Ecological Indicators 129 (2021) 107988

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Analysis of the spillover effect between CO_2 and other pollutants in China

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ARTICLE INFO

Keywords:
Emissions reduction
CO_2 emission
Emissions spillovers
Pollutant discharge fee
Pollutants emission

ABSTRACT

Environmental quality is strongly coupling with the result of emissions reduction in most countries, while emissions reduction is influenced by the diversity of control policies, engineering facilities and development patterns. Further, local in which technical or policy that concern the control of target emissions will impact other pollutants emission. In China, the emissions of both CO_2 and other pollutants increased substantially during the past decades. With the development of emissions reduction, it promoted a considerable risk of emissions spillovers caused by the present mechanism. In this study, we assessed the contributions of emissions spillovers to emission reductions by applying a more comprehensive indicator of pollutants, pollutant discharge fee (PDF), at the national, regional and provincial levels. The results shown positive and significant mutual effect between the PDF and CO_2 emissions. That is, CO_2 emission is significantly related with the process of other pollutants emissions reduction. Additionally, the positive correlation indicated further increases with the Five-Year Plan (FYP) cycle. Emissions spillovers have become an urgent risk for China. With the performance change, emissions reduction and environmental governance should heighten integration. Regional-level and provincial authorities must reconsider the matched emissions sustainability responsibilities and policies to avoid emissions spillovers and achieve meaningful emission controls. The study therefore suggested that a hierarchy of emission reductions, in the hope to promote emission reductions, improve environmental quality and contribute greenhouse gas reductions.

1. Introduction

Together with the unprecedented expansion of the economy, increasing CO_2 emissions and other pollutants emissions not only caused serious problems such as climate change, water pollution and soil erosion and also attracted broad concerns about emissions reduction (Butchart and Watson, 2010; Liu and Diamond, 2008; Oliver, 2013; Wang et al., 2018a). In general, China is the biggest contributor of such emissions, at the same time all-round's environmental issues in domestic have recently become serious (Dan et al., 2018; Han et al., 2016; Lu et al., 2015; Zhang et al., 2017a; Zhao et al., 2017a). Therefore, emissions reduction represents a valid means of changing the situation, and for this Chinese government implemented targeted pollutants emissions control since 1996. For example, twelve pollutants were chosen with quantitative reduction in 9th Five Year Plan (FYP) (Fang et al., 2017; Xue et al., 2014; Yao et al., 2016). However, while the reduction of one target pollutant through the method of end-of-pipe (EOP), it will increase the emissions of other pollutants. Such situation can be referred as pollutants spillover. In the same way, there are large variations among different regions in economic conditions and emissions status (Geng et al., 2014; Liang et al., 2016; Siping et al., 2019; Wang et al., 2015; Ye et al., 2017). Emissions reduction primary reliance on policies existed policy spillover (Ambec and Coria, 2018; Wang et al., 2016a). Moreover, many pollutants and GHGs are from common source, they are associated with the production and consumption of energy and resources, together with the processes of treatment and disposal of pollutants (Ambec and Coria, 2018; Ho et al., 2017; Liu et al., 2016). Meantime, climate policy creates a market for other pollutants from

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https://doi.org/10.1016/j.ecolind.2021.107988
Received 5 July 2019; Received in revised form 30 June 2020; Accepted 13 July 2021
Available online 22 July 2021
1470-160X/

both the perspectives of energy structure and technology and vice versa. Situation proved the emissions spillovers occurred in China, raising an urgent requirement for researchers and policymakers. That is, systematic effort on pollutants emission control still yet to be effective. While the current emissions reduction, the currently top priority is discovering and exploring its temporal and spatial characteristics to further avoid unnecessary emissions spillovers (Table 1).

Further, emissions control is based upon the FYP in China. In this context, many studies and policies focused on the targeted emissions reduction in China (Cai et al., 2016; Xie et al., 2016; Yuan and Ng, 2017), like regulation design, cost-benefit analysis (Liu et al., 2017; Zeng et al., 2017), national carbon trading market establishment, etc (Chang and Chang, 2016). However, official statistics shown SO_2 emissions decrease by 9.64% with the 2010 level in total, and the emissions of other pollutants such as NO_x, CO_2, ammonia nitrogen, COD and soot displayed dramatic increases, in 2014 (Ministry of Environmental Protection and National Bureau of Statistics PR China, 2015). For this a growing number of studies have started investigating the types and amount of pollutants in the hope of promotion the emissions reduction, especially air pollutants (Wang et al., 2018b; Ye et al., 2017; Zhang et al., 2017b). Meanwhile, numerous literatures paid more attentions on the influence of environmental pollutions (Antoniou and Kyriakopoulou, 2015; Cantuaria et al., 2017; Shi et al., 2018; Stranlund and Son, 2019). To the best of our knowledge, the structure between pollutants emissions reduction and environmental governance should be considered as a heighten integration program. In the process of emissions reduction, it must emphasize the integrity of pollutants to avoid unnecessary emissions spillovers. Because the effects of emissions spillovers are obvious and serious (Guo and Fan, 2017; Wang et al., 2016a; Zhang, 2017). These undesirable emissions not only prevented the effectiveness but also raised the cost of emission reduction.

Up to now, there are some researches attempt to find and analysis the emissions spillovers through different methodology, regulation and targeted pollutant. For instance, Stefan (Ambec and Coria, 2018) provided a method to analysis GHGs and particular matter, Li (Li et al., 2018) indicated the spillover's feedback between economy and CO_2 emit in Beijing. However, the common issues of these studies are that still lack a large scale of qualitative and quantitative analysis on temporal and spatial characteristics and trends with a focus on multiple pollutants (Cai and Li, 2018; Chen et al., 2017; Huang et al., 2018). One of the reasons may from the trouble of unified characterization in multiple pollutants.

Focusing on the Administrative Regulations on the Levying and Use of the Pollutant Discharge Fee, all entities that directly discharge pollutants (e.g., SO_2, NO_x, COD, ammonia nitrogen, dust, etc., but not include CO_2) into the environment, they must pay the pollutant discharge fee (PDF). Meantime, although the environmental tax (ET) have replaced the PDF from 2018, the collection range of pollutants in ET system is almost same with PDF, and we are still lacking the actual data (Jian and Yuan, 2017; Wang et al., 2018a). Consequently, we can utilize this comprehensive indicator of multiple pollutants to monetize the other emissions. More importantly, the analysis of the spillover effect between CO_2 and other pollutants can be achieved in China.

Table 1
Descriptive statistics.

	Minimum	Maximum	Mean	Standard Deviation
PDF (millions of Yuan)	1.4190	2873.4350	459.220579	442.8808796
GDP (billions of Yuan)	11.780	7281.255	1134.02530	1233.019124
CO_2 emissions (millions of tons)	0.8000	1553.8000	246.645625	220.0583970

*: CO_2 emissions do not include Xizang.

Our paper attempts to create a study that qualitative and quantitative analysis about emissions spillovers levels of multiple pollutants in China. The propose of this research is to further confirm the emissions spillovers significantly affect emission control and emission reduction, as well as provide a new insight of emission reduction hierarchy. To provide clarity for these processes, PDF is used in analysing to quantities of emissions on the national, regional and provincial levels, which fill the data gap in recent academic study on multiple pollutants (Section 2). After that, we perform an empirical study of emissions reduction spillovers based on quantitative data of the emissions of CO_2 and other pollutants at the beginning of Section 3. Then, we highlight the relationship between emissions of CO_2 and other pollutants for each province. Last, the paper investigates the national, regional and provincial pollutants spillovers, as well as the difference across them on temporal and spatial level in China. The outcomes (Section 4), on the other hand, can improve the current understand of emissions spillovers on coordinating emissions reduction and promote set up and implicate more suitable measures, policies and technologies.

2. Data and method

2.1. Data sources

The impact of economy development on pollutants emissions are to be reflected through its effect on energy consumption and other factors. Accompany with the huge requirement of economic development, CO_2 emissions and other pollutants emissions are increasing accordingly. However, with the promotion of emissions reduction, the existing literatures have indicated the qualitative description of emissions spillovers. Before appropriately respond it, reflecting on emissions spillovers between CO_2 and other pollutants emissions should be pointed out firstly, that must focus on the quantitative coupling relationship (Liang et al., 2016). After that, the study examines the correlation between CO_2 emissions and the PDF during the years 2000–2015 based on a theoretical model and empirical tests. Then, focus on the reduction target is set with the FYP cycle, our study extends to the FYP cycle, specifically the 10th, 11th and 12th FYPs. During the process, more details are given to reveal the endogenous properties, and a relevant analysis is subsequently performed. Finally, we discuss the influence of spillovers and the correlations among emissions in regions and individual provinces.

Data on the PDF, CO_2 emissions and Gross Domestic Product (GDP) on the national level and for the 30 provinces of China from 2000 to 2015 are extracted for analysis using a regression model, correlations and panel data. The specific sources of the data are as follows. The PDF and GDP values and the investments in pollution treatment were obtained from the National Bureau of Statistics of the People's Republic of China, and the CO_2 emission data were provided as China Emission Accounts and Datasets (CEADs).

