Quantifying influences of administrative division adjustment on PM$_{2.5}$ pollution in China’s mega-urban agglomerations

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**ABSTRACT**

China’s mega-urban agglomerations have experienced severe particulate matter pollution that is accompanied by rapid economic growth and extensive administrative division adjustment (ADA). However, the precise roles of ADA on the environmental quality are unknown. Using the geographical detector and evolution tree model, this study quantifies the effects and mechanisms of ADA on the changes in PM$_{2.5}$ concentration in three mega-urban agglomerations: Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD), and Pearl River Delta (PRD) during 2000–2017. Our results showed that: (1) ADA had strong positive effects on PM$_{2.5}$ concentrations in the 0–6 years lag and negative effects in the 7–10 years lag; (2) During 2000–2009, ADA elevated PM$_{2.5}$ concentration by 5.93% via stimulating the development and transfer of heavy industry and urban sprawl in the BTH; (3) YRD and PRD respectively reduced the ADA’s exacerbating effect to 5.26% and 4.98% via reasonable industrial structures and comprehensive cooperation mechanisms; (4) During 2009–2017, BTH and YRD integrated industrial transformation and environmental protection services through ADA, which alleviated 9.51% and 8.49% of PM$_{2.5}$ pollution. PRD, meanwhile, accomplished orderly population dispersal and urban expansion by combining ADA with urban planning, thus reducing the PM$_{2.5}$ concentration by 8.01%. We located three agglomerations in the evolution tree, which provide a basis for formulating relevant policies and region-oriented air pollution joint prevention control strategies.

1. Introduction

In the past four decades, China has experienced unprecedented urbanization and industrialization, making air pollution one of the most serious social problems (Huang et al., 2014; Lelieveld et al., 2015). The efforts to clean China’s air have drawn worldwide attention (Kelly and Zhu, 2016). China’s mega-urban agglomerations, as strategic core areas with the potential to drive continuous economic growth (Fang and Yu, 2017; Feng and Wang, 2021), experienced severe particulate matter pollution, which were accompanied by rapid economic growth and extensive administrative division adjustment (ADA) (Wang and Qi, 2017). ADA, as one of the most prevalent means of redistributing and reconfiguring local government power over China in recent years (Feng and Wang, 2021), was believed to have significant impacts on the ecological environment (e.g., air pollution). However, ADA’s environmental effects are understudied (Li et al., 2021). The quantitative representation of the ADA’s environmental effects can be used for urban planning, urban management, and prediction, which are important driving factors for formulating effective environment protection policies.

Previous studies have associated PM$_{2.5}$ concentrations with natural factors, including air temperature (Al-Hemoud et al., 2019), precipitation (Lorelei de Jesus et al., 2020), wind speed (Dhyani et al., 2017), and topography (Bravo Alvarez et al., 2013). Recently, an increasing number of scholars have focused on the relationship between PM$_{2.5}$ concentrations and socioeconomic factors, such as population density (Ding et al., 2019), industrial structure (Luo et al., 2018), urban expansion (Liu et al., 2017; Luo et al., 2018), policies (Gao et al., 2019; Luo et al., 2018), etc. These studies found that anthropogenic activities were the root cause of high PM$_{2.5}$ concentrations (Platt et al., 2014). As an important anthropogenic and governance factor (Feng and Wang, 2021), the impact of macro governmental governance systems and management (e.g., ADA) on the environment has also become a new hot spot (Li et al., 2021).

