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The Increasing Role of Synergistic Effects in Carbon Mitigation and Air Quality Improvement, and Its Associated Health Benefits in China

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ABSTRACT

A synergistic pathway is regarded as a critical measure for tackling the intertwined challenges of climate change and air pollution in China. However, there is as yet no indicator that can comprehensively reflect such synergistic effects; hence, existing studies lack a consistent framework for comparison. Here, we introduce a new synergistic indicator defined as the pollutant generation per gross domestic product (GDP) and adopt an integrated analysis framework by linking the logarithmic mean Divisia index (LMDI) method, response surface model (RSM), and global exposure mortality model (GEMM) to evaluate the synergistic effects of carbon mitigation on both air pollutant reduction and public health in China. The results show that synergistic effects played an increasingly important role in the emissions mitigation of SO_2, NO_x, and primary particulate matter with an aerodynamic diameter no greater than 2.5 μm ($PM_{2.5}$), and the synergistic mitigation of pollutants respectively increase from 3.1, 1.4, and 0.3 Mt during the 11th Five-Year Plan (FYP) (2006–2010) to 5.6, 3.7, and 1.9 Mt during the 12th FYP (2011–2015). Against the non-control scenario, synergistic effects alone contributed to a 15% reduction in annual mean $PM_{2.5}$ concentration, resulting in the prevention of 0.29 million (95% confidential interval: 0.28–0.30) $PM_{2.5}$-attributable excess deaths in 2015. Synergistic benefits to air quality improvement and public health were remarkable in the developed and population-dense eastern provinces and municipalities. With the processes of urbanization and carbon neutrality in the future, synergistic effects are expected to continue to increase. Realizing climate targets in advance in developed regions would concurrently bring strong synergistic effects to air quality and public health.

1. Introduction

The rapid economic growth in China over the past few decades has substantially relied on fossil fuels, causing massive carbon dioxide (CO_2) and air pollutant emissions [1]. China surpassed the United States to become the largest emitter of CO_2 in 2007, and currently contributes 28.8% of the world's total emissions [2]. China has committed to reaching a carbon peak before 2030 and carbon neutrality by 2060, which requires an annual reduction of 3.3 Mt of CO_2 emissions between 2030 and 2060 [3]. However, although air quality in China has exhibited an evident improvement since the Action Plan on the Prevention and Control of Air Pollution (referred to herein as "Action Plan") was launched in 2013, the annual mean concentration of primary particulate matter with an aerodynamic diameter no greater than 2.5 μm ($PM_{2.5}$) in 2019 still exceeded the national $PM_{2.5}$ standards of 35 $\mu g{\cdot}m^{-3}$ in 180 out of 337 cities at the prefecture or higher level [4]. It remains a challenge in China for all cities to meet the 35 $\mu g{\cdot}m^{-3}$ standard required by the Beautiful China target for 2035—not to mention the World Health Organization (WHO) standard level for good health (5 $\mu g{\cdot}m^{-3}$) in the even longer term [5,6]. Given the intertwined challenges of climate change and air pollution, it is of practical importance for China to seek synergistic development pathways.

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The main emissions of CO_2 and air pollutants are basically rooted in the same source—namely, the fuel combustion process—which implies that control measures on one of them might simultaneously lead to a reduction of the other, in what is generally defined as a "synergistic effect" [7]. Although China's air quality improvement during 2013–2017 was mainly achieved by end-of-pipe control, a study by Zhang et al. [8] indicated that synergistic effects from the adjustment of energy and industrial structures played a non-negligible role. They also pointed out that a future enhanced low-carbon policy would further unfold the potential of synergistic effects to mitigate air pollution in China [8], while the potential for further pollution reduction through end-of-pipe control would simultaneously become limited. A study by Xing et al. [9] suggested that a low-carbon pathway under the nationally determined contribution (NDC)—even coupled with the maximum feasible end-of-pipe control—would be unable to ensure the full attainment of city-level air quality required by the Beautiful China target by 2035. This finding implies that more synergistic efforts from a stronger carbon policy are required in order to meet China's national air quality standard. A comprehensive assessment of the historical synergistic effects between air pollution control and carbon mitigation, with a consistent indicator, is critical in choosing a future pathway with multiple environmental benefits.

Most of the earlier studies on synergistic effects addressed the co-benefits to air quality alone from changes in the energy mix [10–22], improvement in energy efficiency [9,23–32], transition of the industrial structure [33,34], and adjustment of the transport structure [35,36]. Ma et al. [10] reported that the co-benefits of wind power in Xinjiang Uygur Autonomous Region resulted in a reduction in SO_2, NO_x, and $PM_{2.5}$ emissions of 4.31%, 8.23%, and 4.23%, respectively, in 2006–2010. Li et al. [11] demonstrated that, in the "well below 2 °C" scenario, the share of nuclear and renewable energy will be as high as 62% in the energy mix in China in 2050, which will prevent 51.3% of SO_2, 38.3% of NO_x, and 31.6% of $PM_{2.5}$ emissions in the same year. Tong et al. [21] pointed out that, under the 1.5 °C scenario, with the strategic retirement of coal-fired power plants, annual CO_2 emissions in the power industry and $PM_{2.5}$-related deaths will respectively be reduced by 77% and 66% in 2050 relative to 2005 levels. The aforementioned study by Xing et al. [9] also concluded that both changes in the energy structure and an improvement in energy efficiency will provide irreplaceable contributions toward achieving the national standard for $PM_{2.5}$ in 2035.

