연구논문 「환경정책」 제30권 제1호 2022. 3: 1-30

DOI http://dx.doi.org/10.15301/jepa.2022.30.1.1
pISSN 1598-835X eISSN 2714-0601

A Regional Comparison of Production-Based and Consumption-Based PM2.5 Emissions between China and Korea*

한국 및 중국의 지역별 생산기반과 소비기반 미세먼지 배출량에 대한 비교 분석

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Abstract: There has been an increasing focus on the high levels of PM2.5 emissions and the worsening air quality in Korea and China. Recently, the debate over air pollution mitigation strategies has shifted from implementing conventional "end-of-pipe" solutions focusing instead on the direct role played by consumers. Central governments should distinguish different regions' respective pollution burdens to meet national emission reduction targets by considering their economic differences and industry structures. With the use of a multiregional input-output analysis approach, this paper breaks down the PM2.5 emission patterns of 19 different industries in 9 Chinese regions and 16 Korean regions through a comparison of a production-based accounting (PBA) approach and a consumption-based emission accounting (CBA) approach. By constructing an inter-regional PM2.5 emission transfer matrix, this paper offers a more accurate analysis of the allocation of emission reduction responsibility amongst the various regions. The main finding was that there were significant differences in PM2.5 emissions between the regions and industries in China and Korea; and when calculating the regional responsibility for PM2.5 emissions, CBA was the more appropriate method for Korea; while for China, the choice of using either the PBA or CBA approach depended on the specific region.

Key Words: PM2.5 Emissions, Production-Based Accounting Approach, Consumption-Based Accounting Approach, Multiregional Input-Output Analysis, China, Korea

요약: 한국과 중국에서 높은 수준의 PM2.5 배출과 악화되는 대기 질에 대한 관심이 높아지고 있다. 최근 대기 오염 완화 전략에 대한 논의는 기존의 "최종 처리" 솔루션 구현에서 소비자가 수행하는 직접적인 역할에 초점을 맞추는 방향으로 바뀌었다. 중앙 정부는 경제적 차이와 산업 구조를 고려하여 국가 배출량 감축 목표를 달성하기 위해 지역별 오염 부담을 구별해야 한다. 본 논문은 다지역 투입-산출 분석 접근 방식을 사용하여 생산 기반 회계(PBA) 접근법과 소비 기반 회계(CBA) 접근법을 통해 중국 9개 지역과 한국 16개 지역의 19개 산업의 PM2.5 배출 패턴을 분석한다. 주요 결론은 중국과 한국의 지역 및 산업 간에 PM2.5 배출량에 상당한 차이가 있다. 그리고 PM2.5 배출에 대한 지역적 책임을 계산할 때 CBA가 한국에 더 적합한 방법이고, 반면 중국의 경우 특정 지역에 따라 PBA 또는 CBA 접근법을 사용하는 방법은 다르다.

핵심주제어: 미세먼지, 생산기반 배출량, 소비기반 배출량, 다지역 투입산출분석, 중국, 한국

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* This research was funded by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea, Grant Number NRF-2021S1A5A2A03063693.

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I. Introduction

Particulate matter is the primary pollutant of air pollution and made up of heavy metal, organic carbon and aromatic hydrocarbon and complicated chemicals. Fine particulate matter is defined as particles that are 2.5 ㎛ or less in diameter ($PM_{2.5}$), which can be inhalable into the lungs and induce adverse health effects on the lungs, cardiovascular and immune systems; at the same time, it will cause a variety of adverse environmental impacts such as air quality degradation and climate change (Pope et al., 2009). As a result of rapid economic growth, China has in recent years become one of the world's largest emitters of man-made $PM_{2.5}$ emission (Huang et al., 2014). These high levels of $PM_{2.5}$ emissions have not only affected the residents of China, but also those of neighboring countries, due to the high levels of cross-border air pollution (Zhang et al., 2017). In response to the severe air pollution crisis, the Chinese government launched the, "Action Plan for the Prevention and Control of Air Pollution (2013-2017)," and declared the goal of reducing the inhalable particulate matter of the nation's cities by 10%, in comparison with 2012 levels. In 2018, the average annual concentration of $PM_{2.5}$ in China was significantly lower when compared with that of 2013, but there were still 17 provinces that did not meet their $PM_{2.5}$ reduction goals (Zheng and Xu, 2020). Korea has faced similar issues with air pollution due to high levels of $PM_{2.5}$ emissions, and "clean air" has emerged as one of the nation's top priorities in recent years (Kumar et al., 2021). As a result, the Korean government established the, "Comprehensive Plan on Fine Dust Management," which is perceived as one of the most ambitious package of air pollution mitigation measures to be passed by a national government. The plan aims to reduce PM2.5 emissions by 35.8 % by 2022, when compared to the 2014 levels (Ministry of Environment, 2021).

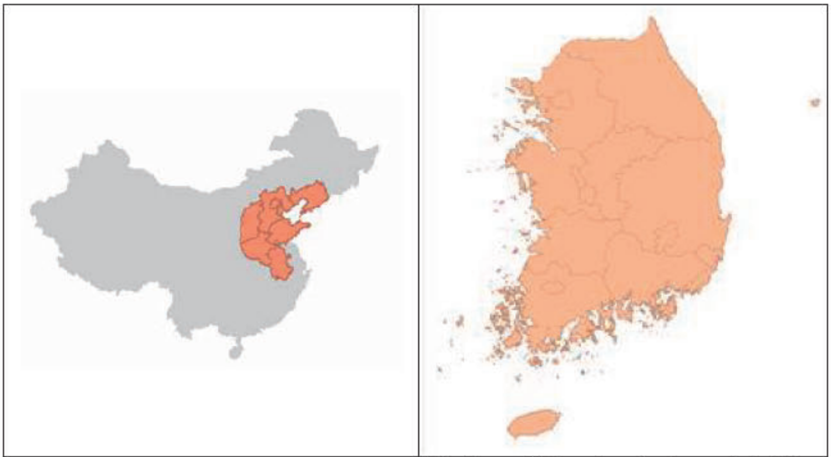
To meet national emission reduction targets, the central government need to pay attention to distinguish the pollution responsibilities of each province under the principle of fairness and impartiality. There are significant differences in the economic development, industrial structure, and resource endowments of the regions in China and Korea, making uniform pollution emissions reduction targets within each country unfeasible. Generally, there are two widely-used approaches to measuring emissions: production-based accounting (PBA) and consumption-based accounting (CBA) (Munksgaard and Pedersen, 2001). PBA is used to measure emissions caused by local production, without taking into consideration where the goods are used or who ultimately uses them. In contrast, CBA attributes all of the emissions occurring along the production chain to the final consumers of the products. The CBA approach thereby gives policymakers the quantitative tools to create policies which focus on altering consumption practices and industrial structure directly (Huo et al., 2014). Overall, these two approaches' differing strengths and weaknesses show that it is necessary to consider both the pollution-producing patterns of the production region and the pollution-producing patterns of the consumption region.