2.2. Methodology

Regression analysis is a statistical method to analysis and determine the quantitative relationship of two or more variables. It has been widely used in the relationship analysis. For instance, loads of previous studies taken GDP as a dependent variable analysed the relationship and performance of CO_2 emissions in time-series (Dinda, 2004; Grossman and Krueger, 2000; Shafik and Bandyopadhyay, 1992). That is, GDP also can be utilized as a dependent variable to assess the relationship between other pollutants and GDP growth. To measure the effects of emissions spillovers, it is priority solve the quantitative relationship of CO_2 and other pollutants emission. In the same way, emissions spillovers analysis can be achieved by this method (Wang et al., 2017).

We noticed there are some studies analysed emissions spillovers through the method of econometric models, input–output models, etc (Li et al., 2018; Zhang, 2017; Zhu et al., 2016). However, these methods used in studies without a more comprehensive index for pollutants representation, as well as the variables missing is still a scientific problem. Combine with the goals of our study, in the national and time series data (FYP cycles), regression is used to derive the relationship between CO_2 emissions and the PDF. Meantime, the regression model is also used to examine the serial correlation with the empirical data.

In addition, it should be point out is there are no missing variables in this research, as well as other variables such as population and areas are not taken into the calculate process. The regression model is established as follows. Here, CE represents CO_2 emissions.

$$PDF = \alpha_0 + \alpha_1 CE \tag{1}$$

As mentioned, pollutant emissions are thought to correlate strongly with economic development (Wang et al., 2016b). Thus, the study concludes that the PDF is affected by GDP fluctuations, and a control variable is taken into the regression model, which can be expressed as:

$$PDF = \alpha_0 + \alpha_1 CE + \alpha_2 GDP \tag{2}$$

More importantly, considering that the PDF, GDP and CE are trend variables that may lead to spurious regressions, the regression models are adjusted using Equ. 3.

$t(PDF_{i+1} - PDF_i) = \alpha_0 + \alpha_1 s(CE_{i+1} - CE_i) + \alpha_2 m(GDP_{i+1} - GDP_i)$;

if $PDF_{i+1} - PDF_i \geq 0$, t = 1; $CE_{i+1} - CE_i \geq 0$, s = 1; $GDP_{i+1} - GDP_i \geq 0$, m = 1;

$$PDF_{i+1} - PDF_i < 0, t = -1; CE_{i+1} - CE_i < 0, s = -1; GDP_{i+1} - GDP_i < 0, m = -1 \tag{3}$$

Here, i indicates the year, PDF_i represents the PDF in year i, CE_i represents the CO_2 emissions in year i, and GDP_i represents the GDP in year i. $PDF_{i+1} - PDF_i$ describes the increase in the PDF from i to i + 1; similar statements can be made for $CE_{i+1} - CE_i$and $GDP_{i+1} - GDP_i$. The coefficients t, s and m are used to determine the absolute values, given that we focus on the variations, instead of the direction of change.

Based on the discussion above, this study includes a comprehensive analysis of the relationship between PDF and CO_2 emissions at the national level and within time series (FYP cycles). We then determine the linear relationships between the PDF and CO_2 emissions for seven regions (North China, Northeast China, East China, Central China, South China, Northwest China and Southwest China). Finally, the linear fit for each province is also discussed.

3. Results

As was shown in Figs. 1 and 2, it could be considered that the spillovers existed. Fig. 1 shows the fluctuations and trends of the PDF, CO_2 and GDP at the national level. It directly proves the shifts existed in pollutant emissions from the trends in CO_2 emissions and PDF. During the initial period, 2000–2003, three indicators follow the same trend. Subsequently, compare with the initial period, the PDF shows a sudden increase during 2003–2007. In this period, it maintains a close relationship with the growth in CO_2 emissions. After that, it displays a small fluctuation in the period of 2007–2015, and the trend also does not decline sharply. Such result is unlike as suggested by the announcement of the Chinese government that the goal of emission reduction was successfully met during the 11th FYP (2006–2010) and 12th FYP (2011–2015). In the meantime, the gap between PDF and CO_2 emissions gradually shrinks after 2007, that may cause by the “successful” emission reductions and adjustments to the structure of the economy and the energy sector (Liang et al., 2016; Ministry of Environmental Protection and National Bureau of Statistics PR China, 2015). Additionally, with the total investment in pollution treatment increases, PDF does not show a decreasing trend from a long-term perspective.

On the other hand, Fig. 2 clearly illustrates the decreasing trend for key pollutants emission. With the slipping of key pollutants, PDF is not showing a quickly declining. Further, it presents sharp increase between 2003 and 2007, by contrast, a small fluctuation during the period of 2007–2015. These features are consistent with Fig. 1. In addition, PDF present a small decrease during 2013–2015, while the CE still growth. We notice this change may cause by the relevant upgrade of environmental legalization. For instance, ambient air quality standard was revised in 2012. On the other hand, it also may cause by the assessment method of FYP. Government makes the total of five years results at the last year to examine the task of emissions reduction.

However, positive performances must emphasize the integrate both from the of emissions reduction and environmental governance. Thus, we infer with high confidence that these disproportionate effects of emission reductions refer to emissions spillovers, which are as Section 1 introduced.

Regional or provincial differences is also important to analysis

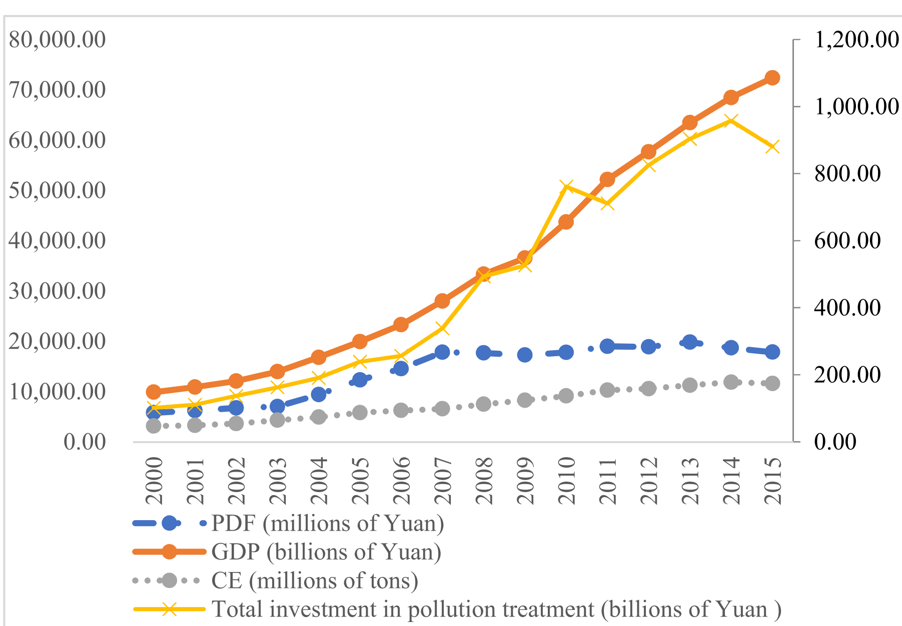


Fig. 1. 2000–2015 trends in the national PDF, CO_2 emissions, GDP and the total investment in pollution treatment.

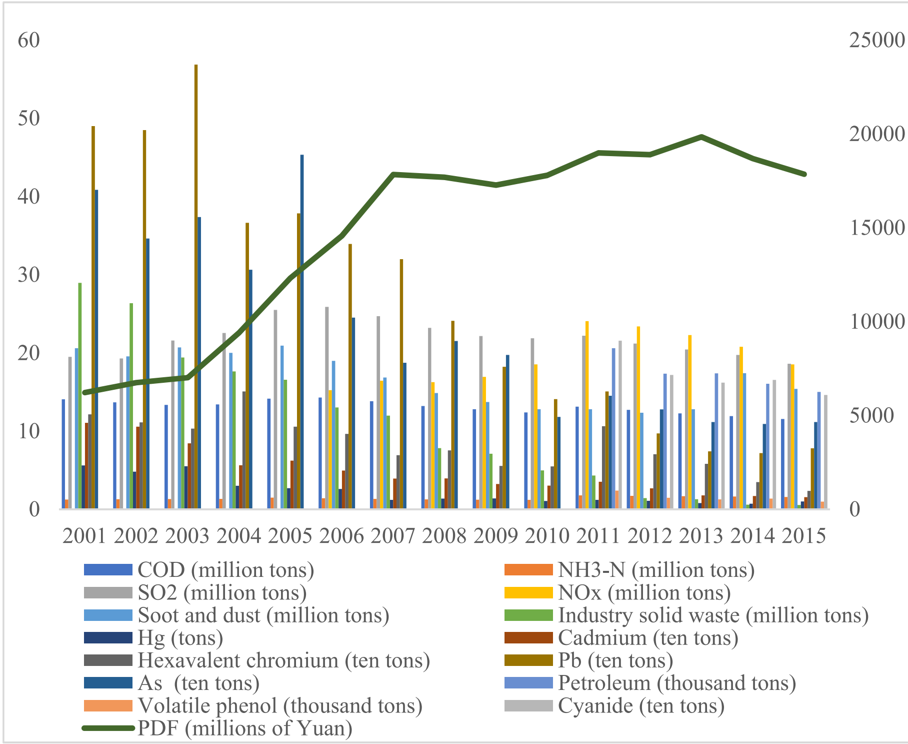


Fig. 2. Decreasing trend for key pollutants emission in China during 2001–2015.

