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A dual strategy for controlling energy consumption and air pollution in China's metropolis of Beijing

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ABSTRACT

It is critical to alleviate problems of energy and air pollutants emissions in the metropolis because these areas serve as economic engines and have large and dense populations. Drivers of fossil fuel use and air pollutants emissions were analyzed in metropolis of Beijing during 1997–2010. The analyses were conducted from both a bottom-up and a top-down perspective based on the sectoral inventories and structural decomposition analysis (SDA). From a bottom-up perspective, the key energy-intensive industrial sectors directly caused the variations in Beijing's air pollution by means of a series of energy and economic policies. From a top-down perspective, variations in production structures caused increases in most materials during 2000–2010, but there were decreases in PM_{10} and $PM_{2.5}$ emissions during 2005–2010. Population growth was found to be the largest driver of energy consumption and air pollutants emissions during 1997–2010. This finding suggests that avoiding rapid population growth in Beijing could simultaneously control energy consumptions and air pollutants emissions. Mitigation policies should consider not only the key industrial sectors but also socioeconomic drivers to co-reduce energy consumption and air pollutions in China's metropolis.

1. Introduction

More than half of the world's population has lived in cities since 2007 [1]. Cities have become the main sink of resources, energy, and the main source of environmental pollution [2–6]. The impact of cities on energy use and associated air pollutions is now increasing, even worse in developing countries because of their rapid urbanization and industrialization [6].

China has already become the second-largest economy and energy consumer in the world after the United States [7]. Along with the booming economy driven by massive industrialization and urbanization, fifty-three percent of China's population lived in cities in 2010 [1], and this rate will grow to 60% (or approximately 900 million urban inhabitants) by 2020 according to China's New Urbanization Plan [8]. Huge urban migrations, expansion of existing cities, and the emergence of new cities during this process of China's urbanization could cause complicated environmental burdens. For example, cities have not only account for the major share (over 80%) of the national total energy consumption and CO_2 emissions [9,10], but also have deleterious health impacts because of increasing air pollution problems [11,12].

In response to these multifaceted environmental challenges, some scholars have proposed the idea of simultaneous beneficial measures ("co-benefits") to mitigate these multiple environmental impacts. The Intergovernmental Panel on Climate Change (IPCC) and the Ministry of the Environment of Japan (MOEJ) have defined co-benefits as a process that could control both greenhouse gasses (GHGs) and other local air pollutants emissions (e.g., CO_2, SO, NO_x, and etc.) simultaneously, and would provide potentially significant savings in abatement costs [13,14]. In particular, because anthropogenic GHGs and air pollutants emissions originate mainly from

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fossil fuel consumptions, there are opportunities to reduce energy consumption and air pollutants emissions simultaneously [15,16].

Most previous studies have explored these co-benefits from a bottom-up perspective. They suggested that advanced technologies should be applied to reduce various air pollutants emissions in the high energy-intensive industrial sectors (e.g., the metals sectors [17]). However, several studies [18] have indicated the possibility of controlling some socioeconomic drivers of energy consumption and the relevant emissions to achieve the co-benefits. This type of analysis is from a top-down perspective, which could be more comprehensive in general.

The techniques that are available for identifying the socioeconomic factors that drive GHGs and air pollutants emissions include index decomposition analysis (IDA) and structural decomposition analysis (SDA). Both techniques have been applied widely for assessing the socioeconomic driving forces for energy consumption and CO_2 emissions at national and regional levels [7,18–23], but they have rarely been to analyze the co-control or co-benefit issues. Comparing to IDA, SDA can capture both direct and indirect environmental impacts depending on input-output (IO) models, and decompose out drivers that uncover more details of an economic structure, such as production structure and final demand structure. We therefore applied the SDA method in this study to analyze the socioeconomic drivers of fossil fuel use and air pollutants emissions and to analyze the co-benefits of mitigating environmental pressures in an urban setting.

Beijing is seen as a special case because it is China's capital and one of the world's largest cities and because of its unique economic status and its serious air pollution. Beijing's per capita GDP (Gross Domestic Product) reached 11,200 U.S. dollars by 2010, and the tertiary industry contribution to the GDP reached 74% by 2010 [24]. These are almost equivalent to comparable values for an entire mid-ranked developed country. Environmental challenges, such as air pollution and climate change, have been recognized as being serious in Beijing over the past two decades, during which time rapid economic development and urbanization have occurred in the city [25]. For example, there was a particularly intense debate among experts, media, and publics in Beijing in December 2011 that focused on $PM_{2.5}$. The debate was triggered by the high frequency of dust storms, and smog, fog, and haze events that occurred in the northern part of China [26].