This study aims to identify the responsibility of PM2.5 generation within China and Korea by conducting a comparison of PBA and CBA results at the regional level. While existing studies have focused merely on allocating PM2.5 emission responsibility to either the producer, the country, or nation, this paper focuses on finding which regions and industries within a country produce the greatest PM2.5

emissions. By analyzing emission production structure from the region, industry, producer, and consumer perspective, policymakers could implement more efficient environmental policies.

The environmentally extended input-output model used for this paper was based on China and Korea's 2012 and 2013 input-output datasets. With these datasets, we used the CBA and PBA approach to analyze the PM2.5 emission patterns of 19 different industrial sectors in 9 Chinese regions and 16 Korean regions (See Figure 1). The rest of this paper is structured as follows: in Section 2, previous studies on production-based and consumption-based accounting emission calculation are reviewed, in Section 3, the data and methods are presented, and Section 4 and 5 presents the main results, and in Section 6, future policy suggestions and concluding remarks are given.

⟨Figure 1⟩ Regional division of two counties



(a) China (9 regions): Beijing, Tianjin, Hebei, Shanxi, Liaoning, Shandong, Henan, Anhui, and the rest 23 provinces and municipalities

(b) Korea (16 regions): 6 municipalities, North Chungcheong, South Chungcheong, Gangwon, Gyeonggi, North Gyeongsang, South Gyeongsang, North Jeolla, South Jeolla, and Jeju

II. Production-Based and Consumption-Based Accounting

The In the 1960s, traditional input-output analysis was further developed to allow for the quantitative analysis of environmental choices, and to more deeply study the flow of resources, emissions, and energy usage (Isard et al., 1968; Leontief, 1970). When calculating emission production patterns, the PBA and CBA methods are the most commonly used, with PBA assigning emission responsibility at the point of production, and CBA allocating emission responsibility at the end of the supply chain. The PBA method in particular aims to directly restrain the emission behavior of producers and incentivize more energy-efficient production. Currently, PBA is used widely in global climate change related agreements, with many cities compiling urban greenhouse gas emission inventories by calculating production-based carbon emissions, making it possible to more directly compare a country's cities (Mi et al., 2019). However, PBA ignores the indirect emissions incurred during interregional trade, leading to the inaccurate distribution of emission reduction burden, as well as the issue of inter-provincial pollution leakage. With the expansion of regional trade, a geographical separation has been created between consumers and the pollution emitted by goods production, revealing the large divide between production and consumption-based emissions (Serrano and Dietzenbacher, 2010). In comparison, the CBA method can better reveal the different driving forces of pollution emissions, and provide a more grounded framework for the distribution of emission reduction. When compared with PBA, the CBA method's advantage is that by addressing emissions at the stage of consumption, it is possible to take into consideration the emission sources of all goods and services, regardless of the place where they were produced (Afionis et al., 2017, Sudmant et al., 2018). Additionally, CBA methods can better facilitate international climate negotiations by connecting emission responsibility with the volume of consumption, thereby preserving the principle of common but differentiated responsibilities (Gupta, 2010). Steinberger et al. (2012) also argued that consumption-based emissions are more closely related to welfare measures, and therefore may be more suitable for decision-making.

Extensive studies have estimated different environmental indicators, such as carbon emissions (Sudmant et al., 2018; Franzen and Mader, 2018; Wen and Wang, 2020; Wang et al., 2019; Meng et al., 2017), greenhouse gases (Liu et al., 2018), air pollution emissions stemming from domestic and international trade at both national and local levels (See Table 1). Sudmant et al. (2018) aimed to compare production-based and consumption-based carbon emissions across a range of urban regions in China, the US, and the UK. They found that consumption-based emissions in urban areas in the UK and US were generally higher than production-based emissions, while the reverse was true for urban areas in China, with Beijing and Shanghai being the exceptions and having levels comparable to or higher than those of UK urban areas. Franzen and Mader (2018) explored the characteristics of production-based and consumption-based carbon emissions across 110 countries, with the results showing no evidence that carbon leaks from from developed to developing countries. On average, countries increase imports of carbon if they become more energy efficient. Because the only small differences between PBA and CBA, they suggest keeping the

PBA of carbon emissions. Wang et al. (2019) constructed production-based carbon emission inventories for 43 energy products and 30 sectors for Kazakhstan from 2012 to 2016, and then used environmentally extended input-output analysis to further analyze demand-driven emissions within the domestic market and international trade. The results suggested that Russia and China were the main consumers of Kazakhstan's energy and associated resources, with the construction sector being the most significant. Meng et al. (2017) calculated the production-based and consumption-based carbon emissions in 2012 for four Chinese megacities: Beijing, Shanghai, Tianjin and Chongqing. The results showed that capital formation was the largest contributor, accounting for 37% to 69% of consumption-based emissions, and that 44% of Chongqing's BC consumption emissions and more than 60% of Beijing, Shanghai and Tianjin's consumption emissions all occurred outside of the cities' boundaries. Liu et al. (2018) analyzed the production and consumption-based industrial greenhouse gas (GHG) mitigation policies in Saskatchewan, Canada using an environmentally extended input-output simulation model. The findings showed that production-based GHG reduction policies were suitable for the primary industry, while consumption-based policies should be applied to industries at the end of the industrial chain.

