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Revealing effectiveness and heterogeneity of the impact of China's coal consumption control policy on air quality

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Whether China's coal consumption control policy (CCCP) improves air quality is controversial. This study used city-level panel data and applied a DID model to identify it. We found that 1) The CCCP has a positive effect on AQI and PM_{25}, which decrease by 7.6327 μg/m3 and 8.4293 μg/m3, respectively, but fails to reduce O_3 concentration. 2) The effect of CCCP has regional heterogeneity. The CCCP has not significantly reduced $PM_{2.5}$ emissions or improved air quality in the PRD region as in the BTHS and YRD regions. Additionally, in the YRD and PRD regions, CCCP can reduce O_3 significantly. But the BTHS region failed to reduce the O_3, and the introduction of CCCP made the O_3 in pilot cities even higher by 4.1539 μg/m3. This study recognized the effects of the CCCP and its regional heterogeneity, which were supportive for policymakers to optimize coal-related policies to ensure environmental sustainability. We suggested that policymakers should differentiate policies according to regional differences and pay attention to reducing O_3 pollution to establish sustainable ecosystems.

KEYWORDS

environmental sustainability, air quality, economy, coal, GIS, China

1 Introduction

The adoption of information and communication technologies (ICT) has progressively been known as crucial for economic affluence, over the last few decades, the rapid growth of China's population and economy has made China the world's largest energy consumer and producer (O'Meara, 2020; EIA, 2020; Jin et al., 2017; Mahfooz et al., 2017, Rasool, Jundong et al., 2017, Sohail, Mahfooz et al., 2017, Yen, Wang et al., 2017). Coal, the most polluting source (Barreira et al., 2017), has remained the dominant energy source in China over the past 20 years (see Figure 1). While the coal-based energy framework has contributed to the economic boom, it also poses significant challenges to China's long-term development, i.e., aggravating environmental pollution (Yang & Teng, 2018; Sohail et al., 2022b; Sohail M. et al., 2022; Yang, Zhou et al., 2022; Zhao, Huangfu et al., 2022), causing substantial health damage (Yang et al., 2013; Sun et al., 2018), and accelerating climate change (Edwards, 2019). Among those problems, air pollution has developed into a major economic and social concern in China (Sohail et al., 2021a; Sohail

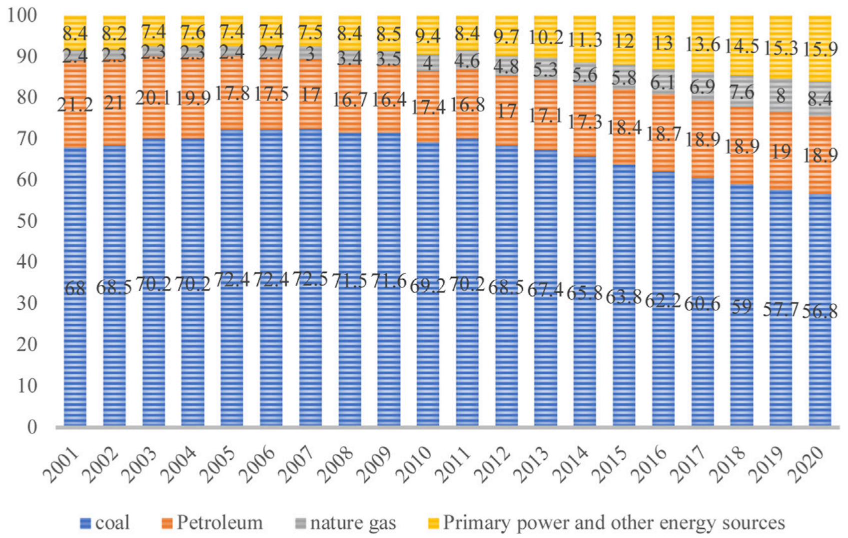

FIGURE 1
China's total primary energy consumption 2001–2020 (%).

et al., 2021b; Chen et al., 2022; Fami and Sohail 2022; Lan et al., 2022; Liu N. et al., 2022). According to the Global Burden of Diseases study, air pollution is one of the top five disease-related risk factors, affecting between 4 and 9 million deaths annually (Burnett et al., 2018; Christopher and Murray, 2019; Sohail et al., 2021a; Chai et al., 2021; Sohail et al., 2021c; Jian et al., 2021; Vohra et al., 2021; Lan et al., 2022). In response to these multiple challenges, China has identified coal control as a crucial measure for environmentally balanced development. In 2016, the National Development and Reform Commission (NDRC) released the [1]*Notice on Coal Consumption Reduction and Substitution*, proposing a two-pronged initiative to control coal—"Reduction + Substitution"—to promote clean air and implement the goal of "dual control" of total energy consumption and energy intensity in polit city. However, as a command-and-control policy, the cost and effect of the CCCP have fueled debates, and the complexity is compounded by renewable energy subsidies. The core of this debate is whether the CCCP has a positive effect on air quality, as initially expected.

