Structural Decomposition Analysis of the Global CO2 Emissions

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Structural Decomposition Analysis of the Global CO_2 Emissions

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Chapter 1 Introduction

1.1 The Present Situation Regarding Global Warming

The problems associated with global warming require immediate attention as the ramifications of perturbations to climate and an increase in the average temperature become apparent (World Metrological Organization, 1986; IPCC, 2014a). The International Panel of Climate Change (IPCC) recently stated that the "Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems" (IPCC, 2014a, p.2). The IPCC summarized the risks that will arise if temperatures continue to rise in the future as follows: "*(i) Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise, (ii) Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions, (iii) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services, (iv) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas, (v) Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings, (vi) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal* *capital in semi-arid regions, (vii) Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic, (viii) Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods*" (see IPCC, 2014b, p.13). Briefly, the problems resulting from increases in temperature are extremely diverse and widespread. Consequently, the phenomenon of global warming has been recognized as a problem that needs to be resolved, not only at the national level, but also at the global level.

The cause of global warming is considered to be the release and subsequent accumulation of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrogen oxide (N_2O) and Freon in the atmosphere. Moderating the quantity of GHG emissions is considered important in maintaining average temperatures at levels suitable for sustaining healthy populations of living organisms. However, the current high levels of GHG emissions into the atmosphere have contributed to a rise in global average temperatures (Houghton *et al*, 1992). According to the IPCC (2014c), GHG emissions have increased considerably from 1970 to 2010, with particularly marked increases (ca. 2.2% per year) observed from 2000 to 2010. Of the GHGs emitted in 2010, 76% was CO_2, and of that, 86% was derived from the combustion of fossil fuels and other industrial processes (see Figure 1.1).

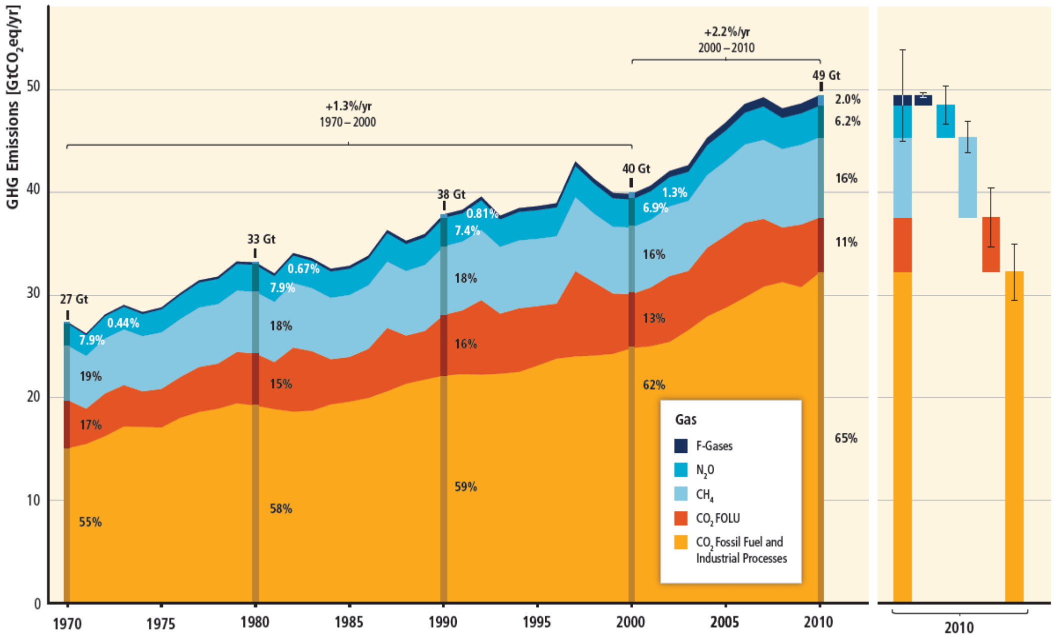

Figure 1.1. Change in annual GHG emissions from 1970 to 2010 (Source: IPCC, 2014c)

Within the context of the level of economic development, GHG emissions of high-income countries have remained almost unchanged from 1970 to 2010 (see Figure 1.2). Since 2000, the GHG emissions of upper-middle income countries such as China and Brazil have increased, and in 2010, GHG emissions from these countries exceeded those of high-income countries. IPCC (2014c) reported that the economies of emerging countries have become industrialized and that this has been associated with a marked increase in CO_2 emissions from these countries. In particular, China has become the largest CO_2 emitter since 2007, which means that the country now plays an important role in the reduction of global CO_2 emissions.

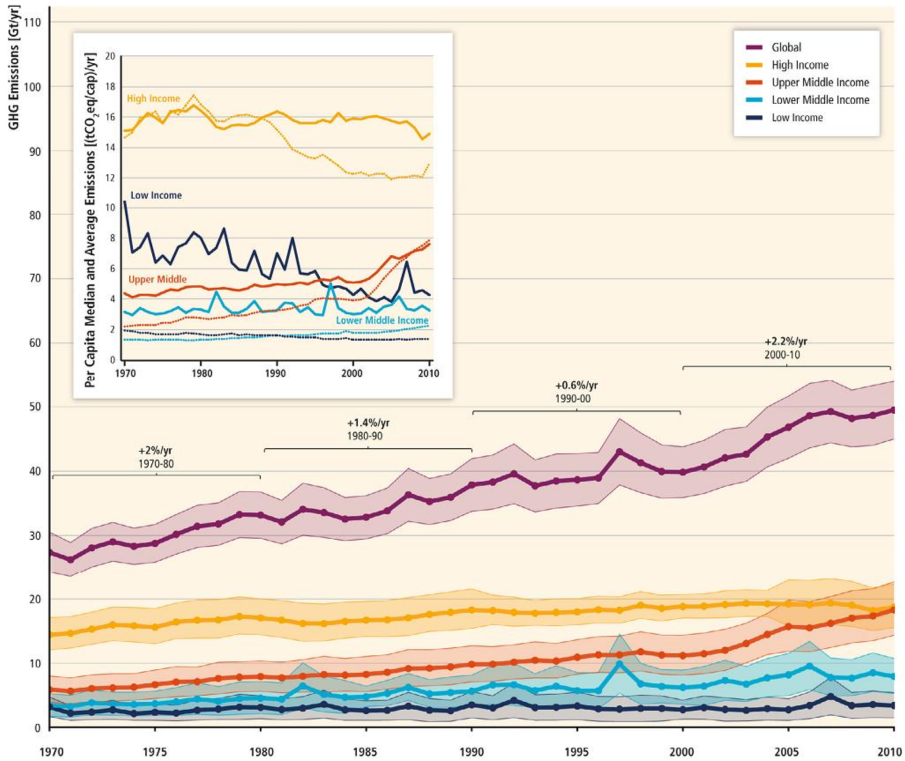

Figure 1.2. Global increase in GHGs emissions by economic region according to national income level per capita (Source: IPCC, 2014)

As mentioned above, while the problems associated with global warming are varied, most have arisen because of an increase in the average temperature of the earth due to an increase in greenhouse gases in the atmosphere. As a result, any mitigation measures directed at reducing global GHG emissions requires international cooperation. Global warming issues started to be discussed when the World Climate Conference was convened in Geneva in 1979. The problem of global warming due to CO_2 emissions, specifically, was first discussed at the international conference on the assessment of the role of carbon dioxide and of other greenhouse gases in climate variations and associated impacts (Villach conference) convened by the United Nations Environment Programme (UNEP) in 1985. Although scientists had discussed global warming before the Villach conference, the conference was the first time that scientists and policy makers committed themselves to cooperating with each other to tackle global warming (World Metrological Organization, 1986).

Subsequently, the Kyoto Protocol and the Paris Agreement were important international efforts directed at reducing global GHG emissions. The Kyoto Protocol was concluded in the conference of the parties to the United Nations Framework Convention on Climate Change (COP 3) in 1997 and came into force in 2005. In The Kyoto Protocol, the Annex I Parties (i.e. developed countries), were obliged to reduce the emissions of six greenhouse gases by 5% compared to 1990 levels. The agreement proposed several instruments, such as emissions trading and clean development mechanism, to achieve the aim of reducing GHG emissions through international cooperation at a global scale (UNFCCC, 2008). However, agreement did not achieve the proposed goals, primarily because America—one of the largest CO_2 emitters—withdrew from the Kyoto Protocol, and developing countries, who were undergoing rapid industrialization at the time, were not obliged to reduce CO_2 emissions (Böhringer, 2003; Böhringer and Vogt, 2003; Lau *et al.*, 2012; Clémençon, 2016).

The Paris Agreement, which is widely recognized as the post Kyoto Protocol, was adopted in 2015. According to a press release from the United Nations, the agreement is "A historical agreement to combat climate change and unleash actions and investment towards a low carbon resilient and sustainable future was agreed by 195 nations in Paris today" (UNFCCC, 2015, p. 1). As a new international framework for the reduction of GHG emissions after 2020, the Paris Agreement is considered to be a fair agreement in that it allows nations to set their own reduction targets, which are referred to as their "Intended Nationally Determined Contribution". In other words, nations can take their own social and economic circumstances into consideration when they set their reduction targets, increasing the support for the agreement from a number of nations. In this way, global warming can be mitigate through a framework of global cooperation that is not based on the level of economic development or geographic area.

1.2 Economic Activities and their Impacts on the Climate Mitigation

Global GHG emissions, especially CO_2 emissions, have increased as the consumption of fossil fuels has increased since the industrial revolution in the 18th century (Canadell *et al.*, 2007; IPCC, 2014a, 2014b). Figure 1.3 shows a breakdown of CO_2 emissions derived from global fossil fuel combustion in 2015 (IEA, 2017). In 2015, the combined direct and indirect global CO_2 emissions (i.e. the total amount of emissions discharged directly by sectors and the emissions produced by generating the electricity and heat for those sectors) for the industrial and service sectors were 36% and 11% of GHG emissions, respectively. These data show that industrial production activities are responsible for a very high proportion of global CO_2 emissions.

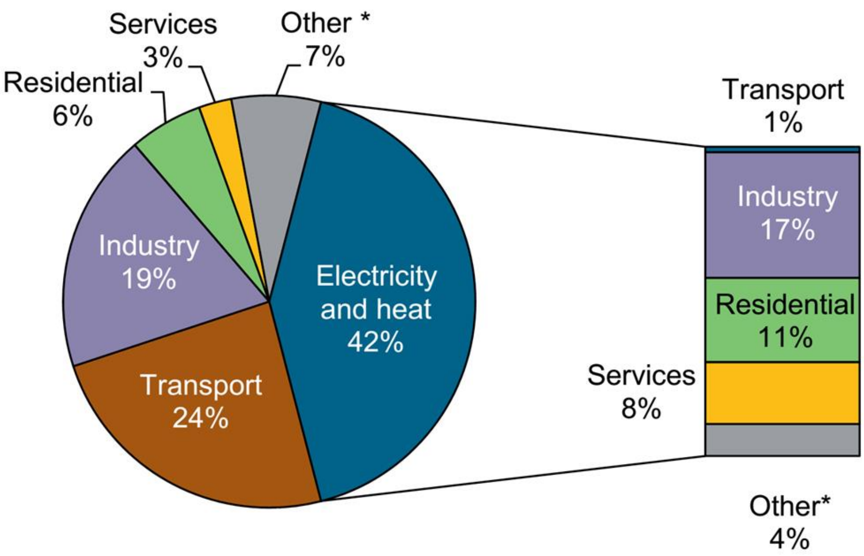

Figure 1.3. Global CO_2 emissions from fossil fuel combustion by sector in 2015 (Source: IEA, 2017)

The issue of anthropogenic GHG emissions, such as GHG emissions derived from fossil fuel combustion, encompasses a broad range of social and economic issues, including population growth, changes in industrial structure, consumption trends, national policy, technological development, and changes in land use. For example, IPCC (2014c) quantified the contribution of social and economic factors to changes in CO_2 emissions from 1970 to 2010 at global and regional levels using the IPAT (I: impact, P: population, A: affluence and T: technology) and Kaya decomposition methods (Ehrlich and Holdren, 1971; Kaya, 1989) (see Figure 1.4). The figure shows that, from 1970 to 2010, human population growth, GDP per capita, energy intensity in GDP (Energy/GDP in Figure 1.4), and CO_2 intensity in energy (CO_2/ Energy in Figure 1.4) contributed to fossil fuel-derived global CO_2 emissions were +87%, +103%, −35%, and −15%, respectively. Thus, increases in population and GDP per capita cancelled out the improvements in energy intensity. Since the ways in which these social factors influence changes in GHG emissions is very complicated, extensive studies will need to be undertaken to clarify the underlying mechanisms in the future (IPCC, 2014c).

As I mentioned above, social factors, such as population growth and economic scale, have been considered in studies of anthropogenic CO_2 emissions. Changes in the industrial structure are also recognized as an important social factor for anthropogenic CO_2 emissions, especially derived from production activities. In developed countries, more than half of the domestic labor market is engaged in the service sectors (Fuchs, 1968; Zucher, 1986; Iversen and Wren, 1998; Buera and Kaboski, 2012). Within the context of GHG emissions, this shift towards a service economy (Wölfl, 2005) has become increasingly important, as services are considered to generate relatively fewer emissions (e.g. SO_2, NO_2 and CO_2) than conventional industrial activities (Pacala and Socolow, 2004; Levinson, 2009; Okamoto, 2013). However, this shift has resulted in countries satisfying their domestic intermediate input and final demand requirements by importing the agricultural and industrial products from overseas. As a result, they effectively pass on the CO_2 emissions associated with production to the country or region exporting the goods (Wiedmann and Minx, 2007; Hertwich and Peters, 2008). Thus, changes in the structure of industrial activities have far-reaching impacts on the production structures that govern the domestic supply chain (Suh, 2006; Nansai *et al.*, 2009). However, since the production structure differs among countries, the distribution of the CO_2 emissions associated with domestic production activities throughout the supply chain will differ from one country to the next. Thus, in order to clarify the characteristics of global CO_2 emissions, we need to thoroughly understand the role of the production structure (i.e. supply chain structure) in the economy.