Many studies have attempted to divide the responsibility for air pollution emission reduction based on PBA and CBA calculations. Lin et al. (2014) used an economic input output model to quantify air pollutant emissions stemming from China's bilateral trade with the United States, and highlighted that around 21% of export-related Chinese emissions could be attributed to China-to-US exports. Zhao et al. (2015) compiled a consumption-based air pollutant emission inventory to quantify the embodied emission flows of China's four key air pollutants (SO_2, NOx, PM2.5 and VOC) within interprovincial trade conducted in 2007, and demonstrated that the emissions were significantly redistributed amongst provinces due to interprovincial trade. The results indicated that large levels of emissions from the northern and central regions were embodied in the imports of eastern regions due to differences in regional economic status and environmental policy. Meanwhile, Meng et al. (2015) focused on comparing energy-related PM emissions from foreign and domestic trade in Beijing and showed that domestic trade was more dominant in transferring consumption-based PM emissions to Beijing. Huo et al. (2014) examined SO_2, NOx, PM2.5, and VOC emissions in China in 2010 from the perspective of both production and consumption by simulating and analyzing the emissions and GDP performance of 7 sectors. The results showed that the equipment, machinery, device manufacturing, and construction sectors contributed more than 50% of all air pollutant emissions, and that the majority of the products were used for capital formation and export.

〈Table 1〉 Previous studies on PBA versus CBA method

Author	Environmental indicators	Analysis unit	Country
Sudmant et al. (2018)	Carbon dioxide	Mulit-country	China, UK, US
Franzen and Mader (2018)	Carbon dioxide	Mulit-country	110 counties
Wang et al. (2019)	Carbon dioxide	National level	Kazakhstan
Wen and Wang (2020)	Carbon dioxide	Provincial level	China
Meng et al. (2017)	Carbon dioxide	Municipal level	China
Liu et al. (2018)	Greenhouse Gas	Provincial level	Canada
Lin et al. (2014)	SO_2, NOx, CO_2, and Black carbon	National level	China, US

Zhao et al. (2015)	SO_2, NOx, PM2.5 and VOC	Provincial level	China
Meng et al. (2015)	PM2.5	Municipal level	Beijing
Huo et al.(2014)	SO_2, NOx, PM2.5, and VOC	National level	China
Wu et al.(2017)	PM2.5	Regional level	China
Kim et al. (2019)	PM2.5	National level	China, Japan, Korea

Though many studies have focused on the regional allocation of trade-based air pollutant emissions through hierarchical analysis, there have been few attempts to further identify the key sectors and the specific emission pathways within interprovincial trade. This paper differs from previous studies in two main ways; firstly, by revealing that consumption-based and production-based emissions differ significantly by region, and second, by adopting a cross-country comparative perspective to examine PM2.5 emission characteristics and their regional concentration.

Ⅲ. Data and Method

When estimating production-based and consumption-based PM2.5 emissions, the PM2.5 emission inventory for each region and industry was first estimated by multiplying the regional energy consumption by industrial sector, and then multiplying each fuel type's emission factors by industrial sector. Thereafter, with the use of a multiregional input-output model, this study estimated the share of emissions resulting from consumption and production, respectively. The energy consumption data for this study were collected from the 2013 China Energy Statistical Yearbook, and the various fuel types' emission factors were taken from the Chinese Ministry of Environment's datasets. For data on Korean emissions by region, the Korean Ministry of Environment's "National Air Pollutant Emission Service" dataset was used. The datasets included coal, coke, diesel oil, fuel oil, gasoline, kerosene, LPG, LNG, and natural gas, and broke down their usage by 19 industrial sectors. For multiregional input-output analysis, the Chinese input-output table was obtained from the National Bureau of Statistics of China, and combined 31 provinces into 9 regions, with a specific focus on the eight heavily polluted regions in eastern China. The Korean input-output table was taken from the 2013 Bank of Korea dataset, and covers 16 provinces. Table 1 summarizes the regional and sector classification data in detail.

〈Table 2〉 Research scope

Country	Regional Classification	Sector classification
China	9 regions: Beijing, Tianjin, Hebei, Shanxi, Liaoning, Shandong, Henan, Anhui, and the rest 23 provinces and municipalities	Agriculture, livestock, forestry and fishery; Mining and quarrying; Food products, beverages and tobacco products; Textiles and leather goods; Printing, wood and paper products; Coke and refined petroleum products; Chemical products; Non-metallic mineral products; Basic metals; Metal products; Machinery and equipment; Electrical equipment; Precision machines; Transportation equipment; Other manufacturing products and processing; Electricity, gas and water supply; Construction; Transportation; Other services.
Korea	16 regions: 6 municipalities (Seoul, Busan, Incheon, Gwangju, Daegu, Daejeon, Ulsan), North Chungcheong, South Chungcheong, Gangwon, Gyeonggi, North Gyeongsang, South Gyeongsang, North Jeolla, South Jeolla, and Jeju	

This paper estimates the production-based and consumption-based PM2.5 emissions in China and Korea based on a multiregional input-output analysis approach.

$$x_i^r = \sum_s \sum_j a_{ij}^{rs} + \sum_s y_i^{rs} + y_i^{re}$$

where r and s represent the origin and destination region; i and j mean the different economic sector.

x_i^r: the total output of sector i in region r,

a_{ij}^{rs}: the input-output coefficient,

y_i^{rs}: the product from sector i in region r consumed in region s, including the final consumption produced locally,

y_i^{re}: a vector indicating the final products of sector i in region r for international export.