emission spillovers, and it may explain the non-linear features in long time series. At the province level, the maximum and minimum values of the PDF are 2,873.43 million Yuan in Shanxi in 2007 and 1.419 million Yuan in Xizang in 2001, respectively. Similarly, the range of CO_2 emissions is wide, and the maximum value (1,553.8 million tons) also occurs in Shanxi in 2014. In contrast, the minimum value (0.8 million tons) is associated with Ningxia in 2000. Additionality, the extrema of GDP are 11.78 billion Yuan for Xizang in 2000, and 7,281.255 billion Yuan for Guangdong in 2015. The standard deviations describe the tremendous disparity in the spatial and temporal dimension among the provinces. Thus, considerable disparities in pollutant emissions and emissions spillovers exist in the corresponding provinces. Because the standard deviation respects the dispersion of data, improvements in environmental quality are normally related to reductions in the maximum extreme value (Bland and Altman, 1996; Lin et al., 2016; Möller and Einax, 2015).

In total, the national maximum and minimum values of PDF and CO_2 emissions appeared in 2013, 2000, 2014 and 2000, respectively. By coincidence, the total investment in the treatment of environmental pollution and the total investment in the treatment of industrial pollution achieve their maxima at the same time as those of the PDF and CO_2 emissions (Fig. 1).

In addition, many academic studies focus on CO_2 emissions and GDP growth in China (Hong et al., 2013; Liang et al., 2014; Xu et al., 2017; Yu et al., 2017; Zhou et al., 2017). Those previous studies have identified a good linear relationship between these variables, indicating a strong correlation between CO_2 emissions and GDP. The result also can be observed in Fig. 1. Similarly, numerous studies have measured the level of decoupling of emissions of different pollutants on different scales; almost none of the results mentioned here consider pollutants as a group (Tang et al., 2014; Yu et al., 2017; Zhao et al., 2017b). In this study, we verified the correlation between the emissions of CO_2 and other pollutants (as a whole) under the consideration of emission reductions at the beginning of the analysis. We then indicate each of these features in the spatial and temporal dimensions.

3.1. National-level analysis

3.1.1. Correlation analysis

Correlation analysis is necessary to ascertain the relationship between CO_2 emissions and the PDF. Table 2 indicates positive mutual effects and significance level at the 0.01 level, which lends credence to the view that spillovers occur, as described in Section 1. The spillover mechanism is described in Fig. 3. Consumption of large amounts of energy and resources has effectively promoted the development of China's economy, and environmental issues have become a major limiting constraint on the country's development. The authorities began to impose pollution controls and emission reductions since the 10th FYP (2001–2005) in this connection to contribute to sustainable development; EOP method was also being used to meet new emission control regulations (Li et al., 2016; Liang et al., 2016; Meng et al., 2016). However, the series of policies and regulations do not consider pollutants as a group in the process of consideration and design, leading to shifts among pollutants, and spillovers increasingly occur (Ambec and Coria, 2018). For instance, the statement following Fig. 1 shows that the PDF grows rapidly during the initial period of emission reductions from 2003 to 2007. It then shows cyclical swings as CO_2 emissions continuously increase.

3.1.2. Regression analysis

The verification of the residuals and collinearities is carried out after the regression analysis is performed. The results of both verifications satisfy the conditions of regression. Table 3 describes the regression results from 2000 to 2015 at the national level using GDP as a control variable, which clearly indicates the correlation between CO_2 emissions and the PDF at the 0.05 significance level. Furthermore, the coefficients are as high as 0.598, which indicates that the direction of the rate of change of growth displays the same direction for both CO_2 emissions and PDF. The correlation is strong and positive, and the growth of CO_2 emissions leads to definite increases in the PDF. These findings greatly support the spillovers effects do exist in China. The accumulation of EOP is sharply for the regulated pollutants, then, the emissions transfer to

Table 2
Correlation analysis at the national scale.

		$t(PDF_{i+1} - PDF_i)$	$m(GDP_{i+1} - GDP_i)$	$s(CE_{i+1} - CE_i)$
$t(PDF_{i+1} - PDF_i)$	Pearson correlation	**1.000**	0.170**	0.268**
	Sig. (two-tailed)		0.000	0.000
	Number of cases	465	465	450
$m(GDP_{i+1} - GDP_i)$	Pearson correlation	0.170**	**1.000**	0.170**
	Sig. (two-tailed)	0.000		0.000
	Number of cases	465	465	450
$s(CE_{i+1} - CE_i)$	Pearson correlation	0.268**	0.170**	**1.000**
	Sig. (two-tailed)	0.000	0.000	
	Number of cases	450	450	450

*: Correlation is significant at the 0.01 level.

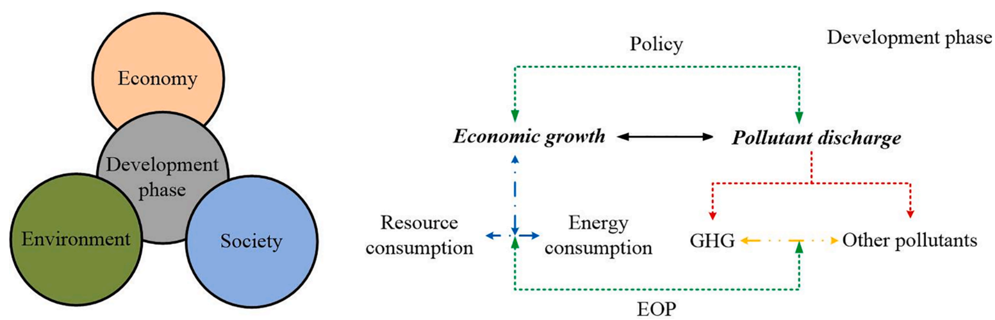


Fig. 3. Mechanism of spillovers between the PDF and CO_2 emissions.

Table 3
Regression analysis.

Model	B	t	Sig.	VIF
α_0	39.333	5.587	0.000	
$m(GDP_{i+1} - GDP_i)$	0.087	2.421	0.016	1.030
$s(CE_{i+1} - CE_i)$	0.598	5.411	0.000	1.030
ANOVA				
F	20.839			
Sig.	0.000^b			
Durbin-Watson	1.397			
Adjusted R-squared (%)	7.9			

non-target pollutant (as Fig. 2 shows the gap does not display a narrow trend and decline rapidly). This result also indicates emissions reduction and environmental governance should heightened integration. That is, the current emission reduction and environmental governance accompany with a high CO_2 emission (Figs. 1 and 2). Cleaner energy, technology and production should be taken into the development program in future.

3.2. FYP cycle analysis

The above sample covers 16 years, including three FYPs (extending from the 10th to the 12th FYP), during which substantial changes took place in China. GDP increased by more than seven times, and CO_2 emissions increased by more than three times. Moreover, great transformations in the economy took place during this period. At the same time, a series of policies regarding emission reductions were established in each FYP, while the investment in environmental treatment reached an unprecedented scale. Therefore, an analysis of the FYP cycle is considered, including three sub-samples coordinated with the FYPs:

1) In the first sub-sample (2000–2005; 10th FYP), no mandatory reductions in pollutant emissions were imposed.
2) In the second sub-sample (2006–2010; 11th FYP) and the third sub-sample (2011–2015; 12th FYP), mandatory reductions in pollutant emissions were imposed. Additionally, corresponding emission reduction goals were assigned to the provinces.

Referring to the temporal trend, the spillovers effects becoming seriously. Ditto when the processes in that followed Section of Correlation analysis and Section regression. Table 4 summarizes the trends among the PDF, CO_2 emissions and GDP. Obviously, the significance changes between the PDF and CO_2 emissions from non-significant in the 10th FYP to significant in the 11th FYP, and the significance of the correlation is even higher in the 12th FYP. In contrast, in the 11th FYP, the correlation between the PDF and GDP becomes non-significant. However, the regression coefficient (Beta) shows a negative value in the 12th FYP, which means that economic development caused a decline in the PDF to some extent. More importantly, the correlation between these variables is non-significant. This result further confirms the considerations as presented at the beginning of this section. There is a positive correlation between the PDF and CE. Meanwhile, traditional (EOP-based) emission reduction methods will further stimulate spillover effects in China.

3.3. Regional-level analysis

The above discussion indicates an obvious correlation on the national level from 2000 to 2015. Considering the challenges produced by regional differences in economic condition, emissions status and geographic situation, we investigate the variations in the correlation among different regions. The results are shown in Figs. 4 and 5. The coefficient of determination (R^2) indicates the goodness of fit (the R^2 values for all of the regions >0.68, and the maximum value is 0.8648, which corresponds to Northeast China). Meanwhile, the slope (0.7462–1.3225) illustrates a good linear relationship between the PDF and CO_2 emissions in seven regions during the period of 2000–2015. In addition, the slopes associated with economically developed regions, such as East China, North China and South China, are higher than those associated with the developing regions (Central China, Northwest China and Southwest China). These results describe the mutual influence between the PDF and CO_2 emissions. More importantly, the R^2 values of

Table 4
Regression analysis by FYP.