The administrative division is the division of administrative regions...
at all ranks by the state, which plays a decisive role in China regional development (Yu et al., 2018). China is currently facing regional air pollution caused by the spread of pollutants across administrative regions (Chen et al., 2019; Zhang et al., 2019), with obvious “spatial spillover” characteristics (Cheng et al., 2017). However, the administrative division has obvious rigid constraints on the establishment of pollution prevention and control coordination mechanisms between different administrative regions (Wang and Wang, 2020), which seriously limits the government’s environmental governance capacity. Furthermore, ADA was an effective means to break administrative boundary constraints and improve environmental governance, which is widespread in urban agglomerations (Wang and Qi, 2017). Based on international experience, it is the common practice to adjust the administrative divisions substantially in the period of rapid industrialization and urbanization (Feiock, 2009; Wheeler, 2002). Previous studies explored the ADA’s influence mechanism on PM$_{2.5}$ pollution include two main aspects: (1) exploring ADA’s indirect effects on environmental pollution from the perspective of socioeconomic development. Some scholars concluded that ADA has a significant impact on urban air pollution by stimulating urban sprawl (Wu and Hao, 2012; Yu et al., 2018), industry transformation, and population transfer (Ma, 2005); (2) More studies were conducted to explore the ADA’s impact on air pollution control across administrative boundaries from a regional perspective. Reasonable ADA was conducive to form a unified environmental regulation (Zhang et al., 2019) and improve the coordinated design and implementation of pollution control policies between different cities (Liu et al., 2017). Main methods used in previous studies include regression discontinuity model (Shi et al., 2019), input-output analysis (Guan et al., 2014), and spatial econometric model (Du et al., 2018; Hao et al., 2015; Liu et al., 2017; Zhang and Wu, 2018; Zhou et al., 2019). A growing number of studies have applied the geographical detector in recent years to quantify the influence of the factors that control the environmental sustainability (Chen et al., 2019; Ding et al., 2019).

There are three critical gaps in the current research regarding mechanism understanding, study scale, and methodology. First, from the perspective of driving factors, policies’ impacts on environmental protection and pollution control have not been fully explored (Zhang and Wu, 2018). Systematic analysis of socioeconomic factors is rare (Cheng et al., 2017). The ADA’s effects on PM$_{2.5}$ are worth of in-depth analysis. Second, from the perspective of geographical scale, due to a lack of large-scale automatic monitoring data (Ding et al., 2019), few studies have analyzed multi-year patterns and trends in PM$_{2.5}$ concentration (Yun et al., 2019). Furthermore, few studies have investigated the cross-region heterogeneity in the effects (Shen et al., 2019). Third, from the perspective of methodology, so far, few studies have quantified the temporal lag effects of policy (e.g., ADA) on PM$_{2.5}$ using rigorous tools. This study tried to fill these critical gaps by identifying the relationship between ADA and PM$_{2.5}$ concentration, which was expected to provide strong policy implications for China’s control of air pollution. Specifically, using remote sensing and statistical data about China’s three mega-urban agglomerations (i.e., Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta), we evaluated the time lag effect and spatiotemporal mechanism of ADA on PM$_{2.5}$ concentration during 2000–2017, and targeted suggestions were put forward.

2. Administrative division adjustment and PM$_{2.5}$ pollution: a theoretical framework

The administrative division can be regarded as a spatial projection structure of state power to a large extent, which is an important form and means for the central government to govern the locality and the decentralization of power between the central and local governments (Zhang et al., 2019). In the current Chinese administrative division system (Appendix Fig. A1), the prefecture-level city government has direct jurisdiction over the municipal districts and the part of the jurisdiction over the counties and county-level cities within the jurisdiction. After China’s reform and opening, China has successively implemented various reforms of administrative division in order to adapt to and promote local economic and social development, including Revoke County to County-level city (CTPC), Revoke County/County-level city to Urban District (CTD), Merger of Administrative Unit (MAU), and Split of Administrative Unit (SAU) (Feng and Wang, 2021). Since 2000, China has mainly implemented the CTPC and CTD of ADAs, aiming to promote and adapt to the rapid development of urbanization (Wang et al., 2021). CTD refers to changing counties or county-level cities into districts under the jurisdiction of prefecture-level cities. Unlike CTPC, CTD expands the area of administrative divisions that are under the direct jurisdiction of cities. This is because although the prefecture-level city has certain management and leadership authority over the county, the financial management, urban planning, and construction of the two administrative units are relatively independent. After the counties or were revoked to urban districts, the administrative boundaries between the counties (county-level cities) and the urban districts were broken, thus conducive to promote the urbanization of the administrative district (Gao et al., 2019).