The core of input-out analysis is a matrix of input-out coefficients. Let A denote the matrix of a_{ij}^{rs} , where A is the intermediate coefficient in which the columns reflect the required input from each sector in region r to produce for each monetary unit of the product of each sector in region s; y denotes the final demand from domestic use, I is the identity matrix, $(I-A)^{-1}$ equals to the Leontief inverse matrix L.

$$x = Ax + y$$

where,

$$A = \begin{bmatrix} A^{11} & A^{12} \cdots & A^{1n} \\ A^{21} & A^{22} \cdots & A^{2n} \\ \vdots & \vdots \ddots & \vdots \\ A^{n1} & A^{n2} \cdots & A^{nn} \end{bmatrix}$$

$$\begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix} \begin{bmatrix} \sum_r y^{1r} \\ \sum_r y^{2r} \\ \vdots \\ \sum_r y^{nr} \end{bmatrix}$$

or, x = $(I-A)^{-1}$ = Ly

The sector emission intensities of PM2.5 are then calculated as the total PM2.5 emissions of sector i in region r divided by the total output from the corresponding sectors in region r, which can be briefly written as:

$$f_i^r = \frac{e_i^r}{x_i^r}$$

f_i^r : PM2.5 emission intensity of sector i in region r,

e_i^r : total PM2.5 emissions of sector i in region r,

x_i^r : total output from the corresponding sectors in region r

$$PBA^r = \hat{f}^r (I-A)^{-1} p^r$$

$$CBA^r = \hat{f}^r (I-A)^{-1} c^r$$

$$p^r = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ y^{rr} + \sum_s y^{rs} \\ \vdots \\ 0 \end{bmatrix}, \quad c^r = \begin{bmatrix} y^{1r} \\ y^{2r} \\ \vdots \\ y^{rr} \\ \vdots \\ y^{nr} \end{bmatrix}$$

PBA^r: production-based PM2.5 emissions in province r,

CBA^r: consumption-based PM2.5 emissions in province r,

$\hat{f}$: diagonal matrix of f with each element on its main diagonal and all other cells equal to 0,

p^r: finished goods produced in province r,

c^r: finished goods produced in other regions and consumed in province r,

y^{rs}: finished goods produced in region r and consumed in province s

Ⅳ. Results

In order to understand the main sources of PM2.5 pollution in the two countries, this paper first analyzes the characteristics of the PM2.5 emissions in different regions's various industries. Through PBA and CBA analysis and the construction of an inter-regional PM2.5 emission transfer matrix, we were able to more accurately calculate a clear system for dividing pollution mitigation among the regions.

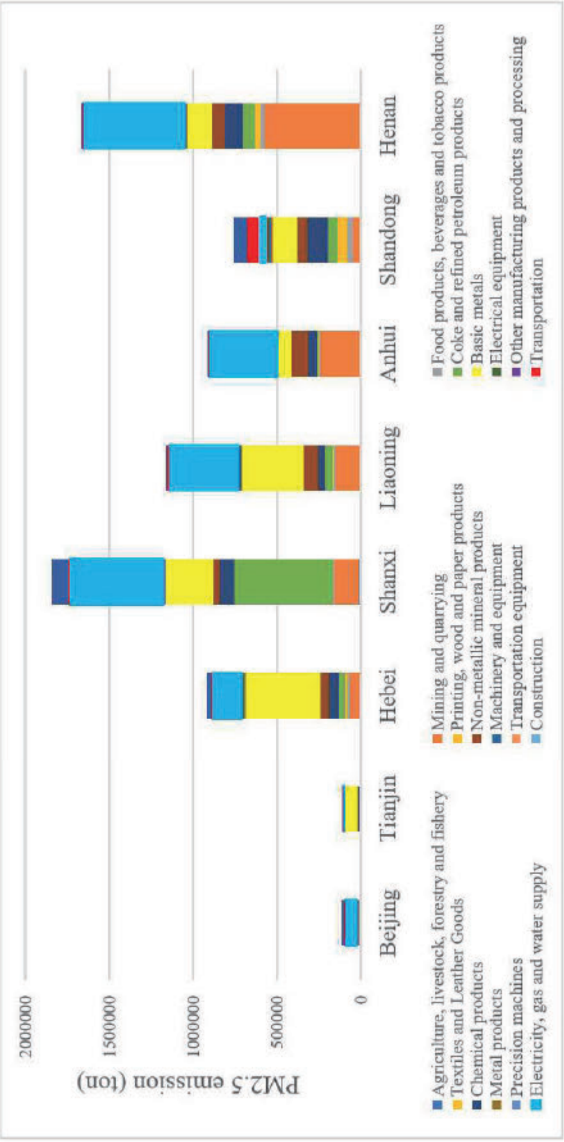
The sectoral data in each province of Korea and China were collected and then used to calculate the PM2.5 emissions embodied in interprovincial trade, and are shown in Figure 2a and 2b. Korea's PM2.5 emissions are relatively more concentrated in the manufacturing of non-metallic mineral products and basic metals (59.61%); while a considerable part of China's emissions (26.91%) comes from the mining and quarrying industry, coke and refined petroleum product manufacturing industries. Overall, around 20% of both countries' emissions stem from the manufacturing of basic metal. More specifically, the top five emission-producing industries in Korea in 2013 were: The manufacturing of non-metallic mineral products (31.19%), the manufacturing of basic metals (27.97%), transportation (20.28%), construction (7.97%), and electricity, gas and water supply (4.88%). In China, the top five emission-producing industries in 2012 were: Electricity, gas and water supply (29.96%), the manufacturing of basic metals (20.59%), mining and quarrying (16.24%), the manufacturing of coke and refined petroleum products (10.67%) and the manufacturing of chemical products (6.49%).

Additionally, in terms of regional spread, Korea's PM2.5 emissions were the most highly concentrated in North Gyeongsang (25.16%), South Chungcheong (24.18%) and South Jeolla (16.91%). For China, the regions with the highest PM2.5 emissions consisted of Shanxi Province (24.59%), Henan Province (22.23%), and Liaoning Province (15.53%). Each respective country's regions had emission characteristics that differed greatly from one other. For instance, in North Gyeongsang and South Jeolla, the manufacturing of non-metallic mineral products alone accounted for 81.40% and 54.23% of total PM2.5 emissions, while in South Chungcheon, PM2.5 emissions mainly came from the manufacturing of basic metals (81.42%). The PM2.5 emissions in Shanxi Province mainly came from the manufacturing of coke and refined petroleum products (31.87%). The main sources of PM2.5 emissions in Henan Province and Liaoning Province were mining and quarrying (34.22%) and the manufacturing of basic metals (31.59%), respectively.