The academics who were confident about the CCCP acknowledged that the CCCP could help control the amount of pollution released. But the increase in air quality comes at the cost of reducing social welfare and economic development. Lin and Jia (2020), Shou et al. (2020) and Yang & Teng (2018) concluded that coal control measures would contribute to pollution reduction and carbon mitigation. While employing the developed CGE model, Xiao et al. (2020) found that coal-cutting policies will promote the environment but reduce residents' consumption welfare, GDP growth, and employment. Zhang et al. (2021) also employed a scenario analysis model that predicts that the CCCP will inevitably reduce social welfare in the short run.

However, there are also some scholars who argue that CCCP is technically infeasible, which will lead not only to an increase in economic costs significantly (Shi et al., 2018; Mahfooz, Yasar et al., 2019; Sohail, Mahfooz et al., 2019; Zhao, Yen et al., 2019; Arif et al., 2020; Mahfooz et al., 2020; Sohail et al., 2020) but also not reduce air pollutant emissions. Some empirical studies supported this opinion. Using empirical data from the BTH region, Shi et al. (2018) have shown that CCCP fails to reduce SO_2 emissions due to cost and technical constraints. Guo et al. (2020) also support the results by using realistic panel data from 289 Chinese cities; they find that only with the help of other supporting policies can CCCP reduce SO_2 emissions as expected. According to the analyses shown in Figures 2A,B, the average Air Quality Index (AQI) has improved in almost all Chinese provinces from (2013 to 2015) to (2016 to 2019). Before and after the implementation of the CCCP, the distinction between CCCP pilot provinces and other provinces is insignificant. Therefore, it is unreasonable to attribute the improvement in air quality to CCCP. Whether the CCCP has successfully reduced air pollution is far from obvious.

As the different methodologies and the heterogeneous group of cities in the various studies, some uncertainty remains. With industrialization and urbanization, regional air pollution in China has seriously threatened people's daily life and health.

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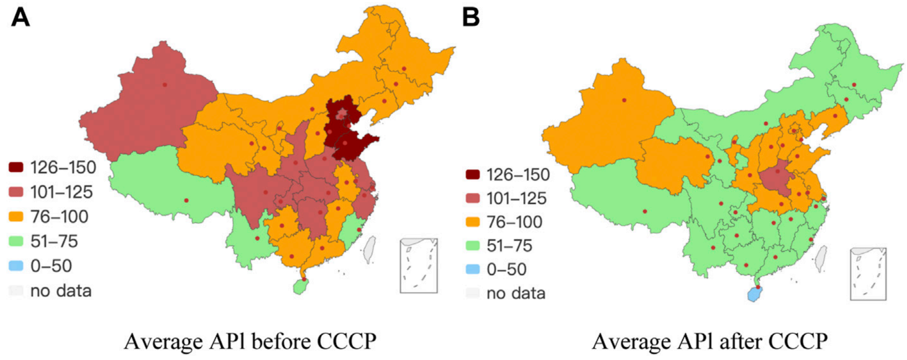
[1] Notice on Coal Consumption Reduction and Substitution in year 2016 defined the new group of CCCP pilot areas: the Beijing-Tianjin-Hebei and surrounding Region; the Yangtze River Delta region Area, the Pearl River Delta Area.



Average API before CCCP

Average API after CCCP

FIGURE 2
China's provincial API before (2013–2015) and after (2016–2019) the implementation of CCCP.