ADA is not only a simple change in the type of administrative district, but also a change in administrative authority and the relationship with the higher-level administrative district government, and subsequently has an important impact on the economy, society, and environment of the administrative district (Li et al., 2021; Wang and Qi, 2017). Furthermore, it is widely believed that ADA can profoundly influence environmental quality through socioeconomic and governance systems (Fig. 1). For example, the increase in urbanization and industrialization was mainly achieved through the growth in the number of cities and the expansion of city size by CTD (Yu et al., 2018). Therefore, environmental pollution (e.g., PM$_{2.5}$) may be closely related to ADA: the ADA indirectly contributed to PM$_{2.5}$ pollution by stimulating large-scale urban construction (Feng and Wang, 2021), heavy industrial development, and energy consumption in the socioeconomic system (Chen et al., 2019). In addition, under the Chinese decentralized system, the ADA essentially expands the boundaries of municipal districts and attracts population and industries to gather in prefecture-level cities, which leads to higher efficient energy consumption and contributes to the development of service industries (Morikawa, 2012). In terms of governance system, the economic and social development of urban agglomerations is integrated, while boundaries between counties have led to local protectionism and local market fragmentation (Bo and Cheng, 2021). ADA (e.g., CTD) has weakened the rigid constraint of administrative boundaries, allowing the government to conduct unified urban planning and industrial layout, promoting the spatial integration of public services and infrastructure (Wang and Wang, 2020). Therefore, ADA can utilize the regional integration of environmental pollution prevention to mitigate PM$_{2.5}$ pollution (Feng and Wang, 2021). In addition, local governments can use ADA to modify the implementation of the environmental governance policies to solve the regional conflicts of interest (Ran, 2013; Zhang and Wu, 2018). However, ADAs may have dual and lag effects on PM$_{2.5}$ pollution through influencing urban construction, population layout (cluster or dispersal), and industrial structure at the later stages of ADA, and such effects were also presented in the environmental feedbacks to the ADA (Fig. 1).

3. Materials and methods

3.1. Study area

In this study, three most developed mega-urban agglomerations with the worst PM$_{2.5}$ pollution were selected (Fig. 2): Beijing-Tianjin-Hebei (BTH), the Yangtze River Delta (YRD), and the Pearl River Delta (PRD), which respectively encompassed 204, 217, and 47 (including Dongguan) county-level administrative districts. In 2019, although these urban agglomerations accounted for only 2.53% of China’s land area, the combined urban population and gross domestic production...
respectively accounted for 19.92% and 25.9%. In addition, the three urban agglomerations belonged to different “PM$_{2.5}$ Zones” (Chen et al., 2019). It was necessary to use the same method to evaluate the impacts of ADA on PM$_{2.5}$ in three agglomerations to evaluate regional heterogeneity. Based on the classification of the ADA as above, the study area mainly has CTD, MAU, and CTPC, which respectively account for 71.2%, 26.6%, and 2.2% of all ADAs. Due to the significant differences in administrative systems between the urban district and the county (or county-level city) (Table 1), MUDs do not change the original administrative structure, and their impact on socioeconomics thus was relatively small (Feng and Wang, 2021). In addition, the proportion of MCD and CTPC was relatively low, so this study took CTD, the main ADA model for urban agglomerations, and no distinction was made between ADA and CTD.

3.2. Data sources and socioeconomic factors

The PM$_{2.5}$ data (2000–2017) were obtained from high-resolution and high-quality average annual PM$_{2.5}$ dataset (i.e., ChinaHighPM2.5). This 1-km PM$_{2.5}$ dataset can be useful in air quality studies, especially when it focuses on urban areas (Wei et al., 2019). The ADA data came from the National Administrative Division Information Inquiry Platform (http://xzqf.mca.gov.cn/map). After performing a thorough literature review (Ding et al., 2019; Guan et al., 2014; Liu et al., 2017; Lorelei de Jesus et al., 2020; Yun et al., 2019), we selected population density (PD), GDP per capita (GDPPC), possession of civil vehicles per capita (VEH), the proportion of secondary industry to GDP (IS), the volume of industrial soot (dust) emission (VOISE), built-up land area (LUB), and the population urbanization rate (PUB) as socioeconomic variables. These variables were collected from the Resource and Environment Data Cloud Platform of the Chinese Academy of Sciences (http://www.resdc.cn), the China Statistical Yearbook, the China Urban Statistical Yearbook, and the China Regional Economic Statistical Yearbook.