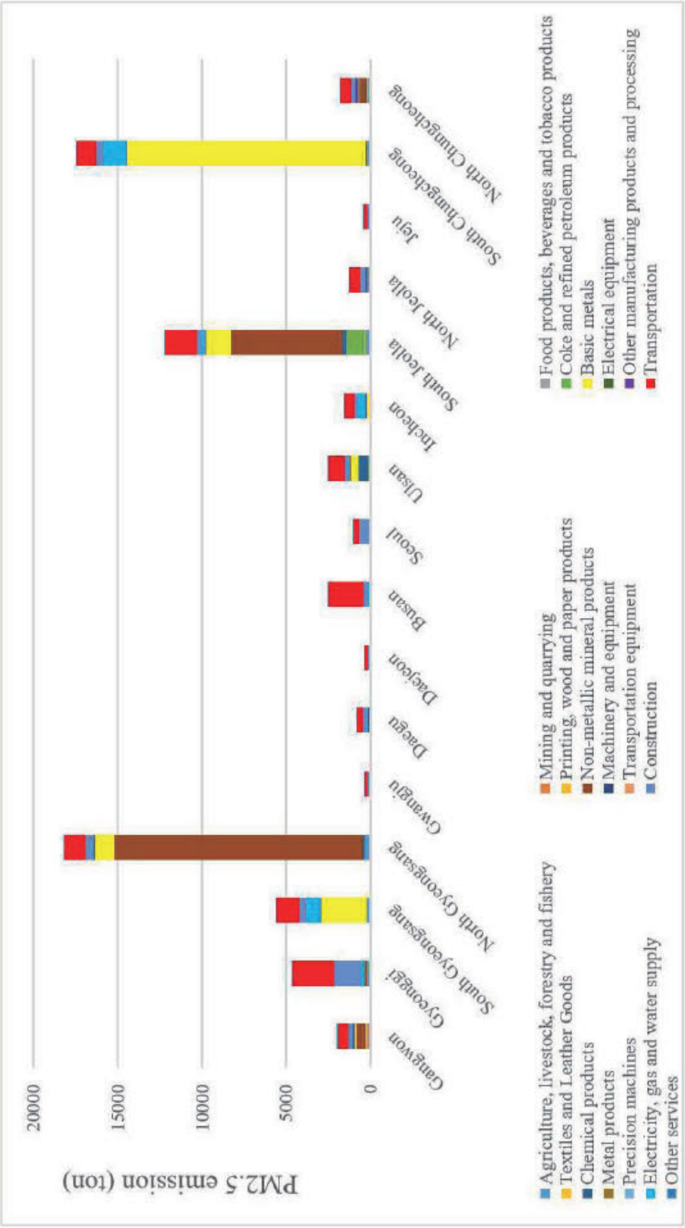
In China and Korea, there are significant differences between consumption-based and production-based emissions in different regions. Table 2 and 3 shows the results of the analysis of the production-based and consumption-based Pa M2.5 emissions. In the table, each row (r) represents production area, and each column (s) represents a consumption area. In other words, the cell where row r and column s meet represents the amount of PM2.5 generated when goods produced in region r are consumed in region s. Therefore, the horizontal sum of each component represents the production-based emissions of the given region, and the vertical sum of each component represents the consumption-based emissions of the given region.

In the term of production-based emissions, North Gyeongsang was the largest direct emitter, producing 24.28% of Korea's total emissions, followed closely by South Chungcheong (24.00%), and South Jeolla (16.42%). In terms of consumption-based emissions, the top three largest indirect emitters consisted of Gyeonggi (15.58% of Korea's total emissions), North Gyeongsang (15.18%), and South Jeolla (10.30%). The consumption-based emissions of nearly every region in Korea, excluding Incheon, were higher than their production-based emissions (See Figure 3 (b)). Specifically, the consumption-based emissions in Gwangju, Seoul, Daejeon were 627.84%, 597.40% and 264.27% higher than their respective production-based emissions. From Figure 3 (c), the results indicated that Seoul, Gyeonggi, Gwangju, Busan, and Ulsan benefited the greatest from the emissions embodied in provincial trade, as the environmental damage incurred from the PM2.5 emissions stemmed from the five most emission-intensive regions, including North Gyeongsang, South Chungcheong, South Jeolla, Gangwon, and Incheon, all of whom had suffered environmental damage due to provincial trade.

〈Figure 2(a)〉 PM2.5 emission by region and industry in Korea (2013)



〈Figure 2(b)〉 PM2.5 emission by region and industry in China (2012)



〈Table 3〉 Production-based pm2.5 emissions and consumption-based PM2.5 emissions by 16 region in Korea (In tons)

	Seoul	Incheon	Gyeonggi	Daejeon	North Chung cheong	South Chung cheong	Gwangju	North Jeolla	South Jeolla
Seoul	794	13	67	6	7	14	6	7	11
Incheon	1009	759	810	55	98	176	54	57	91
Gyeonggi	476	125	3049	48	70	146	63	59	86
Daejeon	29	4	22	174	6	15	3	3	5
North Chung cheong	191	63	249	48	701	129	23	28	29
South Chung cheong	1460	1143	3030	308	671	4225	493	444	939
Gwangju	15	4	20	2	3	5	200	4	15
North Jeolla	131	29	125	20	18	46	24	641	40
South Jeolla	769	278	1065	117	164	511	878	289	5760
Daegu	48	11	52	7	7	13	7	7	8
North Gyeong sang	959	639	1979	133	573	1544	205	172	584
Busan	173	44	198	22	26	66	23	23	49
Ulsan	122	47	203	17	29	65	19	26	36
South Gyeong sang	483	182	741	75	112	225	92	99	169
Gangwon	201	57	266	31	44	73	22	34	45
Jeju	33	8	39	5	5	9	7	8	8
CBA PM2.5	6894	3408	11917	1069	2533	7263	2118	1900	7875
Ratio	9.01%	4.46%	15.58%	1.40%	3.31%	9.50%	2.77%	2.48%	10.30%