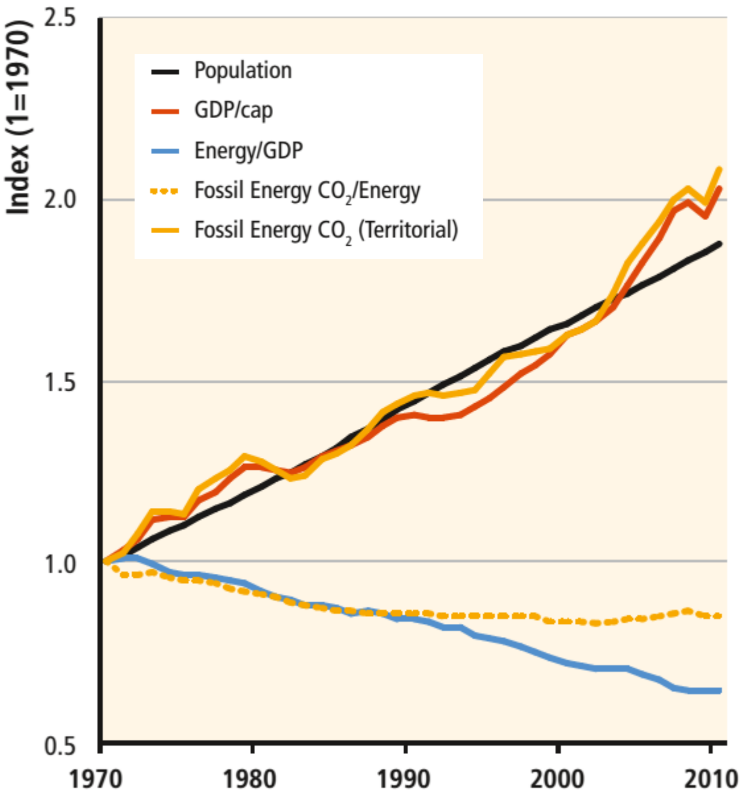

Figure 1.4. Four-factor decomposition of global CO_2 emissions from fossil fuel combustion over the period 1970 to 2010 (Source: IPCC, 2014c).

1.3 Structure of this Dissertation

This doctoral dissertation comprises five chapters (See Figure 1.5). Chapter 2 is a review of relevant literature. In addition, the significance and objectives of this thesis are described in detail. Chapter 3 examines the domestic economic structures of the 40 countries from 1995 to 2009. The changes in CO_2 emissions induced by the industrial activities of these countries are decomposed into five factors—technology, economic scale, industrial composition, import scale and import composition. Chapter 4 is a comprehensive analysis of the effects of production structures on supply-chain segments, such as inputs of material goods to service sectors, which are required for assessing policies related to reducing CO_2 emissions. Finally, Chapter 5 summarizes the results of Chapters 3 and 4 and presents the conclusions of this dissertation.

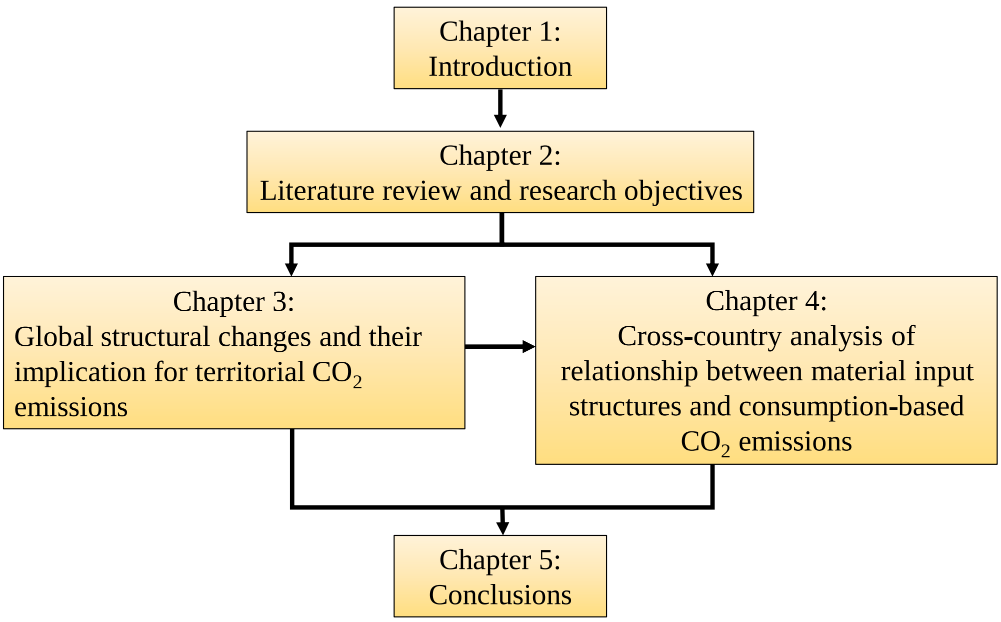

Figure 1.5 Structure of this thesis

Chapter 2 Literature review and research objectives

2.1 Studies on relationship between economic activity and GHG emissions

Many studies have been performed that analyze the relationship between environmental problems and economics and many researchers have noted various macro factors as the main drivers of anthropogenic GHG emissions. One example has been a focus on economic growth as an important driver of GHG emissions (Grossman and Krueger, 1994; Lim *et al.*, 2009; Blodgett and Parker, 2010). The environmental Kuznets curve (EKC) for the relationship between environmental impact and economic growth is particularly well known (Grossman and Krueger, 1994; Levinson, 2002; Carson, 2009). It is an inverted-U curve showing that as an economy grows, the emissions of pollutants and other environmental impacts initially rises, reaches a turning point, and thereafter declines.

Analyses of the relationship between economic growth and GHG emissions have often been based on the EKC hypothesis (Wagner, 2008; Gallagher, 2009; Vollebergh *et al.*, 2009; Stern, 2010; Fodha and Zaghdoud, 2010; He and Richard, 2010; Nasir and Ur Rehman, 2011). These previous studies have shown that GHG emissions continue to increase with rising per capita income, and thus that GHG emissions (environmental impact) do not decrease with growth in per capita income.

As analysis methods that consider not only economic growth but also change in population and technology, the IPAT (I: Impact; P: Population; A: Affluence; T: Technology) method (Ehrlich and Holdren, 1971) and the Kaya identity (Kaya, 1990) provide frameworks for analysis of the factors of overall change in environmental impact. The IPAT identity decomposes overall GHG emissions into three factors: population, per capita income, and GHG emission intensity. It may be noted that the Kaya identity is a special case of the IPAT method and focuses on CO_2 emissions from fossil fuel combustion and production processes. Raupach *et al.* (2007) used the Kaya identity to decompose CO_2 emissions from fossil fuel combustion and production processes into four drivers: population, per capita GDP, energy intensity of GDP (energy/GDP), and carbon intensity of energy (emissions/energy), and showed that from 2000 to 2004, whereas reductions in the energy intensity of GDP and carbon intensity of energy tended to depress the world's GHG emissions from fossil fuels, they ultimately rose as a result of increases in population and per capita GDP.

A change in industrial structure can be considered another macro factor with an impact on anthropogenic GHG emissions (IPCC, 2014c). Changes in industrial structure defined in this doctoral dissertation are changes in the share of industrial sectors in the gross national product of a country. In what is well known as Petty-Clark's law (Clark, 1940), it has been observed that in the course of economic growth, as income grows, the agricultural share in production and employment initially decreases while the industrial share increases but later decreases as the share of the service industry ultimately increases (Hollis *et al*, 1962; Syrquin and Chenery, 1989; Chenery and Syrquin ,1990). This tendency toward increasing weight of the service industry in the economy is known as the shift toward the service economy (Wölfl, 2005).

There are 2 views of the role of shifting toward the service economy in environmental impact. One view is that in a country such a shift contributes to reduction in its domestic GHG emissions (i.e., intraterritorial GHG emissions) because service-oriented nations engage in producing products (i.e., services) with little energy use and with low GHG emission intensity and decrease their GHG emissions from industries manufacturing products with high emission intensity. Pacala and Socolow (2004) estimated future world CO_2 emissions extending from 2004 to 2054 and laid out 15 strategies for CO_2 emission curtailment that would maintain the 2004 emission level. As part of those strategies, they hold that service industry expansion could suppress future world energy demand and that it would as a result be possible to limit CO_2 emissions (Pacala and Socolow, 2004).

For the other view, however, some studies concludes that shifting toward a service economy contributes to increased energy use and higher GHG emissions. Fourcroy *et al.* (2012) have shown that in France the transport and communication sectors are capital-intensive and require large amounts of equipment among the service industry, making energy (e.g., electricity) consumed in that industry important. Suh (2006) has estimated the direct and indirect GHG emissions of industries incidental to U.S. household consumption and noted that the domestic service sector in the U.S. contributes indirectly to increases in GHG emissions.

In the following sections, I review the method of analysis relating to CO_2 accounting systems, which are important for describing these two contrasting views.

2.2 Analysis of CO_2 emission structure by production-based accounting

2.2.1 Production-based accounting

Production-based accounting (IPCC, 1997; Peters, 2008) is an accounting system for measurement of the consumption of energy used directly for production of goods and services and measurement of pollutant emissions and other aspects in a country. This accounting system has been used mainly in studies analyzing the relationship between economic growth and environmental impact as in the EKC discussed in Section 2.1. CO_2 emissions associated with fossil fuel combustion required for production correspond to CO_2 emissions in the usual statistics. Production-based accounting was used to set the emission reduction targets in the Kyoto Protocol and the Paris Agreement (UNFCCC, 2008, 2015). Production-based CO_2 emissions are also known as territorial CO_2 emissions since the accounted CO_2 emissions are those arising in the national territory.

2.2.2 Index decomposition analysis for production-based CO_2 emissions

One important method of analyzing environmental impacts by production-based accounting is index decomposition analysis (IDA), which is a factor decomposition analysis that uses total output, composition ratio, and other statistical data to perform quantitative estimation of the contribution of factors (e.g., change in industrial composition ratio) to changes in total production. Broadly speaking, IDA consists of two approaches. One is based on the Laspeyres or other price indices (Jenne and Cattell, 1983; Marlay, 1984; Sun, 1998; Sun and Ang, 2000; Ang and Liu, 2007) and the other on the Divisia index (Ang and Choi, 1997;Ang *et al*., 1998; Ang and Zhang, 2000; Choi and Ang, 2003; Wood and Lenzen, 2006; Ang and Liu, 2007). In addition, a factor decomposition based on Shapley value proposed in Shapley (1953) are used (Albrecht *et al*., 2002; Shorrocks, 2013; Xu and Ang, 2013; Yu *et al*., 2014; Han *et al*., 2015). Shapley value was developed as an approach to fairly distribute payoff to players in the field of cooperative game theory. Since 1953, Shapley value has been used in cost/income allocation models (Hamlen *et al*., 1977; Young *et al*., 1982; Wan, 2004). Shapley value employs a concept that payoff (or costs) are symmetrically distributed to every player (or factor) involved in game (or model) Shapley decomposition also employs this concept and estimate the contributions of factors based on Shapley Value (Albrecht *et al*., 2002). Ang *et al*. (2003) and Ang (2004) pointed out that there is an similarity between the factor decomposition based on Shapley value and Laspeyres index proposed in Sun (1998). Ang (2004) collectively referred them as S/S method.

In the environmental field, IDA is applied to analysis of total energy consumption, energy intensity, GHG emissions, and so forth (Jenne and Cattell, 1983; Marlay, 1984; Howarth *et al.*, 1991; Ang, 1994; Sun, 1998; Ang *et al.*, 1998; Dietzenbacher and Los, 1998; Dietzenbacher *et al.*, 2000; Ang and Liu, 2001, Albrecht *et al.*, 2002; Hoekstra and van den Bergh, 2003; Ang 2004; Wood and Lenzen, 2006, Levinson, 2009, Kagawa *et al.*, 2012; Su and Ang, 2012; Löschel *et al.*, 2015). The data requirement for IDA is comparatively small, and long-term or international analysis is therefore possible (Hoekstra and van den Bergh, 2003).