3.3. Methods

3.3.1. Geographical detector

Compared to the traditional linear model, the geographic detector is...
4. Results

4.1. Spatiotemporal patterns of PM$_{2.5}$ concentration and ADA

From 2000 to 2017, the average annual PM$_{2.5}$ concentration in the study region showed a gradual increase and then decreased (Fig. 3a), which indicated that the air pollution had been effectively controlled. In addition, the multi-year mean PM$_{2.5}$ concentration in BTH was 50 ± 24 μg/m$^3$, higher than that in the YRD (45 ± 9 μg/m$^3$) and PRD (33 ± 5 μg/m$^3$). It is worth noting that the average annual PM$_{2.5}$ concentration in cities with ADA was higher than that without ADA before 2008, and this phenomenon was the opposite during 2008–2017 (Fig. 3b). The ADAs during 2000–2017 exhibited obvious spatial aggregation and had a good overlap with PM$_{2.5}$ concentration changes (Fig. 4). During 2000–2009, the number of high-pollution cities above level V (≥50 μg/m$^3$) increased from 5.1% to 67.7%. Furthermore, these high-pollution cities are more likely to have ADAs, such as the southwest of BTH (Handan, Shijiazhuang, and Baoding), and the middle of the PRD (Guangzhou and Dongguan). During 2009–2017, 20.3% of cities reduced pollution levels, out of which 42.1% have ADAs such as Tianjin, Hangzhou, Foshan, and Huizhou. These results imply that there may be phase characteristics between ADA and the PM$_{2.5}$ concentration changes.

### 3.3.2. Evolution tree model

The evolution tree model was first used to analyze the evolutionary pathways of growing cities and forecast urban development (Wang et al., 2012). The theoretical basis for the construction of an evolutionary tree is the ergodic theorem of physics: individual evolution will follow the regularity exhibited by group evolution. Therefore, it establishes the mapping relationship between an attribute state space and a spatiotemporal pattern (Hu et al., 2018).

In this study, an evolution tree was established towards the mechanism of ADA on the PM$_{2.5}$ pollution evolution. First, we took the three mega-urban agglomerations as the branch of the evolution tree. Second, according to China’s Environmental Air Quality Standards (GB3095-2012), we divided the average annual PM$_{2.5}$ concentration into seven intervals (Sarnat et al., 2001): Level I (<15 μg/m$^3$), Level II (15–25 μg/m$^3$), Level III (25–35 μg/m$^3$), Level IV (35–50 μg/m$^3$), Level V (50–70 μg/m$^3$), Level VI (70–100 μg/m$^3$), and Level VII (>100 μg/m$^3$). Third, we considered cities as “leaves” and labeled them with classification codes: the capital letters in the code represented the name abbreviation of the “municipality/prefecture-county”, and the roman numeral indicated PM$_{2.5}$ pollution level. For example, the code “BJ-HR–II–IV–III” denoted Huairou of Beijing, whose PM$_{2.5}$ pollution level had undergone levels II, IV, and III, respectively. Fourth, the leaves were ranked subject to GDP per capita, and cities with higher GDP per capita values are located closer to the stem. For more details about the city codes, see Appendix Table A1.
indicating that ADA had an enhancing effect on PM$_{2.5}$ concentration, which was also shown in Fig. 3b. Moreover, when the lag time was more than six years, ADA generally was negatively correlated with PM$_{2.5}$ concentration and reached the highest in the 9th year ($q = 1.6\%$, $p < 0.05$, $\rho < 0$, $p < 0.05$). Therefore, there was a significant mitigation effect of ADA on PM$_{2.5}$ concentration after 6–10 years of implementation. In addition, after more than 10 years of ADA implementation, the impact on PM$_{2.5}$ concentration changes showed a slight fluctuating change.

The results of risk detector analysis also showed statistically
significant differences in the changes of PM$_{2.5}$ concentration across two periods among three urban agglomerations (Appendix Table A2). Specifically, during 2000–2009, the average increase of annual PM$_{2.5}$ concentration in study regions with ADA was 25.4 μg/m$^3$, statistically significantly higher than the average increase in cities without ADA (23.3 μg/m$^3$). In contrast, during 2009–2017, the average annual PM$_{2.5}$ concentration decreased by 14.1 μg/m$^3$ in cities with ADA (3.3 μg/m$^3$, 17.3 μg/m$^3$, and 21.6 μg/m$^3$ in BTH, YRD, and PRD, respectively) and by 3.8 μg/m$^3$ in cities without ADA (−10.4 μg/m$^3$, 6.0 μg/m$^3$, and 15.9 μg/m$^3$ in BTH, YRD, and PRD, respectively), and their significant differences were all enhanced. Therefore, this work divides the study period into two periods (2000–2009 and 2009–2017).

