

Structural Analysis of Air Pollutant Emissions and Its Attributed Mortality in Asia

永島, 史弥

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Structural Analysis of Air Pollutant Emissions and Its Attributed Mortality in Asia

A Dissertation Submitted in Partial Fulfillment of the Requirement for the Degree of
Ph.D. in Economics

Department of Economic Systems
Graduate School of Economics
Kyushu University

by

Fumiya NAGASHIMA

Contents

Chapter 1: Introduction	7
1.1 Air Pollution and Fine Particulate Matter.....	7
1.2 Two perspectives of emissions; production vs consumption.....	12
1.3 Structure of This Dissertation.....	15
Chapter 2: Literature Review and Research Objective	18
2.1. Studies on air pollutant emission inventories	18
2.2. Studies on environmentally-extended input-output analysis.....	20
2.3. Studies on structural supply chain analysis	25
2.3.1. <i>Linkages and key sectors</i>	25
2.3.2. <i>Structural path analysis</i>	27
2.4. Studies on augmented input-output analysis	29
2.5. Contribution of This Thesis	31
Chapter 3: Identifying Critical Supply Chain Paths and Key Sectors for Mitigating Primary Carbonaceous PM_{2.5} Mortality in Asia.....	33
3.1. Introduction	33
3.2. Method.....	36
3.2.1. <i>Consumption-based PM_{2.5} emissions</i>	36
3.2.2. <i>Consumption-based health impacts</i>	38
3.2.3. <i>Identifying key sectors</i>	40
3.2.4. <i>Identifying critical supply chain paths</i>	43
3.3. Data and computation.....	46
3.4. Result.....	48
3.4.1. <i>Consumption-based analysis</i>	48
3.4.2. <i>Key sectors</i>	54
3.4.3. <i>Critical supply chain paths</i>	58
3.4.4. <i>Direct PM_{2.5} emissions from the household sector of countries</i>	63
3.4.5. <i>Comparison between this study and Anenberg et al. (2011)</i>	64
3.5. Discussion and Conclusion.....	66
Chapter 4: Critical Structural Paths of Residential PM_{2.5} Emissions within the Chinese Provinces	68

4.1. Introduction	68
4.2. Methodology.....	72
4.2.1 Consumption-based residential PM _{2.5} emissions.....	72
4.2.2. Identifying structural paths with higher residential PM _{2.5} emissions	76
4.3. Data.....	78
4.4. Results and discussion.....	80
4.4.1. Direct residential PM _{2.5} emissions of the Chinese 30 provinces	80
4.4.2 Embodied residential PM _{2.5} emissions in the Chinese 30 provinces	84
4.4.3 Structural path analysis of embodied residential PM _{2.5} emissions in China.	87
4.5. Discussion and conclusion	91
Chapter 5: Conclusions	92
Acknowledgement.....	95
Appendix	98
References.....	114

List of Figures

Figure 1-1 Access to clean cooking fuels and technologies in Asia from 2000 to 2014 (unit: percent of population)	9
Figure 1-2 Global premature deaths of children from selected environmental risks: 2010 to 2050	10
Figure 1-3 Structure of this Thesis	16
Figure 3-1 PM _{2.5} emissions (horizontal axis) from source countries driven by final demand in driver countries (vertical axis)	49
Figure 3-2 PM _{2.5} emissions (tonnes) of each country triggered by final demand of the Asian nine countries and the U.S. and net emission transfers (tonnes) arising from the consumption-based emissions.....	50
Figure 3-3 Premature deaths due to PM _{2.5} emissions attributable to final demand in driver countries (vertical axis).....	52
Figure 3-4 PM _{2.5} emissions of each country triggered by final demand of the Asian nine countries and the U.S. and net health impact transfers (i.e., premature mortality in persons) arising from the consumption-based emissions	53
Figure 3-5 Relationship between power of dispersion and sensitivity of dispersion in health impacts arising from PM _{2.5} emissions	56
Figure 4-1 Direct and consumption-based residential PM _{2.5} emissions in tonnes. 82	
Figure 4-2 Direct PM _{2.5} emission intensity in kg per thousand yuan (left axis) and residential PM _{2.5} emissions per capita in kg per person (right axis) in Chinese provinces.....	83
Figure 4-3 Residential PM _{2.5} emissions per province (row) triggered by the final demand per province (column).....	86
Figure S3-1 Consumption-based emissions of countries (unit: thousand tonnes-C)	98
Figure S3-2 Consumption-based BC emissions of countries including residential emissions (unit: thousand tonnes-C).....	99

List of Tables

Table 3-1 Top 10 sectors ranked in terms of power of dispersion (backward linkages effect) in consumption-based health impacts in 2005	57
Table 3-2 Top 10 sectors ranked in terms of sensitivity of dispersion (forward linkages effect) in consumption-based health impacts in 2005	57
Table 3-3 Top 30 supply chain paths ranked in terms of health impacts in Asia...	61
Table 3-4 Top 30 supply chain paths ranked in terms of health impacts in other countries due to emissions attributable to final demand of a specific driver country	62
Table 4-1 Top 30 structural paths in terms of residential emissions	88
Table 4-2 Top 30 structural paths in terms of residential emissions in other provinces due to final demand of a specific country.....	90
Table S3-1 Industrial sector classification of the Asian International Input–Output Table of 2005	100
Table S3-2 PM _{2.5} emission data by industry of Indonesia in 2005	101
Table S3-3 PM _{2.5} emission data by industry of Malaysia in 2005	102
Table S3-4 PM _{2.5} emission data by industry of Philippines in 2005.....	103
Table S3-5 PM _{2.5} emission data by industry of Singapore in in 2005	104
Table S3-6 PM _{2.5} emission data by industry of Thailand in in 2005	105
Table S3-7 PM _{2.5} emission data by industry of China in 2005	106
Table S3-8 PM _{2.5} emission data by industry of Taiwan in 2005	107
Table S3-9 PM _{2.5} emission data by industry of South Korea in 2005.....	108
Table S3-10 PM _{2.5} emission data by industry of Japan in 2005.....	109
Table S3-11 Source–receptor relationship (SRR) matrix in agriculture that corresponds to industry no.1 to no.7 in Table S3-1 (unit: premature mortality in 10 ⁻⁶ persons/kg-C)	110
Table S3-12 Source–receptor relationship (SRR) matrix in industry that corresponds to industry no.8-60, 62-65, 67-76 in Table S3-1 (unit: premature mortality in 10 ⁻⁶ persons/kg-C)	110
Table S3-13 Source–receptor relationship (SRR) matrix in power that corresponds	

to industry no.61 in Table S3-1 (unit: premature mortality in 10^{-6} persons/kg-C).....	111
Table S3-14 Source–receptor relationship (SRR) matrix in transport that corresponds to industry no.66 in Table S3-1 (unit: premature mortality in 10^{-6} persons/kg-C)	111
Table S3-15 Direct emissions in household sector of countries (unit: Gg-C)	111
Table S4-1 Province and industrial sector classification of the multi-regional input-output table for 30 regions in China in 2007	112

Chapter 1: Introduction

1.1 Air Pollution and Fine Particulate Matter

Air pollution is caused by emissions of harmful gases and particulates into the atmosphere: carbon monoxide (CO), sulfur dioxide (SO₂), nitrogen oxides (NO_x), ammonia (NH₃), volatile organic compounds (VOC), particulate matter (PM) and so on. Fine particulate matter, 2.5 micrometers or less in aerodynamic diameter (PM_{2.5}), is mainly composed of elemental carbon, organic carbon, nitrate, sulfate, ammonium salt and trace metal compound. This fine particulate matter causes a variety of adverse environmental impacts. It contributes to global climate change, is responsible for local and regional degradation of air quality, and also leads to ill health and deaths. The particles directly emitted into the atmosphere are defined as the *primary* PM_{2.5} whereas *secondary* particles are formed in the atmosphere due to the chemical reaction between precursor gases, e.g. SO₂, NO_x or VOC with light and ozone. These air pollutants are emitted from wide range of natural sources including, for example, volcanic eruptions, forest fires, soil, sea salt and emissions of VOC from plants and trees, and anthropogenic sources including the emissions from motor vehicles, industrial processes, power generation, household combustion of solid fuel and so on (Straif *et al.*, 2013).

According to the latest report from the World Health Organization (WHO, 2018), air pollution levels are still dangerously high in many regions and more than 90% of the world's population lives in places where air quality does not meet WHO guidelines. WHO sets air quality guidelines on the basis of a 10 µg/m³ mean concentration threshold, but

many cities especially in the Eastern Mediterranean region and South-East Asia exceed this threshold, with pollution concentrations above $50 \mu\text{m}/\text{m}^3$ in some cases.

Although the precise chemical and physical composition of air pollutants varies across the world due to difference in emission sources and weather conditions (Karagulian *et al.*, 2015; Hu *et al.*, 2017; Tian *et al.*, 2017), polluted air contains certain amount of hazardous substances. Also, particulate matters are so tiny that they penetrate deep in lung and pass into bloodstream (EEA, 2013). Epidemiological research has shown that $\text{PM}_{2.5}$ concentrations are associated with respiratory and cardiovascular diseases, such as lower respiratory infections (LRTIs), ischemic heart disease (IHD), strokes, chronic obstructive pulmonary disease (COPD), and lung cancer (Dockery *et al.*, 1993; Laden *et al.*, 2006; WHO/Europe, 2013; Burnet *et al.*, 2014; GBD, 2015a, 2015b, 2016, 2017; Cohen *et al.*, 2017; Wang *et al.*, 2017a). WHO (2018) estimated that 4.2 million deaths were associated with ambient (i.e., outdoor) air pollution in 2016, while exposure to air pollutants emitted from households due to the combustion of polluting fuels for cooking and heating, namely, indoor air pollution caused 3.8 million deaths in the same year. Air pollution generated in households mainly originates from the combustion of solid fuel (e.g., coal, charcoal, wood, and dung) and kerosene for heating and cooking. Obviously, an effective method for reducing household air pollution is introducing cleaner technologies for heating and cooking, for example, non-solid fuels and electricity (Wang *et al.*, 2014). However, around 3 billion people in the world still do not have access to clean cooking fuels and technologies in their homes (WHO, 2018). Figure 1-1 shows how the share of the population that has access to clean cooking fuels and technologies changed between 2000 and 2014. This figure indicates low- and middle-income countries in Asia still have a low

proportion of households with clean cooking fuels and technologies in spite of improvements in this respect since 2000.

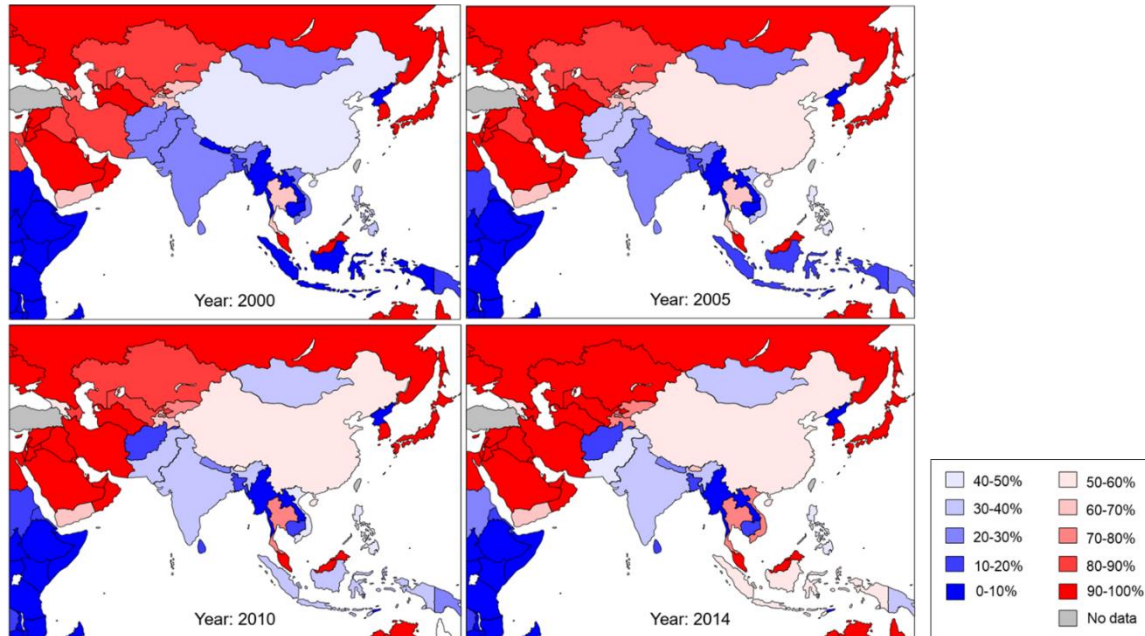


Figure 1-1 Access to clean cooking fuels and technologies in Asia from 2000 to 2014
(unit: percent of population)

(Author's calculation based on World Development Indicators (World Bank, 2018))

Deaths attributable to ambient and household air pollution occur mainly in Asia, especially China and India. In addition, as noted in OECD (2012), particulate matter will be the leading cause of premature deaths of children in the world by 2050, followed by indoor air pollution, if no new air pollution mitigation policies are implemented (Figure 1-2). This emphasizes that air pollution is one of the most critical environmental and health issues that should be urgently addressed.

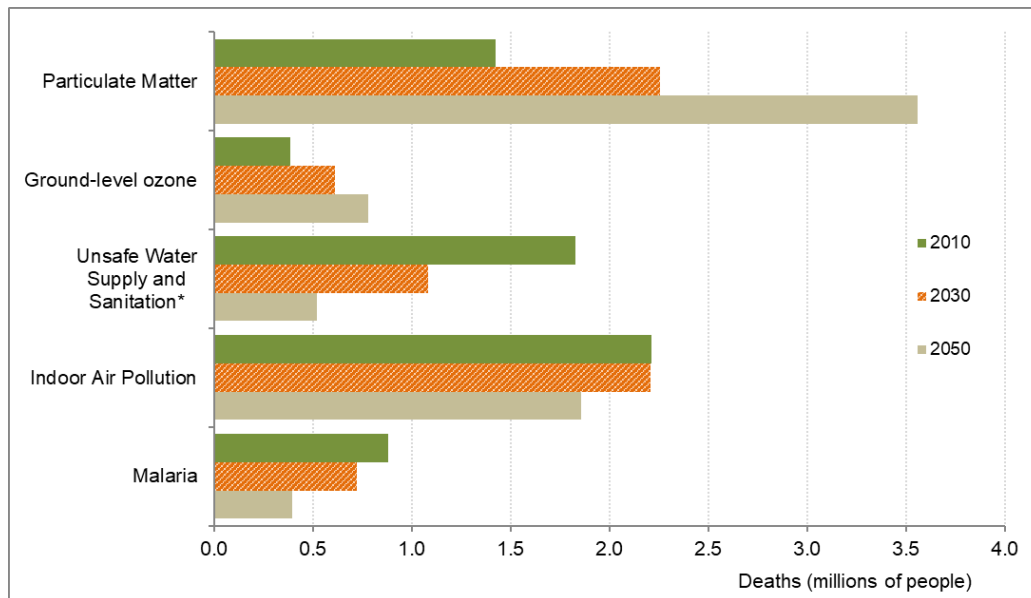


Figure 1-2 Global premature deaths of children from selected environmental risks:
2010 to 2050

(Source: OECD Environmental Outlook Baseline; output from IMAGE)

Air pollution emitted in one region and then transported in the atmosphere to other regions has deleterious impacts on human and ecosystem health in those other regions (Anenberg *et al.*, 2014) and has led to diplomatic conflicts. This shows that long-range transboundary air pollution is not just a local problem, but regional and global as well. In the middle of the 20th century, in Europe and North America, air pollution started to become recognized as an environmental issue that requires an urgent solution through international cooperation. In 1979, the Convention on Long-Range Transboundary Air Pollution (CLRTAP) was signed and it became operational in 1983. This was the first international legally binding policy intervention concerning global transboundary air pollution and it promoted international cooperation through the monitoring and assessment of emissions and information exchanges. Furthermore, eight subsequent protocols extending the CLRTAP, e.g., the Helsinki Protocol and the Sofia Protocol, set

reduction targets for specific air pollutants such as sulfur and nitrogen oxides for each party to the convention.

Agenda 21 (United Nations, 1993), adopted at the UN Conference on Environment and Development in June 1992, stated that such international legislative efforts need to be continued and enhanced, with due emphasis on sharing advice and experience with other countries and regions around the world. Amid growing concern about air pollution and attributed mortality, 13 countries in East Asia, representing a key part of the world where the air is seriously contaminated, established the Acid Deposition Monitoring Network in East Asia (EANET) as a first step towards a cooperative solution to air pollution in the region (EANET, 2018).

Sustainable Development Goals (SDGs) were adopted by the United Nations General Assembly in 2015 and, in the “2030 Agenda”, they are described as a successor to the Millennium Development Goals (MDGs). SDGs represent international objectives to be striven for between 2016 and 2030. Specifically, there are 17 goals at the macro level that in turn comprise 169 targets. Further, the extent to which the goals and targets are met is quantified via 232 indicators. Air pollution and its attributable health impacts are factored into the SDGs indicators. For example, SDG indicator 3.9.1 requires substantially reducing the mortality rate attributed to household and ambient air pollution. Further, indicator 7.1.2 is concerned with universal access to clean fuels and technologies, whilst indicator 11.6.2 focusses on reducing annual mean levels of particulate matter in cities. As described above, actions to improve air quality are critically important and require buy-in from a broad array of stakeholders in developed and developing countries.

1.2 Two perspectives of emissions; production vs consumption

Asia plays a crucial role in terms of international economics. With economic growth due to rapid industrialization, Asian countries accelerated their energy consumption and air pollution emissions rose as a consequence. China has become one of the biggest anthropogenic emitters of PM_{2.5} in the world (Huang *et al.*, 2014). With increasing international trade and the expansion of global supply chains, *consumption-based accounting* (or *footprinting*) has been adopted to assess environmental loads from the perspective of sharing responsibility and equity. Consumption-based accounting covers a wide variety of environmental burdens and resource use associated with the production of goods for the consumers who finally avail of those goods e.g., greenhouse gases (GHGs), air pollutants, energy, water, land, materials, and biodiversity (Davis and Caldeira, 2010; Fang *et al.*, 2014; Hoekstra and Wiedmann, 2014; Wiedmann and Lenzen, 2018). For example, it is estimated that China's consumption-based PM_{2.5} emissions are less than their territorial PM_{2.5} emissions (Guan *et al.*, 2014), which means that a proportion of the PM_{2.5} emitted in China is induced by consumption in other countries.

To explore the concept of consumption-based accounting, suppose that country *a* imports one vehicle from country *b*. A vehicle needs various components as intermediate inputs such tires, an engine, and a battery. Suppose that country *b* bought tires from country *c* for input into the production of a vehicle in country *b*, and furthermore country *c* imports synthetic rubber from country *d* to produce tires. In each part of the production process, environmental burdens, CO₂ emission herein, occur. Based on production supply chains across the world, the traditional emissions account, that is, *production-based*

accounting, attributes CO₂ emissions to countries on a territorial basis. For example, the CO₂ emissions in country *d* due to the production of synthetic rubber would be attributed to country *d*. Conversely, a consumption-based accounting would take account of direct and indirect CO₂ emissions; for example, emissions attributed to country *a* would be calculated by summing the emissions in countries *b*, *c*, and *d* embodied in the purchase of a vehicle by country *a*. The corollary of this is that the territorial CO₂ emitted in country *a* to satisfy demand from other countries would not be included in the consumption-based emissions of country *a*.

Considering the corporation, sector or industry levels, their consumption-based accounting includes not only direct emissions associated with production of their own goods or services but also indirect emissions through the production supply chain they construct. This emission concept has been adopted for corporations to understand and manage their life cycle emissions. The GHG protocol's guideline (2011) about corporations' "Scope 3 emissions", which are defined as the all indirect emissions that occur in their value chain (other than indirect emission associated with the energy generation), promotes the supply chain management for environmental issues of corporations in the world as the part of CSR (Corporate Social Responsibility). In addition to the GHG emissions, "Environmental Footprint" advocated by the European Commission (EC) expanded its environmental impact categories and reducing emissions of particulate matter is now specified as a target. Increasing concern about evaluating consumption-based air pollutant emissions has motivated corporations, sectors and industries in Asia to reduce indirect emissions as well as direct emissions through their supply chains and promotes production of goods and services with less life cycle air

pollutant emission.

Consumption-based accounting is a significant perspective that drives consumers to find new opportunities for emission reductions, and it is expected to enhance cooperation between producers and consumers pursuant of greener technology and more sustainable supply chains in Asia. As such, there is a pressing need to understand the structure of Asian supply chains and identify the key sectors and linkages therein to address air pollution and its attributable health impacts.

1.3 Structure of This Dissertation

This Ph.D. dissertation consists of five chapters (Figure 1-3). Chapter 2 is a comprehensive literature review focusing on air pollution and health impacts, environmentally extended input-output analyses, and related structural analyses, as well as augmented input-output models. The research objectives and the significance of addressing those objectives are also delineated in this chapter.

Chapter 3 employs consumption-based accounting using the Asian International Input-Output Table for 2005. The approach taken links demand to emitter sectors and also incorporates an atmospheric transport model to fully link consumer demand to final pollutant fate and health impacts. An important aim is to clarify the sectors and supply chain paths that are critical for mitigating health impacts in Asia. This chapter also discusses possible ways of improving human health due to air pollution by suggesting policies to reduce or reshape demand in critical sectors and supply chain paths.

Chapter 4 focuses on the residential sector in China, which is the largest emitter of carbonaceous aerosols in Asia. Hitherto, this sector has been treated exogenously and neglected in the context of consumption-based thinking. This chapter extends the endogenous input-output system by incorporating residential PM_{2.5} emissions in China into consumption → production → income processes using a multi-regional input-output table for 30 provinces in China in 2007. This chapter also aims to estimate the residential PM_{2.5} emissions embodied in final demand (except for household consumption) of a specific Chinese province, and further reveal environmentally critical structural paths

with respect to PM_{2.5} in the Chinese provincial economies.

Chapter 5 offers conclusions based on the results of the analyses in chapters 3 and 4 including discussion of salient limitations and suggestions for future research.

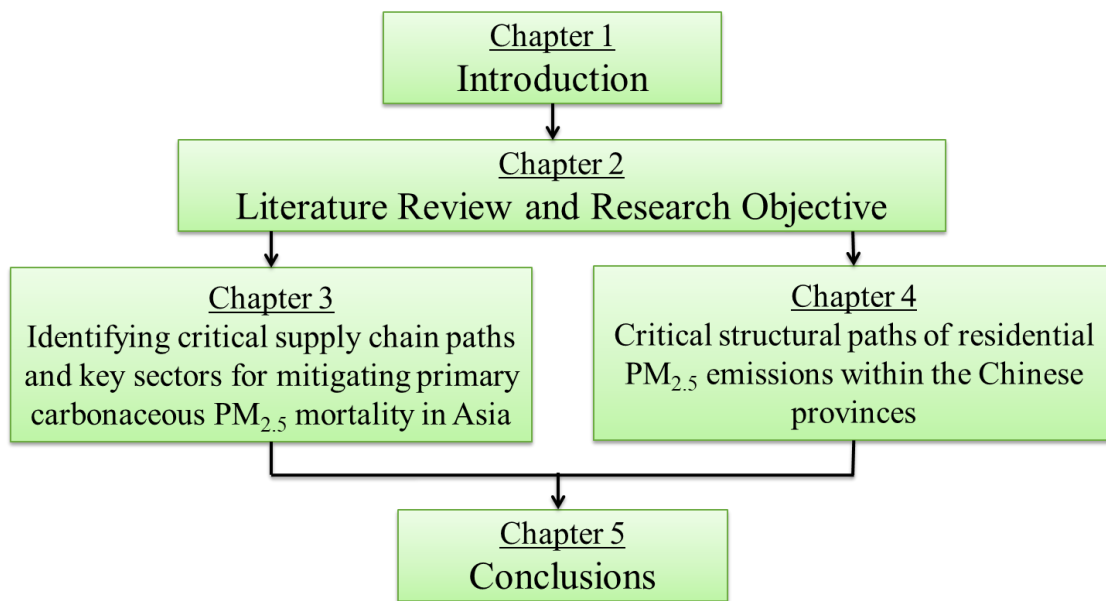


Figure 1-3 Structure of this Thesis

The contents of Chapters 3 and 4 have been published as articles in peer-reviewed journals as follows.