The study by Löschel *et al.* (2015) is an important study using IDA to analyze the relationship between industrial structure and the environmental impact using the production-based accounting. Löschel *et al.* (2015) used the World Input-Output Database (WIOD) (Dietzenbacher *et al.*, 2013; Timmer *et al.*, 2015), which is one of the multi-regional input-output tables, to analyze the changes from 1995 to 2009 in total energy intensity of 27 EU countries decomposed by changes in industrial structure and changes in energy intensity per country unit. The results of this analysis showed that from 1995 to 2009 the reduction in energy intensity in production in the EU was the result of industrial sector reduction of energy intensity by technological improvements and shifting to industrial sectors with low energy intensity. In another analyses with IDA applied to WIOD, Voigt *et al.* (2014) quantitatively assessed the impact of the industrial composition of 40 countries and the energy intensity of their industrial sectors on changes in their domestic energy intensity and showed that changes in the industrial composition of countries such as Japan and America contributed to reduction of their energy intensity. Levinson (2009) decomposed changes from 1972 to 2001 in the emissions of atmospheric pollutants (e.g., SO_2 and NO_2) from production in the American manufacturing industry into the three factors of (1) emission intensity (technology), (2) industrial composition ratio (composition), and (3) manufacturing industry gross product (scale), and quantitatively analyzed the level of contribution by each. The results showed that curtailing the industrial composition ratio of the manufacturing industry contributed to the reduction of pollutant emissions. Moreover, while many of the analyses that used production-based accounting focused on emissions occurring in the 'domestic production' in the countries, Levinson (2009) also focused on changes in the composition ratio of 'imported intermediate materials input' to production. In this way, it showed that growth in the import composition ratio of American domestic industries resulted in substitution for domestically produced manufacturing industry products and suppression of pollutant emissions.

2.3 Analysis of CO_2 emission structure by consumption-based accounting

2.3.1 Consumption-based accounting

Another important accounting system for assessing environmental impact is consumption-based accounting, which measures the energy consumption, pollutant emissions, and other aspects associated with producing final goods and services and intermediate materials for production of these final goods and services in a country. In studies using it, input-output analysis has been applied as a top-down approach and it is therefore possible to estimate indirect emissions associated with the final goods and services through the supply chain (Peters and Hertwich, 2008).

This environmentally extended input-output analysis has been applied to various environmental indicators such as environmental pollution (Leontief, 1970, 1972; Kagawa and Inamura, 2001), GHG and CO_2 emissions (Guan *et al.*, 2008; Weber *et al.*, 2008; Hertwich and Peters, 2009; Peters, *et al.*, 2011; Davis *et al.*, 2011; Oshita, 2011; Okamoto, 2013), amount and intensity of energy use (Bullard and Herendeen, 1975; Park, 1992; Liu *et al.*, 2009; Kagawa *et al.*, 2013; Voigt *et al.*, 2014), water use, resources, and ecology, (Duarte *et al.*, 2002; Hoekstra and van den Bergh, 2006, Lenzen *et al.*, 2012). Particularly in recent years, the development of Chinese domestic input-output tables has progressed, and therefore detailed analysis relating to atmospheric pollutants and CO_2 emissions has become vigorous (Chang *et al*, 2010; Lin *et al*, 2013; Wang *et al.*, 2014; Liu *et al.*, 2015; Lei *et al.*, 2017; Mi *et al.*, 2017; Ou *et al.*, 2017). In further progress of multi-regional input-output database development, it has become possible to estimate environmental impact by consumption-based accounting with more widely covered countries (Lenzen *et* *al.*, 2004, Wiedmann and Minx, 2007; Hertwich and Peters, 2009; Wiedmann, 2009; Davis *et al.*, 2011). Using a multi-regional input-output table (a GTAP model), Hertwich and Peters (2009) estimated the consumption-based carbon emissions of 69 countries and, based on the relationship of consumption-based carbon emissions to the level of final demand and consumption composition, showed that countries with a higher degree of economic development corresponded to a greater impact on the world's GHG emissions. As shown in Hertwich and Peters (2009), analyses using consumption-based accounting have mainly focused on the total amount and composition of the consumption (and import) of final goods and services by developed and developing countries and some have discussed the emissions responsibility between producers and consumers (Lenzen *et al*, 2007; Feng *et al*, 2013).

2.3.2 Structural decomposition analysis for consumption-based CO_2 emissions

Structural decomposition analysis (SDA), like IDA, enables quantitative measurement of the contribution of changes in each factor to changes in total amount and is widely applied in the environmental field (Proops, 1984; Rose, 1990; Lin and Polenske, 1995; Rose and Casler, 1996; Dietzenbacher and Los, 1997; 1998; 2000; Dietzenbacher *et al.* 2000; Casler and Rose, 1998; Wier, 1998; Nansai *et al.*, 2007; Nansai *et al.*, 2009; Minx *et al.*, 2011; Xu *et al.*, 2011; Xu and Dietzenbacher, 2014). Detailed descriptions of SDA (and comparisons between SDA and IDA) have been given by Hoekstra and van den Bergh (2003), Su and Ang (2012), and Lenzen (2016). SDA has become an important method for input-output analysis. In particular, estimating the contribution of change in the production structure including the supply chain shown by the Leontief inverse matrix **L** enables quantitative assessment of structural changes that considers a complex supply chain.

One example is provided by Minx *et al.* (2011), which applied SDA to the Chinese input-output table, identified the causes of increase in Chinese CO_2 emissions from 1992 to 2007, and showed that during that period the expansion in final demand constantly contributed to increase in CO_2 emissions and the change in production structure contributed largely to the increase in CO_2 emissions particularly from 2002 to 2007.

SDA used in environmental input-output analysis studies is generally additive, but the use of multiplicative SDA enables extraction of important supply chain sectors or segments (Nansai *et al*, 2007; 2009). Nansai *et al.* (2009) decomposed the supply chain reflecting the domestic production structure into the four segments; input from goods to goods, input from goods to services, input from services to goods, and input from services to services, and performed multiplier decomposition analysis (Miyazawa, 1966; Sonis and Hewing, 1993; Sonis *et al.*, 1998). The results of this analysis showed that in Japan the intermediate demand for goods such as personal computers, copy machines, and other electronic instrument products increased with the expansion in domestic demand for services. The domestic production structure in Japan tended to be rematerialized (van den Bergh and Janssen, 2004) and the emission intensity of the supply chain segment relating to input of energy and goods for the service industries increased greatly from 1990 to 2000.

2.4 Research objectives and contribution of this Dissertation

A comprehensive overview of the prior studies on CO_2 emissions in light of the two accounting systems shows the following as challenges remaining to be met.

Studies to the present using production-based accounting have included quantitative analysis of the contribution of production technology and industrial composition ratio to changes in national and territorial CO_2 emissions and CO_2 emission intensity, but they have treated emission intensities as technology. In additions, they have lacked information on the supply chains that constitute the domestic production structure and overlooked the potential for reduction of supply chain emissions. In another vein, studies to the present that have used consumption-based accounting centered on discussion of emission transfer and consumer responsibility and have not included comprehensive analysis of the relationship between changes in industrial structure (changes in the industrial composition ratio and other aspects) and production structure and technology materialization (e.g., raising the emission intensity in intermediate input to the supply chain). Recent emission managements like the Paris Agreement are based on the production-based accounting which consequently led to an inconsistency between discussion around consumption-based emissions and such emission managements.

Studies to the present that used domestic input-output tables, moreover, have not enough included international comparisons using widespread country coverage. It is critically important to analyze the impact of the world's composite structural changes on CO_2 emissions through international comparisons.

This doctoral dissertation is predicated to meeting these challenges by developing time-series data relating to multi-regional input-output tables and considering both production-based and consumption-based CO_2 emission accounting systems, and by focusing on changes in industrial structure from the perspective of industrial and import compositions and on changes in domestic production technology from the perspective of supply chains, all with the objective of comprehensive analysis of the relationship between environment and economy. More specifically, I begin in Chapter 3 by using time-series data of world input-output tables and focusing on changes in the intra- and extraterritorial CO_2 emissions (production-based CO_2 emissions) of 40 countries. The causes of these changes in emissions are decomposed into effects of industrial and import compositions, production and import scales, and technology (CO_2 intensity), and the contributions of multiple factors regarded as having caused change in emissions are measured quantitatively. Particularly in this analysis, the role of changes in industrial structure in world CO_2 emissions is considered with a focus on the effects of country industrial and import compositions. In Chapter 4, I utilize data on production structure obtained from world input-output tables to estimate the multiplier effect of CO_2 emissions of supply chain segments on CO_2 emissions in consumption-based accounting. In elucidating the relationship between the estimated CO_2 emission effect and level of economic development, moreover, I discuss the policy for supply chain management in accordance with the level of economic growth in the midst of domestic CO_2 reduction.

Simultaneous analyses of the time series for widespread covered countries from both perspective of production-based and consumption-based CO_2 emissions enable composite and comprehensive analysis of the role that has been played in global warming by past changes in the world's industrial structures, and the findings of these analyses will provide important information that constitutes a basis for simultaneous solution of the world's problems of economic development and global warming in the future.

Chapter 3 Global structural changes and their implication for territorial CO_2 emissions

3.1 Introduction

Global territorial GHG emissions have increased continuously as nations have pursued economic growth. The average annual increase in GHG emissions for the decade 2000 through 2010 is 2.2% (IPCC, 2014c). According to Assessment Report 5 of the IPCC, CO_2 remains the major GHG, accounting for 76% of total GHG emissions. Changes in human population, per capita gross domestic product (GDP), energy intensity of production, and CO_2 emission intensities of energy production have affected fossil fuel-related CO_2 emissions by +87%, +103%, −35%, and −15%, respectively, over the 40-year period from 1970 to 2010 (IPCC, 2014c). These data imply that the positive effects of energy efficiency improvements on CO_2 emissions have been cancelled out by the increase in per capita production and population.

While territorial and consumption-based CO_2 emissions in Asia increased at relatively comparable rates from 1990 to 2010 (i.e., 175% and 197%, respectively), consumption-based CO_2 emissions in the OECD member nations increased at least three times as quickly as territorial CO_2 emissions (i.e., production-based CO_2 emissions) over the same period (IPCC, 2014c). The reason for this remarkable increase in consumption-based CO_2 emissions in OECD member nations has been the growing dependence on Asia for imports, which implies that the increase in CO_2 emissions was attributable to international trade (Hertwich and Peters, 2009; Davis *et al.*, 2011; Peters *et al.*, 2011).

Compared to territorial CO_2 emissions, however, the accounting method for consumption-based CO_2 emissions poses additional challenges, including the requirement for a deeper understanding of the global supply chain complexity associated with the final demand of nations. Conversely, accounting for the CO_2 emissions *directly* generated to produce products (i.e., production-based CO_2 emissions) is relatively straightforward. Therefore, it would be useful to be able to estimate the production-based CO_2 emissions responsible for exports when evaluating how importing countries contribute directly to CO_2 emissions induced by the domestic production activities of exporting countries. It is crucial to monitor the driving fouces of the changes in not only production-based emissions but export-based emissions in making a climate change policy with a focus of territorial emissions.

In this study, I focus on recent changes in domestic economic structure in the world. The World Input-Output Database (WIOD) covering 40 developed and developing countries shows that from 1995 to 2009, the ratio of domestic output in the tertiary sectors of the 40 countries to the total output of those countries grew by 1.1%, whereas that of domestic production in the primary and secondary sectors of those countries declined by 4.4% (Dietzenbacher *et al*., 2013). In addition, the dependence of the 40 countries on imports of primary and secondary products during the same period grew at rates of 2.1%. In other words, domestic industrialization has rapidly weakened from 1995 to 2009 and this structural change has affected the environment.

A wide variety of indexes and structural decomposition techniques have been developed to analyze the effects of structural changes on energy consumption and the environment (Leontief and Ford, 1972; Proops, 1984; Rose and Chen, 1991; Park, 1992; Lin and Polenske, 1995; Rose and Casler, 1996; Casler and Rose, 1998; Sun, 1998; Wier, 1998; Kagawa and Inamura, 2001; Ang *et al*., 2003; Ang, 2004; Levinson, 2009; Wood and Lenzen, 2009; Kagawa *et al*., 2012; Oshita, 2012; Okamoto, 2013). For example, methodological and empirical comparisons of index decomposition analyses (IDA) and structural decomposition analyses (SDA) were presented in Hoekstra and van der Bergh (2003). In a recent important IDA study, Voigt *et al.* (2013) used the WIOD to examine energy intensity trends and drivers in 40 major economies, and estimated the effects of changes in the sectoral composition of the global economy as well as regional structural changes on energy intensities. However, they did not argue that domestic structural changes are strongly related to import structural changes. For climate change policy, it is crucial to examine the effects of both changes in industrial composition and import composition on greenhouse gas emissions (Hertwich and Peters, 2009; Peters *et al*., 2011; Davis *et al*., 2011). Xu and Dietzenbacher (2014) examined driving forces of the growth of CO_2 emissions from 1995 to 2007 by applying the WIOD to a multiplicative decomposition technique (Dietzenbacher *et al*., 2000) and revealed that the growth in *net* export emissions (i.e., emissions embodied in exports minus emissions embodied in imports) in developed countries was mainly due to changes in the trade structure of final and intermediate products. The abovementioned articles focused on consumption-based emissions and so did not include empirical decomposition results that took into account production-based emissions, which should also be discussed by climate policy makers.

This chapter proposes an additive decomposition method of production-based emissions and empirically examines the extent to which changes in the global industrial structure as well as changes in import structure and export structure, have contributed to changes in production-based CO_2 emissions (i.e., territorial CO_2 emissions). Specifically, the territorial CO_2 emissions of each of the 40 aforementioned nations from 1995 to 2009 were estimated using the Environmentally Extended World Input-Output Tables at 2009 prices (Dietzenbacher *et al*., 2013; Timmer *et al*., 2015). The Shapley–Sun–Dietzenbacher–Los additive decomposition method (Park, 1992; Dietzenbacher and Los, 1997; Dietzenbacher and Los, 1998; Sun, 1998; Ang *et al*., 2003; Ang, 2004; Nansai *et al*., 2007; Nansai *et al*., 2009; Kagawa *et al*., 2012) was then applied to examine the sources of changes in the territorial CO_2 emissions. Based on these results, I examine how these structural changes have contributed to changes in CO_2 emissions. It should be noted that empirical results from the additive decomposition used in this study are not directly comparable to those from previous studies using multiplicative decomposition techniques (e.g., Voigt *et al.*, 2013; Xu and Dietzenbacher, 2014).