Synergistic effects for industries were studied in terms of both energy-efficiency improvement from the deployment of advanced technologies and industrial structure adjustment. Ma et al. [25] analyzed the synergistic effects from 29 energy-efficient technologies on China's steel industries and found that these options would reduce emissions by 0.11 Mt for SO_2, 0.09 Mt for NO_x, and 0.03 Mt for $PM_{2.5}$ by 2030. Jiang et al. [33] estimated that the relocation or closure of energy-intensive enterprises achieved a reduction of around 90% of CO_2 and air pollutants in Tiexi District, Shenyang. Furthermore, the change in Suzhou's industrial structure was projected to synergistically reduce emissions of CO_2 by 39.2% and those of $PM_{2.5}$ by 35% in 2020 [34]. As for the synergistic effects from transport structure adjustment, Duan et al. [35] found that shifting freight and passenger transport from highways to railways in Chongqing will promote the reduction of CO_2, SO_2, NO_x, and $PM_{2.5}$ emissions by 29.8%, 32.3%, 31.9%, and 26.7%, respectively, by 2035. Although those studies address synergistic effects in detail for individual driving factors, their results cannot reflect comprehensive synergistic effects for society as a whole and lack a consistent framework for comparison.

To address the inconsistent framework in existing studies, our study aims to introduce a new synergistic indicator and build a comprehensive framework to quantify the synergistic effects from carbon mitigation on air quality and public health. Based on an analysis framework linking index decomposition analysis, air quality model, and exposure–response model, we evaluated the historical synergistic effects from 2006–2010 to 2011–2015 in China and investigated the temporal variation of synergistic effects. Building on this, we further applied the framework developed here to a provincial-level analysis and assessed the spatial disparities of synergistic effects across provinces with differentiated levels of economic development and resource endowments. The results of our study provide a reference for the future policy formation of synergistic control.

2. Methodology and data

2.1. Analysis framework

In our study, we introduce a new synergistic indicator defined as the pollutant generation per gross domestic product (GDP)—denoted as C/G in Eq. (1)—to comprehensively present synergistic effects on the emission mitigation of both air pollutants and CO_2, which differ from emission reduction due to end-of-pipe controls. Based on the extended Kaya identity [37,38], the emissions (E) related to production can be decomposed:

$$E = \frac{E}{C} \times \frac{C}{G} \times \frac{G}{P} \times P = \mathrm{EC} \times \mathrm{CG} \times \mathrm{GP} \times P \tag{1}$$

where C, G, and P are respectively the original pollutant generation, GDP, and population. EC (E/C) and CG (C/G) represent the end-of-pipe control indicator and synergistic indicator, respectively, and GP (G/P) and P denote socioeconomic indicators. In this study, we evaluated the co-benefits from synergistic effects on both air pollutant reduction and public health through an integrated analysis framework (Fig. 1), which combines the logarithmic mean Divisia index (LMDI) analysis, the response surface model (RSM), and the global exposure mortality model (GEMM). The LMDI was adopted to evaluate the reduction in emissions contributed by synergistic effects. The RSM was used to evaluate the change in air quality due to synergistic effects. The GEMM was applied to assess health co-benefits. Historical synergistic effects were evaluated during the period between 2005 and 2015, which covers China's 11th and 12th Five-Year Plans (FYPs). During this period, mandatory targets on reducing the total emissions of SO_2 and NO_x were successively implemented. Data on emissions of CO_2 and air pollutants were respectively derived from the latest version of Carbon Emission Accounts & Datasets (CEAD) and the Air Benefit and Cost and Attainment Assessment Conference (ABaCAS) emission inventory, including eight major sectors and 177 sub-sectors [39,40].

2.2. The LMDI method

As part of the index decomposition analysis, the LMDI has been widely used to identify the key driving factors of energy consumption, CO_2, and atmospheric pollutant emissions [41–43]. Here, we adopt this method to quantify the impacts of end-of-pipe control, synergistic effects, and socioeconomic development on air pollutants and CO_2 emission mitigation.

Based on Eq. (1), we further decompose the synergistic effects into multiple specific driving factors. The production-based emissions (E_1) from six major sectors, including agriculture, industrial combustion, electricity generation, construction, transportation, and services, are decomposed as follows:

$$\begin{aligned} E_1 &= \frac{E_1}{C} \times \frac{C}{G} \times \frac{G}{P} \times P = \sum_i \sum_j \frac{E_{i,j}}{C_{i,j}} \times \frac{C_{i,j}}{F_{i,j}} \times \frac{F_{i,j}}{F_i} \times \frac{F_i}{G_i} \times \frac{G_i}{G} \times \frac{G}{P} \times P \\ &= \sum_i \sum_j \mathrm{EC}_{i,j} \times \mathrm{CF}_{i,j} \times \mathrm{FS}_{i,j} \times \mathrm{FG}_i \times \mathrm{GS}_i \times \mathrm{GP} \times P \end{aligned} \tag{2}$$