Chapter 3:

Nagashima, F., Kagawa, S., Suh, S., Nansai, K., Moran, D. (2017) Identifying critical supply chain paths and key sectors for mitigating primary carbonaceous PM_{2.5} mortality in Asia, *Economic Systems Research*. 29, 105–123.

Chapter 4:

Nagashima, F. (2018) Critical structural paths of residential PM_{2.5} emissions within the Chinese provinces, *Energy Economics*. 70, 465–471.

Chapter 2: Literature Review and Research Objective

2.1. Studies on air pollutant emission inventories

Quantitative evaluations of air pollution in specific domains are needed for assessing environmental and health impacts, predicting future trends, and designing effective mitigation and adaptation policies at different spatial scales. Emission inventory data capture emission magnitudes and their sources, and are basically constructed by multiplying emission factors by activity volumes. To prepare emission inventories, various organizations (e.g., EMEP/EPA and IPCC) have published guidelines (EEA, 2016; IPCC, 2006) under the CLRTAP or United Nations Framework Convention on Climate Change (UNFCCC). These data have been widely used to assess the environmental burden of goods in the context of life cycle assessment (LCA). Numerous studies have provided emission inventory data for air pollutants according to their applications (Nansai *et al.*, 2003; Ohara *et al.*, 2007; Sugiyama *et al.*, 2009; Shen *et al.*, 2010; Lu *et al.*, 2011; Kurokawa *et al.*, 2013; Huang *et al.*, 2014; Cui *et al.*, 2015; Lin *et al.*, 2016; Huang *et al.*, 2017; Crippa *et al.*, 2018).

Regarding emissions in Asia, Ohara *et al.* (2007) developed emission inventories for SO₂, NO_x, CO, NMVOC, BC, and OC from fuel combustion and industrial sources for the period 1980–2020. Their work was the first attempt to integrate historical, contemporary and future emissions in Asia using a consistent methodology. Kurokawa *et al.* (2013) expanded on this work for the period 2000–2008. These updated inventory data include air pollutants and greenhouse gases by country and region broken down by sub-

sector and fuel type, and they show that PM_{2.5} emissions in Asia, for example, were 24.7 Tg in 2008, representing an increase of 42% since 2000. Kurokawa *et al.* (2013) also clarified that China was the largest contributor to Asian emissions although its once high emissions growth rate appears to have been tempered in more recent years as a result of the mitigation measures implemented by the Chinese government. Both Ohara *et al.* (2007) and Kurokawa *et al.* (2013) used country-level inventory data for Asian nations including the publicly available Regional Emission inventory in ASia (REAS) database at <http://www.nies.go.jp/REAS/>. At the global scale, the Emissions Database for Global Atmospheric Research (EDGAR) is available at <http://edgar.jrc.ec.europa.eu/> This is the most popular such database, representing the default choice of many researchers, and it was developed jointly by the European Commission DC JRC and the Netherlands Environmental Assessment Agency. The latest version (EDGAR v4.3.2) provides emission inventories of various gaseous and particulate air pollutants calculated at the 0.1°x0.1° grid level (Crippa *et al.*, 2018).

2.2. Studies on environmentally-extended input-output analysis

Since the seminal works by Wassily Leontief (1936, 1941), input-output analysis has been used and extended in various ways. Among them, applications of input-output analysis to environmental issues can be traced back to Daly (1968), Isard *et al.* (1968), Ayres and Kneese (1969), and Leontief (1970). Leontief (1970) treated the pollutants emitted through the economic system as by-products, and configured a framework to estimate the total amount of pollutants necessary to satisfy a given production of commodities using the Leontief inverse.

In the context of increasing globalization in the world economy, frameworks of environmentally extended input-output analysis are mainly based on multi-region input-output (MRIO) modeling (Isard, 1951; Leontief, 1953). Freely available data (Lenzen *et al.*, 2012, 2013; Tukker *et al.*, 2013; Timmer *et al.*, 2015) serve to increase the scale and scope of studies that can be conducted in this domain. There are numerous examples of studies concerning the measurement of footprints (Peters, 2008; Wiedmann, 2009; Minx *et al.*, 2008, 2009; Davis and Calderia, 2010; Davis *et al.*, 2011; Nansai *et al.*, 2012; Kanemoto *et al.*, 2016), the carbon emissions embodied in international trade (Peter and Hertwich, 2006a, 2008, 2009; Wiedmann *et al.*, 2007; Weber and Matthews, 2007; Peters *et al.*, 2011; Kanemoto *et al.*, 2012), and solutions to environmental issues based on principles of emission responsibility or emission equity (Lenzen and Murray, 2001, 2010; Munksgaard and Pedersen, 2001; Gallego and Lenzen, 2005; Lenzen, 2007b, Lenzen *et al.*, 2007; Andrew and Forgie, 2008; Rodrigues and Domingos, 2008; Marques *et al.*, 2012, Kanemoto *et al.*, 2012). Ensuring “emission transfer” or “carbon leakage” due to

the globalization and outsourcing of production to developed countries are main subjects in these studies. For example, Peters *et al.* (2011) analyzed emission transfers using an MRIO database (GTAP, Narayanan and Walmsley, 2008) and revealed that consumption-based CO₂ emissions in developed countries had tended to increase faster than their own territorial CO₂ emissions with emission transfers from developed to developing countries through international trade growing four-fold in the period 1990–2008.

Air pollution has become one of the main foci of footprinting exercises (Nansai *et al.*, 2003; Sugiyama *et al.*, 2009; Liang *et al.*, 2013; Guan *et al.*, 2014; Huo *et al.*, 2014; Lin *et al.*, 2014; Meng *et al.*, 2015, 2016; Zhao *et al.*, 2015; Moran and Kanemoto, 2016; Wu *et al.*, 2017; Zhang *et al.*, 2018). Huo *et al.* (2014) analyzed sectoral air pollution emissions from production and consumption perspectives, and showed that manufacturing and construction sectors contributed 50% of emissions, mainly induced by capital formation and exports. Guan *et al.* (2014) used an environmentally extended input-output framework and identified the driving forces of primary PM_{2.5} emission changes in China. Guan and his colleagues showed that production for exports drove the 638 thousand tons of PM_{2.5} emitted in China and the emissions embodied in international trade were largely driven by OECD countries. In addition, Moran and Kanemoto (2016) visualized consumption-based air pollution on a world map at the 0.1° resolution and clarified the geographical shifts in air pollutants attributable to consumption by developed countries between 1970 and 2008.

An important characteristic of air pollution is the physical transport of gases and aerosols into neighboring countries, which means that the sources of air pollutants do not

always coincide with the victims of these pollutants. Some air pollution research using a consumption-based accounting approach has connected the atmospheric transport of air pollution with emission inventories (Lin *et al.*, 2014; Li *et al.*, 2016; Lin *et al.*, 2016; Meng *et al.*, 2018; Chen *et al.*, 2018a). Lin *et al.* (2014) used the global GEOS-Chem chemical transport model to calculate the surface concentration of air pollutants in China resulting from physical transport in the atmosphere and analyzed the relationship between the physical and virtual impacts of air pollution through China-US trade. The results of Lin *et al.* (2014) showed that 12-24% of surface sulfate concentrations in the western part of the US were associated with transboundary air pollution emissions embodied in Chinese exports to the US, and increased outsourcing of manufacturing goods to China led to reductions in sulfate air pollution in the eastern, but not the western, US. Furthermore, Li *et al.* (2016) focused on air pollution concentrations in China; they integrated the atmospheric transport of black carbon and interprovincial trade using the Weather Research Forecasting with Chemistry (WRF/Chem) model and the Chinese provincial MRIO table. Li and colleagues revealed that emissions outside the region contributed substantially to regional atmospheric concentrations. For example, 42% and 22% of the surface BC concentration in Beijing and Shanghai, respectively, were attributed to emissions outside the region, and BC concentrations in both of these cities are due to emissions outside the region but induced by local consumption were negligible. On the other hand, the contributions of local emissions in same regions induced by consumption of other provinces were nearly 20% and 40%, respectively.

As in Chapter 1, a significant body of research has shown that air pollution has an epidemiological association with human mortality. In recent years, studies into

consumption-based accounting have focused on health impacts associated with air pollutant emissions and cross-border air pollution (Ma *et al.*, 2011; Takahashi *et al.*, 2014; Jiang *et al.*, 2015; Liang *et al.*, 2017; Wang *et al.*, 2017b; Zhang *et al.*, 2017; Zhao *et al.*, 2017; Xiao *et al.*, 2018). More specifically, these studies have integrated meteorological and epidemiological data to estimate the relationship between emission sources and victims of health impacts. Takahashi *et al.* (2014) analyzed production-based emissions, consumption-based emissions, and consumption-based health impacts of primary black carbon (BC) and organic carbon (OC) for nine Asian countries and regions in 2008. Those authors described the source-receptor relationship (SRR) in matrix form for the first time and connected it with environmental input-output analysis. They estimated that on-site emissions (production-based emissions) of BC and OC in these nine Asian countries totaled 5,990 Gg-C, 75% of which were emitted in China. Further, the consumption-based emissions of China accounted for 77% of Asia's total emissions. China was also the largest contributor to the consumption-based health impacts of primary BC and OC, being responsible for an estimated 111×10^3 premature deaths which is equivalent to 87% of the total consumption-based health impacts in Asia. Thus, the contribution of China to consumption-based health impacts was even greater than that country's consumption-based emissions. Moreover, Zhang *et al.* (2017) also evaluated the human health impacts induced by consumption at the global level. This study estimated that 3.45 million premature deaths around the world were attributable to air pollution in 2007, 12% of which occurred because of air pollution emitted elsewhere and 22% of which was associated with the local production of goods and services satisfying consumption elsewhere.

These impact footprint studies related to the atmospheric transport of air pollution reveal differences in the spatial distribution of emissions and the subsequent health impacts; the changing locations of air pollution sources over time associated with changes in international trade patterns have had a larger influence on health impacts than those from long-range transboundary air pollution.

2.3. Studies on structural supply chain analysis

2.3.1. Linkages and key sectors

The analysis of complex economic production structures has been one of the most important applications of input-output studies, especially in terms of measures of “sectoral interdependencies” or “linkages”. Indeed, quantifying the strength of sectoral linkages has been a focus of research since the 1970s (Kurz *et al.*, 1998). The economic effect of sectoral linkages through the production supply chain can be divided into two indicators, namely *backward* and *forward* linkages (Lenzen, 2003; Miller and Blair, 2009). A backward linkage is defined as the effect resulting from an increasing upstream supply of inputs due to increasing demand in a particular sector, whereas a forward linkage effect occurs when the increase in output from a particular sector induces downstream use of outputs (Lenzen, 2003).

Sectors with strong backward and forward linkages have large impacts on the entire economy. Measurements of the strength of backward and forward linkages were developed by Rasmussen (1956) and Chenery and Watanabe (1958). The difference between them is that indicators in the latter study only measure direct linkages (using technical coefficient matrices) while the former study used the effect of direct and indirect linkages (using the Leontief inverse matrix). They calculated backward and forward linkages by summing the columns and rows of matrices, respectively. Hirschman (1958) applied Rasmussen’s method to identify key sectors in economic development. He normalized Rasmussen’s indicators independent of total output, and rendered them

comparable across sectors. Sectors exhibiting larger backward and forward linkages were defined as key sectors. In the early literature, there are many examples of theoretical and empirical studies concerning the measurement of linkage effects, as well as the definition of key sectors and alternative measures (Baer and Kerstenetzky, 1964; Hazari, 1970; Yotopoulos and Nugent, 1973, 1976; Diamond, 1974, 1976; Laumas, 1975, 1976; Boucher, 1976; Jones, 1976; Riedel, 1976; Hewings, 1982; Cella, 1984, 1986; Clements, 1990; Dietzenbacher, 1992; Sonis *et al.*, 1995, 2000). For example, Dietzenbacher (1992) introduced an alternative measurement of inter-industry linkages using the left-hand Perron eigenvector of the technical coefficient matrix.

Further, sectoral analyses have been expanded by internalizing environmental burdens to production supply chains (e.g., Lenzen, 2003; Ma *et al.*, 2012; Chang and Lahr, 2016; Zhang *et al.*, 2018). Lenzen (2003) calculated the strength of backward and forward linkages for environmental burdens such as GHGs, NO_x, and SO₂ for key sectors in Australia in 1995. He showed that the ‘bauxite mining’, ‘copper mining’, and ‘non-ferrous basic metal’ sectors exhibited relatively strong forward SO₂ linkages, while ‘sheet containers and other sheet metal products’ and ‘alumina, aluminium alloys and aluminium recovery’ sectors have relatively strong backward SO₂ linkages. Chang and Lahr (2016) analyzed key sectors in China for 2005 and 2010 using Hirschman’s method, and identified ‘coal mining and dressing’, ‘metal smelting and pressing’, and others as environmentally critical sectors for CO₂ emissions, and then suggested preferential mitigation policies that these key sectors should adopt.

2.3.2. Structural path analysis

To describe the characteristics of supply chain complexity, graph theoretic approaches have been applied to input-output structures (Rosenblatt, 1957; Yan and Ames, 1965; Weil, 1968; Blin and Murphy, 1974). Later work in this domain has applied complex network theory (Semitiel-Garcia and Noguera-Mendez, 2012; McNerney *et al.*, 2013; Cerina *et al.*, 2015; Liang *et al.*, 2016a, 2016b; Hanaka *et al.*, 2017; Tsekeris, 2017; Xing *et al.*, 2017; Chen *et al.*, 2018b; Tokito, 2018). Structural path analysis (SPA) introduced by Defourny and Thorbecke (1984) is a notable method tracing important supply chain paths from complex input-output structures by decomposing matrix products into elements (paths). Defourny and Thorbecke applied this method in the context of a social accounting matrix (SAM) framework for Korea and identified important paths for increasing total output. SPA has since been used in an input-output framework and also adopted to the environmental studies (Sonis *et al.*, 1997; Treloar, 1997; Sonis and Hewings, 1998; Treloar *et al.*, 2001; Lenzen, 2002, 2003, 2007a; Peters and Hertwich, 2006b, 2006c; Suh, 2005; Suh and Heijungs, 2007; Minx *et al.*, 2008, 2009; Lenzen and Murray, 2010; Mo *et al.*, 2011; Skelton *et al.*, 2011; Llop and Ponce-Alifonso, 2015; Meng *et al.*, 2015; Liang *et al.*, 2016a; Gunluk-Senesen *et al.*, 2018; Zhen *et al.*, 2018).

SPA for environmental analysis identifies the critical supply chain path so that the amount of environmental burden originated through its supply chain is larger. In this sense, SPA can quantify the environmental load from the extracted supply chains. Meng *et al.* (2015) identified the critical supply chain for mitigating primary PM_{2.5} in China in 2007, and revealed that demand on the construction sector drove emissions in upstream sectors,

whilst demand on the power and transportation sectors induced direct emissions. The most critical path extracted, ‘Capital formation → construction → non-metallic products’ contributed 25% of total primary PM_{2.5} emissions in China.

In addition, Liang *et al.* (2016b) developed a method which applied the concept of betweenness centrality from network analysis to input-output systems inspired by structural path analysis. Betweenness centrality of a particular sector becomes larger if many supply chains include this sector; where this is the case, such sectors are termed ‘key transmission sectors’. They calculated betweenness-based CO₂ emissions in China and compared these with production- and consumption-based emissions. They identified ‘plastic products’ and ‘nonferrous metal processing’ as critical transmission sectors. These sectors were not extracted using existing methods (production- and consumption-based accounting) and thus provide novel insights for theory and practice.

2.4. Studies on augmented input-output analysis

Leontief's multiplier matrix does not accommodate effects generated by income on consumption expenditure since the open Leontief model treats household consumption as exogenous (Kurtz *et al.*, 1998). Miyazawa and Masegi (1963) and Miyazawa (1976) solved this problem by integrating Keynes and Kalecki's consumption function, disaggregated by sector and household type, into Leontief's input-output system. This model introduced a feedback mechanism of income generation and induced consumption into Leontief's model; it describes the endogenous relationship between income flow and household consumption, which enables determination of income by type of household associated with exogenous expenditures. The framework is condensed in the so-called 'inter-relational income multiplier' as a matrix whose elements explain how much income in a particular type of household is generated by the expenditure from one unit of additional income in other households through the propagation of production activities (Miyazawa, 1976). To date, Miyazawa's augmented input-output model has been used for various multiplier analyses (Lager, 1988; Rose and Beaumont, 1988; Rose *et al.*, 1989; Sonis and Hewings, 1993, 1995; Cloutier and Thomassin, 1994; Trigg and Madden, 1994; Baty and Madden, 1999; Rose and Li, 1999; Hewings *et al.*, 2001; Lenzen and Schaeffer, 2004; Kagawa, 2005). For example, Rose and Beaumont (1988) disaggregated the consumption and income coefficient by 9 income classes in West Virginia based on the Consumer Expenditure Survey by the Bureau of Labor Statistics, and then calculated the inter-relational income distribution multiplier. They showed that the income generation effects through direct and indirect production activities induced by one unit increase in income in low-income classes are larger than those in high-income classes. As an

environmental extension, Lenzen and Schaeffer (2004) examined the propagation effects of income distribution and household consumption in Brazil on the sectoral use of transportation fuel and electricity. In terms of the former, their results showed that there exists a disparity between rich and poor households because the former can afford to buy mobility. This disparity is exacerbated through expanding the propagation process of consumption, production, and income distribution. Finally, the inequality of transportation fuel use between households was more pronounced than monetary inequality.

Environmental extensions of augmented input-output models have focused on sectoral environmental burdens, but there is a dearth of research with respect to household emissions. Focusing on household emissions from a consumption-based perspective is indispensable to the determination of appropriate mitigation responses to residential environmental load, particularly in countries such as China where household air pollution emissions are of serious concern.

2.5. Contribution of This Thesis

This Ph.D. dissertation reports on the development and execution of comprehensive analyses focusing on Asian supply chains to improve the knowledge base for effectively mitigating anthropogenic ‘atmospheric’ (outdoor) and ‘household’ (indoor) air pollution.

First, an environmentally extended Asian input-output table for the year 2005 is used and, for the first time, a comprehensive economic network analysis is applied including key sector analysis and structural path analysis to identify critical sectors and supply chain paths that contribute significantly to the mortality attributable to primary carbonaceous PM_{2.5}, namely, black carbon (BC) and organic carbon (OC) in Asia. Impact footprint and structural analysis are employed by introducing an atmospheric transport model to combine consumer demand via supply chains to primary emitters, and then linking those emitters via atmospheric transport to fate and health impacts. Countries, such as Japan, which are particularly important in Asian supply chains, are illuminated and explored in terms of direct and indirect emissions, the generating mechanisms thereof, and appropriate policy responses.

Next, the focus shifts to primary PM_{2.5} emissions (including particles other than BC and OC) from the residential sector, which are a substantive contributor to air pollution, especially in Asia. I examine how differences in household consumption and income distributions in each region affect residential PM_{2.5} emissions, and finally discuss possible ways to reduce PM_{2.5} emissions in the future on the basis of the results generated from this analysis. I develop a framework that incorporates household consumption and income

distribution, both of which are treated exogenously, to Leontief's input-output system by using multi-region input-output analysis. This analytical model enables exploration of the interregional propagation effects of consumption, production, and income distributions. As a case study, I used the 2007 environmentally extended multi-provincial input-output table for China. Furthermore, for the first time, a structural path analysis is applied to an augmented input-output model to extract the critical path that contributes to household PM_{2.5} emissions through the consumption → production → income process, thereby enabling identification of the stakeholders that are best placed to make decisions, particularly those related to emission reductions.

Chapter 3: Identifying Critical Supply Chain Paths and Key Sectors for Mitigating Primary Carbonaceous PM_{2.5} Mortality in Asia

3.1. Introduction

Asia produces almost half of all global manufactured goods and plays a vital role as a global production powerhouse (The Economist, 2015). As the industrial production of the region continues to rise, so do concerns about the adverse environmental and health impacts associated with production activities. Among these, fine particulate matter ≤ 2.5 micrometers in aerodynamic diameter (PM_{2.5}) has been one of the most controversial environmental and human health issues in this region in recent years (Pope and Dockery, 2006; Pope *et al.*, 2009; Anenberg *et al.*, 2011; Lepeule *et al.*, 2012). It has been estimated that both per-capita and total mortality attributable to PM_{2.5} are highest in the Asian domain, amounting to 63 deaths per 100,000 persons and 2.3 million total deaths, respectively, in 2010 (Apte and Marshall, 2015).

Recent studies using consumption-based accounting have shown that a large proportion of the PM_{2.5} emissions in China is induced by consumer demand in China (Guan *et al.*, 2014; Huo *et al.*, 2014; Lin *et al.*, 2014; Takahashi *et al.*, 2014; Meng *et al.*, 2016). Guan *et al.* (2014) measured consumption-based emissions of primary PM_{2.5} utilizing an inventory of air pollutant emissions in China to understand the main driving forces behind the emissions and also found that PM_{2.5} emissions embodied in Chinese exports are mainly triggered by consumption in OECD countries. The emission of primary PM_{2.5} and PM_{2.5} precursors originally emitted in China then transported to neighboring countries

via prevailing westerly winds has been a source of diplomatic conflicts in the region (Ohara *et al.*, 2007). Takahashi *et al.* (2014) further combined the consumption-based accounting with an atmospheric transport model (Nishizawa *et al.*, 2012) and analyzed the PM_{2.5}-induced “mortality impacts” in terms of primary black carbon (BC) and primary organic carbon (OC)—both major constituents of PM_{2.5}—by country and by sector of the economy.

Traditional footprinting exercises, including the original work by Leontief (Leontief, 1970; Leontief and Ford, 1971) linking consumer demand to air pollution, connect demand to a resource demand or pollution flux. This approach has been called a “pressure footprint”, standing in contrast to an “impact footprint” in which demand is linked to actual environmental impact (Verones *et al.*, 2017). These concepts are clearly classified in the so-called DPSIR framework (Smeets and Weterings, 1999) used in the EU to form environmental policy.

An effective PM_{2.5} pollution mitigation strategy can benefit from targeted understanding of the key supply chains that drive PM_{2.5} emissions. As increasingly more intermediate products are crossing national borders in the course of the expansion of international trade, however, understanding the structure of the supply chains that induce PM_{2.5} emissions and PM_{2.5}-induced mortality is a challenge.