〈Table 3〉 Continued

	Daegu	North Gyeong sang	Busan	Ulsan	South Gyeong sang	Gangwon	Jeju	PBA PM2.5	Ratio
Seoul	7	15	9	11	15	5	2	989	1.29%
Incheon	64	118	86	93	144	67	19	3702	4.84%
Gyeonggi	59	119	90	106	124	47	15	4684	6.12%
Daejeon	4	8	5	6	7	2	1	293	0.38%
North Chung cheong	37	84	49	48	63	28	7	1777	2.32%
South Chung cheong	416	1390	653	960	1827	296	99	18354	24.00%
Gwangju	3	5	4	4	6	2	1	291	0.38%
North Jeolla	21	32	29	26	32	13	5	1231	1.61%
South Jeolla	190	710	478	457	701	109	82	12558	16.42%
Daegu	490	63	14	25	25	5	2	785	1.03%
North Gyeong sang	893	8473	453	787	922	215	42	18573	24.28%
Busan	33	66	1370	221	171	17	8	2510	3.28%
Ulsan	30	95	51	1691	89	18	6	2544	3.33%
South Gyeong sang	172	345	352	429	2285	57	21	5842	7.64%
Gangwon	34	80	64	51	78	869	18	1966	2.57%
Jeju	6	11	9	10	8	6	210	384	0.50%
CBA PM2.5	2458	11614	3716	4926	6499	1756	537	76481	100%
Ratio	3.21%	15.18%	4.86%	6.44%	8.50%	2.30%	0.70%		

〈Table 4〉 Production-based PM2.5 emissions and consumption-based PM2.5 emissions by 9 regions in China (In Tons)

	Beijing	Tianjin	Hebei	Shanxi	Liaoning	Anhui	Shandong	Henan	PBA PM2.5	Ratio
Beijing	136434	26041	21256	4485	13587	2355	7621	12724	224502	3.00%
Tianjin	25447	87394	6081	2190	5612	983	3512	4891	136111	1.82%
Hebei	40508	17866	514739	15932	18750	4483	18800	23423	654501	8.76%
Shanxi	129752	45336	218668	1555899	67100	9267	50043	62622	2138687	28.62%
Liaoning	76292	56368	52158	16089	1879404	30817	61892	61259	2234281	29.90%
Anhui	30191	16536	33316	8872	22061	58022	968513	437102	1574613	21.07%
Shandong	5753	4212	9390	2132	5476	2739	117888	196804	344393	4.61%
Henan	6795	2692	9159	2375	6495	1438	8384	128878	166216	2.22%
CBA PM2.5	451173	256445	864767	1607974	2018484	110104	1236653	927704	7473303	
Ratio	6.04%	3.43%	11.57%	21.52%	27.01%	1.47%	16.55%	12.41%		

Next, in order to more accurately allocate the PM2.5 emission responsibilities of the most emission-intensive regions, we constructed an inter-regional PM2.5 emission transfer matrix by mapping each consumption region's pollution responsibility (〈Figure 4(a)〉), making it easier to discern which regions should take on the responsibility for PM2.5 emissions generated by the production activities in emission-intensive regions. More than half of North Gyeongsang's PM2.5 emissions was related to other regions' consumption, with the largest two contributors being Gyeonggi (accounting for 10.66%) and South Chungcheon (accounting for 8.31%). According to Figure 2a, the PM2.5 emissions of North Gyeongsang and South Jeolla were mainly sourced from the production of non-metallic mineral products, implying that there is a high likelihood that Gyeonggi and South Chungcheon are partially responsible for North Gyeongsang's high emission levels, mainly due to those two region's high consumption of non-metallic mineral products. Similarly, the responsibility for South Chungcheong's PM2.5 emissions can be traced back to the consumption in Gyeonggi (16.51%), South Gyeongsang (9.95%), North Gyeongsang (7.57%) and Seoul (7.69%). In terms of Incheon, the province's PM2.5 emissions mainly came from consumption activities occurring in Seoul (27.26%), and Gyeonggi (21.87%). These results reveal the weakness in allocating pollution responsibility by production, and how calculating based on trade-embodied emissions is a more equitable approach. Therefore, in order to address such inequities, it would be best for provincial-level governments to establish an emission reduction policy where a province is compensated for emissions incurred by another province's consumption.

〈Figure 3〉 Production and consumption based PM2.5 emissions by province

Figure (3a)

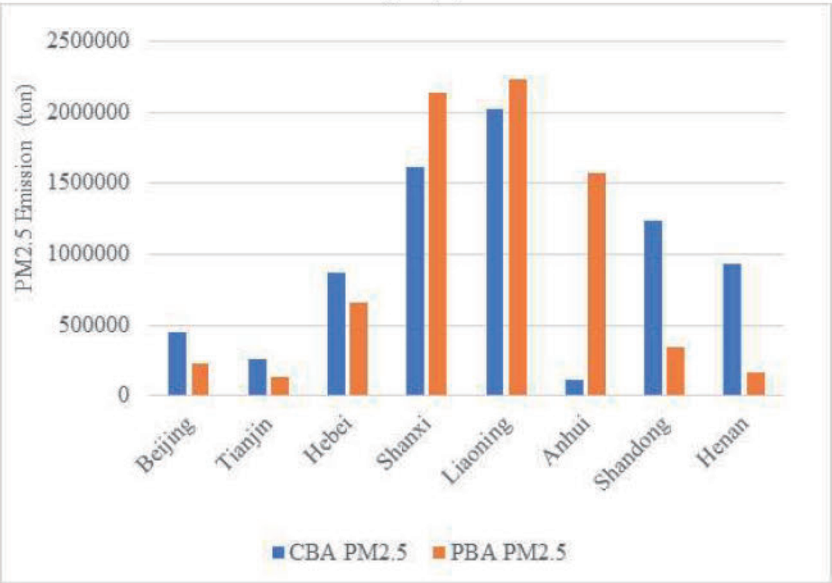


Figure (3b)