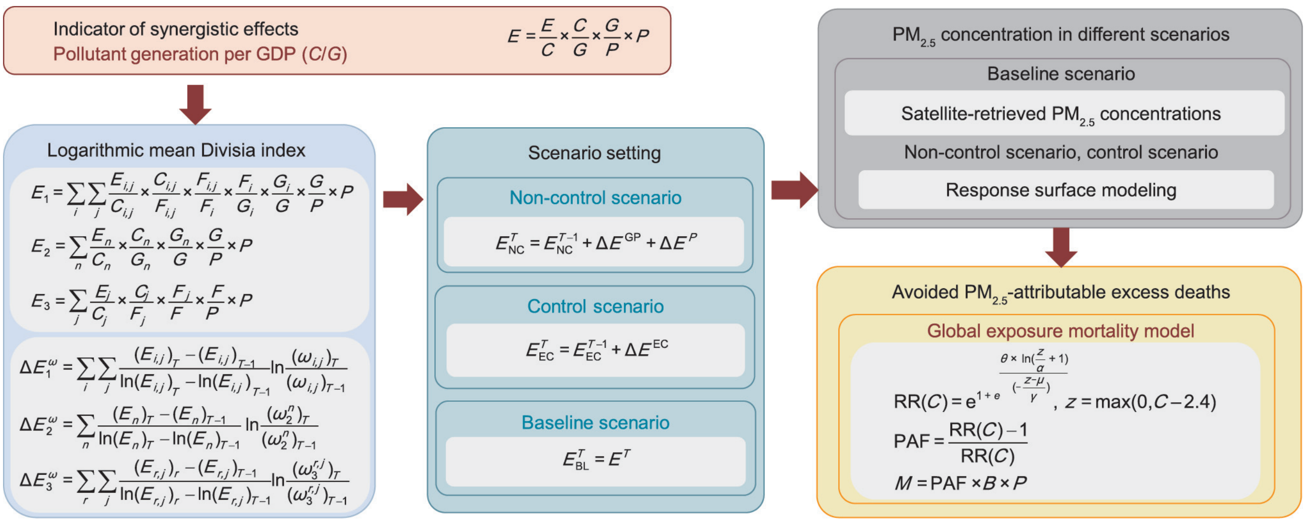

Fig. 1. The integrated analysis framework. The description of each parameter in this figure are showed in detail in the following Sections 2.2–2.5. PAF: population attribution fraction.

where F is the energy consumption, and i and j respectively represent the ith sector of E_1 and the jth fuel type. The fuel type in this study includes coal, crude oil, gasoline, diesel oil, fuel oil, natural gas, and electricity, Energy consumption data were collected from the *National energy statistical yearbooks*. As mentioned in regard to Eq. (1), we use EC, CG, and GP to represent end-of-pipe control, synergistic effects, and GDP per capita, respectively. Here, CF, FS, FG, and GS are the specific driving factors with synergy, respectively representing the emission factor of the fuel source (the pollutant generation per unit fuel), the energy structure (the share of each energy type in the total energy consumption), the energy intensity (the energy consumption per GDP), and the industrial structure (the share of each sector in the GDP).

Due to the inapplicability of some specific measures to certain emitting sources (e.g., energy consumption for industrial process, economic activity for residential consumption), a single identity function is insufficient to cover all emission sources. Multiple decomposition analyses using different identity functions are required. The emissions from industrial processes (E_2) and residential consumption (E_3) can be expressed as follows:

$$E_2 = \frac{E_2}{C} \times \frac{C}{G} \times \frac{G}{P} \times P = \sum_n \frac{E_n}{C_n} \times \frac{C_n}{G_n} \times \frac{G_n}{G} \times \frac{G}{P} \times P = \sum_n \mathrm{EC}_n \times \mathrm{EP}_n \times \mathrm{GS}_n \times \mathrm{GP} \times P \quad (3)$$

$$E_3 = \frac{E_3}{C} \times \frac{C}{P} \times P = \sum_j \frac{E_j}{C_j} \times \frac{C_j}{F_j} \times \frac{F_j}{F} \times \frac{F}{P} \times P = \sum_j \mathrm{EC}_j \times \mathrm{CF}_j \times \mathrm{FS}_j \times \mathrm{FP} \times P \quad (4)$$

where n is the nth sector of E_2. EP and FP represent the emission factor of the process source and the household energy use level, respectively.

The total emission change (ΔE) between year T – 1 and year T is the sum of the emission change in each part, as follows:

$$\Delta E = \Delta E_1 + \Delta E_2 + \Delta E_3 = (E_1)_T - (E_1)_{T-1} + (E_2)_T - (E_2)_{T-1} + (E_3)_T - (E_3)_{T-1} \quad (5)$$

The emission change in each part is expressed in the additive form of the LMDI decomposition analysis as a sum of the contributions from individual factors. Taking ΔE_1 as an example, the emission change can be calculated as follows:

$$\Delta E_1 = \Delta E_1^{\mathrm{EC}} + \Delta E_1^{\mathrm{CF}} + \Delta E_1^{\mathrm{FS}} + \Delta E_1^{\mathrm{FG}} + \Delta E_1^{\mathrm{GS}} + \Delta E_1^{\mathrm{GP}} + \Delta E_1^{P} \quad (6)$$

We use ω for each of the factors, including EC, CF, FS, FG, GS, GP, and P. ΔE_1^{ω} represents the emission change (ΔE_1) contributed by factor ω. ΔE_1^{ω} is evaluated using Eq. (7):

$$\Delta E_1^{\omega} = \sum_i \sum_j \frac{(E_{i,j})_T - (E_{i,j})_{T-1}}{\ln(E_{i,j})_T - \ln(E_{i,j})_{T-1}} \ln \frac{(\omega_{i,j})_T}{(\omega_{i,j})_{T-1}} \quad (7)$$

We further use ΔE^{ω} for the total emission change influenced by factor ω. ΔE^{ω} is calculated as follows:

$$\Delta E^{\omega} = \sum_k \Delta E_k^{\omega} \quad (8)$$

where k is the kth part of the emissions. If the kth part of the emissions is not influenced by ω, then the value ΔE_k^{ω} is set as zero.