Previous studies have not determined environmentally important supply chains that have great potential to effectively reduce the health impacts in polluted countries. In this study, we use the environmentally extended Asian input–output table of 2005 and apply

a comprehensive economic network analysis including key sector analysis (Rasmussen, 1956; Hirschman, 1958; Hazari, 1970; Lenzen, 2003) and structural path analysis (SPA) (Lenzen, 2003; Treloar, 1997; Lenzen, 2002; Lenzen, 2007; Peters and Hertwich, 2006a; Peters and Hertwich, 2006b; Suh and Heijungs, 2007; Minx *et al.*, 2008; Lenzen and Murray, 2010; Skelton *et al.*, 2011; Kagawa *et al.*, 2015; Meng *et al.*, 2015) to identify the environmentally important supply chain paths and key industries that contribute to the “primary carbonaceous” PM_{2.5} emissions of the region. A novelty of this study is that we introduced an atmospheric transport model in order to fully link consumer demand via supply chains to primary emitters, and then link those emitters via atmospheric transport to fate and health impact.

The remainder of this paper is structured as follows: Section 3.2 explains our methodology, Section 3.3 describes the data, Section 3.4 presents and discusses the results, and finally Section 3.5 offers discussion and conclusions.

3.2. Method

3.2.1. Consumption-based $PM_{2.5}$ emissions

The output vector $\mathbf{x} = (x_i^r)$ ($r=1, \dots, M$, $i=1, \dots, N$) in a multi-regional input–output analysis with N industries and M countries can be expressed as a linear equation: $\mathbf{x} = \mathbf{Ax} + \mathbf{f}$, where $\mathbf{f} = (f_j^s)$ is the final demand vector, representing the final global demand for the products of industry j of country s , and $\mathbf{A} = (Z_{ij}^{rs}/x_j^s) = (a_{ij}^{rs})$ is an input coefficient matrix, expressing the intermediate input for industry i of country r that is necessary per unit of production of the product of industry j of country s , for which Z_{ij}^{rs} represents the intermediate input into industry j of country s from industry i of country r . Final demand vector $\mathbf{f}$ can be expressed as the sum of the final demand vectors of each demand country as $\mathbf{f} = \mathbf{f}^1 + \mathbf{f}^2 + \dots + \mathbf{f}^M = \sum_{s=1}^M \mathbf{f}^s$, where $\mathbf{f}^s$ is the domestic final demand vector of country s . Solving the above linear equation for output vector $\mathbf{x}$, we obtain the following equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{f} = \mathbf{L} \mathbf{f}, \quad (1)$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} = (L_{ij}^{rs})$ is the Leontief inverse matrix with elements L_{ij}^{rs} expressing the output of industry i of country r that is directly and indirectly needed to satisfy one unit of final demand from industry j of country s .

If the direct emission intensity vector that contains primary BC and OC particulate emissions ($PM_{2.5}$ emissions in short hereafter) per unit output of industry i of country r is

defined as $\mathbf{d} = (d_i^r)$, then consumption-based PM_{2.5} emissions can be estimated as follows:

$$\mathbf{e}^{s^*} = \hat{\mathbf{d}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f}^{s^*} = \hat{\mathbf{d}}\mathbf{L}\mathbf{f}^{s^*}, \quad (2)$$

where $\hat{\mathbf{d}}$ is the diagonalization of $\mathbf{d}$, and $\mathbf{f}^{s^*}$ is the final demand vector of s^* . An element e_i^r of $\mathbf{e}^{s^*}$ represents the PM_{2.5} emissions induced by industry i of country r associated with final demand in demand country s^* .

3.2.2. Consumption-based health impacts

The relationship data defining how much of the PM_{2.5} emitted within a source country is carried to another, receptor country and impacts the health of the people of the receptor country are given by the source–receptor relationship (SRR) matrix $\mathbf{Q} = (q_i^{wr})$. The SRR matrix element q_i^{wr} represents the number of premature deaths in country w caused per unit of PM_{2.5} emitted by industry i of country r . By combining the SRR matrix with Eq. (2), $\mathbf{m}_1^{s^*}$, the number of premature deaths in each country w due to PM_{2.5} emissions from each industry i of each country r associated with final demand in country s^* , can be estimated using the following equation:

$$\mathbf{m}_1^{s^*} = \mathbf{Q}\mathbf{d}\mathbf{L}\mathbf{f}^{s^*} = \mathbf{Q}\mathbf{e}^{s^*}. \quad (3)$$

A vector element of $\mathbf{m}_1^{s^*}$ represents the number of premature deaths in each country w induced by final demand in country s^* .

The quantity of territorial and cross-border pollution associated *directly* with PM_{2.5} emissions from the household sector of country s^* can be estimated similarly using the SRR matrix $\mathbf{h}^{s^*} = (h^{ws^*})$ for the household sector, as $\mathbf{m}_2^{s^*} = \mathbf{h}^{s^*}g^{s^*}$, where the SRR vector element h^{ws^*} expresses the number of premature deaths in country w due to the cross-border pollution of one unit of PM_{2.5} directly emitted from the household sector of country s^* , and g^{s^*} denotes the total PM_{2.5} emissions from the activities (burning of coal and biomass for heating, use of diesel vehicles and gasoline-powered cars, etc.) of the household sector of country s^* . By adding the number of premature deaths in country

w arising from indirect emissions due to final demand in country s^* to the number of premature deaths in each country w arising from direct emissions from the household sector of country s^* , we can estimate the direct and indirect impact of emissions in country s^* on health in each country w as $\mathbf{m}^{s^*} = \mathbf{m}_1^{s^*} + \mathbf{m}_2^{s^*}$.

3.2.3. Identifying key sectors

The matrix $\hat{\mathbf{dL}}$ on the right-hand side of Eq. (3) shows the direct and indirect PM_{2.5} emissions associated with output of industry i of country r needed to satisfy one unit of final demand from industry j of country s , and therefore it can also be defined as $\hat{\mathbf{dL}} = \mathbf{E} = (E_{ij}^{rs})$. Following previous work (Rasmussen, 1956; Hirschman, 1958; Hazari, 1970; Lenzen, 2003; Ma *et al.*, 2012), the two indices of power of dispersion (i.e., backward linkages) in industry j of country s and sensitivity of dispersion (i.e., forward linkages) in industry i of country r can be defined as

$$PD_j^s = \frac{\sum_{r=1}^M \sum_{i=1}^N E_{ij}^{rs}}{\frac{\sum_{s=1}^M \sum_{j=1}^N \sum_{r=1}^M \sum_{i=1}^N E_{ij}^{rs}}{M \times N}} \quad (4)$$

and

$$SD_i^r = \frac{\sum_{s=1}^M \sum_{j=1}^N E_{ij}^{rs}}{\frac{\sum_{r=1}^M \sum_{i=1}^N \sum_{s=1}^M \sum_{j=1}^N E_{ij}^{rs}}{M \times N}}, \quad (5)$$

respectively. If the backward linkage effect of industry j of country s (i.e., $\sum_{r=1}^M \sum_{i=1}^N E_{ij}^{rs}$ in the numerator of Eq. (4)) is larger than the global average across industries and countries (i.e., $\frac{\sum_{s=1}^M \sum_{j=1}^N \sum_{r=1}^M \sum_{i=1}^N E_{ij}^{rs}}{M \times N}$ in the denominator of Eq. (4)), the power of dispersion in Eq. (4) is larger than one, and vice versa. In other words, sectors with higher power of dispersion indices (thus exceeding 1.0) are environmentally important sectors in the sense that PM_{2.5} is relatively heavily emitted through the entire backward supply chains in the Asian countries associated with one unit of final demand of the specific

sector. Similarly, sectors with higher sensitivity of dispersion indices (thus exceeding 1.0) are also environmentally important sectors in the sense that PM_{2.5} is relatively heavily emitted by producing and supplying products of the specific sector to satisfy one unit of final demand of all the sectors across countries. A key sector can be found by checking the conditions $PD_j^s > 1$ and $SD_i^r > 1$ (Lenzen, 2003). The key sector exhibits both above-average influence and dependence on other sectors regarding PM_{2.5} emissions.

A similar key sector analysis is applied to the consumption-based health impacts. Noting that, from the SRR matrix $\mathbf{Q} = (q_i^{wr})$, the *total* number of premature deaths in all the countries caused per unit of PM_{2.5} emitted by industry i of country r is defined as $\mathbf{q} = (q_i^r) = \sum_{w=1}^M q_i^{wr}$, the direct and indirect premature deaths associated with output of industry i of country r needed to satisfy one unit of final demand from industry j of country s can be defined as $\hat{\mathbf{q}}\hat{\mathbf{d}}\mathbf{L} = \mathbf{G} = (G_{ij}^{rs})$. Substituting G_{ij}^{rs} into E_{ij}^{rs} on the right-hand side of Eqs. (4) and (5) yields the two indices, power of dispersion and sensitivity of dispersion, which in this case are denoted $\widetilde{PD}_j^s$ and $\widetilde{SD}_i^r$, respectively.

As Lenzen (2003) noted, the indices PD_j^s ($\widetilde{PD}_j^s$) and SD_i^r ($\widetilde{SD}_i^r$) ignore the relative importance of sectoral final demand that plays a crucial role in consumption-based accounting. A natural way of addressing this deficit is to define weighted indices of power of dispersion and sensitivity of dispersion as

$$PD_j^{s*} = \frac{\sum_{r=1}^M \sum_{i=1}^N \alpha_j^s E_{ij}^{rs}}{\frac{\sum_{s=1}^M \sum_{j=1}^N \sum_{r=1}^M \sum_{i=1}^N \alpha_j^s E_{ij}^{rs}}{M \times N}} \quad (6)$$

and

$$SD_i^{r*} = \frac{\sum_{s=1}^M \sum_{j=1}^N \alpha_j^s E_{ij}^{rs}}{\frac{\sum_{r=1}^M \sum_{i=1}^N \sum_{s=1}^M \sum_{j=1}^N \alpha_j^s E_{ij}^{rs}}{M \times N}}, \quad (7)$$

respectively, where α_j^s denotes the portion of final demand of products produced by industry j of country s among the total of final demand across industries and countries. Regarding $\widetilde{PD}_j^s$ and $\widetilde{SD}_i^r$, we can similarly define the corresponding weighted indices as $\widetilde{PD}_j^{s*}$ and $\widetilde{SD}_i^{r*}$, respectively.

3.2.4. Identifying critical supply chain paths

Here, we identify the environmentally important supply chain paths by evaluating the contribution made by the supply chain paths linking consumption and production to the consumption-based PM_{2.5} emissions and cross-border pollution obtained above. If we perform a series expansion of the Leontief inverse matrix of Eq. (1), we obtain $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \dots$. Then, from Eq. (2), we can solve for the PM_{2.5} emissions arising from consumption in country s^* as follows:

$$\mathbf{e}^{s^*} = \hat{\mathbf{d}}\mathbf{f}^{s^*} + \hat{\mathbf{d}}\mathbf{A}\mathbf{f}^{s^*} + \hat{\mathbf{d}}\mathbf{A}^2\mathbf{f}^{s^*} + \hat{\mathbf{d}}\mathbf{A}^3\mathbf{f}^{s^*} + \dots \quad (8)$$

If, for example, final demand for a particular product is generated in country s^* , then the quantity of PM_{2.5} emitted in the supplying country at the production stage to satisfy that demand is $\hat{\mathbf{d}}\mathbf{f}^{s^*}$. Furthermore, $\mathbf{A}\mathbf{f}^{s^*}$ denotes intermediate goods needed to meet the final demand, and they yield a quantity of PM_{2.5} emissions $\hat{\mathbf{d}}\mathbf{A}\mathbf{f}^{s^*}$. Through a series expansion of the Leontief inverse matrix, this emissions process continues infinitely. Thus, the element $e_i^{rs^*}$ for computing $\mathbf{e}^{s^*}$ can be estimated by the following equation:

$$\begin{aligned} e_i^{rs^*} &= \sum_{v=1}^M \sum_{j=1}^N d_i^r (I_{ij}^{rv} + a_{ij}^{rv} + (\mathbf{A}^2)_{ij}^{rv} + (\mathbf{A}^3)_{ij}^{rv} + \dots) f_j^{vs^*} \\ &= \sum_{v=1}^M \sum_{j=1}^N d_i^r (I_{ij}^{rv} + a_{ij}^{rv} + \sum_{t=1}^M \sum_{k=1}^N a_{ik}^{rt} a_{kj}^{tv} + \sum_{u=1}^M \sum_{t=1}^M \sum_{l=1}^N \sum_{k=1}^N a_{il}^{ru} a_{lk}^{ut} a_{kj}^{tv} + \dots) f_j^{vs^*} \\ &= d_i^r f_i^{rs^*} + \sum_{t=1}^M \sum_{j=1}^N d_i^r a_{ij}^{rv} f_j^{vs^*} + \sum_{t=1}^M \sum_{r=1}^M \sum_{j=1}^N \sum_{k=1}^N d_i^r a_{ik}^{rt} a_{kj}^{tv} f_j^{vs^*} \\ &\quad + \sum_{u=1}^M \sum_{t=1}^M \sum_{r=1}^M \sum_{j=1}^N \sum_{k=1}^N \sum_{l=1}^N d_i^r a_{il}^{ru} a_{lk}^{ut} a_{kj}^{tv} f_j^{vs^*} + \dots \end{aligned} \quad (9)$$

where i, j, k , and l are industrial indices and r, s, t, u , and v are regional indices. I_{ij}^{rv} takes value 1 when $r=v$ and $i=j$, and is otherwise 0. The first term on the right-hand side of Eq. (9), $d_i^r f_i^{rs^*}$, denotes the PM_{2.5} emissions of industry i of country r induced by final demand in country s^* . The second term, $d_i^r a_{ij}^{rv} f_j^{vs^*}$, expresses the PM_{2.5} emissions induced by the production of the intermediate goods of industry i of country r that is needed for the products produced by industry j of country v in order to satisfy the final demand in country s^* . The third term, $d_i^r a_{ik}^{rt} a_{kj}^{tv} f_j^{vs^*}$, represents the emissions resulting from the supply chain path “final demand in country s^* ” $\rightarrow$ “production of industry j of country v ” $\rightarrow$ “production of industry k of country t ” $\rightarrow$ “production of industry i of country r ”.

Similarly, the element m^{ws^*} for computing $\mathbf{m}_1^{s^*}$ showing the consumption-based health impacts can be estimated by the following equation:

$$\begin{aligned}
m^{ws^*} &= \sum_{r=1}^M \sum_{i=1}^N \sum_{v=1}^M \sum_{j=1}^N q_i^{wr} d_i^r (I_{ij}^{rv} + a_{ij}^{rv} + (\mathbf{A}^2)_{ij}^{rv} + (\mathbf{A}^3)_{ij}^{rv} \dots) f_j^{vs^*} \\
&= \sum_{r=1}^M \sum_{i=1}^N \sum_{v=1}^M \sum_{j=1}^N q_i^{wr} d_i^r (I_{ij}^{rv} + a_{ij}^{rv} + \sum_{t=1}^M \sum_{k=1}^N a_{ik}^{rt} a_{kj}^{tv} + \sum_{u=1}^M \sum_{t=1}^M \sum_{l=1}^M \sum_{k=1}^N a_{il}^{ru} a_{lk}^{ut} a_{kj}^{tv} + \dots) f_j^{vs^*} \\
&= \sum_{r=1}^M \sum_{i=1}^N q_i^{wr} d_i^r f_i^{rs^*} + \sum_{r=1}^M \sum_{i=1}^N \sum_{v=1}^M \sum_{j=1}^N q_i^{wr} d_i^r a_{ij}^{rv} f_j^{vs^*} + \sum_{r=1}^M \sum_{i=1}^N \sum_{t=1}^M \sum_{k=1}^N \sum_{v=1}^M \sum_{j=1}^N q_i^{wr} d_i^r a_{ik}^{rt} a_{kj}^{tv} f_j^{vs^*} + \dots
\end{aligned} \tag{10}$$

The second term on the right-hand side of Eq. (10), $q_i^{wr} d_i^r a_{ij}^{rv} f_j^{vs^*}$, quantitatively expresses the health impacts on country w due to PM_{2.5} emitted by the production of

intermediate goods by industry i of country r that is necessary for the products produced by industry j of country v in order to satisfy final demand in country s^* . In other words, from the second term on the right-hand side of Eq. (10), it is possible to quantify supply chain paths such as “final demand in country s^* (i.e., consumption driver country)” $\rightarrow$ “industry j of country v (transmission country)” $\rightarrow$ “industry i of country r (emission source country)” $\rightarrow$ “health impacts on country w (impact receptor country)”.

3.3. Data and computation

We used the Asian International Input–Output Table (AIIOT) for 2005 provided by the Institute of Developing Economies Japan of the External Trade Organization (IDE-JETRO). AIIOT is a multi-regional input–output table covering 10 countries and regions (Indonesia (IDN), Malaysia (MYS), the Philippines (PHL), Singapore (SGP), Thailand (THA), China (CHN), Taiwan (TWN), South Korea (KOR), Japan (JPN), and the United States (USA)) and 76 industry sectors (see Table S3-1 of *Appendix*). This study thus considers 760 specific sectors.

Considering that there are 760 sectors in our input–output framework, the computation for key sector analysis formulated by Eqs. (4) and (5) or Eqs. (6) and (7) is relatively easy compared to the huge computation for the structural path analysis formulated by Eqs. (9) and/or (10). The number of supply chain paths in the first tier expressed by the first term on the right-hand side of Eq. (10) is $76 \times 10 = 760$, the number of paths in the second tier is $76^2 = 577600$, and the number in the n^{th} tier is 760^n . However, the contribution of total emissions at a given tier rapidly declines as the tier number increases. For the purposes of this study, therefore, we set a threshold in order to disregard supply chain paths that account for less than 0.001% of total $\text{PM}_{2.5}$ emissions. As a result, our computation only considers paths up to the 10^{th} tier.

This study also makes use of data on $\text{PM}_{2.5}$ emissions by sector and SRR matrix in accordance with the international input–output table for Asia estimated by our previous study (see Tables S3-2 to S3-14 of *Appendix*). It should be noted that the SRR matrix

was estimated by using an atmospheric transport model with a focus on the Asian countries (Nishizawa *et al.*, 2012; Skamarock *et al.*, 2008). Modelling simulations were conducted using the Weather Research and Forecasting (WRF) modeling technique (Skamarock *et al.*, 2008) and the Community Multiscale Air Quality (CMAQ) modeling system (Byun and Schere, 2006) with Regional Emission inventory in ASia (REAS) (Ohara, 2007) to determine the yearly averaged regional concentrations of BC and OC emitted from four sectors (power plant, industry, transport, and agriculture) in East and Southeast Asia (Tables S3-12 to S3-14 of Appendix). The human health effects (i.e., premature deaths in persons) arising from the pollution concentrations were estimated by using the concentration-response function (Environmental Benefits Mapping and Analysis Program, 2012), population-weighted annual mean concentration, annual baseline mortality rate, and exposed population. Since we could not obtain PM_{2.5} emissions data and SRR data by U.S. industry sector consistent with the industry classification of the AIIOT, the PM_{2.5} emissions and health impacts in the United States associated with the final demand in other countries were not estimated in this study.

3.4. Result

3.4.1. Consumption-based analysis

We first calculated the consumption-based PM_{2.5} emissions of a given driver country s^* using Eq. (2). The total amount of the consumption-based PM_{2.5} emissions in the major Asian nine countries (Indonesia, Malaysia, the Philippines, Singapore, Thailand, China, Taiwan, South Korea, and Japan) through the final demands of those countries, and the United States and exports to the rest of the countries and regions (Hong Kong, India, EU, and the rest of the world) was 1.6 million tonnes in 2005. China had the largest share of these consumption-driven emissions, driving 53% of total emissions, followed by Japan, Indonesia, and Thailand, contributing 8%, 7.5%, and 6.5%, respectively.

As in the embodied carbon transfer literature (e.g., Peters *et al.*, 2011), a crucial question is whether the final demand in a specific driver country has affected PM_{2.5} emissions in other Asian countries via international trade. From the result of consumption-based PM_{2.5} emissions, we computed a breakdown of the PM_{2.5} emissions in each source country associated with final demand in each driver country (Figure 3-1). Figure 3-1 shows that, of China's consumption-based emissions, 98% are generated within China (see Figure S3-1 in the SI for the consumption-based emissions). The PM_{2.5} emissions of other countries induced by final demand in China (that is, the emissions transfer of China) amount to just 16,000 tonnes, or a low 2% of consumption-based emissions, indicating that final consumers in China have a relatively low environmental impact on other Asian countries.

Using the results shown in Figure 3-1, the bilateral net emission transfer from country A to country B is easily calculable by $PM_{2.5}$ emissions of country B induced by final demand of country A minus $PM_{2.5}$ emissions of country A triggered by final demand of country B. A positive net emission transfer indicates that country A is more responsible for the emissions in country B. Figure 3-2 shows the $PM_{2.5}$ emissions of each country triggered by final demand of the nine Asian countries and the United States and net emission transfers arising from the consumption-based emissions. Figure 3-2 shows that Japan is currently transferring a large quantity, 32789 tonnes, of its $PM_{2.5}$ emissions to other Asian countries. The biggest recipient of Japan's emissions transfer is China, which is followed by Thailand. Thus, Japan plays a crucial role in emitting $PM_{2.5}$ in Asia through the supply chains.

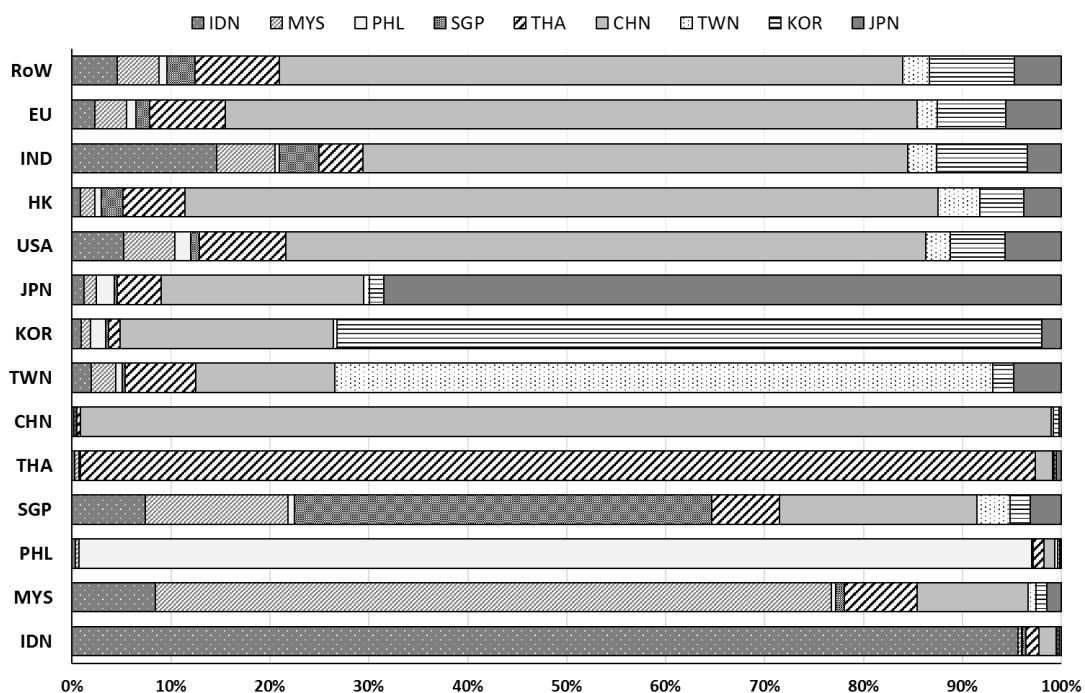


Figure 3-1 $PM_{2.5}$ emissions (horizontal axis) from source countries driven by final demand in driver countries (vertical axis). Note that the $PM_{2.5}$ emissions in the U.S. are not included in this figure.