More than 50% of China's population is exposed to unsafe air, and one-fifth of all deaths can be attributed to air pollution (Hsu et al., 2016), which kills between 1.2 million and 2 million people yearly (X. Yang et al., 2017). Specifically, the life expectancy of people living in urban areas north of the Huai River in China is about 5.5 years less than that of people living in other regions due to coal-fired heating in winter (Chen et al., 2013). Therefore, whether or not CCCP curbs air quality degradation has become one of the most important issues for environmental sustainability. In light of this debate, we quantitatively evaluate the impact of CCCP on air quality using actual data. The empirical findings would not only provide policymakers with strategies for implementing additional plans to improve air quality. Still, they would also serve as guidance for public health researchers developing interventions to create a healthy environment.

2 Materials and methods

2.1 Data

Data for this research was obtained from urban statistical yearbooks, China city statistical yearbooks, and China Air Quality Online Monitoring and Analysis Platform. Specifically, the data of AQI, $PM_{2.5}$, and O_3 are gathered from the "China Air Quality Online Monitoring and Analysis Platform" website, which provides daily data on air quality conditions in 367 cities across the country, with data sourced from the China Environmental Protection General Station. Additionally, we collect meteorological conditions at the city level, including indicators of temperature and precipitation from "2345 Weather.com," which is sourced from the China Meteorological Administration. It should be noted that due to the city-level database being limited, few researchers pay attention to total energy consumption issues at the city level. To fill this gap, original data on 24 energy types are collected from the urban statistical yearbooks. The total energy consumption is then calculated by uniformly converting them to standard coal and adding them up. In addition, the 12 coal energies used by the industry are uniformly converted to standard coal and added to determine coal consumption. The remaining data are obtained from the China city statistical yearbooks. We removed cities lost to follow-up and invalid data, and 462 observations from 73 cities were maintained. All cities' information is reported in Table A1. Table 1 provides descriptive statistics for the variables.

2.2 Variables

2.2.1 Explanatory variables

The three explanatory variables in this paper are AQI, $PM_{2.5}$, and O3. We take AQI, $PM_{2.5}$, and O_3 to measure air quality and pollution emissions.

AQI is a comprehensive key indicator of the status of air quality in a city. It is derived from the concentration limits of six individual pollutants (SO_2, CO, NO_2, O_3, $PM_{2.5}$, and PM_{10}) and takes values from 0 to 500, with higher values representing poorer air quality conditions. The AQI is the main variable used to measure the effectiveness of air quality improvement.

The Global Burden of Disease (GBD) states that O3 and PM2.5 are typically used as indicators to measure the effects of air pollution on human health (Forouzanfar et al., 2016). Thus, in order to test the different effects of the CCCP on the concentrations of various pollutants, $PM_{2.5}$ as well as O_3 were also selected as explanatory variables, all of which are yearly data at the city level. Co-control of $PM_{2.5}$ and O_3 is an important target for environmental protection in the 14th Five-Year Plan period. With the strengthening of air pollution control in China in recent years, $PM_{2.5}$ and other conventional pollutants have considerably improved. However, O_3 concentrations are growing and have become the primary pollutant in many regions (Wang

TABLE 1 Summary statistics of the variables.

Symbol	Variable	Unite	Mean	S.D.
Aqi	Air quality index	μg/m3	93.045	33.461
pm25	N/A	μg/m3	57.597	30.586
o3	N/A	μg/m3	85.251	21.184
Gdp	GDP per capita	CNY/people	11.283	0.624
Industry	The percentage of secondary industry in total output value	%	44.458	8.860
Pop	Total population at the end of the year	Million	6.260	0.624
electric_c	The percentage of electricity consumption in total energy consumption	%	0.136	0.113
coal_c	The percentage of coal consumption in total energy consumption	%	0.643	0.246
Tempreture	N/A	°C	15.955	4.488
Precipitation	N/A	mm	604.549	384.608

et al., 2017; Sohail et al., 2022a, Sohail et al., 2022b, Sohail and Chen 2022, Sohail et al., 2022c; Muhammad, Zhonghua et al., 2014, Sohail et al., 2014a, Sohail et al., 2014b, Sohail, Delin et al., 2015, Shahab et al., 2016). High near-surface O_3 concentrations are major components of photochemical smog, which can damage air quality and adversely affect ecosystems. Controlling O_3 has become a hot topic in current research (Liu et al., 2017; Chen et al., 2019; Wang et al., 2020; Hong et al., 2022, Liu Y. et al., 2022, Mustafa et al., 2022, Sohail et al., 2022d). Therefore, we chose $PM_{2.5}$ as well as O_3 as our explanatory variables to represent air quality improvement.