The total emission change contributed by synergistic effects (ΔE^{CG}) can be expressed by Eq. (9):

$$\Delta E^{\mathrm{CG}} = \Delta E^{\mathrm{CF}} + \Delta E^{\mathrm{FS}} + \Delta E^{\mathrm{FG}} + \Delta E^{\mathrm{GS}} + \Delta E^{\mathrm{EP}} + \Delta E^{\mathrm{FP}} \quad (9)$$

2.3. Scenario setting

To quantify the synergistic effects, we establish three scenarios: the non-control scenario, the control scenario, and the baseline scenario. The non-control scenario assumes that no further control constraints have been established since 2005, and emissions increase with the growth of economic and population. The emissions in year T under the non-control scenario (E_{NC}^T) can be calculated by Eq. (10):

$$E_{\mathrm{NC}}^T = E_{\mathrm{NC}}^{T-1} + \Delta E^{\mathrm{GP}} + \Delta E^{P} \quad (10)$$

The control scenario is based on the non-control scenario but takes the extra end-of-pipe control into account. The emissions in year T under the control scenario (E_{EC}^T) can be expressed as follows:

$$E_{\mathrm{EC}}^T = E_{\mathrm{EC}}^{T-1} + \Delta E^{\mathrm{GP}} + \Delta E^{P} + \Delta E^{\mathrm{EC}} \quad (11)$$

In the baseline scenario, the emissions are controlled by actually existing constraints. This scenario is based on the control scenario but takes extra synergistic control into account in emission mitigation. The emissions in year T under the baseline scenario (E^T_{BL}) are consistent with the actual emissions (E^T). E^T_{BL} can be expressed as follows:

$$E^T_{BL} = E^{T-1}_{BL} + \Delta E^{GP} + \Delta E^{P} + \Delta E^{CG} + \Delta E^{EC} \tag{12}$$

The emissions in the base year 2005 under the three different scenarios are equivalent.

$$E^{2005}_{NC} = E^{2005}_{EC} = E^{2005}_{BL} = E^{2005} \tag{13}$$

2.4. Synergistic effects on reduction in $PM_{2.5}$ concentration

RSM, which was developed from the Community Multiscale Air Quality (CMAQ) model is applied to simulate the spatial change ratio of $PM_{2.5}$ concentrations between the baseline scenario and the other two scenarios at a resolution of 27 km × 27 km across China. Additional description of the RSM and CMAQ model simulation process is provided in the Appendix A.

$$R_1 = \frac{C_{mNC}}{C_{mBL}} \tag{14}$$

$$R_2 = \frac{C_{mEC}}{C_{mBL}} \tag{15}$$

where R_1 and R_2 are the spatial change ratios of $PM_{2.5}$ concentrations in the baseline scenario relative to the other two scenarios. C_{mNC}, C_{mEC}, and C_{mBL} denote the simulated $PM_{2.5}$ concentrations in the non-control, control, and baseline scenarios, respectively.

Satellite-retrieved $PM_{2.5}$ concentrations (C_{sat}) from van Donkelaar et al. [44] are considered to be the $PM_{2.5}$ concentrations in the baseline scenario (C_{BL}). These data have been widely used in previous studies, including the global burden of disease (GBD) project [45].

$$C_{BL} = C_{sat} \tag{16}$$

The simulated spatial change ratios are then multiplied with the satellite-retrieved $PM_{2.5}$ concentrations to calculate the actual $PM_{2.5}$ concentrations in the non-control scenario (C_{NC}) and control scenario (C_{EC}).

$$C_{NC} = C_{sat} \times R_1 \tag{17}$$

$$C_{EC} = C_{sat} \times R_2 \tag{18}$$

The difference between the $PM_{2.5}$ concentrations in the control scenario and the non-control scenario is contributed by end-of-pipe control. Synergistic effects on $PM_{2.5}$ concentration reduction are reflected by the difference between the control scenario and the baseline scenario. The $PM_{2.5}$ concentrations reduction that is attributable to end-of-pipe control (ΔC_{EC}) and the reduction that is attributable to synergistic effects (ΔC_{SC}) can be calculated respectively by Eqs. (19) and (20):

$$\Delta C_{EC} = C_{NC} - C_{EC} \tag{19}$$

$$\Delta C_{SC} = C_{EC} - C_{BL} \tag{20}$$

The population-weighted $PM_{2.5}$ concentration reduction contributed by end-of-pipe control (ΔPC_{EC}) and that contributed by synergistic effects (ΔPC_{SC}) are respectively estimated as follows:

$$\Delta PC_{EC} = \frac{1}{P}\sum_t P_t \times \Delta C_{EC_t} \tag{21}$$

$$\Delta PC_{SC} = \frac{1}{P}\sum_t P_t \times \Delta C_{SC_t} \tag{22}$$

where P is the population; t refers to the geographic unit, with a scale of 27 km × 27 km. ΔC_{EC_t} and ΔC_{SC_t} respectively represent the concentration reduction due to end-of-pipe control and that due to synergistic effects in geographic unit t.

2.5. Health benefits from synergistic effects

The estimate of the excess deaths attributable to $PM_{2.5}$ exposures is evaluated using the GEMM from Burnett et al. [46], which has been widely adopted in previous studies [8,47]. The GEMM provides high confidence in $PM_{2.5}$-mortality relationships at a high pollution level [46] and is therefore suitable for application in China.

Given that almost all $PM_{2.5}$-related non-accidental deaths are attributable to noncommunicable diseases (NCDs) and lower respiratory infections (LRIs), the GEMM restricts the estimates of excess deaths to this subgroup of illness, denoted as GEMM NCD + LRI. The relative risk (RR) of a given $PM_{2.5}$ concentration C in the GEMM NCD + LRI is expressed by Eq. (23):

$$RR(C) = \begin{cases} e^{\frac{\theta \times \ln\left(\frac{C-C_0}{\alpha}+1\right)}{1+e^{(-(C-C_0-\mu)/v)}}} \text{ for } C \geq C_0 \\ 1 \text{ for } C < C_0 \end{cases} \tag{23}$$

where C_0 is the counterfactual $PM_{2.5}$ concentration below which there is no additional risk. Here, C_0 is 2.4 $\mu g{\cdot}m^{-3}$ [46]. θ, α, μ, and v are parameters describing the overall shape of the exposure–response curve. The specific values for these parameters can been seen in the Appendix A.