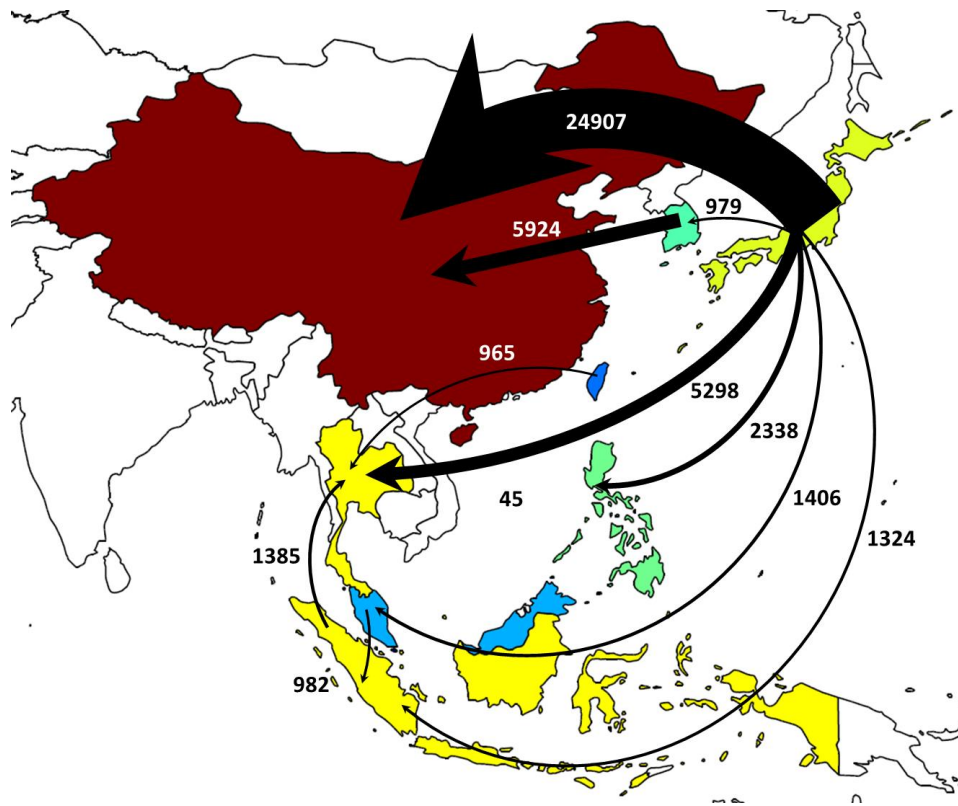


Figure 3-2 PM_{2.5} emissions (tonnes) of each country triggered by final demand of the Asian nine countries and the U.S. and net emission transfers (tonnes) arising from the consumption-based emissions. The background color shows the common logarithms of the consumption-based emissions and the arrows show the top 10 bilateral net transfers of consumption-based emissions.

It is important to note that when addressing the health impact problem associated with PM_{2.5} emissions, we need to distinguish between pollution within countries and cross-border pollution arising from consumption-based emissions. The health impacts (specifically, as measured by the number of premature deaths) due to consumption-based emissions can be estimated using Eq. (3). First, we found that there were 26,000 premature deaths in total in the nine Asian countries for the year 2005, of which China accounted for 75%, demonstrating that China's final demand has an extremely large

impact on air pollution in Asia.

From Eq. (3), we further estimated the number of premature deaths in each country due to cross-border $PM_{2.5}$ emissions associated with final demand in each country. Figure 3-3 shows a breakdown of the number of premature deaths in different receptor countries due to $PM_{2.5}$ emissions that originate from final demand in different driver countries (vertical axis). This figure clearly shows that the country most affected by $PM_{2.5}$ resulting from final demand in China is China itself. This is because almost all of the $PM_{2.5}$ originating from final demand in China is emitted within China, as shown by Figure 3-1. Of other Asian countries, Japan has the most premature deaths, those of 177 persons, attributable to $PM_{2.5}$ emissions originating from final demand in China, whereas the final demand of Japan led to the premature deaths of 644 persons in China. In other word, Japan transferred the $PM_{2.5}$ -induced mortality amounting to the premature deaths of 468 persons to China (Figure 3-4). Looking at the consumption-based health impacts, South Korea also transferred approximately 126 premature deaths to China (Figure 3-4). Although it seems that the impact of cross-border pollution in South Korea and Japan due to $PM_{2.5}$ emissions generated in China is substantial, the health impact in China arising from $PM_{2.5}$ emissions associated with final demand in South Korea and Japan should also be paid more attention (Figure 3-4).

The complexity in atmospheric transport leads to a difference in spatial distribution between $PM_{2.5}$ emissions and health impacts associated with them. We note a few particular cases where this disconnect has an effect: just 4% of Indonesian-consumption-induced emissions occur abroad, yet 28% of the associated mortality occurs abroad.

Similarly for Malaysia, 32% of consumption-induced emissions occur abroad, whereas 92% of the associated mortality occurs abroad.

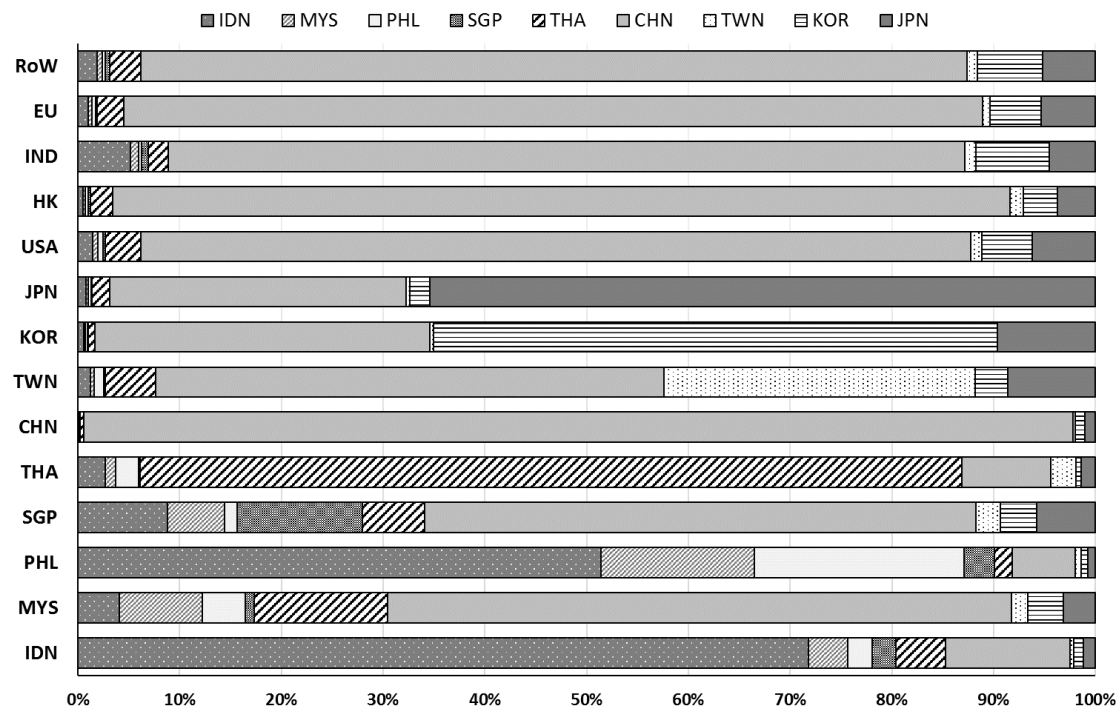


Figure 3-3 Premature deaths due to PM_{2.5} emissions attributable to final demand in driver countries (vertical axis). Note that premature deaths due to PM_{2.5} emissions in the U.S. are not included in this figure.

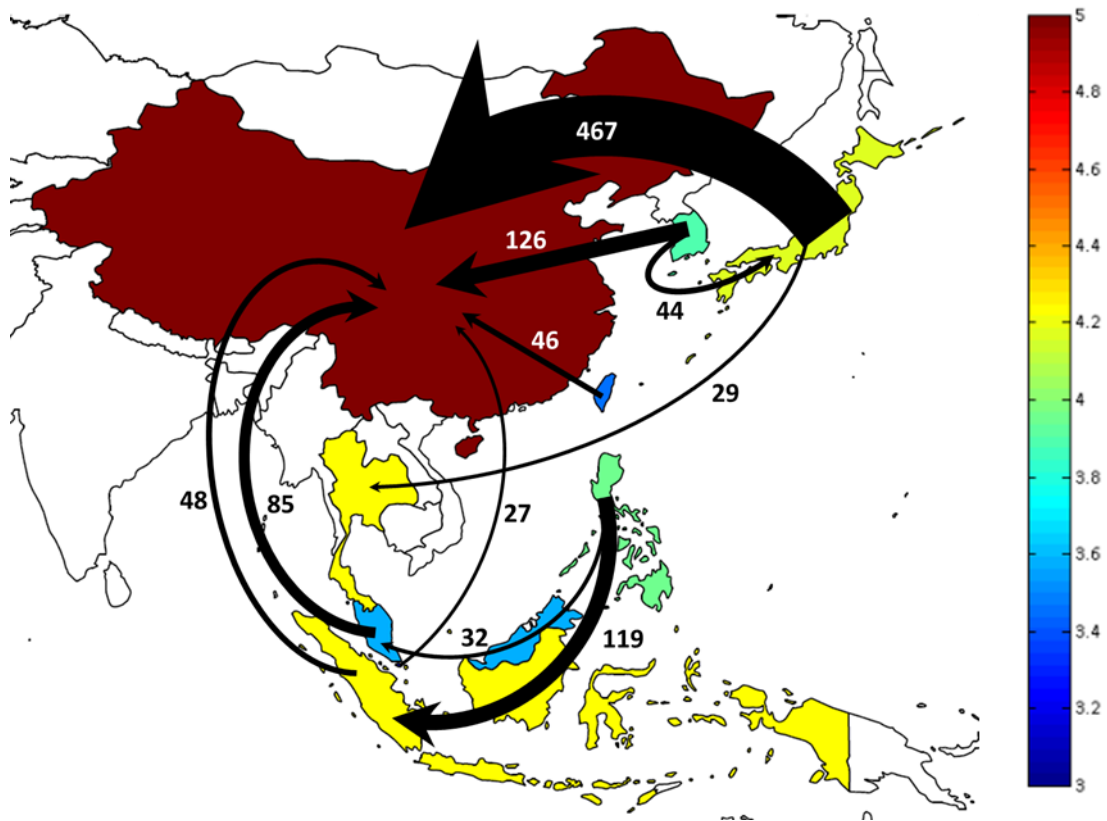


Figure 3-4 PM_{2.5} emissions of each country triggered by final demand of the Asian nine countries and the U.S. and net health impact transfers (i.e., premature mortality in persons) arising from the consumption-based emissions. The background color shows the common logarithms of the consumption-based emissions and the arrows indicate top 10 net health impact transfers from consumption-based emissions.

3.4.2. Key sectors

Although the results of consumption-based emissions and health impacts described in the previous section are important for understanding how a specific country contributes to the emissions and impacts in that and other countries, those results do not provide any policy guidance for mitigating air pollutions. It would be useful for policy makers in a specific Asian country and/or the Southeast Asian community (i.e., Association of South–East Asian Nations: ASEAN) to identify high-priority industrial sectors and critical supply chains in terms of influence on the air pollution in Asia.

We identified high-priority sectors with high power of dispersion and high sensitivity of dispersion using the key sector analysis described in the Methods section. A high power of dispersion indicates that an increase in the final demand of a specific sector has considerable health impacts throughout the “upstream” productions in Asian supply chains. On the other hand, a high sensitivity of dispersion in a sector indicates that increased final demand of all other sectors has considerable health impacts throughout the production of that sector. Table 3-1 shows the top 10 sectors ranked by power of dispersion for 2005. This table highlights that the Asian health impacts tend to increase due to increases in the final demand of “Other grain of Thailand ($\widetilde{PD}_j^s$:129.46)”, “Iron ore of Japan ($\widetilde{PD}_j^s$:65.61)”, “Other grain of China ($\widetilde{PD}_j^s$:43.21)”, “Food crops of Thailand ($\widetilde{PD}_j^s$:24.79)”, and “Other metallic ore of Japan ($\widetilde{PD}_j^s$:21.01)” (see the unweighted index of power of dispersion in Table 3-1 and/or Figure 3-5). An important finding is that if we consider the relative importance of sectoral final demand, the Chinese sectors such as Building construction and Other

grain are ranked among the top 10 sectors (see the weighted index of power of dispersion in Table 3-1). Consequently, these high-ranking sectors can be considered the environmentally important sectors which strongly affect the air pollution through the Asian supply chains. It should be noted that the positions of the high-ranking sectors in terms of sensitivity of dispersion do not change considerably (Table 3-2 and/or Figure 3-5). For the weighted index of sensitivity of dispersion, “Transportation of South Korea” is among the top 10 sectors (Table 3-2).

Any pollution abatement measures employed in these key sectors showing high indices of power of dispersion and sensitivity of dispersion, especially Building construction of China, Other grain of China, and Livestock and poultry of China, are crucial in reducing health impacts arising from the PM_{2.5} emissions throughout the entire economy. For the top-ranked key sectors, it is crucial to monitor the impact of technological changes and support alternative technologies that use less pollution-intensive materials and achieve higher energy efficiencies.

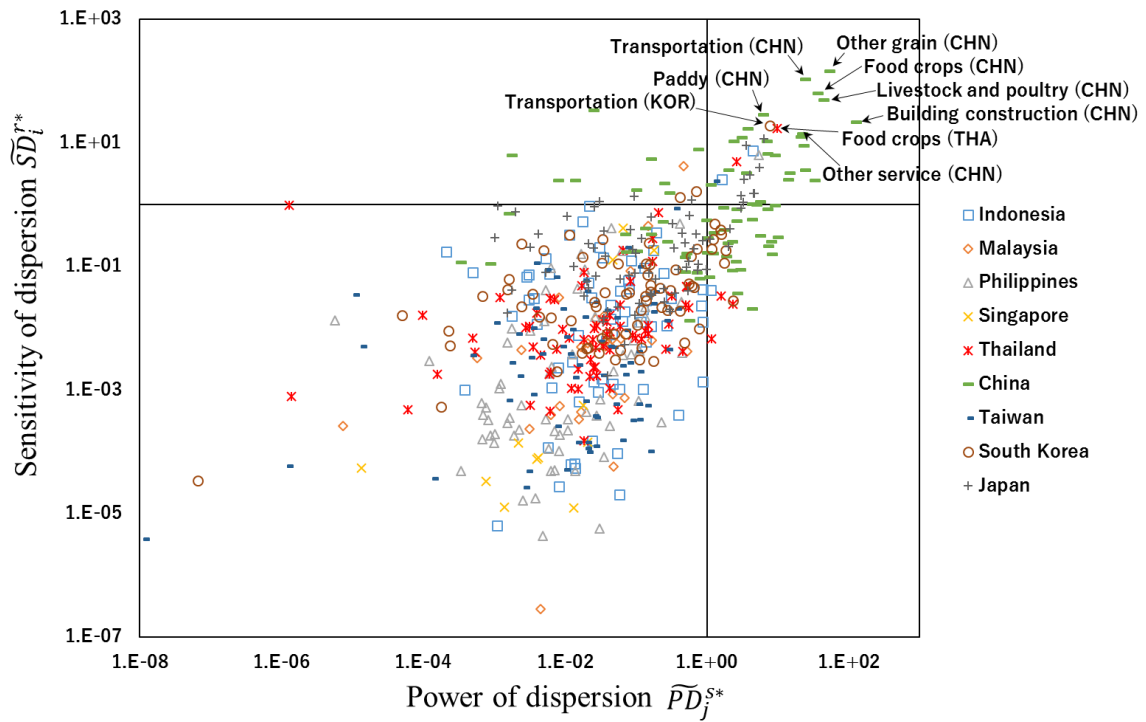


Figure 3-5 Relationship between power of dispersion and sensitivity of dispersion in health impacts arising from PM_{2.5} emissions

Table 3-1 Top 10 sectors ranked in terms of power of dispersion (backward linkages effect) in consumption-based health impacts in 2005

Unweighted index of power of dispersion				Weighted index of power of dispersion			
Rank	$\bar{PD}_j^s$	Country	Industry	Rank	$\bar{PD}_j^{s*}$	Country	Industry
1	129.46	Thailand	Other grain	1	125.22	China	Building construction
2	65.61	Japan	Iron ore	2	53.01	China	Other grain
3	43.21	China	Other grain	3	43.69	China	Livestock and poultry
4	24.79	Thailand	Food crops	4	36.32	China	Food crops
5	21.01	Japan	Other metallic ore	5	33.03	China	Other food products
6	14.32	Malaysia	Food crops	6	24.33	China	Transportation
7	13.56	China	Paddy	7	24.06	China	Other construction
8	12.28	Philippines	Food crops	8	23.03	China	Public administration
9	9.53	China	Food crops	9	22.16	China	Other service
10	7.62	Malaysia	Paddy	10	21.13	China	Education and research

Table 3-2 Top 10 sectors ranked in terms of sensitivity of dispersion (forward linkages effect) in consumption-based health impacts in 2005

Unweighted index of sensitivity of dispersion				Weighted index of sensitivity of dispersion			
Rank	$\bar{SD}_j^s$	Country	Industry	Rank	$\bar{SD}_j^{s*}$	Country	Industry
1	129.59	Thailand	Other grain	1	144.89	China	Other grain
2	79.25	China	Other grain	2	109.50	China	Transportation
3	65.47	Japan	Iron ore	3	64.76	China	Food crops
4	46.60	China	Transportation	4	50.32	China	Livestock and poultry
5	44.49	Thailand	Food crops	5	33.93	China	Iron and steel
6	33.02	Malaysia	Food crops	6	29.05	China	Paddy
7	21.24	Japan	Other metallic ore	7	21.78	China	Building construction
8	20.15	China	Food crops	8	19.15	Korea	Transportation
9	19.86	Korea	Transportation	9	17.18	China	Other non-metallic mineral products
10	19.32	China	Paddy	10	16.97	Thailand	Food crops

3.4.3. Critical supply chain paths

Although the key sector analysis is useful for identifying the high-priority sectors that have contributed to the health impacts in Asia and for formulating an effective mitigation policy aimed at the identified sector, this analysis method was unable to determine which supply chain paths in complex production networks make the greatest contribution to the increase in premature deaths due to air pollution. In this section, we therefore employed structural path analysis (SPA) to try to break down these consumption-based health impacts for different supply chain paths, extending from final demand to producers and including cross-border pollution. We go on to discuss an additional mitigation policy from the point of view of supply chain engagement.

Table 3-3 shows the top 30 supply chain paths ranked by the health impacts among the Asian supply chains. The path ranked as No. 1 here, CHN→CHN.2→CHN, shows that PM_{2.5} emitted from a given industry sector originating from final demand in China (driver country) for China's "Other grain" (No. 2) sector has health impacts on China (receptor country). The PM_{2.5} emissions and pollution (within China) generated throughout this supply chain path induced 1,530 premature deaths within China. The health impacts of PM_{2.5} generated as a result of final demand for pollution-intensive agricultural industry sectors such as "Paddy" (No. 1), "Other grain" (No. 2), "Food crops" (No. 3), and "Livestock and poultry" (No. 5) are striking. Other high-ranking paths shown in Table 3-3 that are centered on agricultural activities are CHN→CHN.15→CHN.3→CHN, CHN→CHN.12→CHN.2→CHN, and CHN→CHN.15→CHN.2→CHN, revealing that direct and indirect PM_{2.5} emissions from the production of agricultural products that serve as

inputs for the production of “Milled grain and flour” (No. 12) and “Other food products” (No. 15) also exert a large influence on health.

Direct emissions arising from final demand for China’s “Building construction” (No. 63) sector also account for a large number of premature deaths (Table S3-1). Interestingly, the fact that the paths $CHN \rightarrow CHN.63 \rightarrow CHN.2 \rightarrow CHN$, $CHN \rightarrow CHN.63 \rightarrow CHN.3 \rightarrow CHN$, and $CHN \rightarrow CHN.64 \rightarrow CHN.2 \rightarrow CHN$ are all ranked highly in Table 3-3 shows that transactions between construction sectors (e.g., “Building construction”, No. 63, and “Other construction”, No. 64) and agricultural sectors (e.g., “Paddy”, “Other grain”, and “Food crops”) are comparatively pollution intensive. In addition to agriculture-related activities, we can note that construction gives rise to substantial $PM_{2.5}$ emissions in the “Transportation” (No. 66) sector; these emissions have large health impacts on people within China. From this, we see that as capital formation continues in China, the adverse health impacts of direct and indirect $PM_{2.5}$ emissions and other forms of air pollution from pollution-intensive transport and agriculture-related activities are likely to increase.

Table 3-4 shows the top 30 supply chain paths that have relatively large health impacts on Asian countries other than the driver country as a result of final demand in a specific driver country. The path having the greatest impact is $PHL \rightarrow PHL.3 \rightarrow IDN$, and we can note that the contribution of final demand in Philippines on food crops in Philippines accounts for 102 premature deaths in Indonesia. As shown for the paths ranked Nos. 1 and 3 in Table 3-4, direct and indirect $PM_{2.5}$ emissions resulting from the “Food crops” (No. 3) sectors in Philippines in particular are widely dispersed, as far as Indonesia and Malaysia, to cause crucial health problems in these countries.

In addition, the relationship shown in the 2nd-ranked path in Table 3-4, USA→CHN.66→CHN, indicates that PM_{2.5} emissions from transportation in China due to final demand in the United States have health impacts on people in China, by way of territorial air pollution.

As shown in the 13th-ranked path, CHN→CHN.2→JPN, while the influence of final demand in China on China's agricultural and transportation sectors has an impact on the health of people within China (Table 3-3), it also contributes to an increase in premature deaths in neighboring countries such as Japan, as a result of cross-border pollution.

From Table 3-4, of these top 30 paths, 22 start with final demand in one of the other eight geographically close Asian countries, whereas the remaining 8 paths (30%) start with final demand in the geographically very distant United States, demonstrating that the United States is a major driver country for air pollution in China (Table 3-4). More specifically, we can say that much of the air pollution in China is driven by the purchase by Americans of Chinese-made industrial products such as those in the "Other manufacturing products" (No. 60) sectors, as well as those in the "Weaving and dyeing" (No. 19) and "Leather and leather products" (No. 23) sectors.

As exemplified by the paths JPN→CHN.66→CHN and KOR→KOR.15→CHN.3→CHN, some supply chain paths give rise to pollution within China by PM_{2.5} emissions generated within China due to direct and indirect demand for industrial activity in China, whereas other supply chain paths, such as KOR→KOR.66→CHN, result in cross-border

pollution through PM_{2.5} emissions generated in other countries (South Korea in this case).

From Table 3-4, we see that the health impacts on China of cross-border pollution occur most notably as a result of emissions from industrial activity in neighboring countries such as Japan, South Korea, Taiwan, and Thailand (in particular from transportation).