2.2.2 Explanatory variables

Explanatory variables: coal consumption control policy (CCCP), a dummy variable for the indicator selected in the base regression as coal consumption control policy.

2.2.3 Control variables

As air quality is also influenced by other factors, the following control variables have been introduced into the model.

Urban characteristics variables: Urban characteristics variables can reflect the development level, and there is a correlation between urban development level and urban air pollution, so controlling urban characteristics variables can eliminate some of the endogeneity. In the study, three indicators are selected to describe the characteristics of the cities and regions in the sample: total population, per capita gross regional product, and industrial structure.

Meteorological conditions variables: meteorological conditions can have a significant impact on air quality (Liu et al., 2020). We collect temperature and precipitation to represent meteorological conditions. The models all control for yearly average temperatures and precipitation.

Energy consumption characteristics variables: the production and consumption of energy is the principal source of human-caused air pollution (IEA, 2019). In the study, the percentage of electricity consumption in total energy consumption and the percentage of coal consumption in total energy consumption are used to measure the regional energy consumption structure.

2.3 Model

The CCCP, introduced in 2016, is expected to reduce air pollution and improve air quality. Additionally, the variables discussed above also affect both air pollution and air quality. CCCP, such a piloted policy can be regarded as a natural experiment, which enables us to explore CCCP's relationship with air quality using a difference-in-differences (DID) specification. By partially controlling for trends in city air quality and pollution emissions that are across different regions, the DID can effectively eliminate the influence of unobservable factors and thus identify the net effects of the CCCP. In the study, the DID is employed to compare the difference in air quality between pilot and non-pilot cities before and after the implementation of the CCCP. Following (Beck et al., 2020), we set pilot cities as the treatment group and others as the control group to assess the impact of the CCCP implementation at the prefecture-level. The baseline regression model is set up as follows:

$$\mathrm{Y} = \alpha + \beta D_{it} + \gamma X_{it} + \tau_t + \mu_i + \varepsilon_{it}$$

$$D_{it} = \mathrm{treated}_i * \mathrm{period}_t$$

Cities in the treatment group: treat = 1, cities in the control group: treat = 0; When the year comes after the CCCP implements date: time = 1, otherwise time = 0; i and t are city and year, respectively; Y is the explanatory variables, representing the annual average concentrations of the AQI, $PM_{2.5,}$ and O_3 at the city level; X_{it} is a set of control variables including lnpgdp, industry, lnpop, Coal_c, electricity_c, temperature, and precipitation; The core explanatory variable D_{it} is a policy dummy, which takes the value of 1 when the year is in the CCCP implementing period, which means after 2016, otherwise,

TABLE 2 Estimation results of the effects of CCCP.

	Aqi	pm25	o3
D	−7.6327**	−8.4293***	−4.3643
	(−2.3129)	(−2.8241)	(−1.5341)
lnpgdp	4.0727	−0.204	−10.508
	−0.3522	(−0.0198)	(−1.1322)
industry	−0.4062	−0.3879	−0.0718
	(−1.0812)	(−1.0941)	(−0.2406)
lnpop	37.1777*	27.8367	−51.7514**
	−1.864	−1.5481	(−2.3501)
electric_c	2.5131	−10.2093	−13.3123
	−0.0996	(−0.4398)	(−0.6950)
coal_c	12.9921	10.3913	−4.9704
	−1.1882	−0.9988	(−0.6451)
temperature	0.9882	0.342	0.0623
	−0.4765	−0.1782	−0.0408
precipitation	−0.0098*	−0.0061	−0.0133***
	(−1.6668)	(−1.2659)	(−2.8452)
_cons	−1.80E+02	−1.00E+02	543.1888***
	(−0.9486)	(−0.5863)	−2.9446
city	Yes	Yes	yes
year	Yes	yes	yes
N	419	419	419
r2_a	0.7944	0.8057	0.6109

Note: *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively. The values in parentheses are the robust standard errors.

it takes the value of 0; The coefficient β is the parameter to be estimated, indicating the net effect of the CCCP policy; if the CCCP is indeed effective in improving air quality, β should be significantly negative; $\tau_t\ and\, \mu_i$ are vectors of year and city dummy variables that represent year and city fixed effects. ε_{it} is the random disturbance term.