The remainder of this paper is organized as follows: Section 2 describes the study methodology, Section 3 presents the data, Section 4 gives results and discussion, and Section 5 concludes this chapter.

3.2 Methodology

In this study, I clarify how a widely used multi-regional input-output database is useful for estimating the effects of changes in industrial composition and trade patterns on production-based emissions. I employ additive decomposition techniques to examine the effects of technology, industrial composition, and economic scale on production-based emissions (Park, 1992; Sun, 1998; Ang *et al.*, 2003; Ang, 2004). Furthermore, I develop a decomposition method for examining the effects of changes in the composition of both regional and sectoral imports on CO_2 emissions.

The WIOD database from 1995 to 2009 (Dietzenbacher *et al.*, 2013; Timmer *et al.*, 2015) covers 35 industrial sectors and 40 countries (Tables S3.1 and S3.2 in the Appendix). Using the time series multiregional input–output tables, total territorial emissions $Q_d^t(s)$ induced by manufacturing activities in country s in year t can be expressed as follows:

$$\begin{aligned} Q_d^t(s) &= \sum_{i=1}^{N} e_i^t(s)\theta_i^t(s)X_d^t(s) \\ &= \mathbf{e}^t(s)\boldsymbol{\theta}^t(s)X_d^t(s) \end{aligned} \tag{1}$$

where $\mathbf{e}^t(s)=\{e_i^t(s)\}$, $\boldsymbol{\theta}^t(s)=\{\theta_i^t(s)\}$, and $X_d^t(s)$ are the emission intensity row vector describing CO_2 emissions per unit output in industrial sector i in country s in year t, the industrial composition column vector describing the fraction of output from industry sector i of total production across all industries in country s in year t, and total industrial output summed over all industrial sectors in country *s* in year *t*, respectively. The subscript *d* denotes "domestic". *N* is the number of industrial sectors.

The annual change in $Q_d^t(s)$ from year *t* to year *t*+1 is then

$$\Delta Q_d(s) = \mathbf{e}^{t+1}(s)\boldsymbol{\theta}^{t+1}(s)X_d^{t+1}(s) - \mathbf{e}^t(s)\boldsymbol{\theta}^t(s)X_d^t(s) \tag{2}$$

which can be re-arranged as

$$\begin{aligned}\Delta Q_d(s) = {} & \Delta\mathbf{e}(s)\boldsymbol{\theta}^t(s)X_d^t(s) + \mathbf{e}^t(s)\Delta\boldsymbol{\theta}(s)X_d^t(s) + \mathbf{e}^t(s)\boldsymbol{\theta}^t(s)\Delta X_d(s) \\ & + \Delta\mathbf{e}(s)\Delta\boldsymbol{\theta}(s)X_d^t(s) + \mathbf{e}^t(s)\Delta\boldsymbol{\theta}(s)\Delta X_d(s) + \Delta\mathbf{e}(s)\boldsymbol{\theta}^t(s)\Delta X_d(s) \\ & + \Delta\mathbf{e}(s)\Delta\boldsymbol{\theta}(s)\Delta X_d(s)\end{aligned} \tag{3}$$

The first term on the right-hand side of Eq. (3) represents the effects of changes in CO_2 emission intensities on the estimated CO_2 emissions, and the second and third terms represent the influence of changes in industrial composition and in gross output on CO_2 emissions, respectively; the remaining four terms are interaction terms. Using the Shapley–Sun–Dietzenbacher–Los decomposition to classify the seven terms (including the interaction terms among the technology effect, the industrial composition effect, and the economic scale effect), the following is obtained:

$$
\begin{aligned}
\Delta Q_d &= \underbrace{\Delta \mathbf{e}\boldsymbol{\theta}^t X_d^t + \frac{1}{2}\left(\Delta \mathbf{e}\Delta\boldsymbol{\theta} X_d^t + \Delta \mathbf{e}\boldsymbol{\theta}^t \Delta X_d\right) + \frac{1}{3}\Delta \mathbf{e}\Delta\boldsymbol{\theta}\Delta X_d}_{\text{Technology effect}} \\
&\quad \underbrace{+\mathbf{e}^t \Delta\boldsymbol{\theta} X_d^t + \frac{1}{2}\left(\Delta \mathbf{e}\Delta\boldsymbol{\theta} X_d^t + \mathbf{e}^t \Delta\boldsymbol{\theta}\Delta X_d\right) + \frac{1}{3}\Delta \mathbf{e}\Delta\boldsymbol{\theta}\Delta X_d}_{\text{Industrial composition effect}} \\
&\quad \underbrace{+\mathbf{e}^t \boldsymbol{\theta}^t \Delta X_d + \frac{1}{2}\left(\Delta \mathbf{e}\boldsymbol{\theta}^t \Delta X_d + \mathbf{e}^t \Delta\boldsymbol{\theta}\Delta X_d\right) + \frac{1}{3}\Delta \mathbf{e}\Delta\boldsymbol{\theta}\Delta X_d}_{\text{Economic scale effect}}
\end{aligned}
\tag{4}
$$

For notational convenience, the symbol *s* denoting country is omitted.

Equation (4) does not allow an examination of the sources of changes in extraterritorial emissions due to direct imports of intermediate products that are necessary for domestic production and direct imports of final products. Therefore, in this study, the emissions associated with the direct imports of intermediate products and final products are formulated as follows:

$$
\begin{aligned}
Q_m^t(s) &= \sum_{r=1,r\neq s}^{R}\sum_{i=1}^{N} e_i^t(r)\lambda_i^{t,rs}(s) IM_z^t(s) + \sum_{r=1,r\neq s}^{R}\sum_{i=1}^{N} e_i^t(r)\pi_i^{t,rs}(s) IM_f^t(s) \\
&= \sum_{r=1,r\neq s}^{R} \mathbf{e}^t(r)\boldsymbol{\lambda}^{t,r}(s) IM_z^t(s) + \sum_{r=1,r\neq s}^{R} \mathbf{e}^t(r)\boldsymbol{\pi}^{t,r}(s) IM_f^t(s)
\end{aligned}
\tag{5}
$$

where $Q_m^t(s)$, $\boldsymbol{\lambda}^{t,r}(s)=\{\lambda_i^{t,rs}(s)\}$, $\boldsymbol{\pi}^{t,r}(s)=\{\pi_i^{t,rs}(s)\}$, $IM_z^t(s)$, and $M_f^t(s)$ are the total territorial emissions caused by imports, the import composition column vectors of the ratios of imports by industrial sector *i* into country *s* to the total imports for intermediate products and final products to country *s*, the total amount of imports of intermediate products, and the total amount of imports of final products for country *s*, respectively. $\mathbf{e}^t(r)=\{e_i^t(r)\}$ is the emission intensity row vector for country *r*, and *R* is the number of countries.

The extraterritorial emissions due to importation can be decomposed in the same way, i.e., into the effects of technology, domestic import structure, and domestic import scale in the importing country:

$$
\begin{aligned}
\Delta Q_m = & \underbrace{\Delta \mathbf{e} \boldsymbol{\lambda}^t IM_z^t + \frac{1}{2}\left(\Delta \mathbf{e} \Delta \boldsymbol{\lambda} IM_z^t + \Delta \mathbf{e} \boldsymbol{\lambda}^t \Delta IM_z^t\right) + \frac{1}{3} \Delta \mathbf{e} \Delta \boldsymbol{\lambda} \Delta IM_z}_{\text{Overseas technology effect for intermedaite products}} \\
& + \underbrace{\Delta \mathbf{e} \boldsymbol{\pi}^t IM_f^t + \frac{1}{2}\left(\Delta \mathbf{e} \Delta \boldsymbol{\pi} IM_f^t + \Delta \mathbf{e} \boldsymbol{\pi}^t \Delta IM_f\right) + \frac{1}{3} \Delta \mathbf{e} \Delta \boldsymbol{\pi} \Delta IM_f}_{\text{Overseas technology effect for final products}} \\
& + \underbrace{\mathbf{e}^t \Delta \boldsymbol{\lambda} IM_z^t + \frac{1}{2}\left(\Delta \mathbf{e} \Delta \boldsymbol{\lambda} IM_z^t + \mathbf{e}^t \Delta \boldsymbol{\lambda} \Delta IM_z\right) + \frac{1}{3} \Delta \mathbf{e} \Delta \boldsymbol{\lambda} \Delta IM_z}_{\text{Import composition effect for intermedaite products}} \\
& + \underbrace{\mathbf{e}^t \Delta \boldsymbol{\lambda} IM_z^t + \frac{1}{2}\left(\Delta \mathbf{e} \Delta \boldsymbol{\pi} IM_f^t + \mathbf{e}^t \Delta \boldsymbol{\pi} \Delta IM_f\right) + \frac{1}{3} \Delta \mathbf{e} \Delta \boldsymbol{\pi} \Delta IM_f}_{\text{Import composition effect for final products}} \\
& + \underbrace{\mathbf{e}^t \boldsymbol{\lambda}^t \Delta M_z + \frac{1}{2}\left(\Delta \mathbf{e} \boldsymbol{\lambda}^t \Delta IM_z + \mathbf{e}^t \Delta \boldsymbol{\lambda} \Delta IM_z\right) + \frac{1}{3} \Delta \mathbf{e} \Delta \boldsymbol{\lambda} \Delta IM_z}_{\text{Import scale effect for intermedaite products}} \\
& + \underbrace{\mathbf{e}^t \boldsymbol{\pi}^t \Delta IM_f + \frac{1}{2}\left(\Delta \mathbf{e} \boldsymbol{\pi}^t \Delta IM_f + \mathbf{e}^t \Delta \boldsymbol{\pi} \Delta IM_f\right) + \frac{1}{3} \Delta \mathbf{e} \Delta \boldsymbol{\pi} \Delta IM_f}_{\text{Import scale effect for final products}}
\end{aligned} \tag{6}
$$

The emissions associated with the direct export of intermediate products and final products are formulated as follows:

$$
\begin{aligned}
Q_x^t(s) &= \sum_{r=1, r \neq s}^{R} \sum_{i=1}^{N} e_i^t(s) \varepsilon_i^{t,sr}(s) EX_z^t(s) + \sum_{r=1, r \neq s}^{R} \sum_{i=1}^{N} e_i^t(s) \delta_i^{t,sr}(s) EX_f^t(s) \\
&= \sum_{r=1, r \neq s}^{R} \mathbf{e}^t(s) \boldsymbol{\varepsilon}^{t,r}(s) EX_z^t(s) + \sum_{r=1, r \neq s}^{R} \mathbf{e}^t(s) \boldsymbol{\delta}^{t,r}(s) EX_f^t(s)
\end{aligned} \tag{7}
$$

where $Q_x^t(s)$, $\boldsymbol{\varepsilon}^{t,r}(s)=\left\{\varepsilon_i^{t,sr}(s)\right\}$, $\boldsymbol{\delta}^{t,r}(s)=\left\{\delta_i^{t,sr}(s)\right\}$, $EX_z^t(s)$, and $EX_f^t(s)$ are the total territorial emissions caused by exports, the export composition column vectors of the ratios of exports by industrial sector i from country s to the total exports of intermediate products and final products to country r, the total amount of exports of intermediate products, and the total amount of imports of final products for country r, respectively. $\mathbf{e}^t(s)=\left\{e_i^t(s)\right\}$ is the emission intensity row vector for country s.