Table 3-3 Top 30 supply chain paths ranked in terms of health impacts in Asia

Premature Deaths (persons)	Driver Country	Path	Receptor Country
1530	CHN	→ CHN.2	→ CHN
875	CHN	→ CHN.3	→ CHN
730	CHN	→ CHN.5	→ CHN
693	CHN	→ CHN.63→CHN.2	→ CHN
619	CHN	→ CHN.63	→ CHN
473	CHN	→ CHN.66	→ CHN
351	CHN	→ CHN.70	→ CHN
276	CHN	→ CHN.75	→ CHN
264	CHN	→ CHN.63→CHN.66	→ CHN
259	THA	→ THA.3	→ THA
211	CHN	→ CHN.63→CHN.40	→ CHN
207	CHN	→ CHN.63→CHN.3	→ CHN
173	CHN	→ CHN.74	→ CHN
160	CHN	→ CHN.1	→ CHN
159	CHN	→ CHN.69	→ CHN
155	CHN	→ CHN.5→CHN.2	→ CHN
147	CHN	→ CHN.15→CHN.3	→ CHN
139	CHN	→ CHN.63→CHN.38	→ CHN
138	CHN	→ CHN.63→CHN.1	→ CHN
135	JPN	→ JPN.66	→ JPN
133	CHN	→ CHN.7	→ CHN
132	CHN	→ CHN.64→CHN.2	→ CHN
122	KOR	→ KOR.66	→ KOR
117	CHN	→ CHN.12→CHN.2	→ CHN
116	CHN	→ CHN.66→CHN.41	→ CHN
104	CHN	→ CHN.15→CHN.2	→ CHN
102	CHN	→ CHN.15→CHN.1	→ CHN
102	PHL	→ PHL.3	→ IDN
101	CHN	→ CHN.64	→ CHN
97	IDN	→ IDN.2	→ IDN

Table 3-4 Top 30 supply chain paths ranked in terms of health impacts in other countries due to emissions attributable to final demand of a specific driver country

Rank	Premature Deaths (persons)	Driver Country	Path	Receptor Country
1	102	PHL	→ PHL.3	→ IDN
2	48	USA	→ CHN.66	→ CHN
3	30	PHL	→ PHL.3	→ MYS
4	27	KOR	→ KOR.15→CHN.3	→ CHN
5	25	KOR	→ KOR.66	→ CHN
6	25	JPN	→ CHN.66	→ CHN
7	19	KOR	→ KOR.66	→ JPN
8	17	CHN	→ KOR.66	→ KOR
9	16	JPN	→ CHN.74	→ CHN
10	13	KOR	→ KOR.12→CHN.12	→ CHN
11	12	USA	→ KOR.66	→ KOR
12	12	TWN	→ TWN.66	→ CHN
13	12	CHN	→ CHN.2	→ JPN
14	10	USA	→ CHN.60→CHN.5	→ CHN
15	10	THA	→ THA.3	→ IDN
16	9	THA	→ THA.3	→ TWN
17	9	THA	→ THA.3	→ PHL
18	8	MYS	→ MYS.3	→ CHN
19	8	IDN	→ IDN.3	→ MYS
20	8	THA	→ THA.66	→ CHN
21	8	USA	→ CHN.19→CHN.2	→ CHN
22	7	CHN	→ CHN.2	→ KOR
23	7	USA	→ CHN.65	→ CHN
24	7	USA	→ JPN.66	→ JPN
25	7	CHN	→ CHN.3	→ JPN
26	7	JPN	→ JP.15→CHN.2	→ CHN
27	7	JPN	→ JPN.66	→ CHN
28	7	IDN	→ IDN.3	→ TWN
29	6	USA	→ CHN.23→CHN.5	→ CHN
30	6	USA	→ CHN.66→CHN.66	→ CHN

3.4.4. Direct $PM_{2.5}$ emissions from the household sector of countries

For the direct emissions from the household sector of countries g^{s*} , China is the largest emitter among the nine Asian countries examined, accounting for about four times the consumption-based emissions of China, an amount equivalent to 3.75 million tonnes in 2005 (Table S3-11). A detailed look at the source of emissions shows that 0.86 million tonnes of these emissions are generated by industries in China to meet final demand of China, whereas 3.75 million tonnes are direct emissions by the household sector. The number of premature deaths in China triggered by the direct emissions from the household sector of China is much more important than that of those triggered by the industrial emissions associated with final demand of China. Thus, energy consumption by the household sector (e.g., by the burning of biomass) has a much greater impact on air pollution than energy consumption by industry. As in previous studies (Yan *et al.*, 2011; Shan *et al.*, 2015), in developing measures to combat air pollution in China and the whole of East Asia, the higher priority should be cutting pollution from China's household sector, by reducing reliance on carbon-based fuels for heating equipment.

3.4.5. Comparison between this study and Anenberg *et al.* (2011)

A seminal article by Anenberg *et al.* (2011) reported that the total of territorial BC emissions (industrial BC emissions plus residential BC emissions) in five East Asian countries (China, Japan, South Korea, North Korea, and Mongolia) was 1800 Gg-C in 2000 (Fig. 1 in Anenberg *et al.* (2011)), whereas the BC emission inventory database used in the present study (Takahashi *et al.*, 2014) shows that the total of territorial BC emissions in only three of these East Asian countries (China, Japan, and South Korea) was 1419 Gg-C in 2005 (Figure S3-2). Although study year and country coverage differ between the two studies, we can see that the annual BC emissions in East Asia constituted more than 1400 Gg-C during 2000 to 2005.

Anenberg *et al.* (2011) also found that the number of avoidable premature deaths per unit of territorial BC emissions was 80 persons/Gg-C in five East Asian countries, whereas our consumption-based accounting analysis shows that the number of avoidable premature deaths per unit of consumption-based BC emissions was 25 persons/Gg-C in three East Asian countries, which is considerably less. We see that this difference in health impact is caused by the parameter settings in the atmospheric simulation models employed in Anenberg *et al.* (2011) and Takahashi *et al.* (2014). Anenberg *et al.* (2011) used the MOZART-4 simulation model configured with a horizontal grid resolution of 200 km and daily concentration estimates, whereas Takahashi *et al.* (2014) used the Community Multiscale Air Quality (CMAQ) modeling system (Byun and Schere, 2006) configured with a horizontal grid resolution of 80 km and seasonal concentration estimates. It is very difficult to examine the differences between these model-oriented results and such a sensitivity analysis over simulation models and a wide range of

parameter settings is beyond the scope of the present paper, but remains as important future work. The absolute magnitude of health impacts is uncertain due to simulation settings, but it is nevertheless important to note that the present study could identify environmentally important supply chain paths and key sectors that have made relatively large contributions to air pollution in East Asian countries.

3.5. Discussion and Conclusion

The results of this study revealed that the supply chain paths with the greatest impact on human health in the Asia region are centered around agricultural activities in China (involving for example, the key sectors of “Paddy”, “Other grain”, and “Food crops”) and construction activities in China. The main cause of emissions from China’s agricultural sector is the incineration of straw, stalks, and other crop residues after harvest. The incineration of rice straw and wheat straw in rural areas makes a particularly large contribution to pollution. Thus, the most important approach to cutting PM_{2.5} emissions across the whole of Asia is for the Chinese government to implement policies and regulations in rural China that promote the recycling of straw, stalks, and other crop residues (e.g., by converting them to livestock feed or bioethanol) and prevent or limit the incineration of such waste. Not only in China but in Thailand and Malaysia, identified as key sectors in Tables 3-1 and 3-2, the highest priority mitigation policy is to aid in the change from pollution-intensive agriculture technologies in other grain and food crops to more environmentally friendly technologies. The related technological improvements would contribute to reducing PM_{2.5} emissions through the entire global supply chains.

The transportation sector, which serves to move products across supply chain networks, also plays a major role in air pollution, as a hub of supply chain paths that generate relatively large quantities of PM_{2.5} emissions (Table 3-3). Of the nine Asian countries analyzed, the transportation sectors of Thailand and China both have relatively high values of PM_{2.5} emissions per unit of output (i.e., are emissions intensive), with values of 1.2 and 0.6 tonnes/million USD, respectively. The corresponding value for Japan is a low

0.06 tonnes/million USD, which means that China's transportation sector is about 10 times more emissions intensive than that of Japan. This wide disparity can be explained by the fact that, whereas Japan's cars, trucks, and other motor vehicles are technically advanced and fuel-efficient, in line with the country's highly developed economy, huge numbers of energy-inefficient, emissions-intensive motor vehicles continue to be used for transportation on China's roadways. In countries like China and Thailand, an effective policy can be a vehicle replacement scheme, replacing older cars that have lower fuel efficiency with greener cars that have higher fuel efficiency, that has been introduced in many developed countries (Kagawa *et al.*, 2013). The results regarding the transportation section also suggest that an important goal for cutting emissions of air pollutants across Asia is to reduce emissions across all of East Asia's supply chains through the adoption of highly efficient transportation technologies like those of Japan, most urgently in China and Thailand.

Figures 3-2 and 3-4 clearly show that Japan has triggered PM_{2.5} emissions and PM_{2.5}-induced human health impacts in Asia through the supply chain network. We conclude that the Japanese government should positively support Asian countries in changing key high-priority technologies and critical supply chain paths into greener ones.

Lastly, as mentioned in Section 4.4, as its highest priority, the Chinese government should implement a more aggressive policy to cut pollution from China's household sector by replacing carbon-based fuels with environmentally friendly heating equipment.

Chapter 4: Critical Structural Paths of Residential PM_{2.5} Emissions within the Chinese Provinces

4.1. Introduction

Fine particulate matter 2.5 micrometers or less in aerodynamic diameter (hereafter PM_{2.5}) causes a variety of adverse environmental impacts such as air quality degradation and climate change and affects human mortality rates. As noted in OECD (2012), air pollution will be the largest risk for premature deaths in the world if no air pollutant mitigation policy is implemented. This underscores the need to prevent air pollution. With its rapid economic growth, China has become one of the huge anthropogenic PM_{2.5} emitters of the world (Huang *et al.*, 2014). The large amount of PM_{2.5} emissions and precursors emitted from China affects human health not only in China but also in neighboring countries via trans-boundary air pollution (Takahashi *et al.*, 2014; Zhang *et al.*, 2017).

Consumption-based emission analysis (Davis and Caldeira, 2010; Peters, 2008) is a powerful tool for understanding the main drivers of environmental loads from the demand side. Recent studies using this approach and Multiregional Input-Output (MRIO) modelling have revealed that a considerable part of PM_{2.5} emissions and premature deaths associated with those emissions in China were triggered by consumer demand outside China (Guan *et al.*, 2014; Huo *et al.*, 2014; Lin *et al.*, 2014; Takahashi *et al.*, 2014; Meng *et al.*, 2015; Li, Meng *et al.*, 2016; Moran and Kanemoto, 2016; Nagashima *et al.*, 2017; Zhang *et al.*, 2017). This is despite domestic final demand within China itself dominating

the health impacts induced by its PM_{2.5} emissions.

For example, Zhang *et al.* (2017) combined consumption-based emissions with the physical transport of air pollutants in the atmosphere using a global MRIO database and chemical transport model, and estimated that the number of deaths in China associated with PM_{2.5} emissions related to its own consumption (770 thousand people) is more than three times larger than that due to other regions' consumption of Chinese products. With similar demand-driven emission approaches, some previous studies have applied key sector analysis and structural path analysis (SPA). Such approaches allow exploration of important supply chain paths that contribute to overall environmental and health impacts within the complex supply chain. These studies have identified key factors for effective PM_{2.5} mitigation strategies (Meng *et al.*, 2015; Nagashima *et al.*, 2017).

Although these consumption-based exercises have provided beneficial information for understanding the key 'industries' driving the huge life-cycle PM_{2.5} emissions, they treated the 'residential sector', which is the largest emitter of carbonaceous aerosols (Liu *et al.*, 2016) exogenously and neglected it in the structural path analysis.

Residential PM_{2.5} emissions in China originate from the incomplete combustion of fossil fuel and biomass, mainly wood and crop residues (Zheng and Smith, 2007) used for heating and cooking. Lu *et al.* (2011) illustrated that the residential sector in China contributed 50% of domestic anthropogenic black carbon and 69% of organic carbon emissions in 2010 even though the sector's energy consumption accounts for merely 18% of the country's total. Furthermore, Li, Li *et al.* (2016) shows that primary PM_{2.5}

emissions from household coal combustion have contributed more than 50% of total emissions from all coal consumption in China since 2009. The characteristics of regional PM_{2.5} emissions differ between urban and rural areas (Kurokawa *et al.*, 2013). This is due to differing household income and expenditure structures in each region as well as to the regions' geography. In implementing a PM_{2.5} mitigation policy that effectively reduces residential PM_{2.5} emissions, it is crucial to understand the interaction between income flow and residential PM_{2.5} emission associated with household energy consumption.

Prominent work by Miyazawa and Masegi (1963) made it possible to describe the endogenous relationship between income flow and household consumption. With the endogenous input-output modelling technique they proposed, we can model the infinite consumption→production→income cycle in an economic system. This study aims to extend the endogenous input-output system by incorporating industrial and residential PM_{2.5} emissions into the consumption→production→income process. As in Defourny and Thorbecke (1984), we further formulate a structural path analysis based on an endogenous input-output model considering the PM_{2.5} emissions from the production→income→consumption→residential chain of relationships as well as income→consumption→production→industrial PM_{2.5} emissions.

As a case study, this paper focuses on PM_{2.5} emissions in the Chinese provinces in 2007 and estimates the 'residential' PM_{2.5} emissions embodied in the final demand (except for household consumption) of a specific Chinese province using an endogenous input-output model. We further reveal environmentally-critical structural paths with higher PM_{2.5} inducements in the Chinese provincial economies. To the best of our

knowledge, this study is the first attempt to identify high priority paths significantly affecting ‘residential’ PM_{2.5} emissions in China. Finally, we make a case for the Chinese government establishing a PM_{2.5} reduction policy targeting high priority paths.

This paper is organized as follows: Section 2 explains the methodology, Section 3 describes the data used in this study, Section 4 provides the results and a discussion, and Section 5 concludes the paper.

4.2. Methodology

4.2.1 Consumption-based residential $PM_{2.5}$ emissions

The output vector $\mathbf{x}[ri \times 1] = (x_i^r)$ ($r=1, \dots, M$, $i=1, \dots, N$) in a Multi-Regional Input–Output (MRIO) analysis with N industries and M regions can be expressed as a linear equation: $\mathbf{x} = \mathbf{Ax} + \mathbf{H}\mathbf{1} + \mathbf{F}\mathbf{1}$ where $\mathbf{H}[ri \times k] = (h_i^{rk})$ and $\mathbf{F}[ri \times k] = (f_i^{rk})$ ($k=1, \dots, M$) are the matrix of household consumption (i.e., residential consumption of goods and services) and the matrix of final demand other than household consumption (i.e., final demand of government consumption, gross fixed capital formation and change in inventories), respectively. More specifically, h_i^{rk} and f_i^{rk} are household consumption and other final demand in income group k for the products produced in industry i of region r . $\mathbf{A}[ri \times sj] = (Z_{ij}^{rs}/x_j^s) = (a_{ij}^{rs})$ ($r, s=1, \dots, M$, $i, j=1, \dots, N$) is the input coefficient matrix expressing the intermediate input for industry i of region r that is necessary to produce one unit of the product created by industry j of country s , for which Z_{ij}^{rs} represents the intermediate input into industry j of region s from industry i of region r , and $\mathbf{1}$ is a vector of ones.

The household consumption vector of final demand countries is calculable as $\mathbf{h}[ri \times 1] = \mathbf{H}\mathbf{1} = \sum_{s=1}^M h_i^{rk}$. It can be transformed further into $\mathbf{h} = \mathbf{CVx}$, where $\mathbf{V}[k \times sj] = (y_j^{ks}/x_j^s) = (v_j^{ks})$ ($k=1, \dots, M$) is the labor income coefficient matrix in which $\mathbf{Y}[k \times sj] = y_j^{ks}$ is the labor income matrix flowing from industry j of region s to income group k described in value added of the MRIO and x_j^s is the gross output of industry j of region s . $\mathbf{C}[ri \times k] = (h_i^{rk}/y^k) = (c_i^{rk})$ is the consumption coefficient matrix obtained

by dividing the household consumptions of income group k by the total income of income group k , where $y^k = \sum_{s=1}^M \sum_{j=1}^N y_j^{ks}$. The final demand vector $\mathbf{f}$ can be expressed as the sum of the final demand vectors of each demand country, $\mathbf{f}[ri \times 1] = \mathbf{F}\mathbf{1} = \sum_{k=1}^M f_i^{rk}$. Substituting $\mathbf{h} = \mathbf{CV}\mathbf{x}$ into the input-output equation $\mathbf{x} = \mathbf{Ax} + \mathbf{h} + \mathbf{f}$, and solving the linear equation for the output vector $\mathbf{x}$, we obtain the following equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A} - \mathbf{CV})^{-1}\mathbf{f}, \quad (1)$$

where $\mathbf{I}$ is the identity matrix. Using the Leontief inverse matrix, $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1} = (b_{ij}^{rs})$, equation (1) can be expressed as follows:

$$\mathbf{x} = \mathbf{B}(\mathbf{I} - \mathbf{CVB})^{-1}\mathbf{f}, \quad (2)$$

The inverse matrix $(\mathbf{I} - \mathbf{CVB})^{-1}$ is called the *subjoined inverse matrix* in Miyazawa and Masegi (1963). They described it as the inter-industry effects of endogenous changes in the household sectors' consumption demand.

A primary concern in this study centers on the residential emissions associated with the income→consumption process. Therefore, we formulated the intra- and inter-regional income flow induced by the final regional demand as follows. The income inducements vector $\mathbf{y} = (y^k)$ is estimated as follows:

$$\mathbf{y} = \mathbf{V}\mathbf{x} = \mathbf{VB}(\mathbf{I} - \mathbf{CVB})^{-1}\mathbf{f} = (\mathbf{I} - \mathbf{VBC})^{-1}\mathbf{VBf} = \mathbf{KVBf}, \quad (3)$$

where $\mathbf{K}[k \times w] = (\mathbf{I} - \mathbf{VBC})^{-1}$. The matrix $\mathbf{L}[k \times w] = \mathbf{VBC} = (l^{kw}) (k, w=1, \dots, M)$ is termed the *inter-income group coefficient matrix* and element l^{kw} represents the income in income group k induced by producing the goods directly and indirectly required to meet one additional unit of household consumption expenditure in income group w . We can also regard matrix $\mathbf{L}$ as including regions' marginal propensity to consume (Miyazawa and Masegi, 1963). Matrix $\mathbf{K} = (\mathbf{I} - \mathbf{L})^{-1}$ is referred to as "*the inter-relational multiplier in the income groups*" and explains the total inter-industry effects resulting from the income generation process. To explain this total inter-industry effect, let $\Delta \mathbf{f}$ represent the additional final demand. The increase in outputs associated with this additional final demand is estimated by $\mathbf{B}\Delta \mathbf{f}$ and the increased output $\mathbf{B}\Delta \mathbf{f}$ further generates household income $\mathbf{VB}\Delta \mathbf{f}$ for each income group (i.e., each region in this study). Each income group consumes by spending additional money and its consumption is estimated by $\mathbf{CVB}\Delta \mathbf{f}$. In this $\mathbf{CVB}$ propagation, it is implicitly assumed that people engaged in *different* industries in a specific province have *an average* lifestyle (i.e., consumption pattern) in the province in question. The additional consumption expenditure shown as $\mathbf{CVB}\Delta \mathbf{f}$ further induces income as $\mathbf{VBCVB}\Delta \mathbf{f}$ as production propagates. As a result, the total income induced by the additional non-household expenditure final demand can be described as follows:

$$\begin{aligned}
\Delta \mathbf{y} &= \mathbf{VB}\Delta \mathbf{f} + \mathbf{VBCVB}\Delta \mathbf{f} + \mathbf{VBCVBCVB}\Delta \mathbf{f} + \dots \\
&= \mathbf{VB}\Delta \mathbf{f} + (\mathbf{VBC})\mathbf{VB}\Delta \mathbf{f} + (\mathbf{VBC})^2\mathbf{VB}\Delta \mathbf{f} + \dots \\
&= (\mathbf{I} + (\mathbf{VBC}) + (\mathbf{VBC})^2 + \dots)\mathbf{VB}\Delta \mathbf{f} \\
&= (\mathbf{I} - \mathbf{VBC})^{-1}\mathbf{VB}\Delta \mathbf{f} = \mathbf{KVB}\Delta \mathbf{f}
\end{aligned}$$

If the *direct* residential emission intensity vector that contains primary PM_{2.5} emissions per unit of income for income group k is defined as $\mathbf{d} = (d^k)$, then the residential regional PM_{2.5} emissions triggered by the other final demand vector of a specific region s^* (i.e., ‘embodied’ residential PM_{2.5} emissions from region s^*) can be estimated as:

$$\mathbf{e}^{s^*} = \hat{\mathbf{d}}\mathbf{KVB}\mathbf{f}^{s^*} \quad (4)$$

where $\hat{\mathbf{d}}$ is the diagonalization of $\mathbf{d}$, and $\mathbf{f}^{s^*}$ is the final demand vector of region s^* . Element e^k of $\mathbf{e}^{s^*}$ represents the PM_{2.5} emissions induced by households in region k associated with final demand in demand region s^* . On the other hand, the *direct* residential PM_{2.5} emissions from region s^* can be calculated by multiplying the *direct* residential emission intensity d^{s^*} by the household income of the region, y^{s^*} .

$$g^{s^*} = d^{s^*} y^{s^*} \quad (5)$$

4.2.2. Identifying structural paths with higher residential PM_{2.5} emissions

Here, I identify the environmentally-important structural paths that have higher residential PM_{2.5} emissions in the regional economies. If we perform a series expansion of the interrelational multiplier in the income groups matrix of Eq. (3), we obtain $\mathbf{K} = (\mathbf{I} - \mathbf{VBC})^{-1} = \mathbf{I} + \mathbf{VBC} + (\mathbf{VBC})^2 + (\mathbf{VBC})^3 + \dots$. Then, from Eq. (4), we can solve for the residential PM_{2.5} emissions arising from consumption in region s^* as follows:

$$\begin{aligned} \mathbf{e}^{s^*} &= \hat{\mathbf{d}}\mathbf{VBf}^{s^*} + \hat{\mathbf{d}}\mathbf{LVBf}^{s^*} + \hat{\mathbf{d}}\mathbf{L}^2\mathbf{VBf}^{s^*} + \dots \\ &= \hat{\mathbf{d}}\mathbf{VBf}^{s^*} + \hat{\mathbf{d}}\mathbf{VBCVBf}^{s^*} + \hat{\mathbf{d}}(\mathbf{VBC})^2\mathbf{VBf}^{s^*} + \dots \end{aligned} \quad (5)$$

If final demand for *a particular product* is generated in region s^* , then the amount of first-tier residential PM_{2.5} emissions embodied in regions' household income brought about by producing goods to satisfy that final demand is obtained as $\hat{\mathbf{d}}\mathbf{VBf}^{s^*}$, which is the first term in the right-hand side of eq. (5). Through a series expansion of the interrelational multiplier in the income groups matrix, this emissions process continues infinitely (see eq. (5)). Thus, element e^{ks^*} for computing $\mathbf{e}^{s^*}$ in eq. (5) can be estimated by the following equation:

$$e^{ks^*} = \sum_{t,r,u=1}^M \sum_{j,i=1}^N d^k (I^{ku} + l^{ku} + (\mathbf{L}^2)^{ku} + \dots) v_i^{ur} b_{ij}^{rt} f_j^{ts^*}$$

$$\begin{aligned}
&= \sum_{t,r,u=1}^M \sum_{j,i=1}^N d^k \left(I^{ku} + \sum_{w,z=1}^M \sum_{o,p=1}^N v_p^{kz} b_{po}^{zw} c_o^{wu} \right. \\
&\quad \left. + \sum_{w,z,\alpha,\beta,\gamma=1}^M \sum_{o,p,q=1}^N v_q^{k\gamma} b_{qp}^{\gamma\beta} c_p^{\beta\alpha} v_p^{\alpha z} b_{po}^{zw} c_o^{wu} + \dots \right) v_i^{ur} b_{ij}^{rt} f_j^{ts*} \\
&= \sum_{t,r=1}^M \sum_{j,i=1}^N d^k v_i^{kr} b_{ij}^{rt} f_j^{ts*} + \sum_{t,r,u,w,z=1}^M \sum_{j,i,o,p=1}^N d^k v_p^{kz} b_{po}^{zw} c_o^{wu} v_i^{ur} b_{ij}^{rt} f_j^{ts*} \\
&\quad + \sum_{t,r,u,w,z,\alpha,\beta,\gamma=1}^M \sum_{j,i,o,p,q,\delta=1}^N v_\delta^{k\gamma} b_{\delta q}^{\gamma\beta} c_q^{\beta\alpha} v_p^{\alpha z} b_{po}^{zw} c_o^{wu} v_i^{ur} b_{ij}^{rt} f_j^{ts*} + \dots
\end{aligned} \tag{6}$$

where i, j, o, p, q and δ are industrial indices and $t, r, u, w, z, \alpha, \beta$, and γ are regional indices. I^{ku} takes the value 1 when $k=u$, and is otherwise 0. The first term on the right-hand side of Eq. (6), $d^k v_i^{kr} b_{ij}^{rt} f_j^{ts*}$, denotes the residential PM_{2.5} emissions of region k induced by the income derived by producing the final and intermediate goods of industry i in region r directly and indirectly needed by industry j of country t in order to satisfy the final demand in region s^* . The second term, $d^k v_p^{kz} b_{po}^{zw} c_o^{wu} v_i^{ur} b_{ij}^{rt} f_j^{ts*}$, represents the emissions resulting from the path “final demand in region s^* ” $\rightarrow$ “production by industry j of region t ” $\rightarrow$ “production by industry i of region r ” $\rightarrow$ “consumption in region u ” $\rightarrow$ “production by industry o of region w ” $\rightarrow$ “production by industry p of region z ” $\rightarrow$ “income in region k ”.