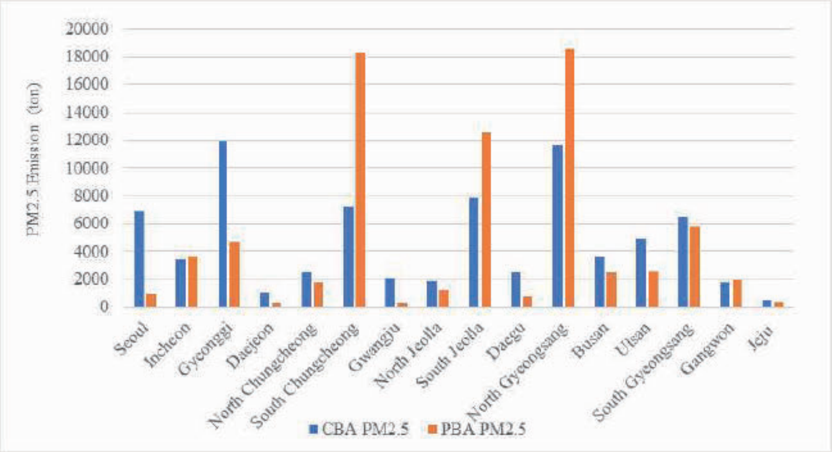
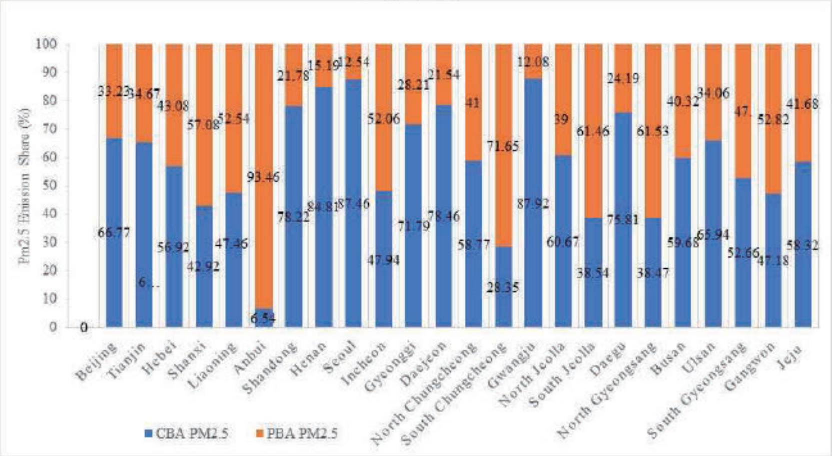


Figure (3c)

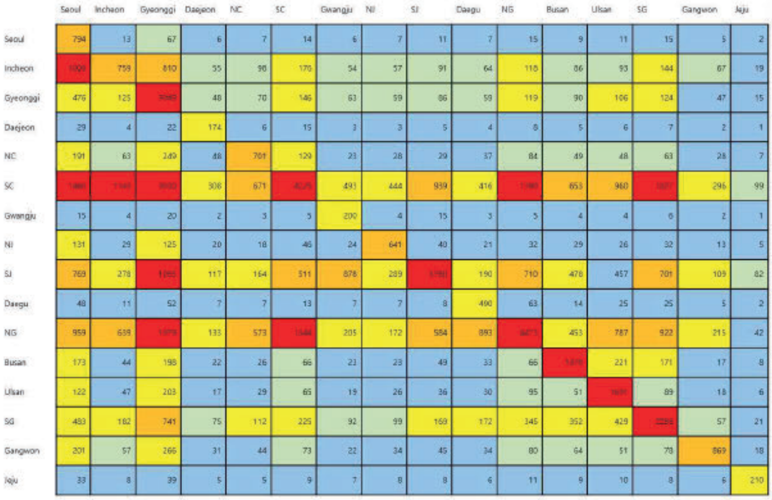


In China, Liaoning and Shanxi are not only the largest direct emitters of PM2.5, but are also the largest indirect emitters. The consumption-based emissions in Beijing, Tianjin, Hebei, Shandong and Henan were 100.97%, 88.41%, 32.13%, 259.09% and 458.13% higher than their respective production-based emissions. The majority of these provinces consist of highly economically-active coastal regions in Eastern China, who in turn generate PM2.5 emissions in lower-income, resource-oriented provinces such as Anhui, Shanxi, and Liaoning.

Figure 3 (a) shows that only three inland provinces, Anhui, Shanxi, and Liaoning, have production-based PM2.5 emissions that are higher than their respective consumption-based emissions. The share of production-based emissions for Anhui, Shanxi, and Liaoning were 93.46%, 57.08% and 52.54%, respectively (See Figure 3 (c)). All three of these emission-intensive provinces are rich in mineral resources and dominated by heavy industry, with their PM2.5 emissions mainly stemming from mining and quarrying activities. More specifically, Anhui's production-based emissions were 1330.11% greater than their respective consumption-based emissions. As shown in Figure 4a, Anhui's PM2.5 emissions mainly stemmed from consumption activities occurring in Shandong (60.51%), and Henan (27.76%).

Differing somewhat from Anhui, the results showed that more than 70 percent of Liaoning and Shanxi's emissions can be attributable to local production and consumption activities. Due to these provinces' more traditional industrial structures, both the production and reprocessing activities related to manufacturing are concentrated in the same region. As a result, these two provinces provide an example where production-based accounting is more suitable than consumption-based accounting, and that the most effective pollution mitigation strategy would focus on end-of-pipe abatement technology.

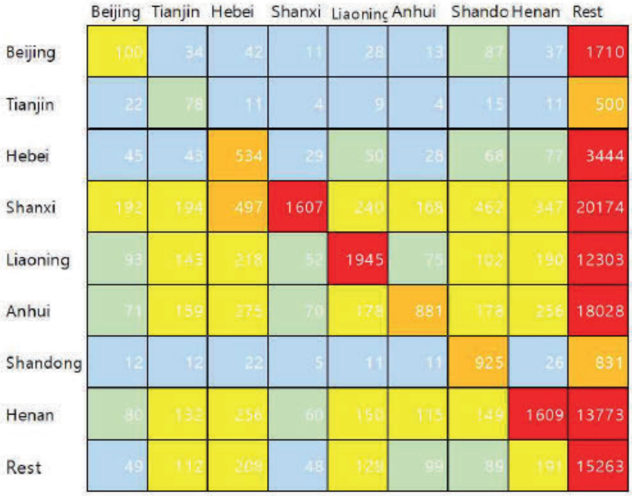
〈Figure 4(a)〉 An interactive PM2.5 emission map of Korea’s interprovincial trade