Territorial CO_2 emissions due to exportation can be decomposed into the effects of technology, domestic export structure, and domestic export scale in the exporting country:

$$
\begin{aligned}
\Delta Q_x = & \underbrace{\Delta\mathbf{e}\boldsymbol{\varepsilon}^t EX_z^t + \frac{1}{2}\left(\Delta\mathbf{e}\Delta\boldsymbol{\varepsilon}EX_z^t + \Delta\mathbf{e}\boldsymbol{\varepsilon}^t\Delta EX_z\right) + \frac{1}{3}\Delta\mathbf{e}\Delta\boldsymbol{\varepsilon}\Delta EX_z}_{\text{Domestic technology effect for intermedaite products}} \\
& + \underbrace{\Delta\mathbf{e}\boldsymbol{\delta}^t EX_f^t + \frac{1}{2}\left(\Delta\mathbf{e}\Delta\boldsymbol{\delta}EX_f^t + \Delta\mathbf{e}\boldsymbol{\delta}^t\Delta EX_f\right) + \frac{1}{3}\Delta\mathbf{e}\Delta\boldsymbol{\delta}\Delta EX_f}_{\text{Domestic technology effect for final products}} \\
& + \underbrace{\mathbf{e}^t\Delta\boldsymbol{\varepsilon}EX_z^t + \frac{1}{2}\left(\Delta\mathbf{e}\Delta\boldsymbol{\varepsilon}EX_z^t + \mathbf{e}^t\Delta\boldsymbol{\varepsilon}\Delta EX_z\right) + \frac{1}{3}\Delta\mathbf{e}\Delta\boldsymbol{\varepsilon}\Delta EX_z}_{\text{Export composition effect for intermedaite products}} \\
& + \underbrace{\mathbf{e}^t\Delta\boldsymbol{\delta}EX_z^t + \frac{1}{2}\left(\Delta\mathbf{e}\Delta\boldsymbol{\delta}EX_f^t + \mathbf{e}^t\Delta\boldsymbol{\delta}\Delta EX_f\right) + \frac{1}{3}\Delta\mathbf{e}\Delta\boldsymbol{\delta}\Delta EX_f}_{\text{Export composition effect for final products}} \\
& + \underbrace{\mathbf{e}^t\boldsymbol{\varepsilon}^t\Delta EX_z + \frac{1}{2}\left(\Delta\mathbf{e}\boldsymbol{\varepsilon}^t\Delta EX_z^t + \mathbf{e}^t\Delta\boldsymbol{\varepsilon}\Delta EX_z\right) + \frac{1}{3}\Delta\mathbf{e}\Delta\boldsymbol{\varepsilon}\Delta EX_z}_{\text{Export scale effect for intermedaite products}} \\
& + \underbrace{\mathbf{e}^t\boldsymbol{\delta}^t\Delta EX_f + \frac{1}{2}\left(\Delta\mathbf{e}\boldsymbol{\delta}^t\Delta EX_f^t + \mathbf{e}^t\Delta\boldsymbol{\delta}\Delta EX_f\right) + \frac{1}{3}\Delta\mathbf{e}\Delta\boldsymbol{\delta}\Delta EX_f}_{\text{Export scale effect for final products}}
\end{aligned}
\tag{8}
$$

3.3 Data

In this study, the WIOD (Dietzenbacher *et al*., 2013; Timmer *et al*., 2015) and the Environmental Accounts, which are downloadable from the data website: http://www.wiod.org/new_site/data.htm, are employed. These data cover 35 industrial sectors and 40 countries and region (Tables S3.1 and S3.2 in the Appendix) and focus on the period of 1995 to 2011. For this study, the nominal World Input-Output Tables for 1995 to 2009 were converted into deflated World Input-Output Tables based on 2009 prices using the double deflation method (United Nations, 1999). The deflators were obtained from the output prices of the nominal World Input-Output Tables and of the real World Input-Output Tables in previous year's prices.

The industrial composition column vector and total industrial output of 40 countries and region are calculable from the domestic outputs described in the deflated World Input-Output Tables, and the industrial CO_2 emissions for 40 countries are obtainable from the Environmental Accounts (Dietzenbacher *et al*., 2013; Timmer *et al*., 2015). The emission intensity row vector can be easily obtained by dividing industrial CO_2 emissions by industrial outputs. The data on intermediate inputs and final demand of goods and services are directly obtainable from the deflated World Input-Output Tables.

3.4 Results and Discussion

In this section, the results of year-on-year changes in territorial CO_2 emissions in 40 countries over the 15-year period from 1995 to 2009 are described using the decomposition method formulated in the previous section. Per capita incomes published by the World Bank for the 40 countries (World Bank, 2013) were used to classify the countries into three groups: high-income nations with per-inhabitant annual incomes of ≥$12,616, middle-income nations with per-inhabitant annual incomes of ≥$4,086 and <$12,616, and low-income nations with per-inhabitant annual incomes of <$4,086. For this study, 31 of the 40 countries were classified as high-income, seven were classified as middle-income, and two were classified as low-income (Tables S3.2).

3.4.1 Economic scale effect, industrial composition effect, and domestic technology effect

This study focused on four periods (1995 to 2000, 2000 to 2005, 2005 to 2008, and 2008 to 2009) and estimated the effects of changes in economic scale, industrial composition, and domestic technology during those periods using Eq. (4). Table 3.1 shows the decomposition results on "country average" in the three groups. It should be noted that the international financial crisis occurred between 2008 and 2009.

Table 3.1. Results of decomposing territorial CO_2 emissions (Unit: Mt CO_2)

	Domestic technology effect			Industrial composition effect			Economic scale effect			Total
	Primary industry	Secondary industry	Tertiary industry	Primary industry	Secondary industry	Tertiary industry	Primary industry	Secondary industry	Tertiary industry	
High-income group including U.S.A										
1995-2000	-1.54	-19.61	-13.98	-0.87	-3.51	-1.04	1.33	45.27	16.92	23.0
2000-2005	-0.54	-0.48	-9.89	-0.70	-33.10	0.95	1.01	38.65	11.16	7.1
2005-2008	-0.70	-17.73	-8.18	-0.39	-10.06	1.32	0.66	25.15	6.24	-3.7
2008-2009	-0.55	-0.47	3.78	0.51	-8.06	0.24	-0.35	-15.63	-4.91	-25.4
Middle-income group including China										
1995-2000	-5.84	-138.22	-14.53	-3.89	-10.06	7.63	8.21	166.22	17.15	26.7
2000-2005	1.81	-198.04	-6.71	-6.10	163.82	-2.86	10.55	287.73	29.21	279.4
2005-2008	-4.49	-121.10	-2.55	-6.56	-24.17	-6.88	9.66	315.29	28.08	187.3
2008-2009	-0.55	-12.21	5.39	-0.48	-28.48	-2.47	1.11	67.65	4.24	34.2
Low-income group										
India										
1995-2000	-3.63	-2.75	-37.15	-4.08	3.95	4.81	8.79	184.48	15.86	170.3
2000-2005	-1.40	-55.62	-29.24	-7.19	-43.27	5.96	12.80	294.91	17.20	194.1
2005-2008	3.99	-12.34	2.69	-7.35	2.06	0.24	10.45	269.26	12.59	281.6
2008-2009	4.92	-67.62	17.94	-4.62	80.48	-0.51	3.53	95.42	5.42	135.0
Indionesia										
1995-2000	3.55	-28.09	-0.83	1.11	57.12	10.32	0.43	5.22	1.05	49.9
2000-2005	0.05	37.81	-14.80	-1.34	-11.90	1.67	3.61	44.89	7.48	67.5
2005-2008	-3.75	-21.13	-3.14	-0.79	-8.98	-0.31	2.63	43.67	5.38	13.6
2008-2009	0.90	-7.31	2.20	-0.03	6.36	-0.08	1.38	21.05	2.98	27.5

The economic scale effect reflects the influence of changes in the overall domestic industrial output on CO_2 emissions. The cumulative economic scale effect in the high-income nations contributed to an increase in emissions of 146 Mt CO_2 in the three industries from 1995 to 2008 (Table 3.1). On the other hand, territorial CO_2 emissions decreased by 21 Mt CO_2 in the three industries in response to the economic recession that followed the international financial crisis between 2008 and 2009 (see the economic scale effect in the high-income nation group during the 2008 to 2009 period in Table 3.1). Interestingly, during the 2008 to 2009 period, when the effect of the financial crisis reduced the average output of the high-income nations by 5.9%, CO_2 emissions in the high-income nations also decreased by 5.4%. In other words, the economic damage resulting from the financial crisis was partially offset by social benefits from a reduction in CO_2 emissions. Prior to 2005, the cumulative effect of output growth in the high-income nations amounted to approximately 50 to 60 Mt CO_2 every 5 years.

Conversely, the cumulative economic scale effect in the middle-income nations, such as China and Turkey, was 872 Mt CO_2, which is six times that of the high-income nations from 1995 to 2008 (see the economic scale effect in the middle-income nations of Table 3.1). The growth in the economic scale effect of the middle-income nations in each of the three periods was extremely high at 192 Mt CO_2 in 1995 to 2000, 328 Mt CO_2 in 2000 to 2005, and 353 Mt CO_2 in 2005 to 2008 (Table 3.1). Indeed, the rapid economic growth of the middle-income nations is the source of much of the world's CO_2 emissions increases. Examining the sectoral breakdown of industries as they relate to the mean cumulative economic scale effect in the middle-income nations, I find that primary industries contributed 28 Mt CO_2, secondary industries contributed 769 Mt CO_2, and tertiary industries contributed 74 Mt CO_2 of CO_2 emissions from 1995 to 2008 (see Table 3.1 and Table 3A1 for industry groups). The growth of secondary industries in the middle-income nations therefore brought about an abrupt increase in CO_2 emissions. Importantly, compared to the high-income nations, the economic scale effect in the middle-income nations during the financial crisis was positive, and consequently, even in the financial crisis, CO_2 emissions in the middle-income nations (especially in China) have increased faster than the decrease in CO_2 emissions in the high-income nations.

The industrial composition effects illustrate how changes in domestic industrial composition influence CO_2 emissions. The cumulative industrial composition effect per country in the high-income nations was −47 Mt CO_2, a reduction in CO_2 emissions in the three industries from 1995 to 2008 (Table 3.1). Breaking down the composition of the industries and their CO_2 emissions, I find that primary industries contributed −2 Mt CO_2, secondary industries contributed −47 Mt CO_2, and tertiary industries contributed 1 Mt CO_2 during the study period (Table 3.1). In addition, the industrial composition effect of secondary industries took on a large negative value because the emission intensities of secondary products are relatively high. On the other hand, the industrial composition effect of tertiary industries was close to neutral on CO_2 emissions. Thus, it is clear that the changes in the industrial composition of the high-income nations, namely, the shift away from manufacturing to services, have contributed to reducing the territorial CO_2 emissions of that group.

The cumulative industrial composition effect of the middle-income nations was 111 Mt CO_2 per country during the 1995 to 2008 period, indicating that the changes in the middle-income nations increased domestic CO_2 emissions (see the third column of Table 3.1). Similarly, from the calculated breakdown by industry, primary industries contributed −17 Mt CO_2, secondary industries contributed +130 Mt CO_2, and tertiary industries contributed −2 Mt CO_2 (Table 3.1). In contrast to the high-income nations, the middle-income nations heavily industrialized, and the resulting increase in emissions (+111 Mt CO_2) due to industrialization in the middle-income nations exceeded the reduction in emissions (−47 Mt CO_2) due to deindustrialization of the high-income nations. Ultimately, changes in industrial activities in both income groups contributed to global warming.

Production technologies have played a crucial role in global warming (IPCC, 2014c). Therefore, I also examined the extent to which changes in emission intensities due to changes in domestic technologies influenced CO_2 emissions. The cumulative domestic technology effect in the high-income nations in the three industries from 1995 to 2008 was −73 Mt CO_2 per country (Table 3.1); this decrease is considered to reflect efforts by the high-income nations to adopt environmentally benign production activities. The secondary and tertiary industries showed particularly high cumulative technology effects, at −38Mt CO_2 and −32 Mt CO_2, respectively, per country from 1995 to 2008 (Table 3.1). During the same period, domestic technology effects in the middle-income nations (e.g., China and Turkey) accounted for −490 Mt CO_2 per country, which was approximately seven times the cumulative domestic technology effect of the high-income nations. Compared to the high-income nations, which are relatively more technologically advanced, the middle-income nations have more room for technological development; as they make further advances in the future, they will have considerable potential to reduce emissions.

3.4.2 Export scale effect and export composition effect

Territorial CO_2 emissions are influenced by the manufacturing of export products, so this is an important factor for understanding the emissions of a country. Table S3.3 shows the results of decomposition, using a structural decomposition analysis of the CO_2 emissions associated with exports, as obtained from Eq. (8). From 1995 to 2008, the export scale effects for intermediate products and final products of the high-income group each show a downward trend. On the other hand, for the export scale effect of the middle-income group, a comparison of the results from 1995 to 2009 with the results from 2005 to 2008 reveals that the export scale effects of intermediate products and final products both rose sharply, increasing by factors of 3 and 2.5, respectively. From Table 3.1, a comparison of the economic scale effect of the middle-income group of countries between the five-year period from 1995 to 2000 and the three-year period from 2005 to 2008 shows that the economic scale effect grew by a factor of 1.8. In light of this finding, it is clear that in the middle-income group of countries, export products are a major driver of territorial CO_2 emissions associated with manufacturing. Furthermore, the export composition effect is negligibly small (Table S3.3) in both the high-income and middle-income group of countries. Focusing on the manufacturing activities within countries, I can assume that as exports continue to decrease in the high-income group, the CO_2 emissions associated with exports will keep falling. Thus, emission controls focused on domestic demand will be important in cutting CO_2 emissions. At the same time, in developing economies such as those of the middle-income group of countries, it is necessary to implement emission control measures that are focused on the volumes of manufactured exports.

3.4.3 Import scale effect, import composition effect, and foreign technology effect

Concomitant with the shift of domestic economies away from manufacturing to services has come an increasing dependence on the importation of manufactured goods, which has increased the emissions associated with imports (in this study, this increase in imports was observed to have the effect of increasing the territorial CO_2 emitted in the import-partner country during production of goods for export). The emissions induced by imports consist of the territorial emissions associated with the production of the intermediate and final imported products. According to the data in the WIOD (Dietzenbacher *et al*., 2013), the import interdependence among the high-income nations in the 1995 to 2009 period decreased to approximately 10%, while the fraction of imports in the high-income nations from the middle- and low-income nations almost doubled. Thus, the import dependence on developing countries is increasing rapidly, and these changes in the import structures of developed nations have accelerated CO_2 emissions in developing nations.