4.3. Data

We used the multi-regional input-output table for 30 regions in China in 2007 developed by Liu *et al.* (2012) and used in Feng *et al.* (2013). This MRIO table covers 30 regions in China, excluding Tibet, Hong Kong and Taiwan, and 30 industry sectors (see Table S4-1 of Appendix). This study thus considers 900 specific sectors.

With 900 sectors in our input–output framework, the structural path analysis formulated by Eq. (6) requires massive computation. The number of structural paths in the first tier, expressed by the first term on the right-hand side of Eq. (6), is $30^2 \times 30^2 = 900^2$, the number of paths in the second tier is $30^5 \times 30^4$, and the number in the n^{th} tier is $30^{3n-1} \times 30^{2n}$. However, the total emission contribution from a given tier rapidly declines as tier number increases. For this study, therefore, we set a threshold at which we would disregard supply chain paths that account for less than 0.001% of total PM_{2.5} emissions. As a result, our computation only considers paths up to the 5th tier.

This study uses the data on residential PM_{2.5} emissions by each province in accordance with multi-regional input–output table for China estimated by the Regional Emission inventory in Asia (REAS) version 2.1 (Kurokawa *et al.*, 2013). The PM_{2.5} emissions are calculated from the fuel combustions listed below: hard coal (ex. coking coal, anthracite, and other bituminous coal), kerosene, other light oil (ex. liquefied petroleum gases and natural gas liquids), gas/diesel oil, other heavy oil (ex. petroleum coke, bitumen, non-specified petroleum products), fuelwood, crop residue used as biofuel (Kurokawa *et al.*, 2013). This emission database is downloadable from the website:

<https://www.nies.go.jp/REAS/>.

4.4. Results and discussion

4.4.1. Direct residential PM_{2.5} emissions of the Chinese 30 provinces

Figure 4-1 shows the direct and embodied residential PM_{2.5} emissions of 30 provinces in China. The total amount of residential PM_{2.5} emissions in China was 4 million tonnes in 2007. Sichuan (SICH) was the largest *direct* residential emitter of the 30 provinces, with 390 thousand tonnes (10% of China's total emissions) coming from household energy consumption. Per household residential PM_{2.5} emissions originating from coal and biomass consumption in Sichuan in 2007 totaled 16 tonnes per household, highlighting the fact that the structure of energy use in Sichuan is a critical contributing factor in residential emissions.

The second largest emitter was Henan (HENA) (280 thousand tonnes), followed Shandong (SHND), Guangxi (GUAX), and Anhui (ANHUI), emitting 270, 260, and 250 thousand tonnes, respectively. The residential PM_{2.5} emissions from highly industrialized urban areas such as Beijing (BEIJ), Tianjin (TIAN), Shanghai (SHAN) and Zhejiang (ZHEJ) were relatively low due to their greener household lifestyles whereas the emissions from developing provinces such as Henan were relatively high.

Figure 4-2 shows the *direct* residential PM_{2.5} emissions per unit of household income in each province in kg per thousand yuan (i.e., the direct emission intensity for each province, d^{s*}) and the *direct* residential PM_{2.5} emissions per capita (kg per person). The average emission intensity for all 30 Chinese regions is 36 kg per thousand yuan (36 kg per 145 U.S. dollars in May 2017). It is important to note that the Guizhou (GUIZ) region

has a surprisingly high emission intensity, amounting to 151 kg per thousand yuan, which is more than a hundred times larger than that of Shanghai (SHAN), which has the lowest emission intensity in China. While Figure 4-1 highlighted the largest emissions, for Sichuan (SICH), Figure 4-2 demonstrates the importance of reducing residential PM_{2.5} emissions in Guizhou (GUIZ) through an emission intensity reduction policy. The household income of urban (developed) areas (Beijing, Tianjin, Shanghai, Zhejiang, Jiangsu and Guangdong) accounts for 36% of the country's total, but those six urban areas contribute just 10% of the direct residential emissions, which implies that the emission intensities in other rural (less-developed) regions were higher than those of the six urban areas.

The Chinese province with the highest per capita emissions was Inner Mongolia (NEMO) (55 kg per person). The per capita emissions in higher latitude areas like Heilongjiang (HEIL), Jilin (JILI), Liaoning (LIAO) and Hebei (HEBE) tend to be higher because of the huge usage of fuel for heating in winter. Conversely, the per capita emissions in Shanghai and Zhejiang, located in lower latitudes, were extremely low. Both per capita emissions and direct emission intensities in the Chinese provinces vary widely due to their different lifestyles and weather.

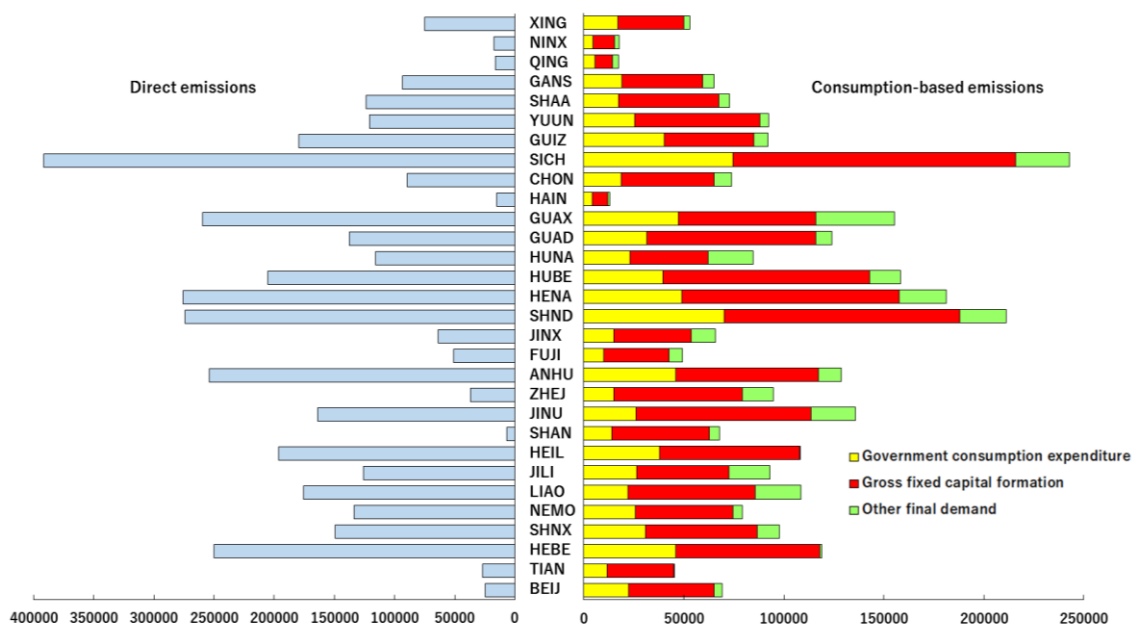


Figure 4-1 Direct and consumption-based residential PM_{2.5} emissions in tonnes

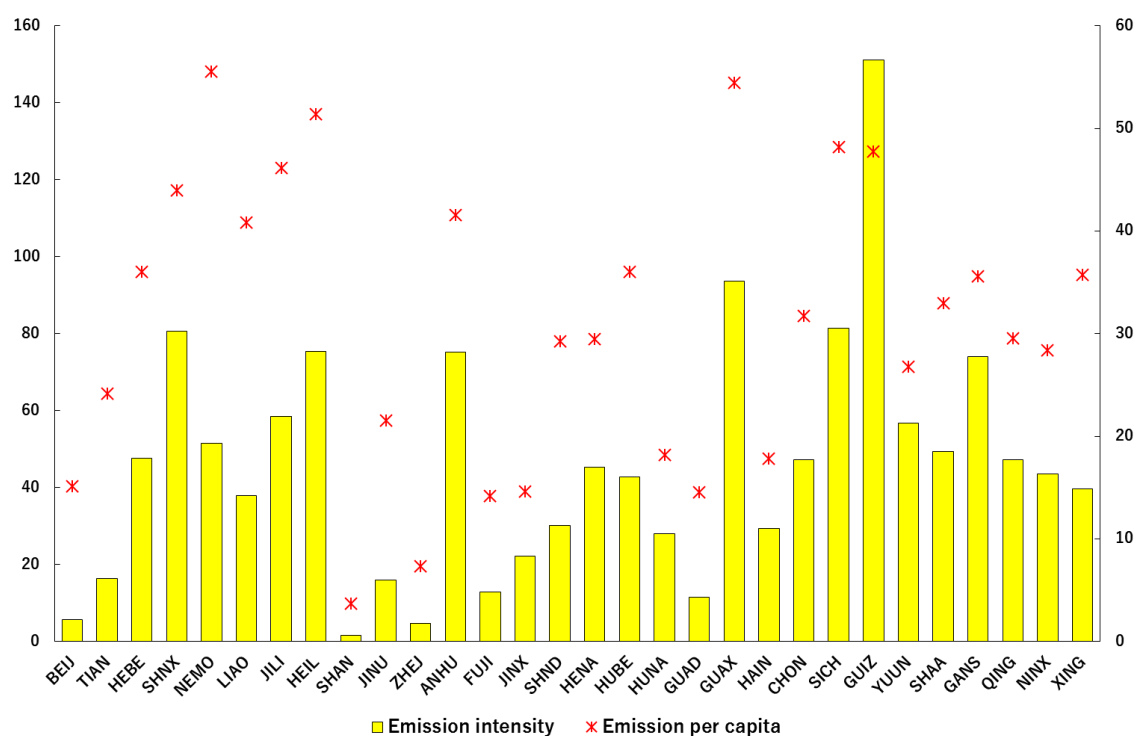


Figure 4-2 Direct PM_{2.5} emission intensity in kg per thousand yuan (left axis) and residential PM_{2.5} emissions per capita in kg per person (right axis) in Chinese provinces

4.4.2 Embodied residential PM_{2.5} emissions in the Chinese 30 provinces

Having information on direct emissions as portrayed above is important to understanding which provinces contribute to air pollution via ‘direct’ household energy consumption. That information, however, does not shed light on the structural relationships whereby final demand of a specific province induces its own household income and/or income in different provinces as a result of commodity production. Neither does it elucidate how that generated income further raises residential PM_{2.5} emissions through ‘income-induced’ household energy consumption.

The right-hand side of Figure 4-1 shows the embodied residential PM_{2.5} emissions of the 30 Chinese provinces estimated using eq. (4). In each of the provinces, the final demand of gross fixed capital formation dominates the embodied emissions (Figure 4-1). It is important to note that the embodied residential PM_{2.5} emissions in the Chinese provinces are almost same as their direct emissions except for in urban areas such as Beijing, Tianjin, Shanghai and Zhejiang. The disparity between embodied and direct emissions in urban areas illustrate that their final demand induces residential emissions not only in the urban regions but in outside provinces as well.

Focusing on residential PM_{2.5} emissions in a specific province (intra-provincial emissions) induced by its own final demand, the largest emitter, Sichuan, gave off 214 thousand tonnes, or 86% of its embodied emissions. Next are Shandong, Guangxi, Hubei and Henan, emitting 146 thousand (69%), 131 thousand (80%), 127 thousand (80%) and 125 thousand tonnes (69%), respectively. On the other hand, the intra-provincial emissions of the Shanghai urban area were only 1.8 thousand tonnes, or 3% of its

embodied emissions. In other words, 97% of the residential PM_{2.5} emissions triggered by final demand in Shanghai was *indirectly* emitted outside Shanghai.

Figure 4-3 shows a matrix of residential PM_{2.5} emissions of each province triggered by final demand by province. Hebei (HE) and Anhui (AH) emitted more than 5000 tonnes of residential sector PM_{2.5} associated with final demand from Shanghai (SH) (Figure 4-3). Importantly, the Hebei (HE) region was indirectly highly polluted by final demand from other provinces, especially industrialized areas such as Beijing (BJ), Tianjin (TJ), Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ) and Guangdong (GD). This is mainly because people in Hebei obtain direct and indirect income by producing products to meet the final demand in those industrialized areas. Consequently, Hebei (HE) emits a large quantity of PM_{2.5} emissions via dirty household energy consumption activities. Anhui (AH) and Sichuan (SC) are similar to Hebei (HE), and a large amount of their residential emissions was driven by neighboring urbanized regions (Figure 4-3).

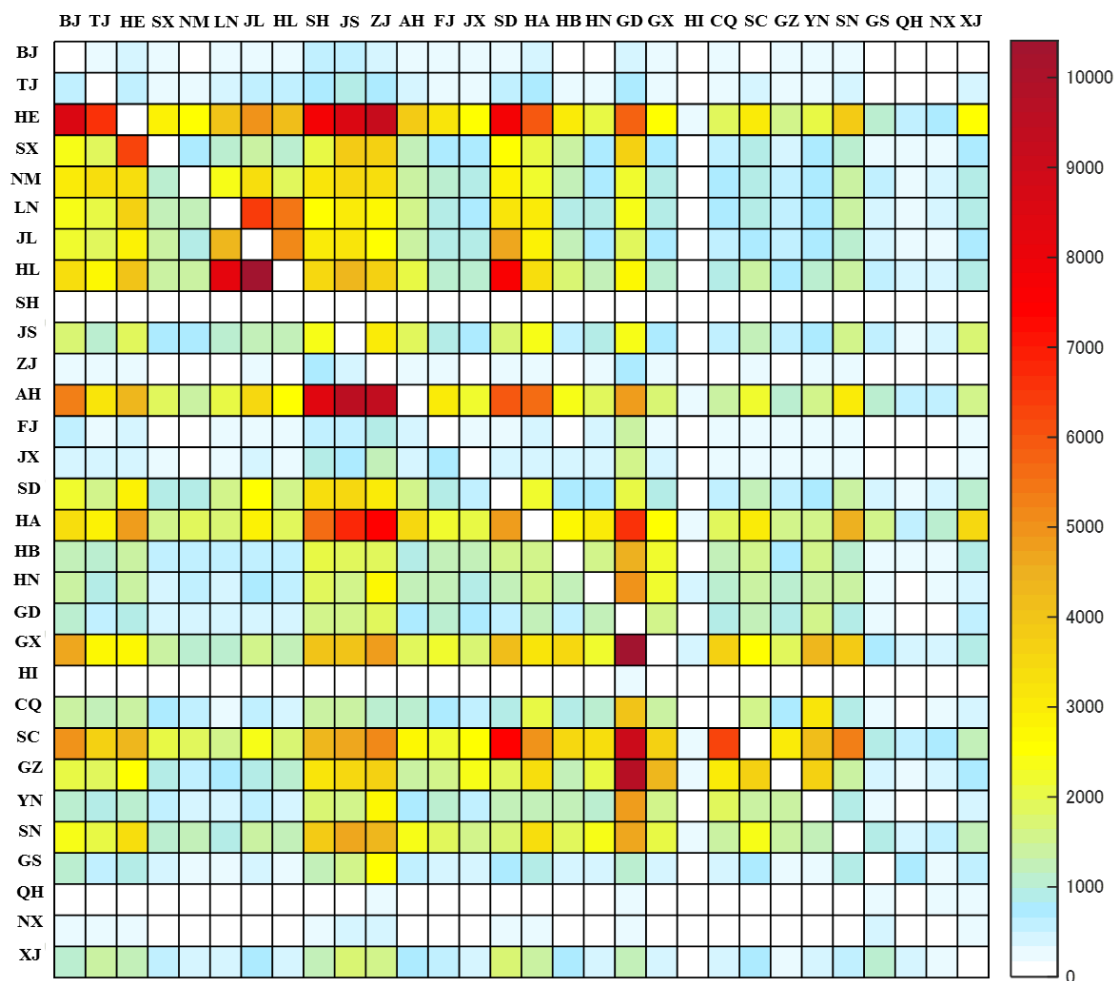


Figure 4-3 Residential PM_{2.5} emissions per province (row) triggered by the final demand per province (column)

4.4.3 Structural path analysis of embodied residential PM_{2.5} emissions in China

This section identifies environmentally-critical structural paths that induce higher *residential* PM_{2.5} emissions in the Chinese provinces. We calculated residential PM_{2.5} emissions associated with each structural path linking final demand for a particular product in one specific province with income of any designated province using eq. (5). Table 4-1 shows the top 30 critical paths in the 1st structural tier (i.e., the first term of eq. (5)). The highest priority path, ranked as No.1 here, SICH → Other services (SICH) → Other services (SICH) → SICH, shows that 38 thousand tonnes of the residential PM_{2.5} in Sichuan (SICH) is attributable to the path linking households in Sichuan providing “other” (not otherwise specified) services in Sichuan with the final demand in Sichuan for “other” services. Sichuan (SICH) was the largest emitter of the 30 Chinese provinces with 390 thousand tonnes of direct residential emissions. Service industries in Sichuan should reasonably be responsible for 10% of the residential PM_{2.5} emissions in Sichuan. In Sichuan, it would be harmful if service industries do not take a leadership role in reducing PM_{2.5} emissions from their workers’ homes and alleviating the PM_{2.5}-induced health impact on their workers and other people. Similar situations can be found with respect to Agriculture in Guangxi and Construction in Shandong (Table 4-1).

Table 4-1 Top 30 structural paths in terms of residential emissions

Rank	Emissions (tonnes)	Driver Region	Path		
			Fo	B0	V0
1	38394	SICH	→ SICH: Other services	→ SICH: Other service	→ SICH
2	33445	SHND	→ SHND: Other services	→ SHND: Other services	→ SHND
3	31890	GUAX	→ GUAX: Other services	→ GUAX: Other services	→ GUAX
4	27736	ANHU	→ ANHU: Other services	→ ANHU: Other services	→ ANHU
5	26831	GUAX	→ GUAX: Agriculture	→ GUAX: Agriculture	→ GUAX
6	25110	SHND	→ SHND: Construction	→ SHND: Construction	→ SHND
7	21919	HEIL	→ HEIL: Other services	→ HEIL: Other services	→ HEIL
8	21509	HUBE	→ HUBE: Other services	→ HUBE: Other services	→ HUBE
9	21417	SICH	→ SICH: Construction	→ SICH: Construction	→ SICH
10	21361	GUIZ	→ GUIZ: Other services	→ GUIZ: Other services	→ GUIZ
11	20077	HEBE	→ HEBE: Other services	→ HEBE: Other services	→ HEBE
12	19945	HENA	→ HENA: Other services	→ HENA: Other services	→ HENA
13	18488	SHNX	→ SHNX: Other services	→ SHNX: Other services	→ SHNX
14	18455	ANHU	→ ANHU: Construction	→ ANHU: Construction	→ ANHU
15	18069	HENA	→ HENA: Construction	→ HENA: Construction	→ HENA
16	16091	NEMO	→ NEMO: Other services	→ NEMO: Other services	→ NEMO
17	16087	HEIL	→ HEIL: Construction	→ HEIL: Construction	→ HEIL
18	15102	GUAX	→ GUAX: Construction	→ GUAX: Construction	→ GUAX
19	14686	NEMO	→ NEMO: Construction	→ NEMO: Construction	→ NEMO
20	14021	JILI	→ JILI: Other services	→ JILI: Other services	→ JILI
21	13603	YUUN	→ YUUN: Other services	→ YUUN: Other services	→ YUUN
22	13491	HUBE	→ HUBE: Construction	→ HUBE: Construction	→ HUBE
23	13026	GUAD	→ GUAD: Other services	→ GUAD: Other services	→ GUAD
24	12590	HEBE	→ HEBE: Construction	→ HEBE: Construction	→ HEBE
25	12372	SICH	→ SICH: Agriculture	→ SICH: Agriculture	→ SICH
26	12096	GANS	→ GANS: Other services	→ GANS: Other services	→ GANS
27	12041	LIAO	→ LIAO: Construction	→ LIAO: Construction	→ LIAO
28	11907	SHNX	→ SHNX: Construction	→ SHNX: Construction	→ SHNX
29	11120	LIAO	→ LIAO: Other services	→ LIAO: Other services	→ LIAO
30	10928	GUIZ	→ GUIZ: Construction	→ GUIZ: Construction	→ GUIZ

Table 4-2 shows the 30 paths that induce the largest residential emissions in other provinces as a result of final demand in a specific driving province. The path having the greatest emissions was JILI → General and specialist machinery (HEIL) → General and specialist machinery (HEIL) → HEIL. The contribution by final demand in Jilin for “General and specialist machinery” in Heilongjiang accounts for 1265 tonnes of Heilongjiang’s PM_{2.5} emissions.

Of these top 30 paths shown in Table 4-2, 27 start with final demand in urban regions such as Beijing and Shanghai, demonstrating that final demand in these urban regions brings about residential emissions in other rural areas as well as commodity production in those regions. For example, urban areas' consumption in the construction sector drives direct and indirect production of "Nonmetal products", "Coal mining" and "Metallurgy" in rural regions as indicated by the paths "BEIJ → Construction (BEIJ) → Nonmetal products (HEBE) → HEBE" and "GUAD → Construction (GUAD) → Coal mining (SHNX) → SHNX".

Moreover, as illustrated by the paths "BEIJ → Other services (BEIJ) → Other services (BEIJ) → BEIJ → Agriculture (GUAX) → Agriculture (GUAX) → GUAX" and "SHAN → Other services (SHAN) → Other services (SHAN) → SHAN → Agriculture (HEBE) → Agriculture (HEBE) → HEBE", the residential emissions from agricultural households in Guangxi and Hebei are associated with consumption in Beijing and Shanghai, where income is generated by demand within those cities for their own industries via commodity production. The emitting regions in the top 30 paths are very similar. Residential PM_{2.5} emissions in Hebei are associated with 7 structural paths, and those of Anhui and Shanxi are associated with 5 paths and 4 paths, respectively (Table 4-2).