Model	10th FYP			11th FYP			12th FYP		
	B	t	Sig.	B	t	Sig.	B	t	Sig.
α_0	10.694	1.493	0.138	44.565	2.519	0.013	59.730	5.144	0.000
$s(CE_{i+1} - CE_i)$	0.125	0.522	0.603	1.041	3.327	0.001	0.417	3.624	0.000
$m(GDP_{i+1} - GDP_i)$	0.544	6.371	0.000	0.039	0.466	0.642	−0.002	−0.048	0.962

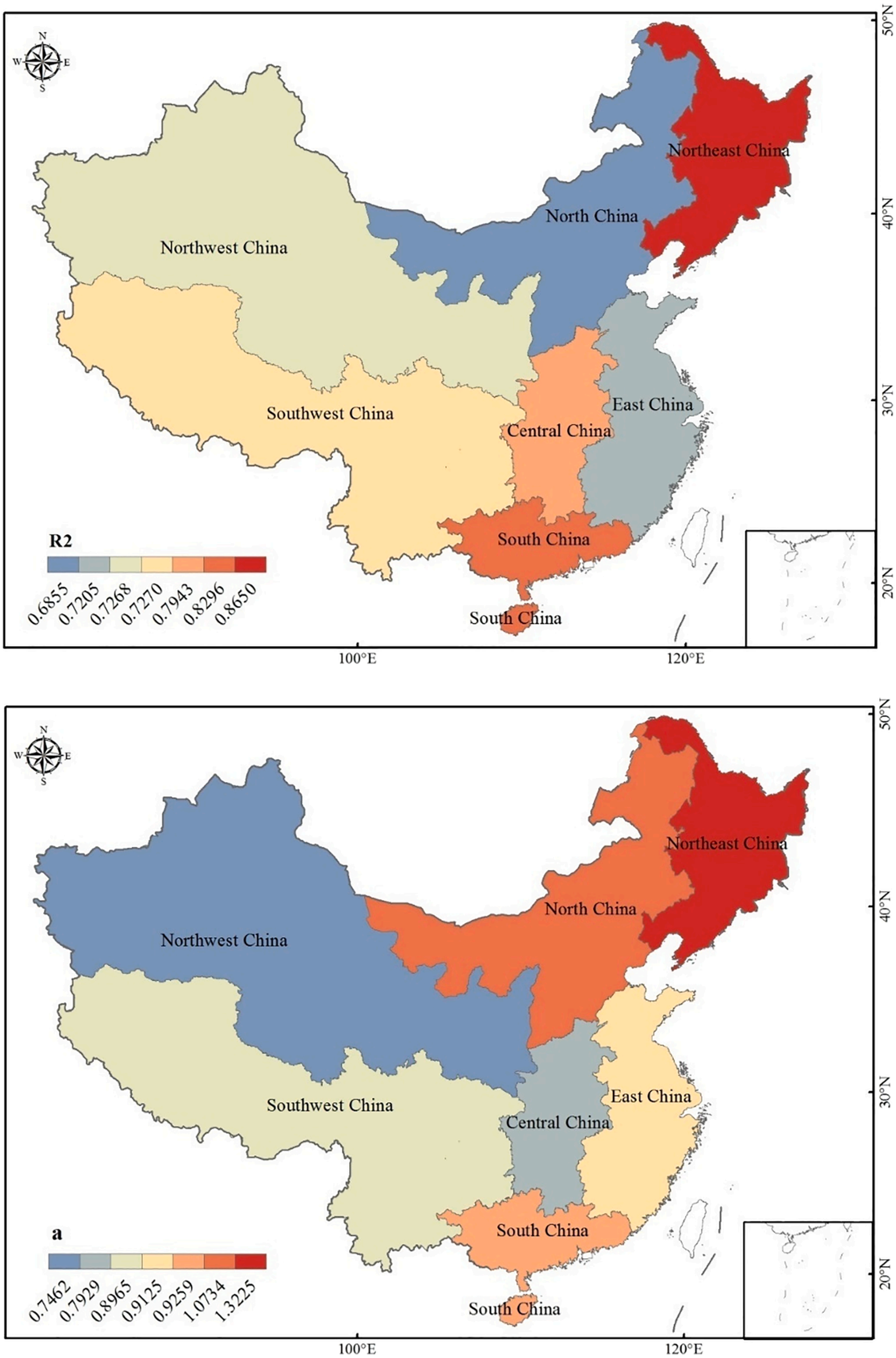


Fig. 4. The different correlations and their distribution in the different regions.

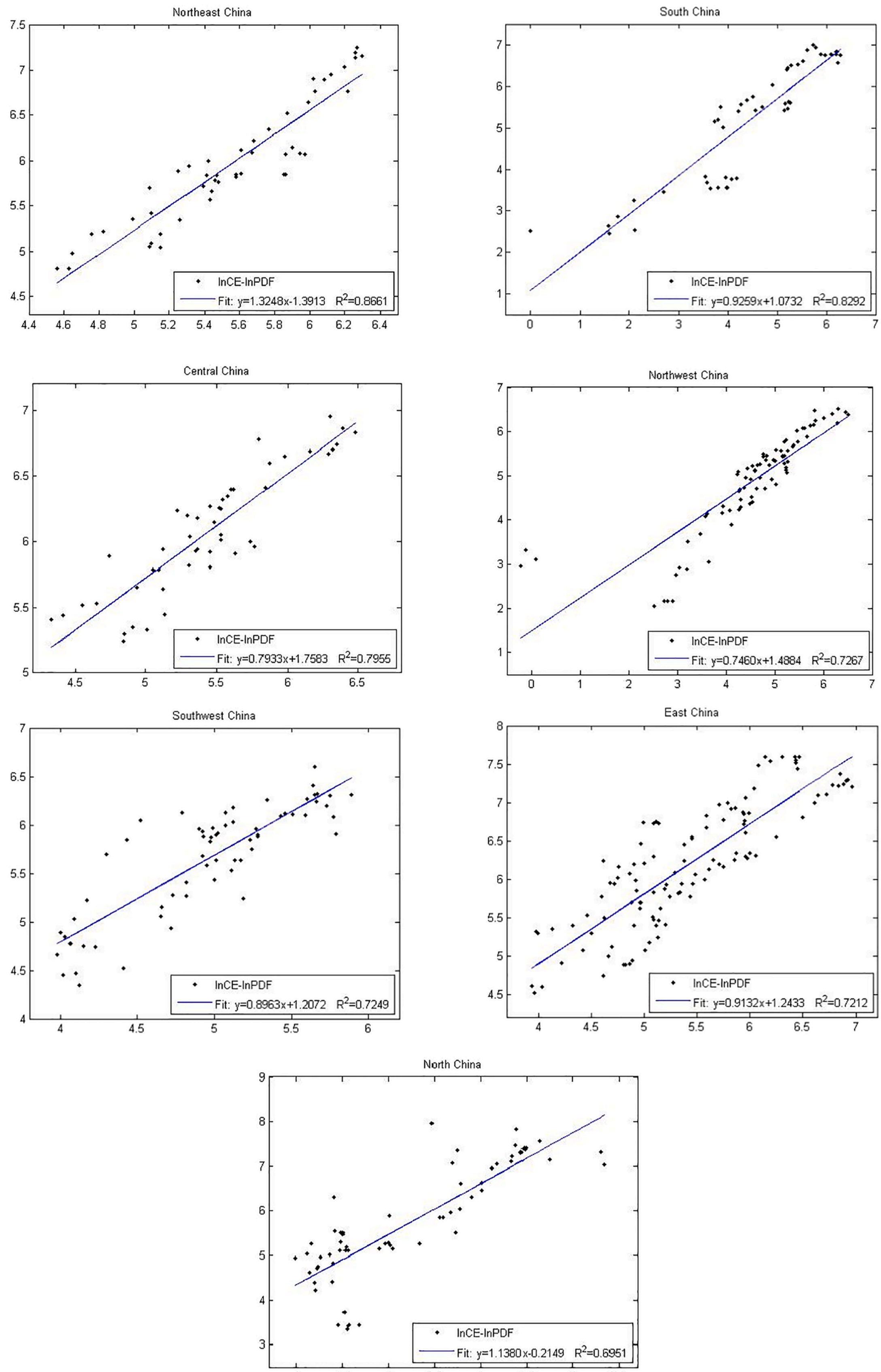


Fig. 5. Correlation between the PDF and CO_2 emissions at the regional level.

developing regions exceed those of East China and North China and are smaller than those of South China, which indicates that emissions increase with rapid economic development. This result is consistent with the course of development in the West. On the other hand, this result can also be explained well by the environmental Kuznets curve (EKC). Finally, we note that the occurrence of the highest values of both the slope and R^2 in Northeast China is caused by historical reasons. Northeast China is the traditional industrial base of China. Economic transformation currently receives increasing amounts of attention, whereas the control of environmental pollution is mainly based on EOP methods in historical industry.