3 Results and discussion

3.1 Basic estimation results

To comprehensively evaluate the impact of the CCCP on air quality improvement, AQI was first introduced as an explanatory variable in Model 1 for regression. Then regression analysis was conducted separately with the concentrations of PM_{25} and O_3, two individual pollutants, as the explanatory variables. The regression results (as shown in Table 2) demonstrate that the AQI of the CCCP polit cities decreased by 7.6327 μg/m3, and the regression coefficients were significant at the 5% statistical level; the PM_{25} decreased significantly after the implementation of the CCCP by 8.4293 μg/m3 at the 1% statistical level. However, the O_3 fell after the implementation of the policy by 4.3643 μg/m3 but not significant. The regression results verified the hypothesis that the CCCP effectively improved the air quality, but it failed to reduce $O_{3,}$ a new focus of pollution by the public and government.

Detailed, $PM_{2.5}$ decreased obviously. $PM_{2.5}$ is mostly produced by the combustion of fossil fuels and biomass (straw, firewood, *etc.*), road and construction dust, industrial dust, and other pollution sources directly discharged by particulate matter. The CCCP focuses on regulating the burning of loose coal and fossil fuels, which will undoubtedly lead to effective control of particulate matter emissions from air pollution. However, little is known about O_3 pollution due in part to the lack of monitoring of atmospheric O_3 and its precursors until recently (Wang et al., 2017).

Therefore, many scholars (Wang et al., 2020; Wang et al., 2021; Xiao et al., 2021) agree that it is urgent for the relevant departments to pay close attention to the O_3 pollution problem and work together to decrease it and update policies to synchronous control the O_3 and $PM_{2.5}$.

3.2 Robustness test

3.2.1 Parallel trend

The DID approach is predicated on a series of assumptions. To ensure the robustness of results, our DID still needs a range of tests.

Before constructing the DID, it is necessary to test whether the parallel trend hypothesis is supported. Therefore, in this paper, the event study is employed to test the parallel trend hypothesis and the dynamic impact analysis of the policy. The test results are shown in Figures 3A–C, which highlight two important points: the reduction in AQI and $PM_{2.5}$ did not occur prior to CCCP, and CCCP has a negative impact on AQI and PM2.5. In more detail, the coefficients of the AQI and $PM_{2.5}$ for the 2 years before the CCCP are not significantly different from zero and do not show any trends, which suggests that the parallel trend assumption is satisfied. The coefficients of the AQI and $PM_{2.5}$ are significantly less than 0 after the implementation of the CCCP and show significant decreasing trends, implying that CCCP has a negative effect on AQI and $PM_{2.5}$. However, the parallel trend assumption of O_3 is not satisfied, indicating the CCCP policy has not had a significant impact on O_3 in the pilot cities.

3.2.2 Placebo test: Re-grouping analysis

To ensure that the conclusions obtained in this paper are induced by CCCP rather than other factors, we randomly selected several virtual experimental groups in the sample and regressed them consistent with the DID basic regression to provide robustness assurance for the original findings. Specifically, we conducted a 1,000 sample among 73 cities, 40 cities were randomly selected as a pseudo-experimental group for each sampling, and for each individual pseudo-

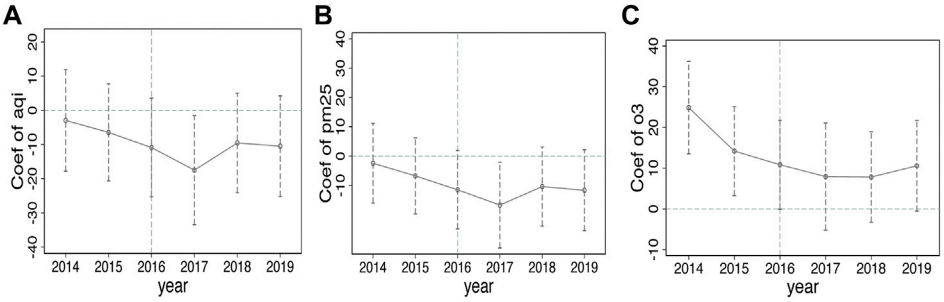


FIGURE 3
Parallel trend hypothesis test.