Table 3.2 shows how the extraterritorial emissions attributed to imports can be decomposed into the import scale effect, import composition effect, and the foreign technology effect estimated by Eq. (6). The import scale effects for intermediate and final products shown in Table 3.2 are the effects of changes in total domestic imports on emissions in the import-partner country. Imports by the high-income nations decreased markedly due to the international financial crisis, resulting in the import scale effect being negative from 2008 to 2009 (see Table 3.2). In the high-income group, the cumulative import scale effects associated with the production of intermediate and final products were 27 Mt CO_2 and 6 Mt CO_2 per country, respectively, during the 1995 to 2008 period.

In the middle-income nations, the cumulative import scale effects associated with the production of imports of intermediate and final products were 53 Mt CO_2 and 10 Mt CO_2, respectively, during the 1995 to 2008 period. The import scale effect in the middle-income nations was greater than that in the high-income nations; in particular, the effect due to imports of intermediate products was twice that in the high-income nations (see Table 3.2). The main reason for this was that during the shift away from manufacturing by the high-income nations, although the demand for imports of intermediate products from secondary industries decreased, the demand for the same secondary industry products increased in the middle-income nations due to increased industrialization capacity and foreign trade.

Table 3.2. Results of decomposing extraterritorial CO_2 emissions (Kt CO_2)

	Intermediate products			Final products			
	Foreign technology effect	Import composition effect	Import scale effect	Foreign technology effect	Import composition effect	Import scale effect	Total
High-income group including U.S.A							
1995-2000	-4122	708	12622	-492	38	2127	10882
2000-2005	-3015	783	6920	-856	283	2033	6148
2005-2008	-2536	-1602	7088	-685	-87	1441	3619
2008-2009	-1490	-795	-8989	-813	-68	-322	-12477
U.S.A							
1995-2000	-27169	21424	118882	-359	-2263	6600	117116
2000-2005	-19536	-7165	42902	-2922	-1220	2640	14698
2005-2008	-18629	-438	14978	-2055	-774	2565	-4354
2008-2009	-5504	-25666	-56293	-1754	553	254	-88410
Middle-income group including China							
1995-2000	-445	-342	11714	-491	-1723	4008	12034
2000-2005	-2715	-1848	16776	-47	-565	3712	15425
2005-2008	-1305	-3191	24823	-1186	-1292	2335	17791
2008-2009	-2471	1474	-7146	-1211	-347	317	-8608
China							
1995-2000	978	204	35284	1315	-2278	3335	37660
2000-2005	-9009	-11775	94489	1824	-656	3864	95604
2005-2008	-5420	-20892	138921	-901	-1821	855	99488
2008-2009	-8881	15244	-21549	-752	609	443	-18692
Low-income group							
India							
1995-2000	-2634	-3697	15998	-783	-60	1778	10602
2000-2005	486	23733	20817	228	1103	1421	47787
2005-2008	-1227	-9402	14751	-282	-536	1273	4578
2008-2009	-12201	-169	-4587	1448	-93	-578	-16179
Indonesia							
1995-2000	-1150	289	3169	-706	885	-398	9998
2000-2005	54	1580	4298	-517	854	217	7802
2005-2008	91	-1302	5162	-476	2	533	-3147
2008-2009	-1800	-1419	-1396	-34	-70	-241	-9571

The import composition of the nations examined here (in other words, their patterns of international trade) and their domestic industrial composition are intertwined with how domestic products were replaced by imported products. For this reason, changes in the output composition of domestic industries have increased the import composition of emissions-intensive products, and it is possible to evaluate how the structural changes with regard to these domestic and imported products affect CO_2 emissions. The third and sixth columns of Table 2 show the import composition effects for intermediate and final products. A comparison of industrial composition effects (Table 3.1) and import composition effects (Table 3.2) for each income group shows that in the 10 years between 1995 and 2005, changes in the industrial composition of the high-income nations helped to reduce CO_2 emissions, but changes in import patterns as a result of factors such as import substitution caused CO_2 emissions to increase. Interestingly, in the three years from 2005 to 2008, changes in the import patterns of intermediate products by the high-income nations mitigated global warming.

Figure 3.1 is a world map showing the net industrial composition effect (that is, the industrial composition effect plus the import composition effect) of 40 countries from 1995 to 2008. The figure shows to what degree a nation's industrial structure (also taking import structure into account)_contributes to increasing or decreasing emissions. As shown, China and the United States have very large net industrial composition effects. While changes in its industrial structure enabled the United States to achieve an 895 Mt CO_2 reduction in emissions, changes in the industrial structure of China resulted in a 720 Mt CO_2 increase in emissions. As in Tian *et al*., (2014), for the study period (1995 to 2008), I found that the industrial composition change of the four heavy manufacturing sectors of Basic Metals and Fabricated Metal, Machinery, Electrical and Optical Equipment, and Transport Equipment in China led to a rapid increase in CO_2 emissions amounting to 17% of the effect of the China's structural changes (119 Mt CO_2). Compared to these two major countries, changes in the industrial structure of European nations have had almost no impact on CO_2 emissions. These data show that these two major countries will have major roles regarding CO_2 emissions forward into the future.

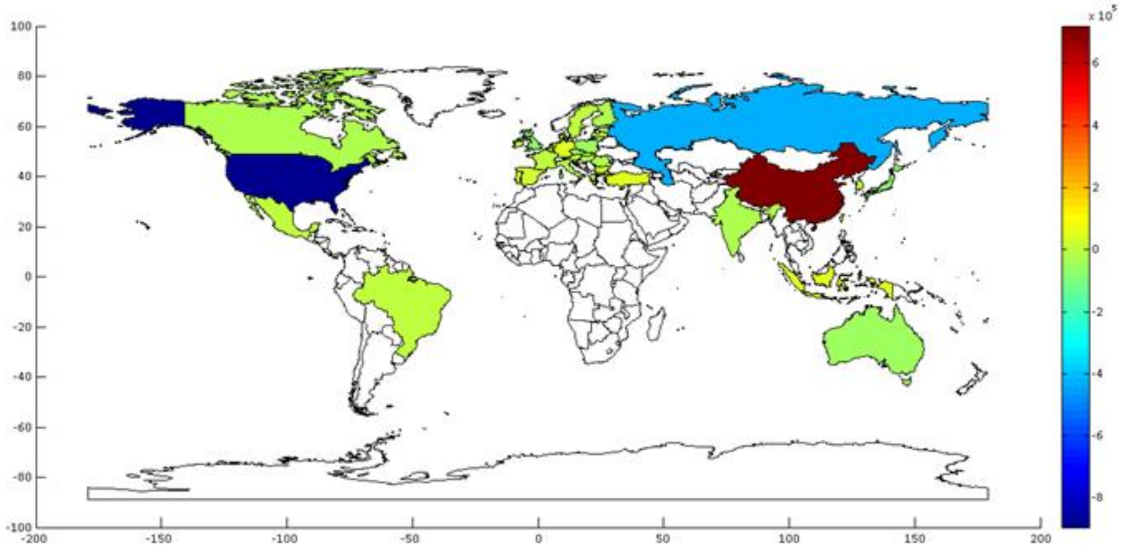

Figure 3.1. Global composition effects from 1995 to 2008 (K t CO_2)

3.4.4 Discussion

Since the import composition effect of intermediate products and final products in Table 3.2 can be estimated from the third and fourth terms, respectively, on the right-hand side of Eq. (6), larger intermediate and final product imports of a country imply a greater import composition effect. To grasp the impact that pure import pattern changes have on CO_2 emissions, the 'normalized' import composition effect was estimated by dividing the import composition effect of intermediate products and that of final products by their respective import values. Similarly, the larger a country's domestic output value is, the greater its industrial composition effect will be; thus, a 'normalized' industrial composition effect was estimated by dividing the industrial composition effect by the domestic output. By comparing the estimated normalized import composition effect and the normalized industrial composition effect for each country, it is possible to analyze the role that each country's pure structural changes plays in global warming.

Table 3.3 shows the normalized import composition effect and normalized industrial composition effect for intermediate and final products in the 40 countries examined in this study. Based on the estimation results, the patterns of structural change in the 40 nations can be classified into eight types. The largest type group is Type II, which comprises nations for which the normalized industrial composition effect and normalized import composition effect for intermediate products are both negative but normalized import composition effect for final products is positive. Type II countries, which include Japan, the United Kingdom, and Mexico, have reduced their emissions through structural changes (e.g., transitioning to a service economy), but have increased their emissions indirectly by increasing their import composition of emissions-intensive products for final products. The net composition effects (i.e., the sum of the normalized import composition effect for intermediate products, the normalized import composition effect for final products, and the normalized industrial composition effect) for most of countries of Type II are negative, which implies that their structural changes are environmentally good in the sense that they reduced emissions. However, the normalized import composition effects of final products for Japan, Luxembourg, and Mexico are relatively large compared to other countries classified as Type II, which resulted in positive net composition effects. This was especially high for Japan, which had the largest normalized import composition effect of final products among the high-income nations and its structural changes, including its import structure changes, have contributed to increasing its CO_2 emissions.

Interestingly, the net composition effect is very high (2.805; the total shown in Table 3.3) in Bulgaria (Type V), which was industrializing more rapidly than other countries between 1995 and 2008. Despite of significant structural changes in Bulgaria, the composition effects of both intermediate product imports and final product imports were negative and these import activities contributed greatly to mitigate its responsibility for global warming. At 2.219, Indonesia (Type VIII) had the second highest net composition effect, but that is still markedly different from Bulgaria**.** Domestic structural changes in Indonesia have also caused emissions to increase, as in Bulgaria, but in Indonesia changes in import patterns have also contributed to global warming. Indonesia should therefore try to mitigate its contribution to global warming by encouraging the importation of substitutes for products that cause *significant* emissions. As for Bulgaria, it underwent its emissions-intensive industrial structural change relatively early compared to other countries and therefore should adopt policies aimed at reducing emissions from emissions-intensive industries. Thus, the impacts that structural changes have on CO_2 emissions vary and are independent of a nation's level of development.

Recently implemented climate policies are conducted under a framework based on each country's level of economic development (e.g., per-capita income) and regional groupings, but the relationship between changes in industrial structure and global warming has been ignored. From Table 3.3, it can be found that domestic industrial structure changes and import structure changes have different roles according to group type. For example, in countries belonging to Type II, changes in import structure of final products contribute to global warming, and therefore mitigation countermeasures should be focused on shifting emissions-intensive technologies of final products produced overseas and/or trade patterns of final products. In countries belonging to Type IV or VIII, changes in import structure contribute to global warming; consequently, mitigation countermeasures adopted by these countries need to focus on trade patterns. On the other hand, in countries of Types V to VIII, industrial structure change contributes to global warming and therefore these countries need to take warming countermeasures that focus on reducing emissions from emissions-intensive industries. Thus, this study has shown the need for global warming countermeasures that consider the differences in the role of the structural changes in the eight country groups identified in this study.

Table 3.3. Effects of industrial and import composition changes on CO_2 emissions

Country	Income group	Normalized import composition effect of intermediate products	Normalized import composition effect of final products	Normalized industrial composition effect	Total	Type for structural changes
EST	High	-0.079	-0.075	-0.577	-0.731	Type I
FIN	High	-0.125	-0.020	-0.045	-0.189	
ITA	High	-0.119	-2.319	-0.009	-2.446	
SVK	High	-0.181	-0.017	-0.037	-0.234	
CZE	High	-0.097	0.020	-0.158	-0.236	Type II
GBR	High	-0.076	0.076	-0.059	-0.058	
HUN	Middle	-0.173	0.065	-0.130	-0.238	
JPA	High	-0.474	0.955	-0.098	0.383	
LUX	High	-0.078	0.202	-0.016	0.108	
LVA	High	-0.145	0.100	-0.030	-0.074	
MEX	Middle	-0.002	0.102	-0.010	0.090	
POL	High	-0.072	0.016	-0.102	-0.158	
ROM	Middle	-0.087	0.004	-0.209	-0.292	
RUS	High	-0.145	0.001	-0.411	-0.554	
BEL	High	0.399	-0.155	-0.039	0.206	Type III
BRA	Middle	0.028	-0.114	-0.007	-0.094	
CAN	High	0.103	-0.091	-0.022	-0.010	
KOR	High	0.040	-0.712	-0.006	-0.678	
SVN	High	0.143	-0.051	-0.038	0.054	
SWE	High	0.048	-0.007	-0.019	0.022	
USA	High	0.034	-0.108	-0.120	-0.194	
AUS	High	0.033	0.047	-0.091	-0.011	Type IV
IND	Low	0.083	0.016	-0.033	0.066	
LTU	High	0.039	0.603	-0.066	0.577	
NLD	High	0.099	0.029	-0.031	0.097	
BGR	Middle	-0.109	-0.152	3.066	2.805	Type V
CHN	Middle	-0.030	-0.136	0.072	-0.095	
FRA	High	-0.041	-0.219	0.001	-0.259	
TWN	High	-0.123	-0.029	0.254	0.102	
CYP	High	-0.121	0.419	0.146	0.444	Type VI
ESP	High	-0.031	0.002	0.031	0.003	
PRT	High	-0.012	0.161	0.124	0.273	
AUT	High	0.042	-0.240	0.016	-0.182	Type VII
DEU	High	0.029	-0.010	0.026	0.046	
TUR	Middle	0.053	-0.104	0.063	0.012	
DNK	High	0.028	0.042	0.066	0.137	Type VIII
GRC	High	0.067	0.267	0.054	0.387	
IDN	Low	0.016	2.066	0.137	2.219	
IRL	High	0.003	0.080	0.012	0.095	
MLT	High	0.103	0.013	0.094	0.210	

3.5 Conclusion

This chapter proposed a decomposition method to estimate how changes in domestic economic scale, industrial composition, domestic technology, import scale of intermediate products, import composition of intermediate products, import scale of final products, import composition of final products, and foreign technology affect the volumes of both territorial and extraterritorial CO_2 emissions induced by imports during the 1995 to 2009 period. In addition, I similarly decomposed the changes in the export-based CO_2 emissions into the changes in domestic technology, export scale of intermediate products, export composition of intermediate products, export scale of final products, and export composition of final products.