	Seoul	Incheon	Gyeonggi	Daejeon	NC	SC	Gwangju	NI	SJ	Daegu	NG	Busan	Ulsan	SG	Gangwon	Jeju
Seoul	794	13	67	6	7	14	6	7	11	7	15	9	11	15	5	2
Incheon	[illegible]	759	810	55	90	170	54	57	91	64	118	86	93	144	67	19
Gyeonggi	476	125	[illegible]	48	70	146	63	59	86	59	119	90	106	124	47	15
Daejeon	29	4	22	174	6	15	3	3	5	4	8	5	6	7	2	1
NC	101	63	249	48	701	129	23	28	29	37	84	49	48	63	28	7
SC	[illegible]	[illegible]	[illegible]	308	671	[illegible]	493	444	939	416	[illegible]	653	960	[illegible]	296	99
Gwangju	15	4	20	2	3	5	200	4	15	3	5	4	4	6	2	1
NI	131	29	125	20	18	46	24	641	40	21	32	29	26	32	13	5
SJ	769	278	[illegible]	117	164	511	878	289	[illegible]	190	710	478	457	701	109	82
Daegu	48	11	52	7	7	13	7	7	8	490	63	14	25	25	5	2
NG	959	639	[illegible]	133	573	[illegible]	205	172	584	893	[illegible]	453	787	922	215	42
Busan	173	44	198	22	26	66	23	23	49	33	66	[illegible]	221	171	17	8
Ulsan	122	47	203	17	29	65	19	26	36	30	95	51	[illegible]	89	18	6
SG	483	182	741	75	112	225	92	99	169	172	345	352	429	[illegible]	57	21
Gangwon	201	57	266	31	44	73	22	34	45	34	80	64	51	78	869	18
Jeju	33	8	39	5	5	9	7	8	8	6	11	9	10	8	6	210

(Note: NC=North Chungcheong; SC=South Chungcheong; NJ=North Jeolla; SJ=South Jeolla; NG=North Gyeongsang; SG=South Gyeongsang.)

〈Figure 4b〉 An interactive PM2.5 emission map of China’s interprovincial trade



	Beijing	Tianjin	Hebei	Shanxi	Liaoning	Anhui	Shando	Henan	Rest
Beijing	100	34	42	11	28	13	87	37	1710
Tianjin	22	78	11	4	9	4	15	11	500
Hebei	45	43	534	29	50	28	68	77	3444
Shanxi	192	194	497	1607	240	168	462	347	20174
Liaoning	93	143	218	52	1945	75	102	190	12303
Anhui	71	159	275	70	178	881	178	256	18028
Shandong	12	12	22	5	11	11	925	26	831
Henan	80	132	256	60	150	115	149	1609	13773
Rest	49	112	209	48	128	99	89	191	15263

Ⅴ. Conclusion

Using multiregional input-output analysis, this paper aims to identify the PM2.5 emission responsibilities of different regions through the PBA and CBA methods, with results showing that the PM2.5 emissions in each region and sector differ greatly. In Korea, the manufacturing of non-metallic mineral products and basic metals were a major contributor to PM2.5 emissions, while in China, the main sources of PM2.5 emissions came from the mining and quarrying industry and the manufacturing of coke and refined petroleum products. When calculating the production-based and consumption-based PM2.5 emissions of Korea and China's provinces, the CBA method was more appropriate than the PBA method in Korea; while in China, the choice between PBA or CBA depended on the specific region in question.

When tracing the damage incurred by PM2.5 pollution through consumption and production, the emissions embodied in provincial trade have exacerbated high-emission regions' economic losses, as these regions not only often engage in more emission-intensive, resource-oriented industries, but they also incur additional costs stemming from pollution mitigation. Due to the diversity in regions' resource endowments and industrial structures, pollutant reduction targets at the national scale should be implemented at the provincial scale. Additionally, it is necessary to make cities and regions more accountable for indirect emissions and establish matching interregional cooperation in emission reduction schemes and mechanisms to coordinate emissions.

To realize the goal of abating PM2.5, the results of this paper proposes that the local governments of the two countries undertake emission reduction policies and provide corresponding technical and financial support for emission-intensive sectors, with a full consideration of regional actual situation. In the case of Korea, the improvement of energy use efficiency is necessary considering the situation of poor energy resources in Korea. The key policy for the Korean local government is to extend financial supports for the development of energy conservation technology, clean energy technology, and resource technology, especially for North Gyeongsang, South Chungcheong and South Jeolla. The main sources of PM2.5 emissions in China are mining and quarrying industry, manufacture of coke and refined petroleum products. Therefore, more attention needs to be given to areas of cleaning technology investment and innovative activities in mineral exploration, mine development, mineral processing, product design and manufacturing, and recycling. In terms of consumption-based policy, policy instruments that aiming to reduce the consumption of emission-intensive commodities and change consumer behavior could be taken into consideration, including taxes on emissions, cap-and-trade, subsidy programs, environmental labeling, and green marketing.

This paper contributes to the literature in three respects. First, this study highlights the importance of conducting analysis at the regional level, as it allows policymakers to take into account how regions' economies vary on a wide variety of factors, allowing for more nuanced policymaking. Secondly, this paper highlights how consumption-based and production-based emissions can differ greatly depending on the specific region. Third, this paper focuses on a case study of two major East Asian countries, China and Korea, whose regional economies differ greatly in different characteristics, therefore making our analysis more relevant to wider variety of countries. One of the limitations of this paper is that it only focuses on PM2.5, leaving room for further study of other pollutants in the future. This paper mainly analyzes the division of regional responsibility for domestic PM2.5 emission in Korea and China since it is difficult to quantify the trans-boundary PM2.5 emissionamong countries. In future research focused on PM2.5 embodied emissions, other methods, such as structure path analysis, could be used to quantify trans-boundary PM2.5 at the sectoral level, tracking its transaction paths and mapping the linkages between the consumption and production responsibilities of China and Korea. This would thereby provide better policy guidance for eliminating PM2.5 emissions in Northeast Asia, and establishing a more cohesive framework for international cooperation.

▌Referemce ▌

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투 고 일: 2021년 09월 10일
심 사 일: 2021년 09월 16일
게재확정일: 2021년 09월 28일