Table 4-2 Top 30 structural paths in terms of residential emissions in other provinces
due to final demand of a specific country

Rank	Emissions (tonnes)	Driver Region	Path					
			Fo	B0	V0	C1	B1	V1
1	1265	JILI	→ HEIL: General and specialist machinery	→ HEIL: General and specialist machinery	→ HEIL			
2	1181	BEIJ	→ BEIJ: Construction	→ HEBE: Nonmetal products	→ HEBE			
3	909	YUUN	→ CHON: Transport equipment	→ CHON: Transport equipment	→ CHON			
4	701	SHAN	→ ANHU: Transport equipment	→ ANHU: Transport equipment	→ ANHU			
5	695	GUAD	→ GUAD: Construction	→ SHNX: Coal mining	→ SHNX			
6	687	SHAA	→ GUAX: Agriculture	→ GUAX: Agriculture	→ GUAX			
7	569	GUAD	→ CHON: Transport equipment	→ CHON: Transport equipment	→ CHON			
8	543	ZHEJ	→ HEBE: Agriculture	→ HEBE: Agriculture	→ HEBE			
9	522	JINU	→ JINU: Construction	→ SHNX: Coal mining	→ SHNX			
10	508	ZHEJ	→ ZHEJ: Construction	→ SHNX: Coal mining	→ SHNX			
11	508	GUAD	→ SHAA: Construction	→ SHAA: Construction	→ SHAA			
12	507	GUAD	→ GUAD: Construction	→ GANS: Coal mining	→ GANS			
13	501	ZHEJ	→ ANHU: Agriculture	→ ANHU: Agriculture	→ ANHU			
14	490	YUUN	→ GUAX: Agriculture	→ GUAX: Agriculture	→ GUAX			
15	464	ZHEJ	→ ZHEJ: Construction	→ ANHU: Coal mining	→ ANHU			
16	440	GUAD	→ HENA: Construction	→ HENA: Construction	→ HENA			
17	433	BEIJ	→ BEIJ: Construction	→ SHNX: Coal mining	→ SHNX			
18	416	ZHEJ	→ ZHEJ: Construction	→ GANS: Metallurgy	→ GANS			
19	408	TIAN	→ TIAN: Construction	→ HEBE: Nonmetal products	→ HEBE			
20	408	ZHEJ	→ ZHEJ: Construction	→ HEBE: Metallurgy	→ HEBE			
21	366	BEIJ	→ BEIJ: Other services	→ BEIJ: Other services	→ BEIJ	→ GUAX: Agriculture	→ GUAX: Agriculture	→ GUAX
22	366	GUAD	→ SICH: Construction	→ SICH: Construction	→ SICH			
23	350	GUAD	→ GUAD: Construction	→ GUAX: Agriculture	→ GUAX			
24	344	SHAN	→ SHAA: Other services	→ SHAA: Other services	→ SHAA			
25	343	BEIJ	→ BEIJ: Other services	→ BEIJ: Other services	→ BEIJ	→ ANHU: Agriculture	→ ANHU: Agriculture	→ ANHU
26	337	SHAN	→ SHAN: Other services	→ SHAN: Other services	→ SHAN	→ HEBE: Agriculture	→ HEBE: Agriculture	→ HEBE
27	328	TIAN	→ HEBE: Agriculture	→ HEBE: Agriculture	→ HEBE			
28	322	SHAN	→ HEBE: Other services	→ HEBE: Other services	→ HEBE			
29	309	SHAN	→ SHAN: Other services	→ SHAN: Other services	→ SHAN	→ ANHU: Agriculture	→ ANHU: Agriculture	→ ANHU
30	305	ZHEJ	→ ZHEJ: Construction	→ HENA: Nonmetal products	→ HENA			

4.5. Discussion and conclusion

The results of this study revealed environmentally-critical structural paths that induce higher residential PM_{2.5} emissions in the Chinese provinces. As indicated by the results of the structural path analysis, households engaged in high income industries such as “other services”, “agriculture” and “construction” in Sichuan, Shangdong, Guangxi and Anhui mainly contributed their own residential PM_{2.5} emissions. Furthermore, the final demand of urban areas for construction, transport equipment and agriculture drove rural areas’ residential emissions through production of commodities such as nonmetal products, coal mining, agriculture, and metallurgy. From these results, I propose that firms and governments undertake policies that promote replacing emission-intensive heating and cooking equipment with cleaner technologies (e.g. Li *et al.*, 2016) or improve the structure of residential energy consumption, giving additional income or subsidies to laborers engaging in high-priority industries. In particular, the three sectors identified in this study, “services”, “agriculture”, and “construction” should positively aid their workers in reducing the residential PM_{2.5} emissions through the above energy policy. Another policy to be considered is for firms to provide laborers with housing allowances for apartment buildings that use cleaner equipment like central heating systems or stoves that use cleaner energy. Furthermore, local governments should give incentives for households to promote environmentally friendly activities like the eco-point system for housing implemented by the Ministry of Land, Instructure, Transport and Tourism in Japan, for example. From the view of final demand, urban areas, especially Beijing, Shanghai, Zhejiang and Guangdong, that drive relatively large embodied residential emissions should take the initiative to adopt such policies for high-priority industries and provinces.

Chapter 5: Conclusions

This Ph.D. dissertation reports on the design and execution of comprehensive analyses focusing on Asian supply chain structures to provide the necessary basis for effectively mitigating anthropogenic air pollution from two perspectives: industry and household.

In Chapter 3, I used an environmentally extended Asian input-output table for 2005 and, for the first time, applied a comprehensive economic network analysis including key sector analysis and structural path analysis to identify the critical sectors and supply chain paths that contribute most to the mortality attributable to primary carbonaceous PM_{2.5}, namely, black carbon (BC) and organic carbon (OC) in Asia. A novel impact footprint exercise is also conducted that links emission sources and victims of health impacts through the atmospheric transport of carbonaceous air pollutants in Asia. The results suggest that other grain, food crops, transportation, livestock, and construction are the key sectors in China responsible for air pollution induced mortality. Agricultural, transportation, and construction sectors in Thailand, South Korea, and Japan were also identified as critical in this respect. From the results of SPA, the paths CHN (driver) → other grain in CHN (source) → CHN (receptor) and CHN (driver) → construction in CHN → other grain in CHN (source) → CHN (receptor) contributed most to health impacts.

Chapter 4 focused on primary PM_{2.5} emissions (including particles other than BC and OC) from the residential sector, which contribute significantly to air pollution in Asia. Differences in the consumption and income distribution of households in each region

were examined vis-à-vis their effects on residential PM_{2.5} emissions, and finally possible ways of reducing PM_{2.5} emissions in the future are discussed. A novel framework is presented that incorporates household consumption and income distributions, both of which are treated exogenously to Leontief's input-output system using multi-region input-output analysis with respect to an environmentally extended multi-provincial input-output table for China in 2007. Furthermore, this analysis applies the concept of SPA to an augmented input-output model to extract the critical path that contributes to household PM_{2.5} emissions through the consumption → production → income process. Finally, stakeholders that are best placed to implement emission reduction policies are considered and discussed. The results suggest that households engaged in high income industries such as “other services”, “agriculture”, and “construction” in Sichuan, Shangdong, Guangxi, and Anhui were mainly responsible for their own residential PM_{2.5} emissions. In addition, final demand in urban areas for construction, transport equipment, and agriculture drove rural areas' residential emissions through the production of nonmetal and metal products, coal mining, and agriculture.

This Ph.D. dissertation reveals critical inter-industrial linkages for mitigating health impacts attributable to air pollution in Asia in terms of a consumption-based accounting approach. The results testify to the importance of large emitting countries and those nations that contribute significantly to Asian supply chain such as Japan, South Korea, United States, and EU countries for developing and delivering cooperative mitigation strategies considering direct and indirect emissions.

In common with applied research more generally, this study is not without its

limitations. Importantly, the effects of air pollution are not captured in their entirety in this work. For example, Chapter 3 did not consider all components of PM_{2.5} such as secondary components, which are substantive. Calculations and attributions of concentrations of secondary particles are difficult due to various complexities, e.g., nonlinearities in the relationships between chemical reactions and health risks. At present, it is difficult to integrate the effects of secondary particles; thus, this remains pertinent for future research. Furthermore, environmental applications using the Miyazawa analysis described in Chapter 4 assume a fixed propensity to consume at the ‘provincial-average level.’ This model cannot divide environmental effects associated with income disparity within a province and also cannot incorporate positive changes in households’ environmental preferences resulting from increases in income. To do this, more detailed information about the income type of each household in each province would be required in conjunction with a different modeling approach based on computable general equilibrium (CGE) analysis. Again, this represents a potentially fruitful avenue for future research.

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Fumiya Nagashima

Appendix

Chapter 3

Supplementary Figure

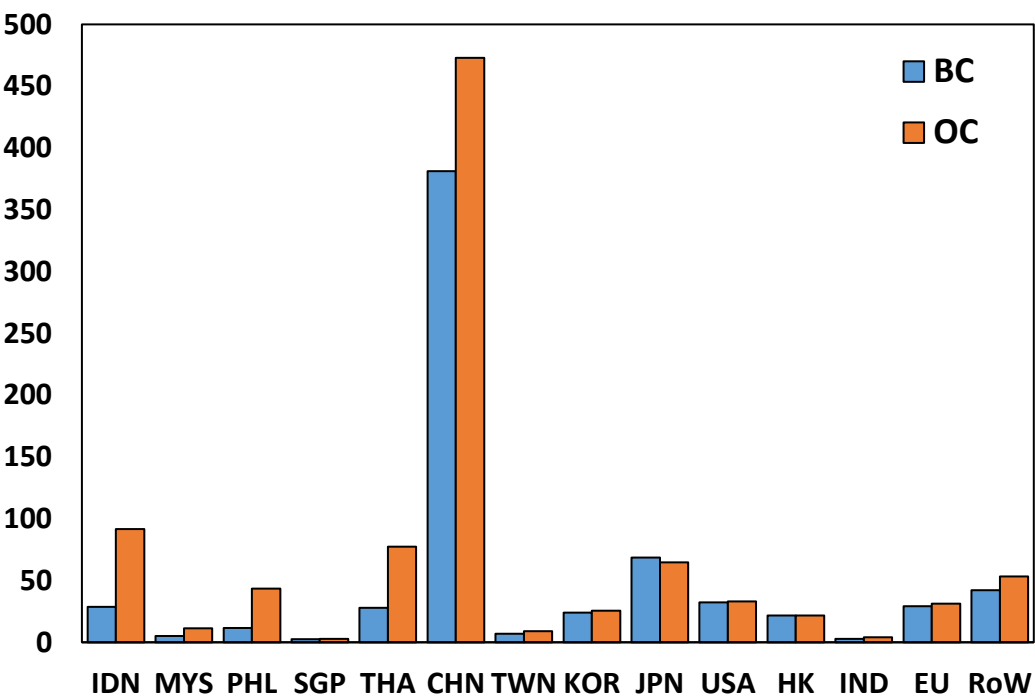


Figure S3-1 Consumption-based emissions of countries (unit: thousand tonnes-C).

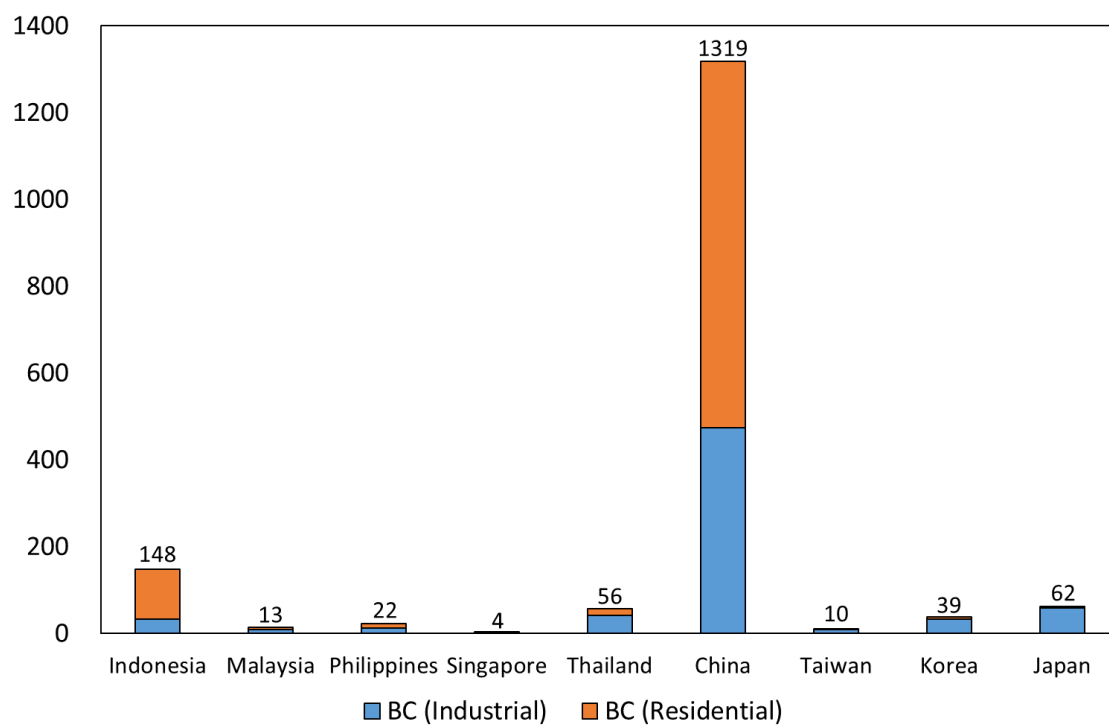


Figure S3-2 Consumption-based BC emissions of countries including residential emissions (unit: thousand tonnes-C).

Supplementary Table

Table S3-1 Industrial sector classification of the Asian International Input–Output Table of 2005

No.	Sector name	No.	Sector name
1	Paddy	39	Glass and glass products
2	Other grain	40	Other non-metallic mineral products
3	Food crops	41	Iron and steel
4	Non-food crops	42	Non-ferrous metal
5	Livestock and poultry	43	Metal products
6	Forestry	44	Boilers, engines and turbines
7	Fishery	45	General machinery
8	Crude petroleum and natural gas	46	Metal working machinery
9	Iron ore	47	Specialized machinery
10	Other metallic ore	48	Heavy electrical equipment
11	Non-metallic ore and quarrying	49	Television sets, radios, and other audio and communication equipment
12	Milled grain and flour	50	Electronic computing equipment
13	Fish products	51	Semiconductors and integrated circuits
14	Slaughtering, and meat and dairy products	52	Other electronics and electronic products
15	Other food products	53	Household electrical equipment
16	Beverages	54	Lighting fixtures, batteries, wiring and others
17	Tabacco	55	Motor vehicles
18	Spinning	56	Motorcycles
19	Weaving and dyeing	57	Shipbuilding
20	Knitting	58	Other transport equipment
21	Wearing apparel	59	Precision machines
22	Other made-up textile products	60	Other manufacturing products
23	Leather and leather products	61	Electricity and gas
24	Timber	62	Water supply
25	Wooden furniture	63	Building construction
26	Other wooden products	64	Other construction
27	Pulp and paper	65	Wholesale and retail trade
28	Printing and publishing	66	Transportation
29	Synthetic resins and fiber	67	Telephone and telecommunication
30	Other basic industrial chemicals	68	Finance and insurance
31	Chemical fertilizers and pesticides	69	Real estate
32	Drugs and medicine	70	Education and research
33	Other chemical products	71	Medical and health services
34	Petroleum and petrol products	72	Restaurants
35	Plastic products	73	Hotel
36	Tires and tubes	74	Other service
37	Other rubber products	75	Public administration
38	Cement and cement products	76	Unclassified

Table S3-2 PM_{2.5} emission data by industry of Indonesia in 2005

Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)	Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)
1	12105.63	8870131	1.365	39	336.83	1573653	0.214
2	1636.39	2815024	0.581	40	461.46	1818837	0.254
3	97087.48	17755857	5.468	41	812.36	3292045	0.247
4	38.91	7081076	0.005	42	0.00	4354494	0.000
5	13.03	7158200	0.002	43	18.42	8322944	0.002
6	167.01	2839881	0.059	44	0.06	684274	0.000
7	556.58	7624855	0.073	45	0.17	3193194	0.000
8	193.73	30745121	0.006	46	0.02	300692	0.000
9	2.45	38995	0.063	47	0.16	2925534	0.000
10	109.94	8681142	0.013	48	1.68	2887519	0.001
11	210.88	9187791	0.023	49	2.98	4683850	0.001
12	27.93	13925777	0.002	50	2.51	277325	0.009
13	15.08	4352941	0.003	51	0.21	3263783	0.000
14	24.21	5709947	0.004	52	0.05	4745374	0.000
15	114.05	21343522	0.005	53	0.14	947081	0.000
16	45.55	3305956	0.014	54	3.08	4487123	0.001
17	167.61	7428010	0.023	55	0.00	11542253	0.000
18	260.88	4626450	0.056	56	0.00	13671585	0.000
19	169.70	5339228	0.032	57	0.00	622914	0.000
20	60.36	2993703	0.020	58	0.00	1860608	0.000
21	72.67	5662243	0.013	59	18.82	861052	0.022
22	7.49	1505053	0.005	60	99.94	2498176	0.040
23	39.96	3351488	0.012	61	977.59	8273213	0.118
24	0.00	1183302	0.000	62	0.26	886627	0.000
25	84.76	2307973	0.037	63	49.77	29691938	0.002
26	0.00	5202873	0.000	64	91.47	29912357	0.003
27	153.82	7704953	0.020	65	71.84	52330747	0.001
28	0.00	2168027	0.000	66	17160.64	31260187	0.549
29	222.22	3122953	0.071	67	3.40	9794715	0.000
30	92.31	4754991	0.019	68	3.53	17979614	0.000
31	38.40	1999737	0.019	69	2.08	10121005	0.000
32	30.30	2010613	0.015	70	14.05	12585100	0.001
33	223.53	3868268	0.058	71	0.88	6461491	0.000
34	1300.67	15259204	0.085	72	3.05	19961450	0.000
35	432.67	6313714	0.069	73	0.73	3025393	0.000
36	371.81	2200875	0.169	74	29.90	15751787	0.002
37	74.77	1516330	0.049	75	23.85	14923057	0.002
38	374.05	2162960	0.173	76	0.45	243831	0.002

Table S3-3 PM_{2.5} emission data by industry of Malaysia in 2005

Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)	Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)
1	517.20	251381	2.057	39	0.00	655982	0.000
2	0.00	227899	0.000	40	0.00	1150228	0.000
3	21840.52	6043353	3.614	41	0.00	6804915	0.000
4	1.62	1934607	0.001	42	0.00	8518217	0.000
5	1.39	2102143	0.001	43	0.00	2272050	0.000
6	14.03	2217113	0.006	44	0.00	124288	0.000
7	21.61	1855627	0.012	45	0.00	3184134	0.000
8	0.00	21945854	0.000	46	0.00	1584338	0.000
9	0.00	18081	0.000	47	0.00	1720962	0.000
10	0.00	88844	0.000	48	0.00	557179	0.000
11	0.00	893744	0.000	49	0.00	17749227	0.000
12	0.00	784717	0.000	50	0.00	21238506	0.000
13	0.00	629311	0.000	51	0.00	30001173	0.000
14	0.00	1251144	0.000	52	0.00	3775081	0.000
15	0.00	16606578	0.000	53	0.00	921004	0.000
16	0.00	1159153	0.000	54	0.00	6633363	0.000
17	0.00	838558	0.000	55	0.00	8087974	0.000
18	0.00	80291	0.000	56	0.00	263839	0.000
19	0.00	630787	0.000	57	0.00	1416704	0.000
20	0.00	799561	0.000	58	0.00	1241594	0.000
21	0.00	847753	0.000	59	88.57	3931575	0.023
22	0.00	966168	0.000	60	1388.57	3496229	0.397
23	0.00	122931	0.000	61	376.75	6861855	0.055
24	0.00	1200885	0.000	62	4.31	1164363	0.004
25	113.13	3270277	0.035	63	0.00	6871704	0.000
26	0.00	2587216	0.000	64	0.00	9314861	0.000
27	0.00	2050480	0.000	65	56.28	50083663	0.001
28	0.00	1591851	0.000	66	7537.51	15021527	0.502
29	0.00	598827	0.000	67	5.66	7387862	0.001
30	0.00	9993466	0.000	68	1.19	27595998	0.000
31	0.00	1196333	0.000	69	55.60	8899190	0.006
32	0.00	436466	0.000	70	8.56	5935673	0.001
33	0.00	1600260	0.000	71	7.33	3512944	0.002
34	76.32	20666767	0.004	72	51.26	5003961	0.010
35	211.25	5080259	0.042	73	5.85	2045539	0.003
36	71.33	480911	0.148	74	84.13	18652985	0.005
37	670.39	3880725	0.173	75	64.27	9751741	0.007
38	0.00	2353120	0.000	76	0.00	1051461	0.000

Table S3-4 PM_{2.5} emission data by industry of Philippines in 2005

Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)	Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)
1	3264.19	3673090	0.889	39	32.57	330439	0.099
2	686.39	958532	0.716	40	66.50	836947	0.079
3	48773.30	5967978	8.172	41	841.23	1315122	0.640
4	0.00	3957529	0.000	42	0.00	810663	0.000
5	2.33	6807317	0.000	43	0.98	1508019	0.001
6	1.24	114142	0.011	44	0.08	139820	0.001
7	28.39	3924527	0.007	45	0.54	762526	0.001
8	496.99	355818	1.397	46	0.09	97411	0.001
9	0.00	0	0.000	47	0.29	504285	0.001
10	13.64	2267973	0.006	48	0.03	906027	0.000
11	68.72	812596	0.085	49	0.03	2779610	0.000
12	18.55	10072649	0.002	50	1.78	7715612	0.000
13	0.00	1539422	0.000	51	0.00	16541778	0.000
14	107.61	6836954	0.016	52	0.33	2634651	0.000
15	128.34	11936851	0.011	53	0.67	792658	0.001
16	18.43	1924938	0.010	54	0.29	3844017	0.000
17	0.94	1087405	0.001	55	0.00	1993747	0.000
18	3.24	541405	0.006	56	0.00	236531	0.000
19	17.48	279235	0.063	57	0.00	158841	0.000
20	2.62	224471	0.012	58	0.00	729944	0.000
21	61.92	4159942	0.015	59	10.53	4333723	0.002
22	1.30	622630	0.002	60	2.10	670763	0.003
23	3.54	217946	0.016	61	1287.21	8571336	0.150
24	1.58	384983	0.004	62	1.90	769391	0.002
25	1.74	931508	0.002	63	3.08	4300700	0.001
26	5.53	640327	0.009	64	67.18	9903758	0.007
27	60.89	468951	0.130	65	77.69	18551388	0.004
28	47.80	711774	0.067	66	3529.58	8391943	0.421
29	1.16	370369	0.003	67	2.19	4927148	0.000
30	7.45	663337	0.011	68	4.28	7374092	0.001
31	2.19	331163	0.007	69	0.40	7670890	0.000
32	1.37	1251224	0.001	70	9.24	4476011	0.002
33	1.26	1408121	0.001	71	1.80	2826158	0.001
34	228.89	7131980	0.032	72	25.21	4741001	0.005
35	1.02	1183089	0.001	73	2.22	859906	0.003
36	0.32	176278	0.002	74	24.81	10229510	0.002
37	0.75	341379	0.002	75	28.95	11523560	0.003
38	211.22	706434	0.299	76	0.00	0	0.000