Based on the results obtained from the comprehensive decomposition analysis of territorial and extraterritorial CO_2 emissions, the patterns of structural change in the 40 nations can be classified into eight types (Table 3.3). I found that structure changes and trade pattern changes have different roles according to the group type. Considering that economic growth increases global warming (IPCC, 2014c), the role that structural changes play in global warming is important for decision makers. There is thus an urgent need to draft comprehensive CO_2 emissions reduction guidelines that consider the structural changes of each country. Specifically, international guidelines are needed that include, among other things, emissions reduction policies that set reduction targets from three sources (CO_2 emissions associated with intermediate product import composition, CO_2 emissions associated with final product import composition, and CO_2 emissions associated with domestic output composition) and that consider groups of countries in terms of those three sources, as in Table 3.3.

I also found that the export scale in the middle-income group of countries contributed as a major driver of territorial CO_2 emissions associated with manufacturing during 1995 to 2008, whereas the export composition effect was negligibly small in both the high-income and middle-income group of countries during the same period and it has not played an important role in climate change.

Chapter 4 Cross-country analysis of relationship between material input structures and consumption-based CO_2 emissions

4.1 Introduction

As a consequence of economic growth, worldwide CO_2 emissions continued to increase during the 40-year period from 1970 to 2010 (IPCC, 2014c). According to Assessment Report 5 of the IPCC, CO_2 was the principal greenhouse gas (GHG) component, making up 76% of total GHG emissions. The important fact is that, from 1970 to 2010, the contributions of changes in human population, GDP per capita, product energy intensity, and energy product CO_2 intensity to fossil fuel-derived CO_2 emissions were +87%, +103%, −35%, and −15%, respectively (IPCC, 2014c). Thus, increases in population and GDP per capita cancelled out the improvements in energy intensity. For a recent important study, Löschel *et al.* (2015) demonstrated through an index decomposition analysis (IDA) that changes in overall energy intensity in EU countries can be attributed to two different drivers: changes in the industrial composition of the economy and changes between 1995 and 2009 in its sectoral energy intensities. They found that structural changes which were presented as changes in the industrial composition of an economy had the relevant effect of greatly reducing the energy intensity of the nation (Löschel *et al.*, 2015). This situation in EU countries might reflect structural changes toward service economies and consequently these structural changes in EU countries led to reducing production-based CO_2 emissions that are caused by *direct* sectoral energy consumptions.

In the period from 1990 to 2010, production- and consumption-based CO_2 emissions in the Asian region increased at very high growth rates (+175% and +197%, respectively), but consumption-based CO_2 emissions in OECD member countries increased at least three times as fast as CO_2 emissions in the Asian region (IPCC, 2014c). The striking increase in consumption-based CO_2 emissions in OECD member countries is attributed to their high dependency on imports from Asia, which means that greater international trade in emission-intensive material goods has increased CO_2 emissions (Hertwich and Peters, 2009; Davis *et al*., 2011; Peters *et al*., 2011).

Thus, previous studies (Hertwich and Peters, 2009; Davis *et al*., 2011; Peters *et al*., 2011) highlighted the importance, in terms of climate mitigation policy, of reducing the CO_2 emission transfers associated with the international trade of goods and services. Suh (2006) and Nansai *et al*. (2009) focused on the "domestic" production structures of developed countries and analyzed the relationship between the structural shift toward an industrialized economy and/or a service economy and CO_2 emissions for respectively the U.S. and Japan, and concluded that the structural changes toward service economies contribute to increasing GHG emissions because the service sectors in these countries have absorbed substantial amounts of energy and material goods.

Minx *et al.* (2011) used structural decomposition analysis (SDA) to identify the drivers for Chinese emission growth and reported that the structural change in China was the second biggest driver of its increase in domestic CO_2 emissions for the period 2002 to 2007. Thus, the structural change in China's economy shifted it toward more carbon-intensive activities.

The above-mentioned previous studies limit their focus to understanding empirically how a specific country or region contributed to production- and/or consumption-based CO_2 emissions (Suh, 2006; Nansai *et al.*, 2009; Peters *et al.*, 2011; Minx *et al.*, 2011; Löschel *et al*., 2015). It is important to estimate the CO_2 emissions of countries based on a consistent carbon accounting method and compare them by analyzing how the CO_2 emissions of a specific country or region are induced along the domestic supply chains (i.e., domestic production structure). This analysis provides important information on a greener production system toward a decarbonized economy for climate policy making.

The seminal literature about the relationship between structural changes and the environment is that of van den Bergh and Janssen (2004), who provided us a crucial insight into the importance of analyzing impacts of dematerialization and/or rematerialization on the CO_2 emissions and discussing a low-carbon society. In the spirit of van den Bergh and Janssen, I analyzed the inputs of material goods with a focus on the production structure of a nation and estimated the multiplier effects of the inputs on domestic CO_2 emissions associated with final demand.

The novelty of this study is threefold. Firstly, this study used global multi-regional input-output tables covering 40 countries and regions for 1995 to 2008 (Dietzenbacher *et al*., 2013; Timmer *et al*., 2015) and estimated consumption-based CO_2 emissions of the 40 countries and regions on the basis of the national input-output table of each country compiled from a database. Secondly, the consumption-based CO_2 emissions associated with the domestic final demand were analyzed focusing on four supply chain segments: (i) material goods (including energy) absorbed by material goods, (ii) material goods absorbed by services, (iii) services absorbed by material goods, and (iv) services absorbed by services. In doing so, I used the input-output partitioning technique (see Miyazawa, 1968; Sonis *et al*., 1995, 1997) based on the notion of the full “multiplicative” structural decomposition technique (Dietzenbacher *et al*., 2001; Nansai *et al*., 2009) and analyzed the contribution of the above-mentioned four supply chain segments to the consumption-based CO_2 emissions during the study period: 1995 to 2008. The findings of this study contribute to explaining quantitatively how the production structures of countries have had impacts on consumption-based CO_2 emissions and should be useful to policymakers for deciding which segment is important for reducing CO_2 emissions. Finally, I examined whether there exists a clear correlation between economic growth and the contribution of each production segment to the consumption-based emissions.

The remainder of this chapter is organized as follows: Section 2 explains the methodology and Section 3 introduces the data used for an empirical analysis, Section 4 presents and discusses the results, and finally Section 5 offers a conclusion.

4.2 Methodology

There are many studies applying factor decomposition analysis such as structural decomposition analysis (SDA) to the environmental issues (Proops, 1984; Dietzenbacher and Los, 1997; Nansai *et al.*, 2007; Xu and Dietzenbacher, 2014). Lenzen (2016) also provided an overview of the structural decomposition analyses of energy use and carbon emissions.

Applying an economic input-output model (Leontief *et al.*, 1985) to an environmental analysis, the consumption-based CO_2 emissions of country *c*, e_c, can be formulated as follows:

$$e_c = \mathbf{d}_c (\mathbf{I} - \mathbf{A}_c^d)^{-1} \mathbf{f}_c^d = \mathbf{d}_c \mathbf{L}_c^d \mathbf{f}_c^d \tag{1}$$

Here, vector $\mathbf{f}_c^d = [f_{i,c}^d]$ is a column vector of household consumption having as its elements final consumption expenditure by households $f_{i,c}^d$ from each industry *i* of country *c*. Vector $\mathbf{d}_c = [d_{j,c}]$ is a row vector of CO_2 emission intensity expressing CO_2 emissions $d_{j,c}$ generated directly by producing one unit of output of each industry *j* of country *c*. $\mathbf{A}_c^d = [a_{ij,c}]$ is an input coefficient matrix indicating the input of the commodity from each industry *i directly* required for a unit production of the commodity from each industry *j* in country *c*, and using identity matrix **I**,

$\left(\mathbf{I}-\mathbf{A}_c^d\right)^{-1}=\mathbf{L}_c^d=\left[l_{ij,c}^d\right]$ is the domestic Leontief inverse matrix (i.e., direct and indirect requirement matrix) showing the input of the commodity from each industry *i directly and indirectly* required for a unit production of the commodity from each industry *j* in country *c*. Consequently, Eq. (1) can estimate the direct and indirect CO_2 emissions triggered by the household consumptions of country *c* (i.e., consumption-based CO_2 emissions of country *c*).

It is important to analyze the inter-industry emission propagation effects for the consumption-based emissions because an inter-industry structure with less emission-intensive inputs does not generate much consumption-based emissions. By proposing the input-output partitioning technique (see Miyazawa, 1968; Sonis *et al*., 1995, 1997) based on the notion of the full "multiplicative" structural decomposition technique (Dietzenbacher *et al*., 2001; Nansai *et al*., 2009), the consumption-based CO_2 emissions of a specific year can be partitioned into the emissions induced in each inter-industry propagation block (i.e., CO_2 emission multiplier effects).

More specifically, in this study, I partitioned and decomposed the input coefficient matrix of country *c* as follows:

$$\begin{aligned}\mathbf{A}_c^d &= \begin{pmatrix}\mathbf{A}_{c,11}^d & \mathbf{A}_{c,12}^d \\ \mathbf{A}_{c,21}^d & \mathbf{A}_{c,22}^d\end{pmatrix} \\ &= \underbrace{\begin{pmatrix}\mathbf{A}_{c,11}^d & \mathbf{0} \\ \mathbf{0} & \mathbf{0}\end{pmatrix}}_{\mathbf{B}_1^d}+\underbrace{\begin{pmatrix}\mathbf{0} & \mathbf{A}_{c,12}^d \\ \mathbf{0} & \mathbf{0}\end{pmatrix}}_{\mathbf{B}_2^d}+\underbrace{\begin{pmatrix}\mathbf{0} & \mathbf{0} \\ \mathbf{A}_{c,21}^d & \mathbf{0}\end{pmatrix}}_{\mathbf{B}_3^d}+\underbrace{\begin{pmatrix}\mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_{c,22}^d\end{pmatrix}}_{\mathbf{B}_4^d}\end{aligned} \tag{2}$$

where *k, l* = 1 indicate the group of commodities for material goods including energy and *k, l* = 2 indicate the group for services. $\mathbf{A}_{c,11}^{d}$ is the input coefficient submatrix for material goods (including energy) absorbed by material goods, $\mathbf{A}_{c,12}^{d}$ is the input coefficient submatrix for material goods absorbed by services, $\mathbf{A}_{c,21}^{d}$ is the input coefficient submatrix for services absorbed by material goods, and $\mathbf{A}_{c,22}^{d}$ is the input coefficient submatrix for services absorbed by services. In this way, I can decompose the entire domestic production system into the four production system segments, $\mathbf{B}_{s}^{d}$.

By multiplicatively decomposing $\mathbf{L}_{c}^{d}$ in Eq. (1) into four segments $\mathbf{B}_{s}^{d}$, e_c can be expressed as shown in Eq. (3) below, in terms of $\mathbf{L}_{s}^{d}$, as defined in Eqs. (4) to (7) (see Miyazawa, 1968; Sonis *et al*., 1995, 1997).

$$e_c = \mathbf{d}_c \mathbf{L}_4^d \mathbf{L}_3^d \mathbf{L}_2^d \mathbf{L}_1^d \mathbf{f}^d \tag{3}$$

$$\mathbf{L}_1^d = \left(\mathbf{I} - \mathbf{B}_1^d\right)^{-1} \tag{4}$$

$$\mathbf{L}_2^d = \left(\mathbf{I} - \mathbf{L}_1^d \mathbf{B}_2^d\right)^{-1} \tag{5}$$

$$\mathbf{L}_3^d = \left(\mathbf{I} - \mathbf{L}_2^d \mathbf{L}_1^d \mathbf{B}_3^d\right)^{-1} \tag{6}$$

$$\mathbf{L}_4^d = \left(\mathbf{I} - \mathbf{L}_3^d \mathbf{L}_2^d \mathbf{L}_1^d \mathbf{B}_4^d\right)^{-1} \tag{7}$$

Furthermore, to estimate the CO_2 emission multiplier effect of each block matrix $\mathbf{A}^d_{c,kl}$, the direct and indirect CO_2 emissions associated with household consumption e_c is converted as shown in Eq. (8) as the emissions resulting from multiplicative addition of the direct emissions associated with household consumption $\mathbf{d}_c\mathbf{f}^d_c$ by each block matrix $\mathbf{A}^d_{c,kl}$ in the domestic supply chains. When the effect of the partial matrix $\mathbf{A}^d_{c,kl}$ is defined as in Eqs. (4) to (7), the structural decomposition multiplier of supply chain No. 1 ($\mathbf{L}^d_1$) q_1 is estimated from Eq. (9) (see Miyazawa, 1968; Sonis *et al.*, 1995, 1997). Also, the structural decomposition multiplier of supply chain No. 2 ($\mathbf{L}^d_2$) q_2, the multiplier of supply chain No. 3 ($\mathbf{L}^d_3$) q_3, and the multiplier of supply chain No. 4 ($\mathbf{L}^d_4$) q_4, are obtained from Eqs. (10) to (12), respectively.