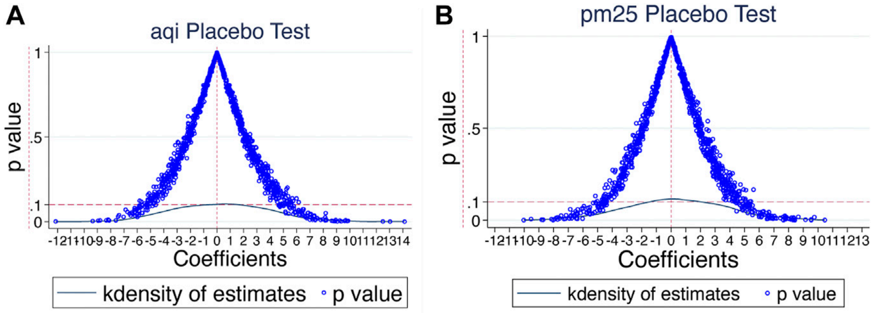


FIGURE 4
Placebo test.

experimental group, 1 year was chosen randomly as its policy time.

Figures 4A,B shows the kernel density distribution and *p*-values of the estimated coefficients (the *X*-axis denotes the magnitude of the estimated coefficients of the "pseudo-policy dummy variables," and the *Y*-axis indicates the magnitude of the density values and *p*-values). As seen, the estimated coefficients of the dummy pseudo-policies are mostly concentrated around 0. Whereas the true coefficients of the policies are all significant outliers; the *p*-values of most of the estimates are greater than 0.1 representing the CCCP pilot cities in these 40 samples without any significant effect.

Therefore, the conclusion of DID is again verified by the placebo test, which suggests that the effect of CCCP on AQI and PM$_{25}$ has no causal relationship with other unknown factors.

4 Regional heterogeneity analysis

In this section, we implemented the estimation of regional heterogeneity. The reasons for implementing this estimation are two: 1) In the process of China's urbanization, urban agglomerations have become the main spatial organizational form in China, and regionalized environmental management based on urban agglomerations has become a new trend. 2) There were differences in policies implemented between regions due to the inequality of resources, economic development, and geographical location. This study consolidates our study area into three key regions based on the priority areas defined by the CCCP policy and the needs of environmental management during the 14th Five-Year Plan period, namely: 1) The BTH region and surrounding areas(BTHS), including Tianjin, Beijing, Shijiazhuang, Tangshan, Handan, Weifang, Jinan, Qingdao, Jining, Nanyang, Zhengzhou; 2) the Yangtze River Delta region (YRD): Shanghai, Nanjing, Taizhou, Nantong, Jiaxing, Hefei, Suqian, Ningbo, Changzhou, Wenzhou, Wuxi, Yancheng, Huzhou, Suzhou, Shaoxing, Lianyungang, Zhenjiang, Jinhua, Maanshan; and 3) the Pearl River Delta region (PRD): Zhongshan, Foshan, Huizhou, Guangzhou, Shenzhen, Jiangmen, Zhuhai, Zhaoqing. Except for the above cities, the remaining cities are collectively referred to as non-focused cities for regional atmospheric management.

TABLE 3 Estimation results of the heterogeneity effects of CCCP.