According to the GBD project, the $PM_{2.5}$-attributed deaths in grid cell o (M_o) can be calculated as follows:

$$M_o = \sum_m P_{o,m} \times B_m \times \frac{RR(C_{o,m}) - 1}{RR(C_{o,m})} \tag{24}$$

where M_o is calculated by age for adults with every five-year interval from 25 to greater than 85, and m represents the mth age interval. P represents the population, and B stands for the base mortality incidence of NCD + LRI. We obtained the gridded population distribution at a resolution of 1 km × 1 km in 2015 from LandScan and scaled to the 2015 level based on population statistics from the National Bureau of Statistics of China. Base mortality (B) incidence was retrieved from a GBD 2015 study at the national level in China [48]. The 95% confidential intervals (CIs) of mean $PM_{2.5}$-attributed deaths were calculated based on a distribution of 1000 point estimates of θ provided by Burnett et al. [46].

The difference between the premature mortality in the non-control scenario and that in the baseline scenario reflects the combined benefits from both synergistic effects and end-of-pipe control. Following the earlier literature [8,49], we assume that the unit concentration reduction contributes equally to preventing premature mortality. This implies that the prevented premature mortality as a result of either end-of-pipe control or synergistic effects is directly proportional to the reduction in $PM_{2.5}$ concentration. The prevented premature mortality from a specific control measure was calculated at the provincial level.

3. Results

3.1. Increasing synergistic effects on emission mitigation

As illustrated in Fig. 2, synergistic effects (purple area) made an important contribution to air pollution mitigation, reducing emissions of SO_2 by 8.7 Mt, primary $PM_{2.5}$ by 2.2 Mt, NO_x by 5.1 Mt, and CO_2 by 2.8 Gt during the period of 2005–2015. End-of-pipe control (dark green area in Fig. 2) also played a major role in the mitigation of air pollution, preventing emissions of 25.2 Mt of SO_2, 9.7 Mt of primary $PM_{2.5}$, and 14.0 Mt of NO_x relative to the non-control scenario. In contrast to the non-control scenario, where emissions of SO_2, primary $PM_{2.5}$, and NO_x would respectively increase by 75.9%, 51.8%, and 106.8% in 2015 relative to 2005 levels, the combination of synergistic effects and end-of-pipe control led to a reduction in the emissions of SO_2, primary $PM_{2.5}$, and NO_x by 115.2%, 90.9%, and 99.7%, respectively, between 2005 and 2015.

The emission reduction due to synergistic effects continuously increased from 2005 to 2015, with a more rapid rate in the second five-year period. The synergistic effects on the reduction of emissions of SO_2, primary $PM_{2.5}$, and NO_x nearly doubled from the 11th FYP to the 12th FYP, with increased reductions from 3.1, 0.3, and 1.4 Mt, respectively, to 5.6, 1.9, and 3.7 Mt. Unlike the synergistic effects, the emission reductions from end-of-pipe control exhibited mixed trends for different air pollutants. The emission reductions of SO_2 and $PM_{2.5}$ due to end-of-pipe control respectively decreased from 14.3 and 5.6 Mt in the 11th FYP to 11.0 and 4.1 in the 12th FYP, while the reduction of NO_x emissions increased from 3.1 to 10.9 Mt. In the 11th FYP (2006–2010), about 86% of the coal-fired power plants in this period installed and effectively operated flue gas desulfurization (FGD)—that is, end-of-pipe equipment to remove SO_2 from flue gases—driven by a portfolio of policies including a cap on total SO_2 emissions, political accountability, verification of SO_2 emissions, and financial incentives [5,50]. Thus, the space for further reduction of SO_2 emissions through end-of-pipe control in the 12th FYP became limited. However, the success of SO_2 emission control in the 11th FYP promoted a similar mandatory regulation of NO_x emissions during the 12th FYP, and many of the management practices that had been adopted to control SO_2 emissions were tailored for NO_x emission mitigation. By the 12th FYP, selective catalytic reduction (SCR)—that is, the end-of-pipe equipment used to remove NO_x emission—had been installed in more than 80% of thermal power plants, contributing to significant reductions in NO_x emissions during this period [5,51].

The increasing synergistic mitigation from 2005 to 2015 can be attributed to changes in four impacting factors: industrial structure, energy structure, energy intensity, and emission factors (Fig. 3). Adjustment of the industrial structure, which occurred through a switch from highly energy-intensive industries to services and businesses, was one of the most important driving factors. In 2005–2015, the share of heavy industries decreased by 6.3% and that of services increased by 10.7% [52], which resulted in decreases in the emissions of SO_2, primary $PM_{2.5}$, and NO_x of 12.8%, 4.4%, and 20.0%, respectively, in the 11th FYP and decreases of 11.3%, 8.1%, and 13.2% in the 12th FYP. Given that a large portion of primary $PM_{2.5}$ was emitted from residential consumption, the adjustment of industrial structure had a relatively smaller influence on primary $PM_{2.5}$ compared with its influence on SO_2 and NO_x. Similarly, since the transportation sector gradually replaced the industry sector to become the largest source of NO_x emissions (Fig. S1 in Appendix A), the mitigation effects of the adjustment of the industrial structure on NO_x decreased in the 12th FYP. In addition, the adjustment of industrial structure resulted in important savings of CO_2 emissions of 17.3% and 18.0%, respectively, in the 11th FYP and 12th FYP.

