from 2015 to 2018, which was exceeding two times larger than the rising proportion of population in all UWS (6.5%, from 185 million to 197 million). At provincial level, figure 4 presented the total population in UWS and UNS of each province. The population in UWS were higher than those in UNS in most provinces except Henan, Hebei, Fujian and Liaoning. The differences of population between UWS and UNS were 29 million in 2015 and 15 million in 2018, respectively. At municipality level, about 122 prefectural-level municipalities had more population in UNS in 2015, accounting for 47.7% of all the municipalities. But in 2018, the proportion of these municipalities increased to 51.2%.

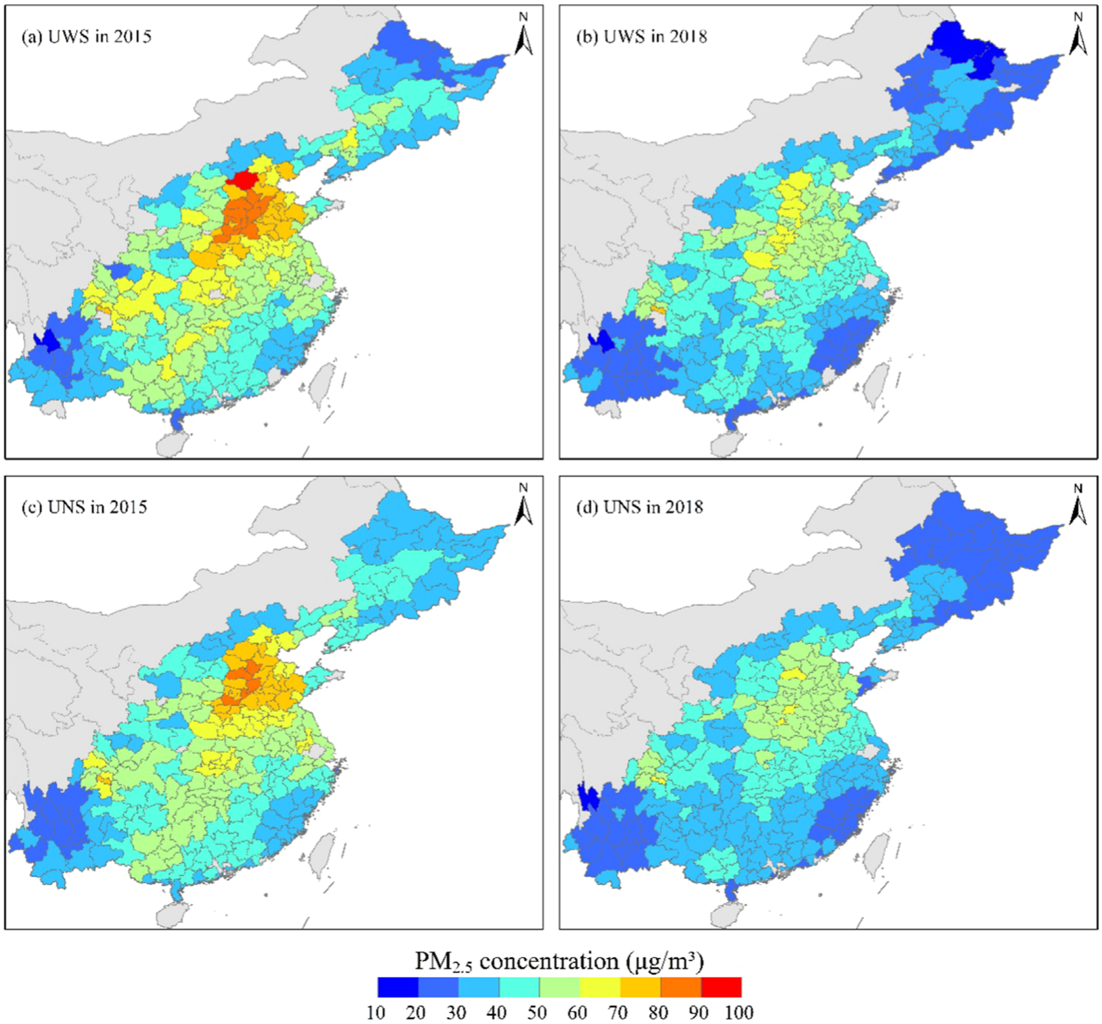

Figure 2. Average $PM_{2.5}$ concentrations of each prefectural-level municipalities in UWS in 2015 (a); UWS in 2018 (b); UNS in 2015 (c); UNS in 2018 (d). The $PM_{2.5}$ concentrations were obtained from the CHAP dataset.