### 4.3. Effects of ADA and socioeconomic factors on PM$_{2.5}$

The determinant power (q value) of ADA on PM$_{2.5}$ concentration was calculated by using the factor detector. All the q values were statistically significant at the 0.05 level, which means that ADA had significant impacts on PM$_{2.5}$ (Table 2). Overall, ADA’s determinant power during 2009–2017 (1.89%) was significantly higher than during 2000–2009 (0.64%), but in completely opposite directions. Specifically, during 2000–2009, ADA promoted 0.64% of PM$_{2.5}$ concentration in the study area, which was shown as the BTH (0.95%) > YRD (0.30%) > PRD (0.07%). However, during 2009–2017, ADA’s impact significantly increased, reducing 1.89% of PM$_{2.5}$ pollution in the study area. And the q values (negative effect) on the BTH, YRD, and PRD increased to 2.60%, 1.52%, and 1.04%, respectively. The impact of ADA on PM$_{2.5}$ was continuously increasing, but its driving direction shifted from promotion to mitigation.

Taking the cities with ADA as the research objects, the socioeconomic factors’ q values of PM$_{2.5}$ concentration were shown in Fig. 6. In general, VOISE, PD, and GDPPC could be regarded as dominant factors that strongly explain the spatial pattern of PM$_{2.5}$ concentrations in the study region, and all the driving factors were statistically significant at the 0.05 level. In addition, the q values for all factors increased slightly with time. For the BTH, VOISE, IS, and PD were the dominant factors, and the VEH’s explanatory power increased by 15.6% during 2000–2017, indicating that the influence of traffic on PM$_{2.5}$ pollution has been significantly enhanced. The dominant factors of PM$_{2.5}$ in the YRD were VOIS and IS. From 2000 to 2017, the q value of PD declined by 40.9%, while that of GDPPC improved by 60.9%, suggesting that PM$_{2.5}$ was less sensitive to population and more responsive to economic development. For the PRD, from 2000 to 2009, the determinant power of GDPPC, VOISE, and PD was 0.76, 0.66, and 0.62, respectively. And from 2009 to 2017, the q value of PD increased by 30.6%, while other factors changed steadily, demonstrating that the population showed an increasing marginal effect on PM$_{2.5}$.

### 4.4. Association between PM$_{2.5}$ and socioeconomic development

The evolution tree method was used to illustrate the association between economic development and PM$_{2.5}$ pollution evolution (Fig. 7). In the context of the ADA, there is a certain correlation between the PM$_{2.5}$ pollution and the economic development of three mega-urban agglomerations. Specifically, for the BTH, the lower the economic development (GDP per capita) level, the more serious the PM$_{2.5}$ pollution, while in the YRD, the opposite is true; for the PRD, there is little distinction in the PM$_{2.5}$ pollution evolution between cities at different economic development levels.

It is worth noting that the connections between cities were revealed after they were projected onto the evolution tree. Two or more cities can be extracted to compare them with each other by identifying their location, color, and code. First, cities located in different branches (urban agglomerations) have very different economic backgrounds. In contrast, if they were in the same branch and near each other, they shared similar economic backgrounds and may follow similar evolution paths (Wang et al., 2012). Second, if they had the same color, then they had the same PM$_{2.5}$ pollution evolution and similar economic development structures. In this case, they had a high possibility of following similar evolution paths. Moreover, if they had the same color during 2000–2017, they were likely to have the same evolution trend. For example, in BTH, the air quality in Fengnan (TS-FN) and Baodi (TJ-BD) was improved after the ADA, and they had similarities in industrial development structure with Yongnian (HD-YN), Jizhou (TJ-JZ), and Daxing (BJ-DX), which are “neighbors” in the evolution tree. Therefore, Yongnian, Jizhou, and Daxing can refer to the development model of Fengnan or Baodi to mitigate PM$_{2.5}$ pollution. In addition, for the YRD, Gaochun (NJ-GC) can also provide a guideline for PM$_{2.5}$ pollution control in Jiangyan (code TZ-JY) and Dantu (code ZJ-DT). For the PRD, further analysis and comparison of ADA cities are needed based on their functional positioning.