Adjustment of energy structure, which is an important measure to tackle climate change, was emphasized in the 12th FYP for Energy Development [53]. The launch of Action Plan further promoted the energy structure transition [54]. As a result, the share of non-fossil fuels increased by 2.6% and the use of coal fell by 5.2% during the period of 2011–2015 [55]. The resulting cleaner

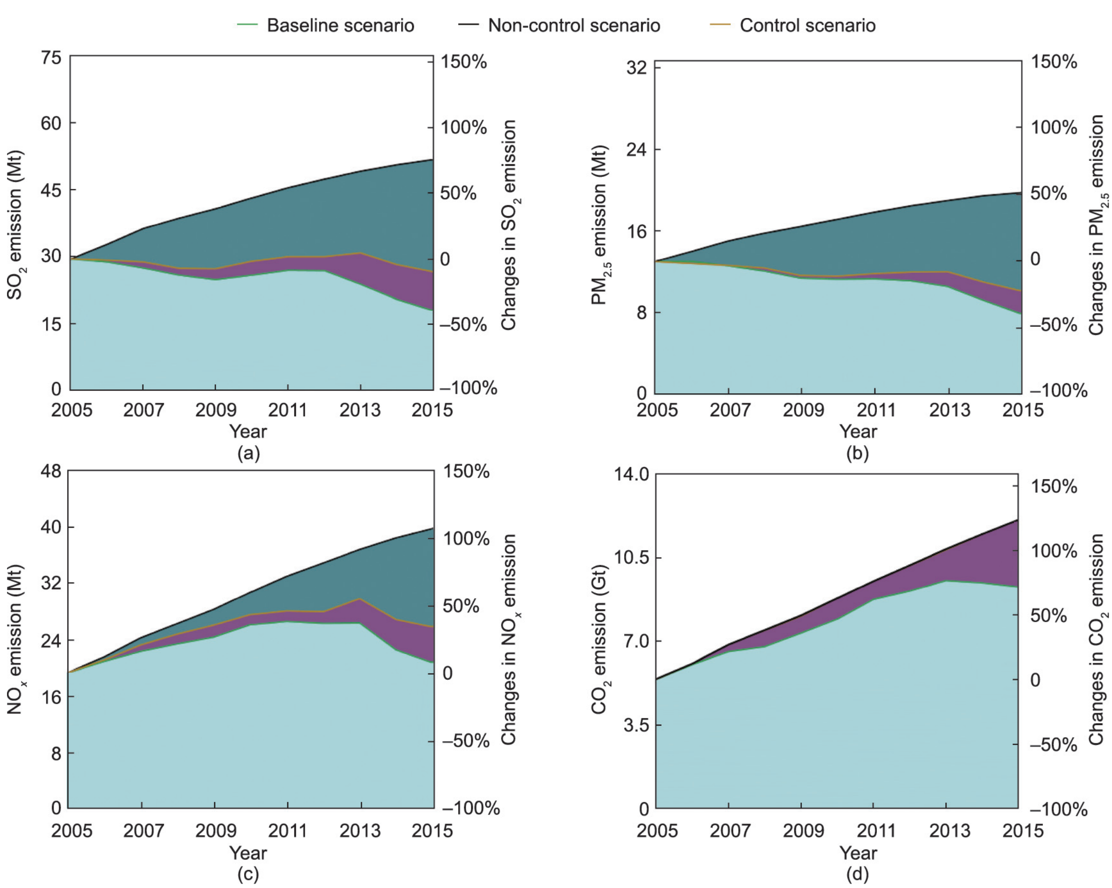

Fig. 2. Changes in China's air pollutants and CO_2 emissions under different scenarios during 2005–2015, assuming that the emission changes in the base year 2005 are 0. Emission differences between the non-control scenario and the control scenario indicate the emission reductions contributed by end-of-pipe control, while emission differences between the control scenario and the baseline scenario indicate emission reductions contributed by synergistic effects. (a) SO_2; (b) $PM_{2.5}$; (c) NO_x; (d) CO_2.