In the present study, we examined Beijing's fossil fuel use and air pollutants emissions during the period of 1997–2010 to measure the contributions of various drivers from both a sectoral perspective (a bottom-up perspective) and a socioeconomic perspective (a top-down perspective). We focused on the use of coal, fossil oil, and natural gas and the emission of SO_2, NO_x, PM_{10}, $PM_{2.5}$, and CO_2. Section 2 introduces the methods and data, and Section 3 presents the results. A discussion of the results and policy implications is presented in Section 4, and conclusions are presented in Section 5.

2. Methods and data

2.1. Methods

SDA quantifies the drivers of economic structural changes, using a varying set of key parameters in IO tables (IOTs) with a temporal dimension [19,27–31]. SDA has broad applications for examining the socioeconomic drivers of an economic system's environmental impacts, such as its CO_2 emissions and water consumption [10,31–37]. The principal formula of an IO-based SDA can be expressed as:

$$E = F(I-A)^{-1}Y = FLY = p_d PFLy_{ss}y_{ds} \tag{1}$$

Environmental impacts E can be decomposed into six drivers: per capita final demand (p_d [a constant value]), population (P [a constant value]), materials intensities (energy consumption or emissions per unit of output) (F [$1 \times n$ vector]), production structures (L [$n \times n$ matrix]), the sectoral structures of final demand types (y_{ss} [$n \times m$ matrix]), and the composition of final demand (final demand structure) (y_{ds} [$m \times 1$ vector]). The types of final demand are rural and urban household consumption, government consumption, capital formation, and domestic and international exports. Here, n is the number of sectors and m is the number of final demand types. The environmental impacts in the time of (t) and ($t-1$) can be respectively expressed as:

$$E_{(t)} = p_{d(t)}P_{(t)}F_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)} \tag{2}$$

$$E_{(t-1)} = p_{d(t-1)}P_{(t-1)}F_{(t-1)}L_{(t-1)}y_{ss(t-1)}y_{ds(t-1)} \tag{3}$$

Therefore, the changes in environmental impacts (ΔE) from time ($t-1$) to time (t) can be calculated through equation (4), which could be also decomposed into changes in the component driving forces according to the method of SDA (equation (5)).

$$\Delta E = E_{(t)} - E_{(t-1)} = p_{d(t)}P_{(t)}F_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)} - p_{d(t-1)}P_{(t-1)}F_{(t-1)}L_{(t-1)}y_{ss(t-1)}y_{ds(t-1)} \tag{4}$$

However, there is a non-uniqueness of the decomposing results of the IO-based SDA model [19,36,38]. If the number of decomposed factors is n, the number of possible decomposition forms is $n!$ [29,38]. In our study, there are $6! = 720$ first-order decompositions. One of the 720 possible decompositions is shown as:

$$\begin{aligned}\Delta E = {} & \Delta p_d P_{(t)}F_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)} + p_{d(t-1)}\Delta PF_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)} \\ & + p_{d(t-1)}P_{(t-1)}\Delta FL_{(t)}y_{ss(t)}y_{d(st)} \\ & + p_{d(t-1)}P_{(t-1)}F_{(t-1)}\Delta Ly_{ss(t)}y_{ds(t)} \\ & + p_{d(t-1)}P_{(t-1)}F_{(t-1)}L_{(t-1)}\Delta y_{ss}y_{ds(t)} \\ & + p_{d(t-1)}P_{(t-1)}F_{(t-1)}L_{(t-1)}y_{ss(t-1)}\Delta y_{ds}\end{aligned} \tag{5}$$

Each of the six terms in Eq. (2) represents its contribution to the change in environmental impacts that is triggered by one driving force while keeping the rest of variables constant. For example, the first term, $\Delta p_d P_{(t)}F_{(t)}L_{(t)}y_{ss(t)}y_{ds(t)}$, represents the changes in environmental impacts that are due to changes in per capita final demand, with all other variables (P, F, L, y_{ss}, and y_{ds}) remaining constant. While many equivalent decomposition forms exist, we use the average of all possible first-order decompositions in this research [29]. The equation (Eq. (A.1)) of the average of all possible first-order decomposition for the first term as an example is shown in Appendix A.

To further analyze the effects of various drivers of energy consumption and air pollutants emissions in Beijing, we divided the period of 1997–2010 into three stages according to China's Five-Year Plans: 1997–2000 (9th Five-Year Plan), 2000–2005 (10th Five-Year Plan), and 2005–2010 (11th Five-Year Plan).

2.2. Data sources

This study mainly requires two types of data. One is time-series IOTs, and the other is the corresponding environmental satellite accounts at the sectoral level, including energy consumption (coal,