	BTHS region			PRD region			YRD region		
	aqi	**pm25**	**o3**	**aqi**	**pm25**	**o3**	**aqi**	**pm25**	**o3**
D	−14.1517***	−13.7035***	4.1539	7.3817*	2.9266	−10.6535**	−12.3679***	−13.2597***	−6.1876*
	(−2.9418)	(−2.8298)	−1.0327	−1.8212	−1.0322	(−2.1510)	(−3.2269)	(−3.9432)	(−1.8974)
lnpgdp	20.3774*	14.2846	−12.4198	−1.9982	−5.3837	−19.1314	1.3868	−4.1224	−15.1471
	−1.7002	−1.3359	(−1.1713)	(−0.2045)	(−0.7690)	(−1.5919)	−0.1144	(−0.4164)	(−1.3899)
industry	−0.6237	−0.5712	−0.0601	0.0667	0.0048	0.3001	−0.1764	−0.0674	0.0401
	(−1.3163)	(−1.2793)	(−0.1526)	−0.1711	−0.0161	−0.7586	(−0.4273)	(−0.1967)	−0.1199
lnpop	25.9153	17.0792	−62.2843***	30.797	23.9105	−51.0895**	35.3963	22.7189	−64.3298**
	−0.8917	−0.6452	(−2.6437)	−1.3545	−1.2027	(−2.3055)	−1.0812	−0.7894	(−2.4847)
electric_c	−20.3858	−18.4969	−31.7954	−16.6284	−24.8105	−9.9551	−28.5596	−33.2582	−5.7837
	(−0.4965)	(−0.5608)	(−1.0246)	(−0.4830)	(−0.8783)	(−0.3385)	(−0.7999)	(−1.0312)	(−0.2037)
coal_c	16.7707	11.6279	11.1036	−3.3179	−7.4571	7.5318	7.1047	2.2321	−5.862
	−0.877	−0.667	−0.9368	(−0.2286)	(−0.5857)	−0.7035	−0.5298	−0.1806	(−0.6604)
tempreture	−0.9429	−1.3733	0.8253	−0.2378	−0.0605	−2.3655	−0.4272	−0.0296	−0.5016
	(−-0.4652)	(−0.6560)	−0.5093	(−0.1216)	(−0.0412)	(−1.2433)	(−0.2054)	(−0.0181)	(−0.2969)
precipitation	−0.0201**	−0.0103	−0.0236***	−0.0137*	−0.0074	−0.0112*	−0.0163**	−0.0092*	−0.0142***
	(−2.3081)	(−1.4951)	(−3.3060)	(−1.8759)	(−1.4823)	(−1.8665)	(−2.5432)	(−1.8534)	(−2.6325)
_cons	−2.50E+02	−1.60E+02	607.7524***	−66.2837	−19.2697	633.1200***	−1.20E+02	−22.3122	669.7477***
	(−1.1286)	(−0.7878)	−2.9174	(−0.3507)	(−0.1240)	−3.011	(−0.4759)	(−0.1051)	−3.0058
city	yes	yes	yes	yes	yes	yes	yes	yes	yes
year	yes	yes	yes	yes	yes	yes	yes	yes	yes
N	252	252	252	226	226	226	295	295	295
r2_a	0.789	0.7937	0.6327	0.7745	0.8343	0.4875	0.798	0.8339	0.6208

The regression results of the three regions are shown in Table 3. We can see that CCCP significantly reduces $PM_{2.5}$ emissions and improves air quality in the BTHS region and YRD after controlling for other influencing factors. In contrast, in the PRD, air quality shows the opposite trend that does not decrease but increases.

Specifically, in the BTHS and YRD regions, CCCP can significantly reduce AQI by 14.1517 μg/m3 and 12.3679 μg/m3, respectively; CCCP can also reduce $PM_{2.5}$ by 13.7035 μg/m3 and 13.2597 μg/m3, respectively, demonstrating that the introduction of CCCP reduces the emission of $PM_{2.5}$ and improves the regional air quality significantly. There may be reasons for this result: In April 2014, the State Council put out a notice called "Notice on the Issuance of the Measures to Assess the Implementation of the Action Plan for the Prevention and Control of Air Pollution." This notice made it clear that the percentage of reduction in $PM_{2.5}$ and AQI would be the main basis for controlling air pollution, and the assessment measures reflected this. Furthermore, local governments have a strong motivation to increase the control of the pollutants since the public is more sensitive to $PM_{2.5}$ and AQI in daily life.

CCCP can lower O_3 by 6.1876 μg/m3 at the 10% significant level in the YRD region and 10.6535 μg/m3 at the 5% level in the PRD region. However, BTHS has not been able to do so, and the implementation of CCCP made O_3 even higher in pilot cities by 4.1539 μg/m3. It might be that in the BTHS region, strong solar radiation and high summertime temperatures favor the development of O_3. Especially in the BTHS region, the temperature in spring is lower than in summer; the dryness, low rainfall, and strong solar radiation make the meteorological conditions conducive to ozone production. Additionally, the high winds in springtime in the BTHS area make it easier for O_3 to travel long distances, which is also a key reason why O_3 levels in the area are higher than in other regions. And in the southern part of Hebei, where the mainstay industries are high emission industries such as iron, steel, oil refining, chemicals, and coal, resulting in higher O_3 concentrations in summer in northern Hebei and cities such as Beijing and Tianjin.