Table S3-5 PM_{2.5} emission data by industry of Singapore in in 2005

Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)	Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)
1	0.00	0	0.000	39	0.00	320387	0.000
2	0.00	0	0.000	40	0.00	418085	0.000
3	0.00	0	0.000	41	0.00	886825	0.000
4	0.00	86733	0.000	42	0.00	407014	0.000
5	0.00	24424	0.000	43	0.00	3894528	0.000
6	0.00	0	0.000	44	0.00	75653	0.000
7	0.00	138709	0.000	45	0.00	948414	0.000
8	0.00	0	0.000	46	0.00	421939	0.000
9	0.00	0	0.000	47	0.00	3392863	0.000
10	0.00	0	0.000	48	0.00	1220667	0.000
11	0.00	0	0.000	49	0.00	679807	0.000
12	0.00	87900	0.000	50	0.00	17008529	0.000
13	0.00	138949	0.000	51	0.00	23252451	0.000
14	0.00	402414	0.000	52	0.00	5024807	0.000
15	0.00	1596721	0.000	53	0.00	160975	0.000
16	0.00	339506	0.000	54	0.00	157221	0.000
17	0.00	201655	0.000	55	0.00	426817	0.000
18	0.00	10970	0.000	56	0.00	320850	0.000
19	0.00	33888	0.000	57	0.00	5134469	0.000
20	0.00	36618	0.000	58	0.00	2902741	0.000
21	0.00	359458	0.000	59	0.62	2265555	0.000
22	0.00	36224	0.000	60	0.48	348381	0.001
23	0.00	126901	0.000	61	4267.03	6352278	0.672
24	0.00	3095	0.000	62	0.00	388118	0.000
25	0.26	312791	0.001	63	0.00	7097451	0.000
26	0.00	152987	0.000	64	0.00	2401267	0.000
27	0.00	579272	0.000	65	0.00	33747279	0.000
28	0.00	2224341	0.000	66	1872.95	36687906	0.051
29	0.11	3657686	0.000	67	0.00	5213766	0.000
30	6.69	10134416	0.001	68	0.00	22269079	0.000
31	0.00	6610	0.000	69	0.00	14795937	0.000
32	0.12	9352219	0.000	70	0.00	4090442	0.000
33	0.57	1549108	0.000	71	0.00	3771234	0.000
34	1941.02	24051080	0.081	72	0.00	4254039	0.000
35	1.26	1324703	0.001	73	0.00	1563384	0.000
36	0.54	3505	0.153	74	0.00	31938179	0.000
37	0.00	270730	0.000	75	0.00	13149656	0.000
38	0.00	13498	0.000	76	0.00	0	0.000

Table S3-6 PM_{2.5} emission data by industry of Thailand in in 2005

Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)	Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)
1	6812.62	4567755	1.491	39	51.90	1237945	0.042
2	515.15	8955	57.526	40	79.45	2195735	0.036
3	95454.33	8532406	11.187	41	135.05	7123655	0.019
4	14.38	5321423	0.003	42	96.88	1193492	0.081
5	25.69	4492700	0.006	43	57.70	5887785	0.010
6	2.24	526247	0.004	44	49.47	2701463	0.018
7	685.95	3502036	0.196	45	60.07	4060949	0.015
8	159.47	6126813	0.026	46	2.34	231807	0.010
9	0.00	2263	0.000	47	69.29	212393	0.326
10	2.04	59969	0.034	48	30.93	1536743	0.020
11	46.72	1472933	0.032	49	35.92	6802801	0.005
12	37.79	7123631	0.005	50	53.53	13503883	0.004
13	49.19	4617356	0.011	51	51.68	7369701	0.007
14	102.13	6688395	0.015	52	14.23	4744608	0.003
15	174.76	9718514	0.018	53	9.21	976706	0.009
16	100.80	8556296	0.012	54	49.36	8342231	0.006
17	8.44	1293031	0.007	55	164.65	22888855	0.007
18	35.81	1445528	0.025	56	19.93	1829018	0.011
19	168.34	4848200	0.035	57	0.74	1240685	0.001
20	10.02	1507336	0.007	58	29.84	1269948	0.023
21	54.56	9858306	0.006	59	41.52	3020771	0.014
22	55.32	1301022	0.043	60	61.00	10222416	0.006
23	42.72	4754378	0.009	61	1708.70	18690002	0.091
24	9.07	995099	0.009	62	2.03	936209	0.002
25	4.71	2453231	0.002	63	17.05	9048469	0.002
26	4.93	1439605	0.003	64	189.00	6979541	0.027
27	149.70	3394723	0.044	65	215.94	54812677	0.004
28	21.49	1457678	0.015	66	28380.11	23890242	1.188
29	19.28	1046762	0.018	67	18.01	6774251	0.003
30	380.26	8879707	0.043	68	23.36	11867118	0.002
31	6.80	511537	0.013	69	11.43	6146994	0.002
32	1.96	1996893	0.001	70	55.36	8581795	0.006
33	26.47	3728100	0.007	71	31.60	4464631	0.007
34	3818.32	21966259	0.174	72	115.69	13554141	0.009
35	37.80	3762287	0.010	73	20.02	2980094	0.007
36	84.20	5074339	0.017	74	309.23	13445620	0.023
37	22.46	905182	0.025	75	0.00	22067564	0.000
38	819.98	4079062	0.201	76	923.92	2812000	0.329

Table S3-7 PM_{2.5} emission data by industry of China in 2005

Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)	Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)
1	57752.00	30455544	1.896	39	2863.17	36497967	0.078
2	286245.73	41957655	6.822	40	20275.52	85961044	0.236
3	126956.07	99754047	1.273	41	41232.96	295175980	0.140
4	24726.03	60661266	0.408	42	5014.67	97947074	0.051
5	99018.18	153222130	0.646	43	858.20	130236833	0.007
6	3967.74	31406643	0.126	44	335.33	20401682	0.016
7	20242.73	46222686	0.438	45	1432.84	160166737	0.009
8	10135.20	73681476	0.138	46	200.60	18864103	0.011
9	78.26	24468298	0.003	47	1126.04	109085234	0.010
10	134.57	14367947	0.009	48	304.34	30721476	0.010
11	6839.48	125101432	0.055	49	196.33	118492929	0.002
12	329.05	32629321	0.010	50	39.99	156694232	0.000
13	114.52	20508460	0.006	51	656.70	67266796	0.010
14	182.21	38521778	0.005	52	23.69	17891410	0.001
15	2828.86	162044093	0.017	53	401.36	46350030	0.009
16	1182.98	35969359	0.033	54	1307.89	125188146	0.010
17	139.95	26250325	0.005	55	1044.61	154868133	0.007
18	1144.75	52413361	0.022	56	170.19	21746391	0.008
19	1505.47	91252935	0.016	57	124.27	20308911	0.006
20	560.57	49901462	0.011	58	379.85	18105829	0.021
21	391.87	67705372	0.006	59	173.13	26184761	0.007
22	47.43	22960657	0.002	60	949.68	73670748	0.013
23	301.98	58502012	0.005	61	19263.13	234277101	0.082
24	94.44	6234805	0.015	62	407.71	11776838	0.035
25	217.97	28677039	0.008	63	23144.18	426304176	0.054
26	672.74	44842421	0.015	64	3882.66	93150704	0.042
27	2282.47	67317058	0.034	65	9122.09	290534866	0.031
28	213.41	37694906	0.006	66	171226.08	296451585	0.578
29	201.11	29607151	0.007	67	467.66	96824780	0.005
30	2949.20	80035862	0.037	68	648.51	125228696	0.005
31	2525.39	38617619	0.065	69	6796.22	125088871	0.054
32	80.24	52574871	0.002	70	13552.52	127308539	0.106
33	1319.98	137726491	0.010	71	2781.61	107702346	0.026
34	6796.95	154013100	0.044	72	3807.89	98602171	0.039
35	579.66	115809786	0.005	73	2155.64	26882574	0.080
36	377.54	20869218	0.018	74	17135.87	368913426	0.046
37	302.18	13402736	0.023	75	9475.00	156379331	0.061
38	11852.87	65801023	0.180	76	88.42	2065696	0.043

Table S3-8 PM_{2.5} emission data by industry of Taiwan in 2005

Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)	Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)
1	436.22	844334	0.517	39	118.90	3762311	0.032
2	58.33	154149	0.378	40	94.53	1782686	0.053
3	1773.85	3711646	0.478	41	470.68	34118265	0.014
4	70.54	987347	0.071	42	55.73	6353941	0.009
5	6.77	4447142	0.002	43	9.54	20313606	0.000
6	12.26	261831	0.047	44	0.11	285574	0.000
7	110.23	3348618	0.033	45	3.20	8930169	0.000
8	0.30	440894	0.001	46	0.95	6040376	0.000
9	5.66	549451	0.010	47	1.72	8464640	0.000
10	0.02	50060	0.000	48	0.77	3029525	0.000
11	19.08	2181564	0.009	49	1.86	10643312	0.000
12	19.13	1716232	0.011	50	0.79	22519149	0.000
13	21.27	404053	0.053	51	0.84	40037557	0.000
14	15.57	5795725	0.003	52	3.87	39715146	0.000
15	151.56	7254742	0.021	53	0.57	2347507	0.000
16	55.70	2761233	0.020	54	1.38	1585156	0.001
17	3.16	871784	0.004	55	2.60	13004774	0.000
18	68.26	1971795	0.035	56	0.58	2858724	0.000
19	581.88	8515188	0.068	57	0.29	1132726	0.000
20	90.67	2310432	0.039	58	0.99	4087495	0.000
21	39.16	2767611	0.014	59	9.82	4442958	0.002
22	120.40	2242092	0.054	60	28.47	4681393	0.006
23	32.39	1345556	0.024	61	3916.03	14718966	0.266
24	0.00	207898	0.000	62	0.21	1075621	0.000
25	11.65	931193	0.013	63	17.38	14302497	0.001
26	0.00	839752	0.000	64	77.71	19231412	0.004
27	194.46	5963178	0.033	65	83.12	75277068	0.001
28	30.97	5325337	0.006	66	9600.18	24220964	0.396
29	121.17	5288926	0.023	67	2.73	12428135	0.000
30	775.96	36373876	0.021	68	1.62	47300653	0.000
31	16.53	547796	0.030	69	7.26	8480901	0.001
32	6.31	1790775	0.004	70	8.24	25185726	0.000
33	88.42	7248153	0.012	71	10.52	14766448	0.001
34	1117.00	23974372	0.047	72	10.31	9190276	0.001
35	158.49	13167107	0.012	73	2.79	1648856	0.002
36	18.65	1018861	0.018	74	54.79	90264284	0.001
37	40.03	2661370	0.015	75	92.92	37416746	0.002
38	134.99	3243614	0.042	76	3.16	6693461	0.000

Table S3-9 PM_{2.5} emission data by industry of South Korea in 2005

Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)	Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)
1	1126.46	8164921	0.138	39	147.76	6354839	0.023
2	26.95	306820	0.088	40	199.67	4692504	0.043
3	140.50	12706946	0.011	41	478.85	95968470	0.005
4	63.45	2027929	0.031	42	79.69	24395592	0.003
5	305.86	11480391	0.027	43	73.96	44396758	0.002
6	16.06	1309768	0.012	44	11.12	5742071	0.002
7	661.03	4930947	0.134	45	37.64	24857233	0.002
8	58.14	192890	0.301	46	8.21	5981166	0.001
9	0.05	12964	0.004	47	36.85	30765284	0.001
10	0.06	4930	0.013	48	23.38	20154105	0.001
11	25.79	2944064	0.009	49	14.85	50304885	0.000
12	15.32	9550332	0.002	50	5.84	10649431	0.001
13	34.74	4554977	0.008	51	11.64	36347057	0.000
14	76.08	14882816	0.005	52	26.77	46617225	0.001
15	291.20	24010121	0.012	53	6.23	9916690	0.001
16	71.25	10722900	0.007	54	9.50	6102876	0.002
17	4.87	6727177	0.001	55	456.27	110406038	0.004
18	109.84	2620821	0.042	56	4.33	374515	0.012
19	358.77	7998585	0.045	57	49.64	22675900	0.002
20	22.35	3626214	0.006	58	12.80	2761409	0.005
21	238.32	13003731	0.018	59	35.22	11190765	0.003
22	166.49	8116240	0.021	60	68.26	5138211	0.013
23	72.39	4100229	0.018	61	3771.74	41732593	0.090
24	9.03	1147473	0.008	62	6.51	3564177	0.002
25	59.44	7069491	0.008	63	42.22	94608517	0.000
26	37.87	3456205	0.011	64	167.98	52418758	0.003
27	524.68	14440893	0.036	65	711.88	103764854	0.007
28	187.59	14691374	0.013	66	44030.33	76881947	0.573
29	40.66	24585164	0.002	67	66.65	38872095	0.002
30	795.19	42525821	0.019	68	146.10	86077664	0.002
31	26.67	2887998	0.009	69	82.14	101926898	0.001
32	12.51	11470744	0.001	70	314.87	76651456	0.004
33	55.52	17165307	0.003	71	69.75	43328674	0.002
34	2638.17	76069657	0.035	72	529.25	50296505	0.011
35	224.90	28928845	0.008	73	80.92	5091945	0.016
36	41.16	4259337	0.010	74	821.02	142629654	0.006
37	58.96	4837706	0.012	75	416.49	67250741	0.006
38	274.80	11070351	0.025	76	150.35	2395765	0.063

Table S3-10 PM_{2.5} emission data by industry of Japan in 2005

Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)	Industry No.	PM _{2.5} emission (tonnes)	Total output (1,000 U.S. dollars)	Emission coefficient (kg/1,000 U.S. dollars)
1	1943.60	18406585	0.106	39	572.84	15526647	0.037
2	609.35	1530784	0.398	40	903.34	22196057	0.041
3	1975.37	29976174	0.066	41	1844.76	229672377	0.008
4	553.30	7968762	0.069	42	361.21	55127638	0.007
5	214.12	27476510	0.008	43	582.86	120359306	0.005
6	232.60	11511169	0.020	44	57.06	19754167	0.003
7	1903.88	14608939	0.130	45	223.92	95795840	0.002
8	4.05	1016939	0.004	46	78.41	48213808	0.002
9	2.95	254	11.624	47	194.82	121709196	0.002
10	754.08	203669	3.702	48	46.94	47113501	0.001
11	1811.26	7928106	0.228	49	92.51	70072099	0.001
12	171.32	28486826	0.006	50	70.74	42041929	0.002
13	210.84	29196384	0.007	51	204.64	47560398	0.004
14	372.69	39494974	0.009	52	236.68	156116302	0.002
15	1708.90	133163158	0.013	53	38.01	25023787	0.002
16	506.89	72445145	0.007	54	92.61	56035115	0.002
17	31.23	21402675	0.001	55	539.63	481978851	0.001
18	39.96	1464888	0.027	56	6.18	6182139	0.001
19	484.88	8911339	0.054	57	25.27	22129861	0.001
20	27.31	4936789	0.006	58	81.48	30293202	0.003
21	29.69	9312136	0.003	59	99.86	37269812	0.003
22	130.39	15067013	0.009	60	415.67	39162224	0.011
23	44.79	5210819	0.009	61	17517.94	169456586	0.103
24	81.94	6138671	0.013	62	980.63	41358852	0.024
25	39.20	10599702	0.004	63	2952.81	361420739	0.008
26	200.63	20862999	0.010	64	2912.58	212326961	0.014
27	2875.86	71711499	0.040	65	8303.14	972119781	0.009
28	157.30	102396287	0.002	66	22929.89	370026965	0.062
29	997.69	30996634	0.032	67	479.13	148416720	0.003
30	2959.38	90239407	0.033	68	247.50	377313914	0.001
31	139.82	8200122	0.017	69	527.95	600681694	0.001
32	121.84	60305631	0.002	70	4949.05	230434230	0.021
33	793.27	61077664	0.013	71	2116.39	337581257	0.006
34	2518.36	153515488	0.016	72	821.13	190069744	0.004
35	379.79	96492143	0.004	73	719.03	59480502	0.012
36	106.46	9590022	0.011	74	6099.12	1114555544	0.005
37	110.94	16743971	0.007	75	2719.54	349651391	0.008
38	1855.96	27202526	0.068	76	688.25	36001551	0.019

Table S3-11 Source–receptor relationship (SRR) matrix in agriculture that corresponds to industry no.1 to no.7 in Table S3-1 (unit: premature mortality in 10^{-6} persons/kg-C)

		Receptor country								
		IDN	MYS	PHL	SGP	THA	CHN	TWN	KOR	JPN
Source country	IDN	1.997	0.170	0.109	0.095	0.134	0.081	0.008	0.000	0.000
	MYS	0.033	0.477	0.764	0.009	1.591	6.846	0.181	0.314	0.000
	PHL	2.703	0.789	0.508	0.152	0.002	0.000	0.000	0.000	0.000
	SGP	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	THA	0.207	0.071	0.188	0.009	5.533	0.023	0.199	0.000	0.000
	CHN	0.003	0.001	0.019	0.000	0.028	16.943	0.027	0.083	0.131
	TWN	0.000	0.000	0.001	0.000	0.000	0.000	1.799	0.000	0.000
	KOR	0.000	0.000	0.007	0.000	0.000	0.000	0.000	11.222	0.382
	JPN	0.000	0.002	0.012	0.000	0.000	0.000	0.012	0.000	10.684

Table S3-12 Source–receptor relationship (SRR) matrix in industry that corresponds to industry no.8-60, 62-65, 67-76 in Table S3-1 (unit: premature mortality in 10^{-6} persons/kg-C)

		Receptor country								
		IDN	MYS	PHL	SGP	THA	CHN	TWN	KOR	JPN
Source country	IDN	14.830	0.032	0.003	0.020	0.003	0.000	0.000	0.000	0.000
	MYS	0.331	2.494	0.011	0.200	0.127	0.000	0.000	0.000	0.000
	PHL	0.057	0.038	6.698	0.006	0.044	0.000	0.019	0.000	0.000
	SGP	1.054	0.963	0.002	2.944	0.002	0.000	0.000	0.000	0.000
	THA	0.039	0.045	0.016	0.001	7.600	0.087	0.009	0.000	0.000
	CHN	0.004	0.002	0.017	0.000	0.091	29.198	0.048	0.221	0.208
	TWN	0.007	0.005	0.062	0.001	0.050	1.757	6.592	0.011	0.064
	KOR	0.002	0.001	0.035	0.000	0.011	1.856	0.043	17.387	1.766
	JPN	0.000	0.001	0.021	0.000	0.006	0.277	0.022	0.124	15.856

Table S3-13 Source–receptor relationship (SRR) matrix in power that corresponds to industry no.61 in Table S3-1 (unit: premature mortality in 10^{-6} persons/kg-C)

		Receptor country								
		IDN	MYS	PHL	SGP	THA	CHN	TWN	KOR	JPN
Source country	IDN	12.619	0.023	0.002	0.018	0.004	0.073	0.000	0.000	0.000
	MYS	0.108	1.389	0.000	0.064	0.044	0.000	0.000	0.000	0.000
	PHL	0.000	0.001	5.047	0.000	0.000	0.000	0.000	0.000	0.000
	SGP	1.102	0.960	0.004	2.929	0.003	0.054	0.000	0.002	0.000
	THA	0.000	0.010	0.000	0.000	6.472	0.000	0.000	0.000	0.000
	CHN	0.002	0.003	0.002	0.000	0.038	6.200	0.014	0.021	0.000
	TWN	0.011	0.009	0.098	0.001	0.210	4.163	4.380	0.017	0.216
	KOR	0.004	0.001	0.040	0.000	0.007	1.775	0.048	12.171	1.959
	JPN	0.002	0.001	0.023	0.000	0.008	0.677	0.025	0.136	16.827

Table S3-14 Source–receptor relationship (SRR) matrix in transport that corresponds to industry no.66 in Table S3-1 (unit: premature mortality in 10^{-6} persons/kg-C)

		Receptor country								
		IDN	MYS	PHL	SGP	THA	CHN	TWN	KOR	JPN
Source country	IDN	5.400	0.053	0.012	0.037	0.004	0.000	0.000	0.000	0.000
	MYS	0.384	1.840	0.042	0.152	0.108	0.014	0.002	0.000	0.000
	PHL	0.105	0.052	4.431	0.008	0.104	0.320	0.039	0.001	0.012
	SGP	1.226	0.961	0.006	2.920	0.001	0.030	0.000	0.000	0.000
	THA	0.050	0.049	0.031	0.001	5.916	1.111	0.026	0.002	0.006
	CHN	0.006	0.003	0.022	0.000	0.181	24.277	0.056	0.173	0.194
	TWN	0.020	0.011	0.127	0.002	0.179	4.572	6.436	0.020	0.179
	KOR	0.002	0.001	0.039	0.000	0.027	2.769	0.055	13.591	2.170
	JPN	0.001	0.001	0.027	0.000	0.009	0.808	0.029	0.147	16.693

Table S3-15 Direct emissions in household sector of countries (unit: Gg-C)

Country	Household emissions	(Gg-C)
Indonesia	641.5	
Malaysia	23.6	
Philippines	52.6	
Singapore	0.0	
Thailand	84.5	
China	3754.8	
Taiwan	0.6	
South Korea	11.1	
Japan	7.0	

Chapter 4

Supplementary Table

Table S4-16 Province and industrial sector classification of the multi-regional input-output table for 30 regions in China in 2007

No	Province name	Abbreviation	No	Sector name
1	Beijing	BEIJ, BJ	1	Agriculture
2	Tianjin	TIAN, TJ	2	Coal mining
3	Hebei	HEBE, HE	3	Petroleum and gas
4	Shanxi	SHAN, SX	4	Metal mining
5	Neimeng	NEIM, NM	5	Nonmetal mining
6	Liaoning	LIAO, LN	6	Food processing and tobaccos
7	Jilin	JILI, JL	7	Textile
8	Heilongjiang	HEIL, HL	8	Clothing, leather, fur, etc.
9	Shanghai	SHAN, SH	9	Wood processing and furnishing
10	Jiangsu	JINU, JS	10	Paper making, printing, stationery, etc.
11	Zhejiang	ZHEJ, ZJ	11	Petroleum refining, coking, etc.
12	Anhui	ANHU, AH	12	Chemical industry
13	Fujian	FUJI, FJ	13	Nonmetal products
14	Jiangxi	JINX, JX	14	Metallurgy
15	Shandong	SHND, SD	15	Metal products
16	Henan	HENA, HA	16	General and specialist machinery
17	Hubei	HUBE, HB	17	Transport equipment
18	Hunan	HUNA, HN	18	Electrical equipment
19	Guangdong	GUAD, GD	19	Electronic equipment
20	Guangxi	GUAX, GX	20	Instrument and meter
21	Hainan	HAIN, HI	21	Other manufacturing
22	Chongqing	CHON, CQ	22	Electricity and hot water production and supply
23	Sichuan	SICH, SC	23	Gas and water production and supply
24	Guizhou	GUIZ, GZ	24	Construction
25	Yunnan	YUNN, YN	25	Transport and strage
26	Shaanxi	SHAA, SN	26	Wholesale and retailing
27	Gansu	GANS, GS	27	Hotel and restaurant

28	Qinghai	QING, QH	28	Leasing and commercial services
29	Ningxia	NINX, NX	29	Scientific research
30	Xinjiang	XING, XJ	30	Other services

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