Given the above discussion, and based on the R^2 results, we consider that the current emission reduction hierarchy is as follows: Northeast China, South China, Central China, Northwest China, Southwest China, East China and North China. In addition, the authorities must pay special attention to policies that implement the co-control of pollutant emissions to achieve meaningful emission controls. Such policies can focus on the slope values from Northeast China to Northwest China. Finally,

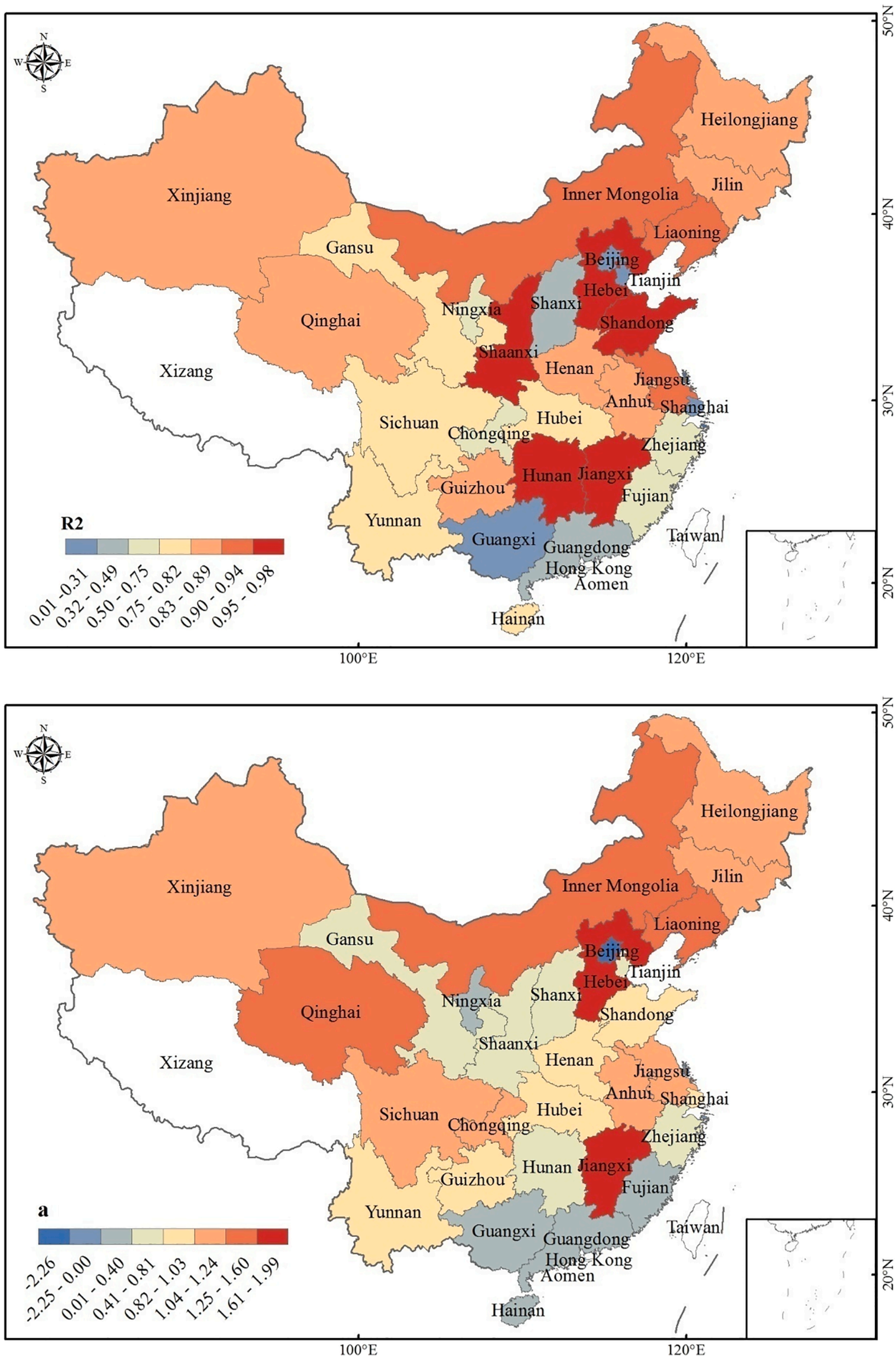


Fig. 6. The different correlations associated with each province.

the spillovers should be pointed out because they have a significant effect on the relationship between the PDF and CO_2 emissions under the current emission reduction policy and the use of EOP method, as well the same order as the slope values presented in Fig. 4. The government also should pay more attention on the impact (*a* values). Those regions, especially with high *a* value's, should do more about the communication and cooperation of the relation with climate change, emission reduction and environment pollution treatment plans.

3.4. Provincial-level analysis

Views for each province are now introduced. As in Section Regional-level analysis (Fig. 6) describes the different correlations and their distributions for the 30 provinces of China (not including Tibet). Most of the R^2 values exceed 0.64, and the extreme records are associated with Hebei (0.9798) and Tianjin (0.1748). Meanwhile, the slope values range from 1.9878 in Jiangxi to −2.2578 in Beijing. As in the regional assessment, the R^2 and slope values accurately indicate the emission reduction hierarchy, the co-control of pollutant emissions and spillovers, which are shown by the colour gradient in Fig. 6. Almost without exception, the province-level analysis yields similar results as the regional-level analysis according to the R^2 values and *a* values.

In addition, relatively low R^2 values occur in South China (Guangdong and Guangxi), North China (Shanxi, Beijing and Tianjin) and East China (Shanghai), whereas the relatively low slope values happen primarily in South China (Hainan, Guangdong and Guangxi) and Beijing. In particular, Beijing displays a negative slope. Thus, the following aspects need to be considered on the provincial level. Clearly, as the political and economic capitals of China, Beijing and Shanghai began their economic transitions earlier. For example, Beijing contributed more than 80% of the GDP from tertiary industry in 2017, whereas stricter environment management is imposed in the Jing-Jin-Ji region, leading to low-carbon development. The developed provinces of South China consume large amounts of energy but benefit from the "west power to east" policy, which transfers emissions. Thus, these provinces display low values of both R^2 and the slope. Moreover, they all indicate good spillover effects. Finally, Shanxi is undergoing the transformation of its coal industry. Its remaining issues and economic development together created its situation. This province also needs further contributions to the co-control of pollutant emissions and to try to avoid spillovers.

In total, provincial disparity exists need to be considered so that more precision policies can be set up. Especially, deeper co-benefits approach by policy integration must implement to avoid emission spillovers, as well as the design of emission reduction hierarchy based on the difference of spillovers effects. Also, since emissions reduction and environment treatment implemented during the FYPs, to achieve effectiveness in both of CO_2 emission and other pollutants emission, it will be critical to keep mutual promotion in long term. In addition, the irrational addition of EOP is not advisable, as well the cooperation need enhance by regions and provinces.

4. Discussion

Our study provides a novel framework that can be used to analyse emissions of pollutants, including CO_2, and explores the spillovers based on the PDF and CO_2 emissions. It can further contribute to the co-control of pollutant emissions and thus the meaningful achievement of sustainable development. Meantime, the method is useful for the implementation of the subsequent ET to guide emission controls, as well as the further quantitative study of spillovers can also be conducted in the future.

The research can be used to support emission reductions at different levels. Provincial, regional, national and even international efforts to co-control the emissions of both CO_2 and other pollutants are important for sustainable development. During the process, China announced that its CO_2 emissions will peak in 2030, and investing in EOP methods remains the normal way of handing environmental issues. Such situations require the authorities to devote more attention to the co-control of pollutant emissions, especially the spillover effect. Our study provides a clear result that supports this point.

In addition, this study can also help the authorities avoid additional losses caused by excessive emission reductions, and it also indicates the correct direction of emission reductions in China:

First, strengthened supervision and systematized policies design about emissions control and emission reduction should be developed and accessed to avoid emissions spillovers. Without any co-control measure for emissions, the positive correlation become increasingly between the emissions of CO_2 and other pollutants at the temporal distribution (Table 4). Doing so, the current efforts have a negligible impact on pollution control and emission reduction. In turn, such progress could be abated chiefly by design more substitutable policy. For instance, develop and operate carbon tax within the framework of ET. Once the pollutants are set up as a group, the spillovers impact will under control to some extent. Also, it requires the national design for the transform of energy structure and industry structure. More clean energy plan and industrial structuring and upgrading is the substantial in this practice, especially for the area of northeast China (Figs. 4, Fig. 5). Similarly, with the plan of western China development, economy development should refer to green model is necessary (Fig. 4, Fig. 5), toward to decoupled from environment.