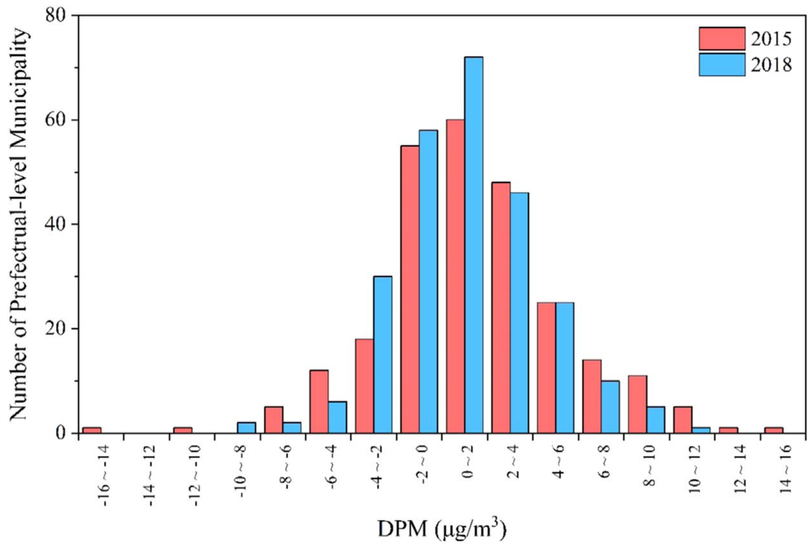

Figure 3. The distribution of the number of prefectural-level municipalities with respect to the DPM.

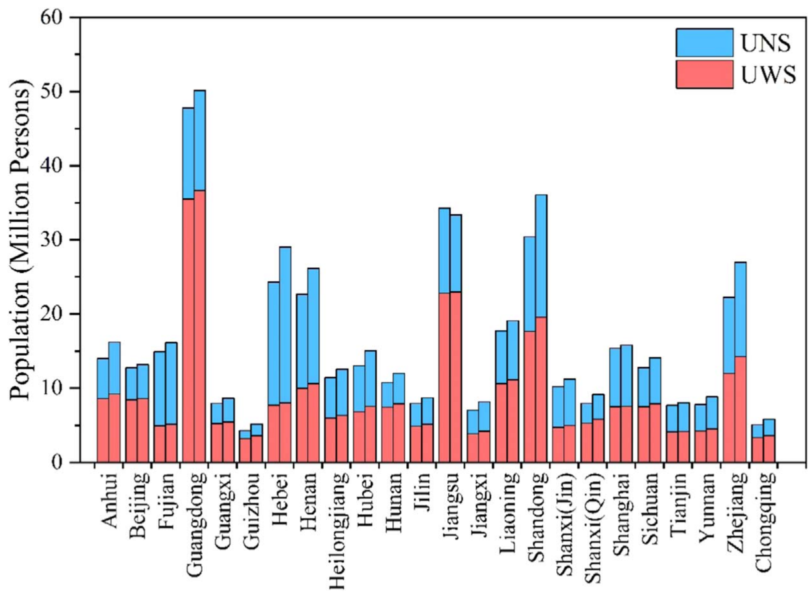

Figure 4. The population in the UWS and UNS of each province in the study area. The bars in the left and right side represent population in 2015 (left bar) and 2018 (right bar), respectively.

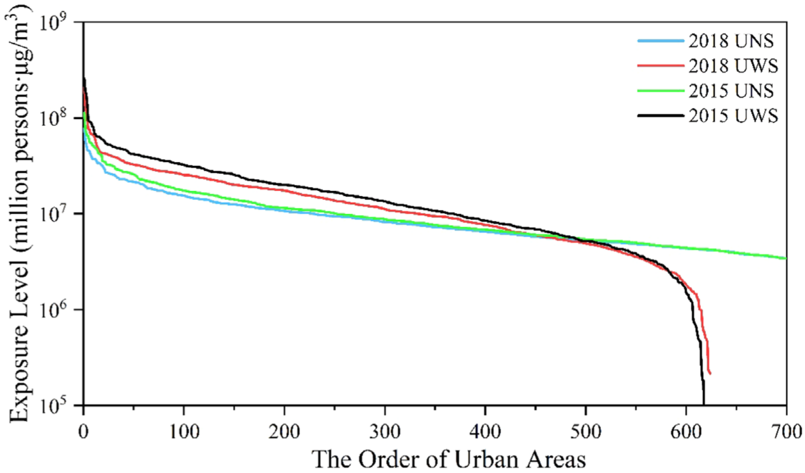

Figure 5. The ranking of exposure levels of every single UWS and UNS urban areas.