### 5. Discussion and implications

#### 5.1. Discussion

In general, there are significant temporal lag effects of policy actions on environmental responses (Bouranis and Grizzetti, 2014; Xu et al., 2019). Some major socioeconomic development policies, such as planning, industrial restructuring, and energy trade (Lee, 2019), may have lag effects on the local environment (Xu et al., 2019). The complex policy needs time to adapt to these changes (Di Maria et al., 2012), like Title IV
of the U.S. Clean Air Act Amendments of 1990 was phased in over a 10-year period, giving companies time to respond to anticipated future measures (Schmalensee et al., 1998), which resulted in a lag of approximately 5–10 years for the Act; the European Union Emissions Trading Scheme was first announced in 2001, with an initial “pilot” phase from 2005 to 2007, and the scheme is likely to have a significant impact with a lag of about seven years. The disclosure of the lagging effect and influencing factors of the ADA on the environment is the extension and deepening of researches on the effects of relevant policies and further reveals the effect and process of policy effects.

There is a 10-year time lag between the implementation of ADA and the actual production of significant effects. Specifically, ADA performed a significant 0–6 years’ positive effect on PM$_{2.5}$ concentration changes. This may be due to the five-year transition period for the city with ADA to ensure stable socioeconomic development (Wang and Qi, 2017; Yu et al., 2018). The post-ADA acceleration of urbanization and industrialization exacerbated atmospheric pollution, which was found in previous studies (Li and Xu, 2015). After the transition period, local governments typically formulate five-year development plans under the guidance of prefecture-level governments, accelerating their industrial transformation and environmental services integration (Gao et al., 2019; Liang et al., 2019; Zhang et al., 2019), which significantly improves the treatment of urban air pollutants in the next five years. For instance, three mega-urban agglomerations have established a regional air pollution joint prevention and control mechanism (Ran, 2013; Zhang and Wu, 2018) to promote cooperation in haze management and industrial restructuring, which has effectively alleviated PM$_{2.5}$ pollution (Yu et al., 2018). When the lag effects exceed 10 years, it is difficult to fully distinguish the degree of ADA’s impacts on PM$_{2.5}$ concentration change and the gradually fading effect of ADA itself.

Unlike other environmental policies, ADA’s policy design does not directly affect the environmental quality (i.e., PM$_{2.5}$). Instead, its effects relied on the changing socioeconomic and governance systems that have lagged and phased effects on PM$_{2.5}$ (Chen et al., 2019; Liu et al., 2017; Ding et al., 2019). First, ADA has had a two-way impact on PM$_{2.5}$ concentration through changes in land use planning and industrial structure (Feng and Wang, 2021). After the implementation of ADA in the BTH of Fengnan, the ADA attracted a large number of urban immigrants, which

Fig. 6. Determinant power ($q$ value) of socioeconomic factors on PM$_{2.5}$ from 2000 to 2017. BTH: Beijing-Tianjin-Hebei, YRD: Yangtze River Delta and PRD: Pearl River Delta. Abbreviations and descriptions of each factors are listed in Section 2.2.

Fig. 7. The evolution tree of the PM$_{2.5}$ pollution. Tree branches corresponding to three urban agglomerations. Each leaf represents a city with administrative division adjustment (ADA) based on the three capital letters in the first line of the code. The combination of Roman numerals in the second line of the code represents the PM$_{2.5}$ pollution level in 2000, 2009, and 2017, respectively. The color change in leaves represents a change in the pollution level, and the abbreviations of each city code are listed in Appendix Table A1. BTH: Beijing-Tianjin-Hebei, YRD: Yangtze River Delta, and PRD: Pearl River Delta. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
caused traffic congestion and increased vehicle emissions. The rapid growth of steel, cement, energy, and power industries caused a large consumption of fossil fuels such as coal, resulting in increased concentrations of PM$_{2.5}$ (Ding et al., 2019; Luo et al., 2018). Second, the ADA facilitated industrial innovation, environmental policy implementation, and population distribution by weakening the rigid constraints of administrative boundaries on the collaborative management of cities. For example, YRD’s ADA in Gaochun weakened the rigid constraint of the boundary and promoted a flow of talent and technological innovation in the environmental industry to Gaochun. The change of “rural-type political area” to “urban-type political area” has made residents more willing to implement environmental policies (Wang and Qi, 2017). Similarly, PRD implemented ADA in Zengcheng, which relieved Guangzhou’s overpopulation and huge traffic pressure and further reduced vehicle emissions. Moreover, in terms of administrative management, Zengcheng was under the jurisdiction of Guangzhou, which also made it easier to achieve synergy in coordinated PM$_{2.5}$ pollution control (Gao et al., 2019).