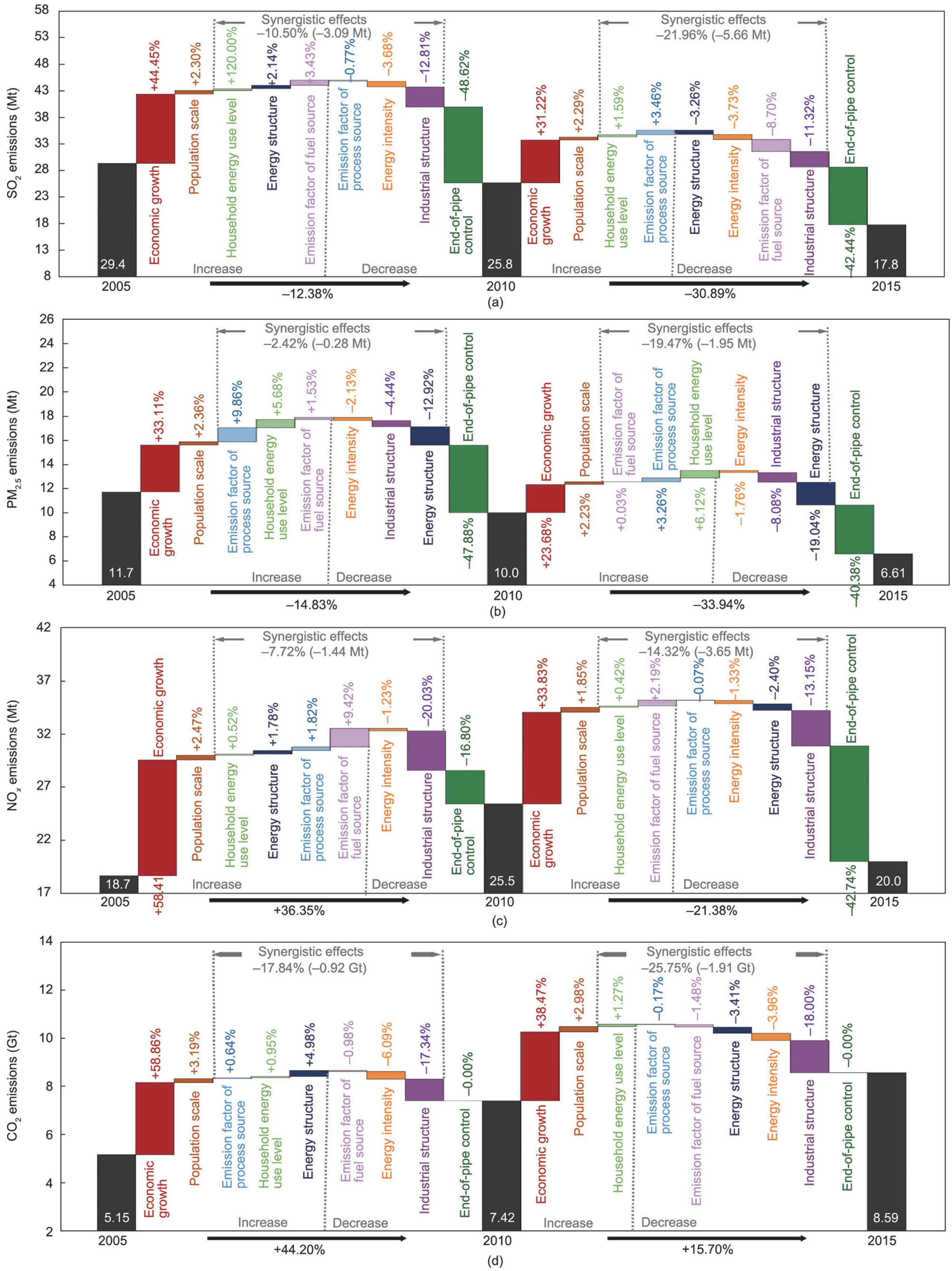

Fig. 3. The contribution of each driving force to the changes in China's (a) SO_2, (b) $PM_{2.5}$, (c) NO_x, and (d) CO_2 emissions in the 11th FYP and 12th FYP. The length of each bar reflects the contribution of each driving force. The contribution of synergistic effects to emission changes is the sum of the contributions of six specific driving forces: industrial structure, energy structure, energy intensity, the emission factor of fuel source, the emission factor of process source, and the household energy use level.

energy structure helped to reduce emissions in the 12th FYP, contributing to reductions in the emissions of SO_2 and NO_x of 3.3% and 2.4%, respectively. In addition, household coal burning was banned and the transition to clean-energy-based heating was promoted in rural areas during this period, as residential coal burning emits a mixture of harmful air pollutants—in particular, high concentrations of $PM_{2.5}$—into homes and surrounding communities [56]. Due to the energy structure transition in households, primary $PM_{2.5}$ emissions were further reduced. The adjustment of energy structure contributed to more than 19% of the reduction in primary $PM_{2.5}$ emissions in the 12th FYP, which was much higher than its share in the reduction of NO_x and SO_2 emissions.

The decline in energy intensity, which was reflected by the improved efficiency of energy utilization, has been shown to be primarily associated with technological improvement [57]. Driven by the 20% and 16% energy intensity reduction targets in the 11th FYP and 12th FYP, respectively, the penetration rate of energy-saving technology significantly increased. For example, the use of coke dry-quenching technology in the iron and steel industry increased from less than 30% to more than 80% in the 11th FYP, and the application rate of low-temperature waste heat recovery for power-generation technology increased from nearly zero to 55% in the 11th FYP and further to 70% in the 12th FYP [58]. The improved efficiency of energy utilization reduced SO_2, primary $PM_{2.5}$, NO_x, and CO_2 emissions by 3.7%, 2.1%, 1.2%, and 6.1% in the 11th FYP and by 3.7%, 1.8%, 1.3%, and 4.0% in the 12th FYP.

In addition, improved energy quality, such as the use of lower-sulfur coal, realized a declining trend in the SO_2 emission factor of fuel source, reducing SO_2 emissions by 8.7% during the 12th FYP. In contrast, the primary $PM_{2.5}$ emission factor of fuel source showed a slight increase, because the ash content of coal—where ash is the primary ingredient in forming particulate matter—increased during the period 2006–2015 [59]. Due to the increasing emission factor of fuel source, the primary $PM_{2.5}$ increased by 1.53% and 0.03% in the 11th FYP and 12th FYP, respectively.

3.2. Spatially differentiated reductions in $PM_{2.5}$ concentration and health benefits due to synergistic effects

Evident spatial disparities existed in both synergistic effects and end-of-pipe control in terms of reducing the annual mean $PM_{2.5}$ concentration. A decline in $PM_{2.5}$ concentrations was notable in most regions except for northwest China (Figs. S3(a) and (b) in Appendix A). At the national level, synergistic effects alone contributed to a 15.0% reduction in $PM_{2.5}$ concentration from 2005 to 2015, while nearly half of the total reduction was realized by the deployment of end-of-pipe control (36.8%). Synergistic effects played a relatively important role in municipalities such as Beijing and Shanghai and in developed coastal provinces such as Zhejiang and Guangdong, contributing to reductions in $PM_{2.5}$ concentration of 47.6%, 33.5%, 25.3%, and 21.1%, respectively, in the same period (Fig. S4(a) in Appendix A). Here, the major driving factor was the adjustment of industrial structure. In these municipalities or provinces, the proportion of industries respectively decreased by 9.8%, 16.8%, 7.4%, and 5.9% during the study period, while the proportion of services and business respectively increased by about 10.6%, 17.3%, 9.8%, and 7.7% (Fig. S5 in Appendix A). In Beijing, synergistic effects even surpassed the impacts of end-of-pipe control on the reduction of $PM_{2.5}$ concentration (47.6% versus 35.0%) (Table S1 and Fig. S4(b) in Appendix A). This finding reflected the fact that, although the equipment of end-of-pipe control such as FGD and SCR was widely applied, Beijing's coal-intensive industries and power plants are very limited [60].