3.3. PPME in UWS and UNS urban areas

The exposure level of an urban area was determined by ambient $PM_{2.5}$ concentration and population together. Hence, comparing the $PM_{2.5}$ concentration or population between UWS and UNS individually was insufficient to assess the exposure level. In about 31 prefectural-level municipalities, exposure levels of UWS were not the largest among all the urban areas in the same prefectural-level municipality in 2015. This revealed that about 12.1% of the municipalities had higher exposure levels in certain UNS than those in UWS. And the number of municipalities with this feature expanded to 32 in 2018 (figure S1 (available online at stacks.iop.org/ERC/4/011001/mmedia)). As to all the identified areas, we sorted the exposure levels of all the urban areas from the largest value to the smallest and the results were shown in figure 5. In the high exposure level region, although the UWS had much higher exposure levels than the UNS, several tens of UNS also confronted serious exposure and these urban areas mainly consisted of the suburbs of mega-cities, such as Beijing, Shanghai and Guangzhou, and some county-level cities. The decrease of UNS exposure level was much lower than that of UWS. As a result, in the low exposure level region the exposure levels in UWS were lower than those in UNS when the ranking of urban areas larger than about 450. These UWS with lower exposure levels were mostly the downtown areas of smaller prefectural-level municipalities with less population.

4. Discussion and conclusions

The differences between $PM_{2.5}$ concentrations in capital downtown areas (mainly UWS) and non-capital urban areas (mainly UNS) of same prefectural-level municipalities were unexpectedly small. This might be caused by the transportation of pollutants from relatively polluted downtown areas to surrounding areas (Wang *et al* 2014). And these differences of $PM_{2.5}$ concentrations decreased significantly from 2015 to 2018. One reason of this phenomenon might be the acceleration of urbanization process in the non-capital urban areas, which could be supported by the increase of population as shown in section 3.2. The population in the non-capital urban areas grew at a faster rate than those in the capital downtown areas. This led to growing pollutant emissions from vehicles, energy consumption (Lin and Zhu 2018) and construction (Xu and Lin 2016). Furthermore, widespread transfer of industries from capital downtown areas to non-capital areas very likely increased the potential emissions in latter areas (Fang *et al* 2019) . Moreover, in non-capital areas usually there were lower proportions of clean energy usage (Zhao *et al* 2018, Chen and Chen 2019), more poorly managed small factories, less usage of emission reduction techniques with poorer efficiency (Cheng *et al* 2020) and even looser governmental supervision (Liu *et al* 2018).

As to the $PM_{2.5}$ exposure level, in most prefectural-level municipalities the exposure levels in capital downtowns were higher than the non-capital urban areas and the differences were more obvious than the $PM_{2.5}$ concentration differences. This were mainly caused by less population in non-capital urban areas. Still, the gaps of exposure levels were narrowing in most prefectural-level municipalities because of the faster growing rate of population in the non-capital urban areas. The number of prefectural-level municipalities with higher $PM_{2.5}$ exposure levels in non-capital urban areas than those in capital areas was increasing. This might be caused by the transfer of industries from capital areas to non-capital areas and the migration of population from rural areas to non-capital areas. Along with the rapid and sustained development of economy, these processes will be promoted in more cities. Therefore, it is expected that the $PM_{2.5}$ exposure levels in non-capital urban areas would to be of the same importance as those in capital areas in the future.

Considering that the primary purpose of monitoring $PM_{2.5}$ is assessing the population exposure, and that the current administration-based state-controlled-stations cover the most exposed areas in exceeding 87.9% of the prefectural-level municipalities, we concluded that the spatial coverage of current administration-based $PM_{2.5}$ monitoring stations are good enough. However, in the future, the administration-based selection principle of site locations might miss substantial urban areas with relatively high $PM_{2.5}$ exposure. Thus, we suggest that more monitoring stations should be established based on the exposure level rather than simply based on the administrative level.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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