What surprised us is that the CCCP has not reduced $PM_{2.5}$ emissions and also improved the regional AQI in the PRD region. As a leading rapid economic development region in China, the PRD region has suffered from environmental problems such as air pollution earlier. Since 2014, Guangzhou has been the first in China to promote "ultra-clean emissions" from coal-fired power plants from the source of pollution. The environmental quality standards for the six primary pollutants have been met by the PRD for 4 years running as of 2015. It has also performed well in the three major pollution control regions in China, namely BTH, YRD, and PRD regions. Therefore, although the CCCP further adjusted the energy mix of the PRD region, it did not significantly impact the overall air quality due to the fact that the PRD region has already gotten rid of the air problem disturbance.

5 Conclusion and policy implementations

To improve air quality, China introduced the coal capacity cutting policy. Based on the background of such a policy, in this study, we have identified whether CCCP improves the quality using panel data of 73 cities from 2013 to 2019. Compared with previous studies, this paper reconciles the contradiction of the influence of CCCP on air quality by using realistic data. The result was robust, supported by a parallel trend test and re-grouping test.

The main results can be summarized as follows:

(1) This study has identified that the CCCP has reduced AQI and $PM_{2.5}$ in the pilot cities by 7.6327 μg/m3 and 8.4293 μg/m3, respectively, as compared to other cities. CCCP also had a negative effect on O_3, but it was not significant.

(2) The effect of CCCP has regional heterogeneity. The CCCP has not significantly reduced $PM_{2.5}$ emissions or improved air quality in the PRD region as in the BTHS and YRD regions. Additionally, in the YRD and PRD regions, CCCP can reduce O_3 significantly. But the BTHS region failed to reduce the O_3, and the introduction of CCCP made the O_3 in pilot cities even higher by 4.1539 μg/m3.

The aforementioned conclusions have important policy implications:

From the macro perspective, to comprehensively maintain the environmental effects of coal control-related policies, how to effectively reduce O_3 concentration to establish a healthy environment should be focused on a sustainable topic. More work is required to ensure the anticipated effectiveness and lower O_3 concentration. Firstly, scientific research is the foundation of pollution control policies. We should attach importance to scientific research on O_3 pollution control. Secondly, policymakers should strengthen the construction of O_3 monitoring networks to provide timely and comprehensive data support for the adjustment and evaluation of ozone prevention and control policies. Thirdly, focus on regional co-control of ozone pollution. The central government must take action to carry out organizational planning and regional coordination to achieve regional synergy and policy synergy in O_3 prevention and control. Fourth, further restructuring the energy structure. Burning fossil fuels like oil and coal is the primary source of O_3. To reduce O_3 pollution in the long run, China needs to control its use of coal and work hard to develop green energy sources, increase its supply of renewable energy, and optimize its energy mix. From the micro perspective, under the trend of regionalized environmental management, the management of coal consumption control requires differentially implemented related policies according to regional differences. In summary, the effect of CCCP was estimated in this study, and the difference between regions showed that heterogeneity existed in CCCP. The results suggest the role of coal-related policies in environmental sustainability in the age of environmental-concentration prevalence. This study was conducted in China, so results of this study maybe use for China.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

WZ: Software, validation, data curation, writing—original draft. MC: Formal analysis, conceptualization, supervision, visualization. JH: Methodology, writing—review and editing, project administration, funding acquisition. LY: Conceptualization, writing—review and editing, funding acquisition.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Appendix

TABLE A1 List of 73 cities.

CCCP pilot cities	Without CCCP cities
Tianjin, Beijing, Shijiazhuang, Tangshan, Handan, Weifang, Jinan, Qingdao, Jining, Nanyang, Zhengzhou, Shanghai, Nanjing, Taizhou, Nantong, Jiaxing, Hefei, Suqian, Ningbo, Changzhou, Wenzhou, Wuxi, Yancheng, Huzhou, Suzhou, Shaoxing, Lianyungang, Zhenjiang, Jinhua, Maanshan, Zhongshan, Foshan, Huizhou, Guangzhou, Shenzhen, Jiangmen, Zhuhai, Zhaoqing, Dalian, Shenyang	Baotou, Fuzhou, Chengdu, Guiyang, Guilin, Haikou, Jincheng, Harbin, Jingzhou, Huhehaote, Kunming, Nanchang, Nanning, Shangrao, Shuozhou, Xiamen, Siping, Taiyuan, Xi'an, Xianyang, Xianning, Xinzhou, Urumqi, Xinyu, Yangquan, Yinchuan, Yichang, Yulin, Changchun, Zunyi, Changsha, Chongqing, Changzhi