In contrast, synergistic effects in provinces such as Shanxi, Shaanxi, and Inner Mongolia Autonomous Region (hereinafter referred to as Inner Mongolia), which have massive coal mining and energy-intensive manufacturing industries, made a relatively small contribution (10%) toward reducing $PM_{2.5}$ concentration (Fig. S4(a) in Appendix A). These provinces still largely relied on end-of-pipe control for mitigating $PM_{2.5}$ concentration. As illustrated in Fig. S4(b) in Appendix A, the ratio of synergistic effects to end-of-pipe control in Shanxi, Shaanxi, and Inner Mongolia was as low as 0.21, 0.36, and 0.21, respectively. Although synergistic effects had a slight increase in these energy-intensive regions from 2005 to 2015, end-of-pipe control remained dominant in the emission reduction of primary $PM_{2.5}$ and the precursors of secondary $PM_{2.5}$ (Fig. S6 in Appendix A). In the short term, further reductions in $PM_{2.5}$ concentration in these regions may still rely on more restricted end-of-pipe control during the transformation period. In the long term, achieving the transition to a carbon–neutral economic and energy system will inevitably unfold synergistic effects on $PM_{2.5}$ concentration reduction in these regions.

Synergistic effects prevented 0.29 million (95% CI: 0.28–0.30) $PM_{2.5}$-attributable excess deaths across China in 2015. The regional distribution of health benefits from synergistic effects broadly followed the distribution pattern of population-weighted $PM_{2.5}$ concentration reduction (Figs. S4(c) and (d) in Appendix A). Developed regions benefited more from synergistic effects on $PM_{2.5}$ concentration reduction. The health benefits from synergistic effects in those regions were further magnified due to the high population density. For example, synergistic effects helped Shanghai and Beijing to respectively prevent 120 and 100 mortalities per 100 square kilometers, which was well above the national average of three prevented mortalities per 100 square kilometers (Fig. S4(d) in Appendix A). In contrast, few health benefits were found in underdeveloped regions with low population density; the prevented mortality contributed by synergistic effects in Inner Mongolia and Ningxia Hui Autonomous Region was less than 0.01 per square kilometer. With the expected higher urbanization rate in the future, more people will gather in developed regions. Synergistic effects in these regions will then be of greater significance for public health.

4. Conclusions and policy implications

This study developed a comprehensive framework to evaluate the synergistic effects of carbon mitigation on air quality improvement and public health, based on a newly introduced indicator: pollutant generation per GDP. The results show that synergistic effects played an increasingly important role in the mitigation of air pollutants, including SO_2, NO_x, and primary $PM_{2.5}$, during 2005–2015. Significant synergistic benefits for air quality and public health occurred in the more developed provinces or municipalities during the study period.

The spatial disparity of the synergistic effects identified in this analysis may have important implications for future development in three key areas of air pollution control—namely, Beijing–Tianjin–Hebei (BTH) and its surrounding areas, the Yangtze River Delta (YRD), and the Fenhe–Weihe River Plain (FWRP)—during China's 14th FYP (2021–2025). As one of the most developed regions in China, the YRD, which includes Shanghai and the provinces of Zhejiang, Jiangsu, and Anhui, has a relatively low-carbon economic and energy system and has established goals to reach a carbon peak earlier than the national carbon-peaking year of 2030 [61,62]. In this case, the synergistic effects from further decarbonizing the existing industrial and energy structure in the YRD region would significantly drive air quality improvement. In contrast, the developing region of the FWRP, which mainly covers Shanxi and Shaanxi provinces, contains massive energy-intensive industries, and its current $PM_{2.5}$ concentrations still exceed the second-level national standards [63]. Under these circumstances, attaining air quality standards in the near term not only requires stricter end-of-pipe control but also synergistically accelerates the low-carbon transition of the economic and energy system.

In the long term, the in-depth low-carbon energy transition toward the goal of carbon neutrality will play a critical role in synergistically attaining national $PM_{2.5}$ standards across China. It has been projected that realizing carbon neutrality in China requires increasing the proportion of non-fossil energy in primary energy to 84% and limiting coal consumption to no more than 7% [64]. The synergistic effects from this profound transition are expected to significantly improve air quality as key emission sources from fossil-fuel combustion are displaced. Furthermore, considering that the developed regions are the main destination for population migration in the process of urbanization [65], if these regions act as pioneers in achieving carbon neutrality, they will continuously enjoy the strong synergistic effects on public health from improved air quality.

This study has some limitations. End-of-pipe control devices themselves consume energy and produce extra emissions, which are not individually considered in the emission inventories adopted for this analysis. This might lead to an overestimation of the effects of end-of-pipe controls. In addition, the health co-benefits from carbon mitigation in our study only considered prevented $PM_{2.5}$-related deaths. The co-benefits of a reduction in O_3 pollution, another key air pollution in China, could also be influenced by carbon mitigation, and require further analysis in the future.

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Compliance with ethics guidelines

Jie Wang, Xi Lu, Pengfei Du, Haotian Zheng, Zhaoxin Dong, Zihua Yin, Jia Xing, Shuxiao Wang, and Jiming Hao declare that they have no conflicts of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2022.06.004.

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