The significant differences in ADA’s impacts in the three mega-urban agglomerations strengthen our conclusion regarding the driving mechanism described above. Specifically, in terms of industrial structure, the proportion of heavy industry in BTH was significantly higher than that in the YRD and the PRD (Appendix Fig. A2), which makes ADA’s effects on industrialization and PM$_{2.5}$ pollution stronger. In addition, with the vibrant economic ties and market integration, the YRD and PRD have helped break administrative barriers (Gao et al., 2019), which has contributed to the mitigation of PM$_{2.5}$ pollution and weakened the negative impacts of the ADA. In terms of environmental policy, air pollution control in BTH and YRD mainly focuses on industrial restructuring and green transportation (Wu et al., 2020; Zhang et al., 2019). PRD meanwhile relied more on regional air pollution prevention and clean energy promotion (Gao et al., 2019). Therefore, the environmental effects of ADA in the BTH and the YRD were more significant in the short term than PRD.

5.2. Management implications

To making rational use of ADA for guiding industrial transformation and inter-regional joint governance, city managers should pay special attention to the lag effect of ADA on PM$_{2.5}$ pollution. Specifically, building a scientific and reasonable industrial pattern within five years after ADA is highly recommended to reduce the air pollution caused by urbanization and industrialization. Other useful methods include accelerating secondary industry transformation within 5–10 years after the ADA, giving full play to the radiating force for the central cities in talent introduction and environmental protection upgrading, and realizing the integration of environmental protection services and facilities. In addition, managers should reduce air pollutant emissions by minimizing the impact of human activities through measures such as rational population evacuation, reduction of vehicle, and transformation of economic patterns of urban agglomerations.

Decision makers of the three mega-urban agglomerations should strengthen air pollution information sharing and joint prevention and control while considering their own industrial structure, political status, and characteristics of pollution sources. Cities can be located nearby in the evolution tree. These similarities can provide a basis for the reference for formulating relevant policies and region-oriented air pollution joint prevention control strategies. For example, for the BTH and YRD, Jizhou and Jiangyan can refer to the industrial development models of Fengnan and Gaochun, respectively, and leverage the ADA’s positive effect on regional cooperation and public service integration to mitigate PM$_{2.5}$ pollution. Moreover, urban planners in the PRD should fully understand and make use of the dominant factors’ impact mechanism on PM$_{2.5}$, such as increasing the rational design and layout of the urban landscape by ADA to improve the adaptability and resilience of cities.

5.3. Limitations and future directions

There are two main limitations worth mentioning. First, the PM$_{2.5}$ concentration was influenced by many factors. ADA is one of the key elements. Many other factors can also play significant roles in impacting air pollution concentrations, like topography, climate, and environmental governance policies. In future studies, the results can be improved by isolating the effects of some hidden variables (e.g., wind speed, temperature, and precipitation) to enhance the accuracy of the policy assessment. Second, the current study was based on mega-urban agglomerations, and thus the issue of generalizability should be considered along with emerging evidence seeking elsewhere. For example, in the future, we can investigate the heterogeneous impacts of ADA on PM$_{2.5}$ and explore the continuous feedback processes and environmental effects between the two on a larger scale.

6. Conclusion

China’s mega-urban agglomerations have experienced dramatic PM$_{2.5}$ pollution and ADA over the past two decades. However, few researches are done by connecting ADA with PM$_{2.5}$ with the quantitative methods due to theoretical, methodological, and practical difficulties. In this study, we found that ADA and PM$_{2.5}$ pollution evolution had a typical relationship of spatiotemporal coupling and lagging in the three mega-urban agglomerations. Specifically, ADA had a strong lag effect of 0–6 years (positive) and 7–10 years (negative) on PM$_{2.5}$ concentration changes. ADAs significantly influenced PM$_{2.5}$ pollution by adjusting industrial structure and land-use models, weakening administrative boundary constraints, and improving the level of public service equalization. Moreover, cities with similar economic backgrounds and ADA’s effect are plotted along the same branch and follow similar evolutionary paths. Therefore, the findings were beneficial to decision-makers through the moderate implementation of ADA and the development of differentiated environmental policies aimed to achieve sustainable development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113993.

Author contribution