Second, the choice and regulation of region and province are important for the spillovers effects. In particular, there is a gap in the future through economy and emissions, they have a disparity contribution in emissions spillovers (Fig. 4, Fig. 5, Fig. 6). Whether the abatement of CO_2 emission or other emissions depends on the economic development. In this case, to avoid the spillovers effects require a joint mechanism. On one hand, enhance the cooperation on pollution control between regions and provinces. The developing regions and provinces (eg. Guizhou province and Yunnan province) need get more output of capital and technology from developed areas (eg. Shanghai, Guangdong province, etc.), which means break up the traditional geographic distribution to promote emission control and reduction, as well focus on the effort of gas and electricity send from west to east during the past decade. Also, the obligation and allocation of emission permits should depend on the cooperation mechanism. On another hand, neighbouring provinces, especially emissions spillovers serious regions (like Hebei, Shandong and Inner Mongolia), further formation mechanisms for joint prevention and control, achieving emissions and pollution control in a short time, then avoid emissions spillovers over the long time by effective effort of emission control and reduction.

Third, emission reduction and pollution treatment should create positive direction. Top policy makers need to develop more appropriate policies and mechanism to meet the local demands based upon regional and provincial disparity. This is especially crucial for global climate change, local emission reduction and environmental governance. The process and final benefits should toward to a common source and future.

Last, future work will also need to evaluate the emissions from Tibet. At present, the study has produced reliable results for the country, seven regions and 30 provinces. After that, we will also update and improve the data using the ET in the future. Meantime, research also need to get clear on the which pollutants are the major contributors for the emissions spillovers in current China. Because the value of R^2 shows the correlation and the value of *a* describes the variation, there may have a case that greatly spillovers lead by some major pollutants. Build up classified pollutant database is especially important. Then, more variables should be considered in models, including population, economic institutions, energy structure, technology portability, etc. Also, the model should be upgrade accompany with the more variables. Besides, the model can only measure the elasticity of emissions spillover right now, and other relevant tasks are based on the elasticity, which may limit the ability of the model to some degree.

CRediT authorship contribution statement

Siping Ji: Conceptualization, Methodology. **Weishi Zhang:** Investigation. **Shixiong Wang:** Supervision.

Declaration of Competing Interest

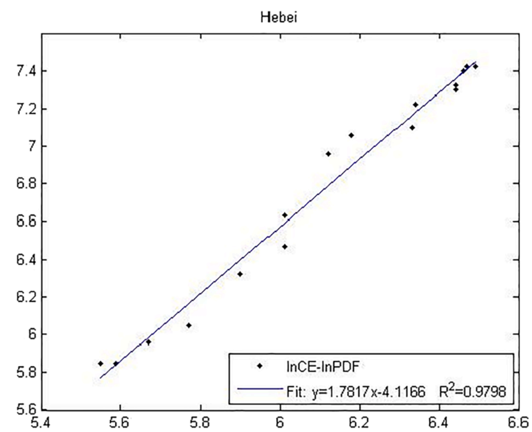
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

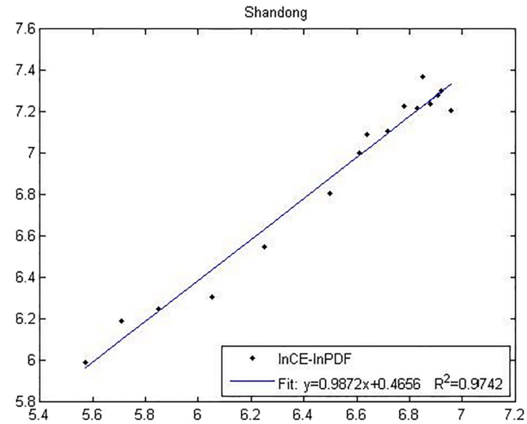
Acknowledgements

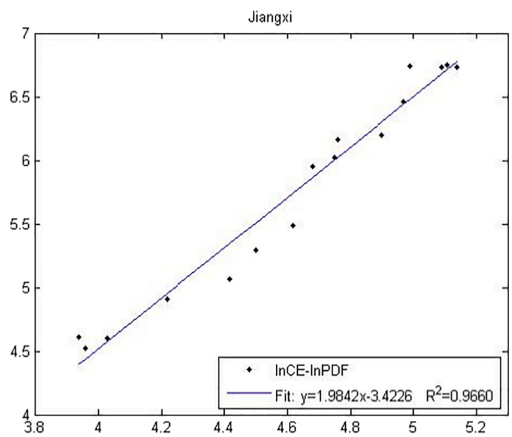
This study was supported by grants from the National Natural Science Foundation of China (Projects No. 51764051), the Natural Science Foundation of Yunnan Province (Projects No. 2018FB014), and the Talent Development Programme of the Foundation of Yunnan Province (Project No. KKSY201508012). The authors also thank the CEADs Team for CO_2 emission data.

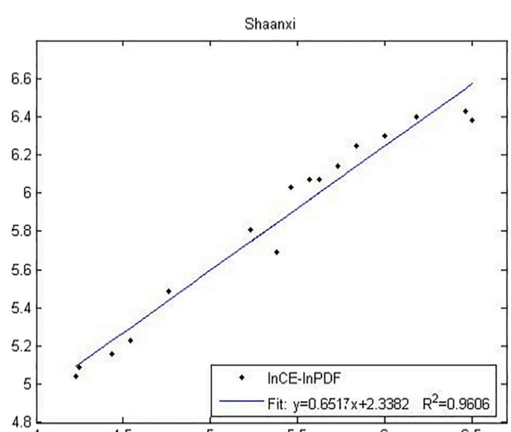
Appendix A

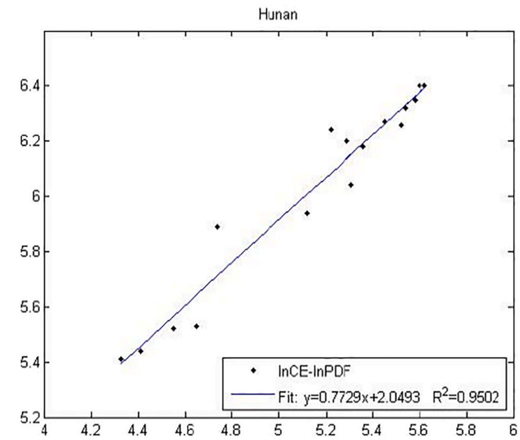
The correlation between the PDF and CO_2 emissions for 30 provinces as follow:

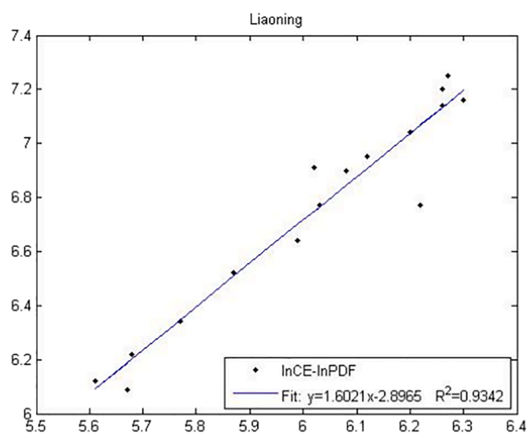


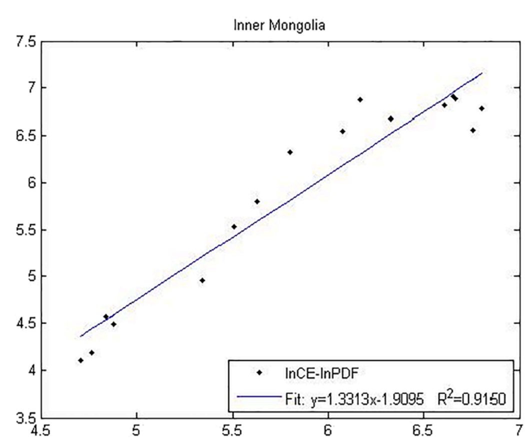

Shandong
lnCE-lnPDF
Fit: y=0.9872x+0.4656 R2=0.9742


Jiangxi
lnCE-lnPDF
Fit: y=1.9842x-3.4226 R2=0.9660


Shaanxi
lnCE-lnPDF
Fit: y=0.6517x+2.3382 R2=0.9606


Hunan
lnCE-lnPDF
Fit: y=0.7729x+2.0493 R2=0.9502


Liaoning
lnCE-lnPDF
Fit: y=1.6021x-2.8965 R2=0.9342


Inner Mongolia
lnCE-lnPDF
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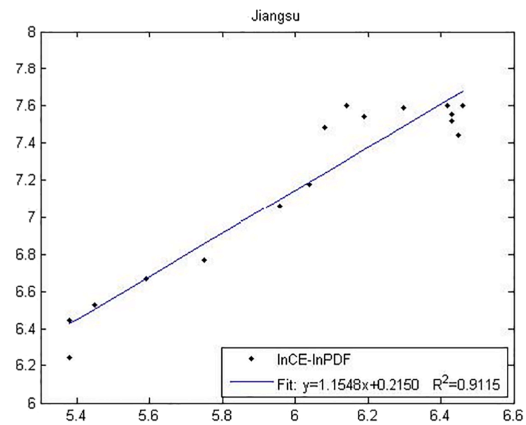
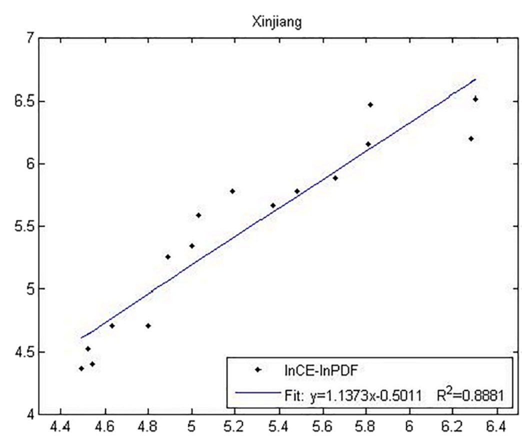

Jiangsu
lnCE-lnPDF
Fit: y=1.1548x+0.2150 R2=0.9115


Xinjiang
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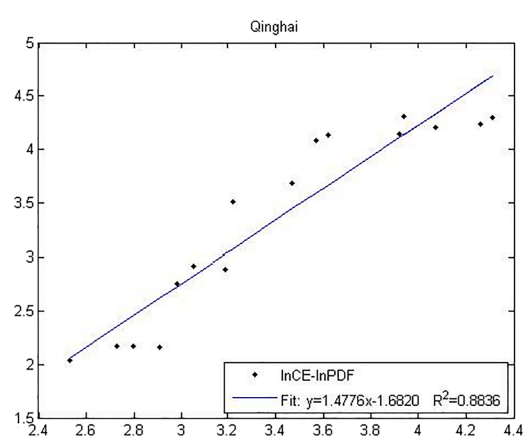
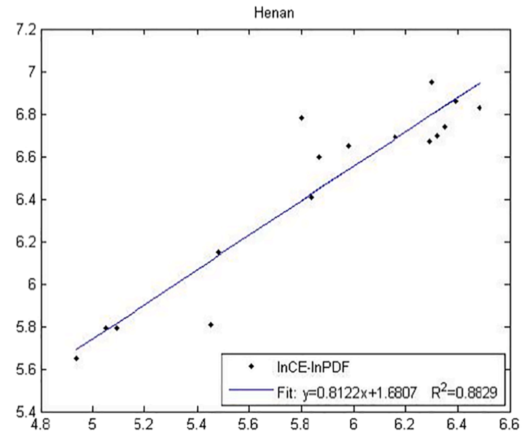

Qinghai
lnCE-lnPDF
Fit: y=1.4776x-1.6820 R2=0.8836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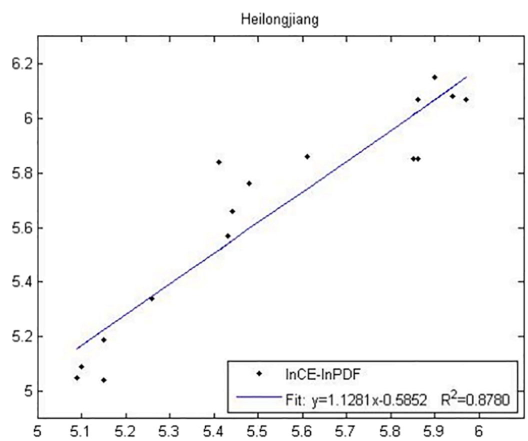
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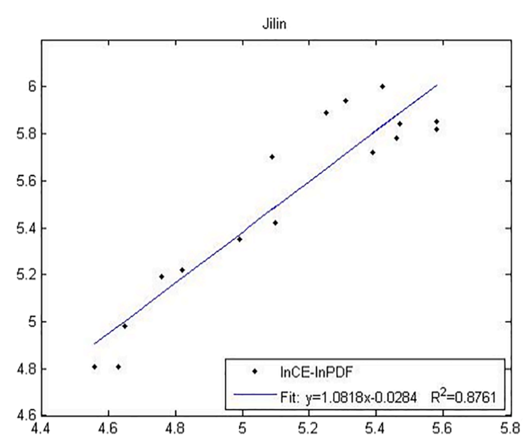
lnCE-lnPDF
Fit: y=1.1281x-0.5852 R2=0.8780


Jilin
lnCE-lnPDF
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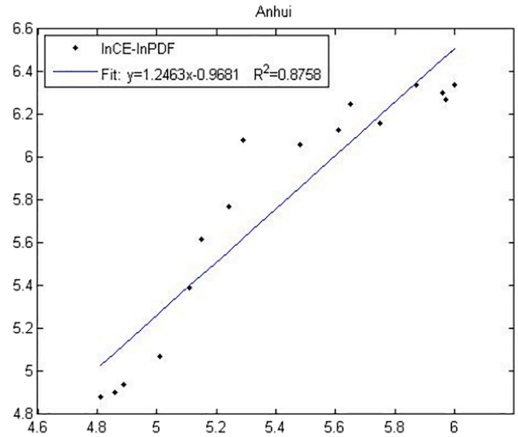
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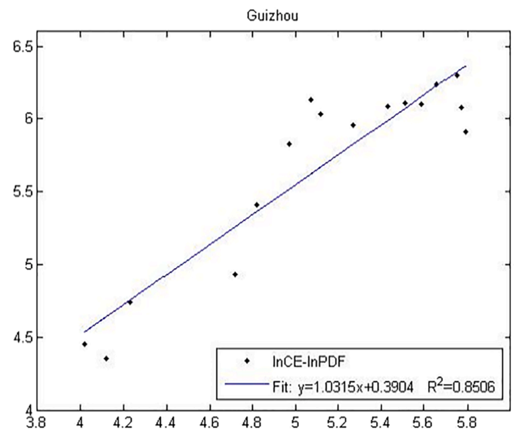
Guizhou
lnCE-lnPDF
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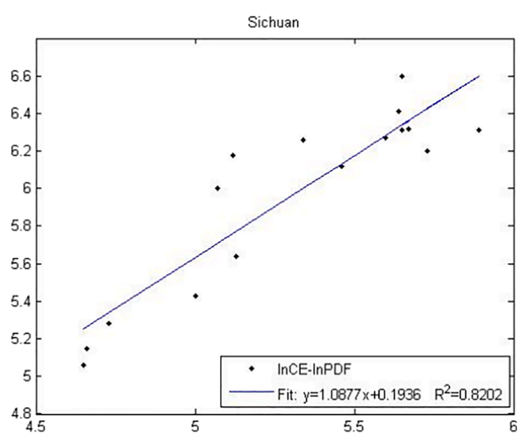
Sichuan
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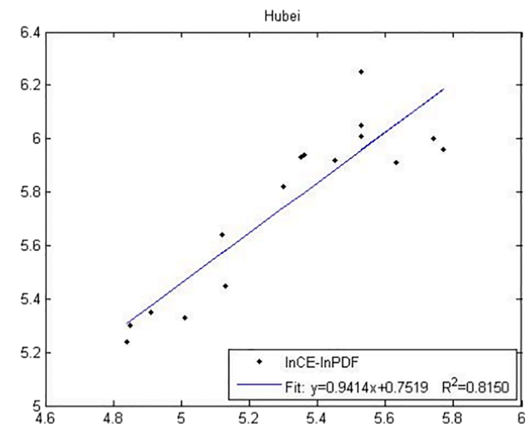
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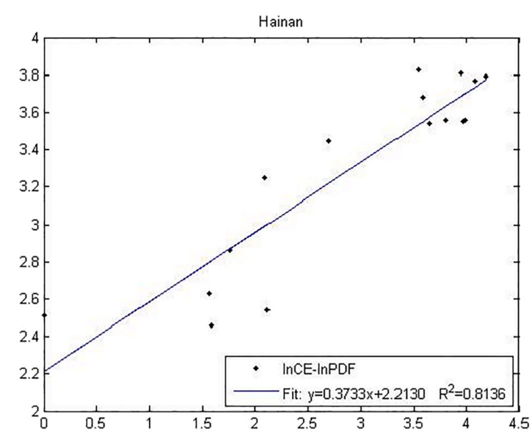
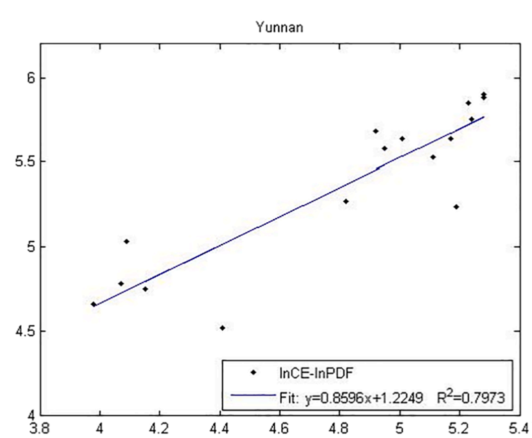
Fit: y=0.9414x+0.7519 R2=0.8150


Hainan
lnCE-lnPDF
Fit: y=0.3733x+2.2130 R2=0.8136


Yunnan
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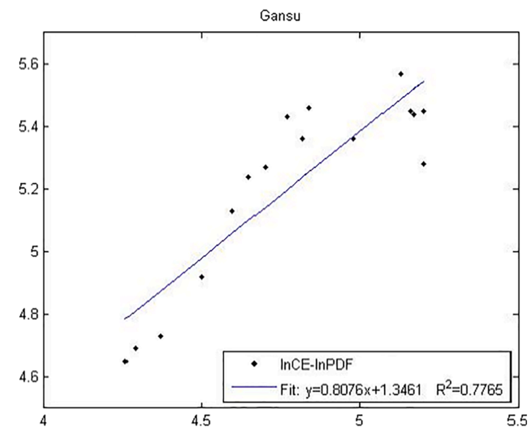
Fit: y=0.8596x+1.2249 R2=0.7973


Gansu
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Fit: y=0.8076x+1.3461 R2=0.7765
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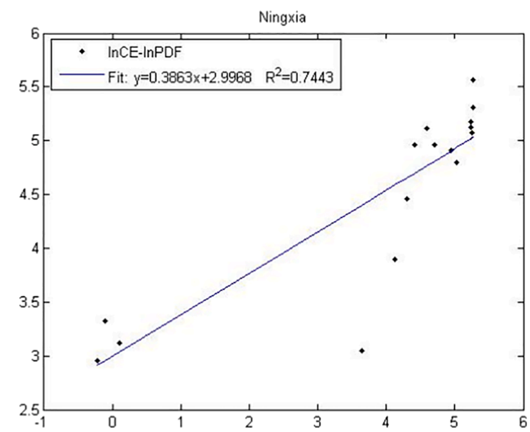
5.2
5
4.8
4.6
4
4.5
5
5.5


Ningxia
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5
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3
2.5
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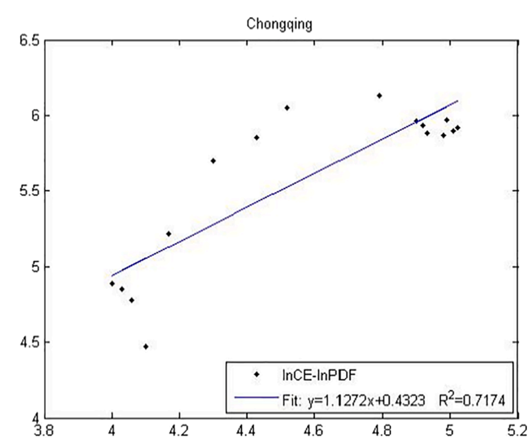
2
3
4
5
6


Chongqing
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3.8
4
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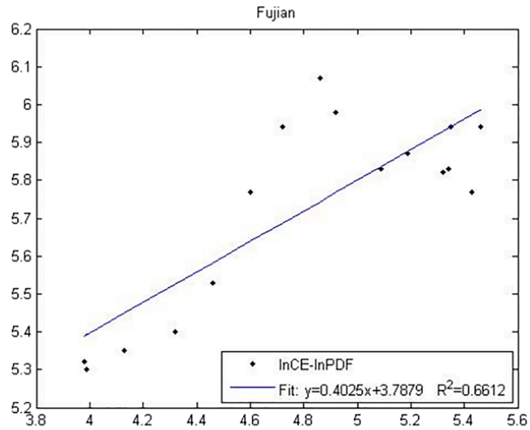
4.8
5
5.2


Fujian
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6.1
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3.8
4
4.2
4.4
4.6
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5
5.2
5.4
5.6
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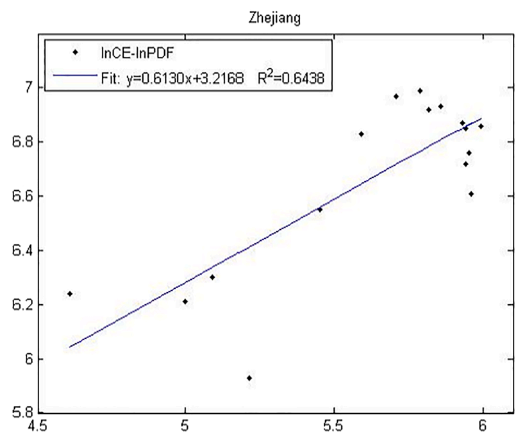
Fit: y=0.4025x+3.7879 R2=0.6612


Zhejiang
lnCE-lnPDF
Fit: y=0.6130x+3.2168 R2=0.6438
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6.2
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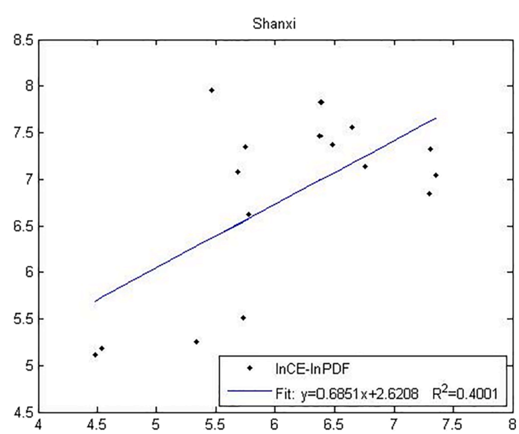
5.8
4.5
5
5.5
6


Shanxi
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6
6.5
7
7.5
8
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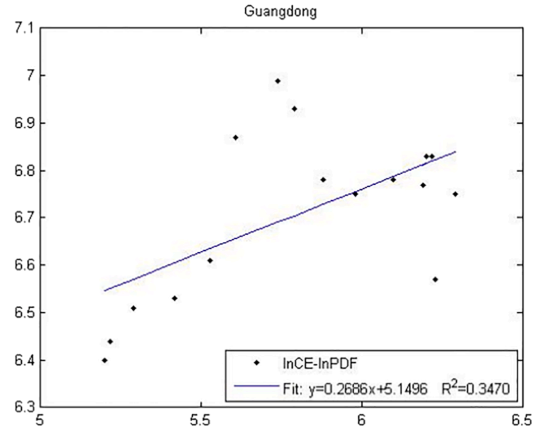
Guangdong
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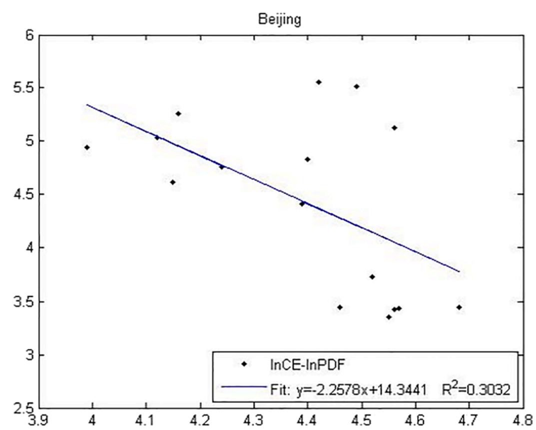
Beijing
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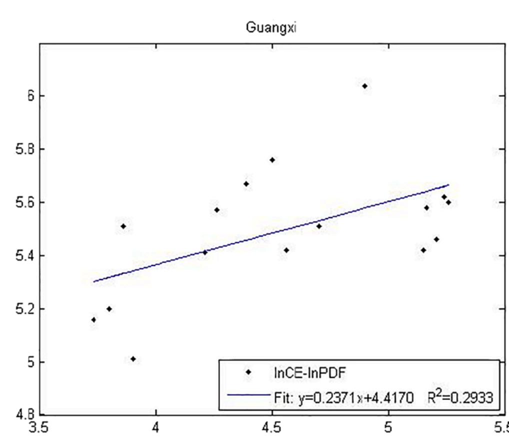
Guangxi
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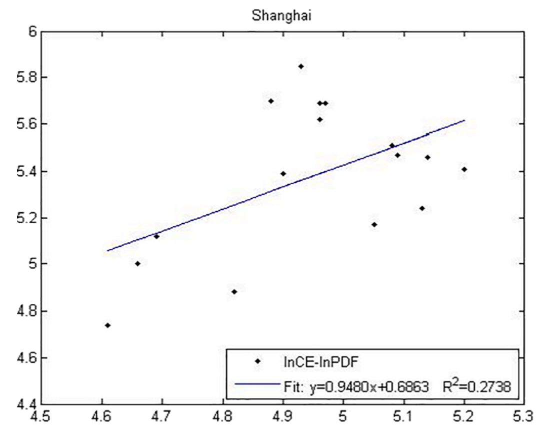

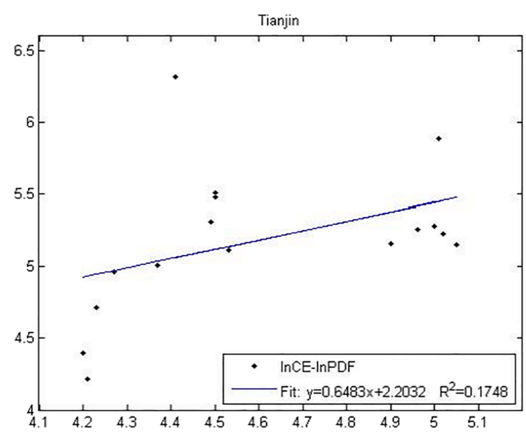

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