$$e_c = q_4 q_3 q_2 q_1 \mathbf{d}\mathbf{f}^d_c \tag{8}$$

$$q_1 = \frac{\mathbf{d}\mathbf{L}^d_1\mathbf{f}^d}{\mathbf{d}\mathbf{f}^d} \tag{9}$$

$$q_2 = \frac{\mathbf{d}\mathbf{L}^d_2\mathbf{L}^d_1\mathbf{f}^d}{\mathbf{d}\mathbf{L}^d_1\mathbf{f}^d} \tag{10}$$

$$q_3 = \frac{\mathbf{d}\mathbf{L}^d_3\mathbf{L}^d_2\mathbf{L}^d_1\mathbf{f}^d}{\mathbf{d}\mathbf{L}^d_2\mathbf{L}^d_1\mathbf{f}^d} \tag{11}$$

$$q_4 = \frac{\mathbf{d}\mathbf{L}^d_4\mathbf{L}^d_3\mathbf{L}^d_2\mathbf{L}^d_1\mathbf{f}^d}{\mathbf{d}\mathbf{L}^d_3\mathbf{L}^d_2\mathbf{L}^d_1\mathbf{f}^d} \tag{12}$$

It should be noted here that the partial matrix $\mathbf{B}^d_s$ of Eq. (2) has multiple patterns, defined according to the choice of the block matrix $\mathbf{A}^d_{c,kl}$. More specifically, in addition to $\mathbf{A}_{c,11}^{d}$, $\mathbf{B}_{1}^{d}$ can include $\mathbf{A}_{c,12}^{d}$, $\mathbf{A}_{c,21}^{d}$, and $\mathbf{A}_{c,22}^{d}$. Thus, the structure of Eq. (4) can be expressed in a number of different ways equal to the factorial of the number of $\mathbf{B}_{s}^{d}$ (4!=24). Thus, $\mathbf{L}_{s}^{d}(s=1,2,3,4)$, which appears in Eqs. (4) to (7), can have different values, depending on the choice of block matrix $\mathbf{A}_{c,kl}^{d}$. For example, if $\mathbf{A}_{c,12}^{d}$ is included as a structural factor in supply chain No. 1 $\mathbf{L}_{1}^{d}$, then the remaining supply chains $\mathbf{L}_{2}^{d}$, $\mathbf{L}_{3}^{d}$, and $\mathbf{L}_{4}^{d}$ can be expressed in 6 [(4–1)!=6] different ways, using the structural factors $\mathbf{A}_{c,11}^{d}$, $\mathbf{A}_{c,21}^{d}$, and $\mathbf{A}_{c,21}^{d}$. In this case, each of Eqs. (9) to (12) can be expressed by 6 different formulas, and the values obtained from the 6 equations for the effect of supply chain No. 1 $\mathbf{L}_{1}^{d}$ having structural factor $\mathbf{A}_{c,12}^{d}$, as formulated in Eq. (9), are defined as $q_{1,t}^{12}(t=1,\ldots,6)$. Similarly, the values obtained from the 6 equations for each of supply chain No. 2 $\mathbf{L}_{2}^{d}$, supply chain No. 3 $\mathbf{L}_{3}^{d}$, and supply chain No. 4 $\mathbf{L}_{4}^{d}$, having structural factor $\mathbf{A}_{c,12}^{d}$, are defined as $q_{2,t}^{12}(t=1,\ldots,6)$, $q_{3,t}^{12}(t=1,\ldots,6)$, and $q_{4,t}^{12}(t=1,\ldots,6)$, respectively. Thus, the mean structural decomposition multiplier of supply chain segments that include the structural factor $\mathbf{A}_{c,12}^{d}$ can be obtained by the equation $\bar{q}_{12}=\left(\prod_{t=1}^{(4-1)!} q_{1,t}^{12}\times\prod_{t=1}^{(4-1)!} q_{2,t}^{12}\times\prod_{t=1}^{(4-1)!} q_{3,t}^{12}\times\sum_{t=1}^{(4-1)!} q_{3,t}^{12}\right)^{\frac{1}{4!}}$. On the basis of this, as shown in Eq. (13), the direct and indirect CO_2 emissions associated with household consumption e_c can be structurally decomposed, and the structural decomposition multipliers of the block matrix $\mathbf{A}_{c,kl}^{d}$ that expresses supply chain segments can be quantitatively expressed by Eqs. (14)

to (17) below (Dietzenbacher *et al*., 2001; Nansai *et al*., 2009).

$$e_c = \overline{q}_4\overline{q}_3\overline{q}_2\overline{q}_1\mathbf{d}\mathbf{f}_c^d \tag{13}$$

$$\overline{q}_{11} = \left(\prod_{t=1}^{(4-1)!} q_{1,t}^{11} \times \prod_{t=1}^{(4-1)!} q_{2,t}^{11} \times \prod_{t=1}^{(4-1)!} q_{3,t}^{11} \times \sum_{t=1}^{(4-1)!} q_{3,t}^{11} \right)^{\frac{1}{4!}} \tag{14}$$

$$\overline{q}_{12} = \left(\prod_{t=1}^{(4-1)!} q_{1,t}^{12} \times \prod_{t=1}^{(4-1)!} q_{2,t}^{12} \times \prod_{t=1}^{(4-1)!} q_{3,t}^{12} \times \sum_{t=1}^{(4-1)!} q_{3,t}^{12} \right)^{\frac{1}{4!}} \tag{15}$$

$$\overline{q}_{21} = \left(\prod_{t=1}^{(4-1)!} q_{1,t}^{21} \times \prod_{t=1}^{(4-1)!} q_{2,t}^{21} \times \prod_{t=1}^{(4-1)!} q_{3,t}^{21} \times \sum_{t=1}^{(4-1)!} q_{3,t}^{21} \right)^{\frac{1}{4!}} \tag{16}$$

$$\overline{q}_{22} = \left(\prod_{t=1}^{(4-1)!} q_{1,t}^{22} \times \prod_{t=1}^{(4-1)!} q_{2,t}^{22} \times \prod_{t=1}^{(4-1)!} q_{3,t}^{22} \times \sum_{t=1}^{(4-1)!} q_{3,t}^{22} \right)^{\frac{1}{4!}} \tag{17}$$

Here, the indirect domestic CO_2 emissions associated with household consumption can be multiplicatively decomposed into $\mathbf{d}_c\mathbf{f}_c^d$ for the on-site emissions of the industries concerned and the structural decomposition multiplier $\overline{q}_{kl}$ for supply chain emissions. As expressed in Eq. (2), *k, l* = 1 indicate the group of commodities for material goods including energy and *k, l* = 2 indicate the group for services. Then, each multiplier $\overline{q}_{kl}$ estimates the effect of one of the four supply chain segments on CO_2 emissions, which represents the magnitude of the amplification effect in CO_2 emissions due to the particular supply chain segment. For example, $\overline{q}_{11}$ = 1.4 means that 40% of CO_2 emissions are added by going through the supply chain segment that represents absorption of material goods by material goods. Therefore, in the following sections, I will consider structural decomposition multipliers as CO_2 multiplier effects.

4.3 Data

To model the domestic input structures of nations, I used the World Input-Output Database (WIOD) (Dietzenbacher *et al.*, 2013; Timmer *et al.*, 2015). This database comprises multi-regional input-output tables covering 35 industrial sectors for 40 countries and regions and "Rest of the World". To analyze the impact of the changes in structural changes on the CO_2 emissions from 1995 to 2008, firstly a deflator for 1995-base prices from Socio Economic Accounts (currency base for each country) and the exchange rates for conversion to U.S. dollars were used to create 1995-base deflators for the 35 industrial sectors in the 40 countries and regions and Rest of the World. With these deflators, the multi-regional input-output tables with current prices were converted to those with constant prices by using the GRAS method (Lenzen and Wood, 2007). Furthermore, these multi-regional input-output tables were converted to non-competitive import-type single-country input-output tables for 40 countries and regions (but not Rest of the World) to evaluate the impact of domestic input structures on CO_2 emissions. Therefore, $\mathbf{A}_c^d$ in Eq. (1) comprises only domestic input coefficient matrices, which means I do not consider intermediate inputs of imported goods and services. I separated the domestic production system into 4 segments with regard to industry group in Table 4.1. The CO_2 emission intensity vector $\mathbf{d}_c^d$ in Eq. (1) was obtained by dividing sectoral CO_2 emissions from the Environmental Accounts of the WIOD by the sectoral output at 1995 prices of the WIOD (Genty, 2012).

Table 4.1. Industry segment groups

Number	Sector name	Segment group
1	Agriculture, Hunting, Forestry and Fishing	
2	Mining and Quarrying	
3	Food, Beverages and Tobacco	
4	Textiles and Textile Products	
5	Leather, Leather and Footwear	
6	Wood and Products of Wood and Cork	
7	Pulp, Paper, Paper , Printing and Publishing	
8	Coke, Refined Petroleum and Nuclear Fuel	
9	Chemicals and Chemical Products	
10	Rubber and Plastics	Material goods
11	Other Non-Metallic Mineral	
12	Basic Metals and Fabricated Metal	
13	Machinery, Nec	
14	Electrical and Optical Equipment	
15	Transport Equipment	
16	Manufacturing, Nec; Recycling	
17	Electricity, Gas and Water Supply	
18	Construction	
19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	
20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	
21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	
22	Hotels and Restaurants	
23	Inland Transport	
24	Water Transport	
25	Air Transport	
26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	
27	Post and Telecommunications	Service
28	Financial Intermediation	
29	Real Estate Activities	
30	Renting of M&Eq and Other Business Activities	
31	Public Admin and Defence; Compulsory Social Security	
32	Education	
33	Health and Social Work	
34	Other Community, Social and Personal Services	
35	Private Households with Employed Persons	

4.4 Results

4.4.1 CO_2 multiplier effects of countries and regions

Based on the WIOD, Table 4.2 shows the change in the total of the intermediate inputs of domestically produced goods and services for the 40 countries and regions during the period from 1995 to 2008. Averaged over countries and regions, the total intermediate input increased 1.59-fold between 1995 and 2008 (last column of Table 4.2). In this study, I divided the 40 countries and regions into two groups—high-income countries (national income per capita ≥ \$12,236) and low-income countries (national income per capita < \$12,236)—in accordance with the national income per capita-based criterion of the World Bank (2017). I found that the total amount of the intermediate inputs differed with the level of economic development (i.e., national income per capita) (Table 4.2). For example, the total inputs in the high-income group remained roughly unchanged relative to the low-income group (Table 4.2). The demand of intermediate inputs to the material goods (non-services) sectors in high-income countries, such as the United Kingdom (GBR) or Japan (JPN), decreased from 1995 to 2008 (Table 4.2). On the other hand, the service sectors in the high-income group have required more intermediate inputs as the economies shifted toward service-oriented ones. The total input of low-income counties such as China (CHN) and Turkey (TUK) grew 3.24-fold, a very large increase, during the study period. This growth in the total input in low-income countries was caused by increased intermediate inputs to material good sectors, which accounted for approximately 80% of total input in 2008. This difference in input structures should have some influence on emitting CO_2 associated with domestic final demand through the domestic supply chains. Therefore, I evaluated the entire supply chain effects on domestic consumption-based CO_2 emissions.

Table 4.2. Changes in domestic input to the domestic production system (unit: billon $)

	Input to material goods			Input to services			Total input		
	1995	2008	2008/1995	1995	2008	2008/1995	1995	2008	2008/1995
High-income countries									
AUS	161	225	1.40	179	287	1.60	339	511	1.51
AUT	67	116	1.73	61	106	1.74	128	222	1.73
BEL	89	97	1.10	101	161	1.59	190	258	1.36
CAN	187	306	1.63	162	287	1.78	349	594	1.70
CYP	2	3	1.73	1	5	3.54	3	8	2.61
CZE	39	61	1.56	21	41	1.92	60	102	1.69
DEU	891	1118	1.25	724	952	1.31	1615	2070	1.28
DNK	47	51	1.09	53	86	1.62	100	137	1.37
ESP	297	451	1.52	190	314	1.65	486	765	1.57
EST	2	3	1.68	1	3	2.20	3	6	1.90
FIN	57	90	1.59	37	68	1.82	94	158	1.68
FRA	574	866	1.51	532	837	1.57	1106	1703	1.54
GBR	415	384	0.93	413	823	1.99	828	1207	1.46
GRC	42	43	1.01	32	48	1.51	74	91	1.23
IRL	25	52	2.04	19	39	2.04	45	91	2.04
ITA	514	606	1.18	368	544	1.48	883	1151	1.30
JPN	2637	2462	0.93	1763	1989	1.13	4400	4451	1.01
KOR	354	904	2.55	140	292	2.09	494	1197	2.42
LTU	3	4	1.40	2	3	1.92	4	7	1.57
LUX	2	5	2.28	6	18	3.26	8	23	3.00
LVA	2	2	1.42	2	4	2.30	3	6	1.85
MLT	1	1	1.05	1	2	3.29	1	3	2.04
NLD	136	157	1.16	129	211	1.64	265	369	1.39
POL	74	167	2.24	41	71	1.72	116	237	2.05
PRT	52	61	1.17	33	49	1.47	85	110	1.29
RUS	166	264	1.59	94	238	2.53	260	503	1.93
SVK	13	20	1.60	7	8	1.17	20	29	1.44
SVN	9	12	1.40	6	9	1.54	15	22	1.46
SWE	81	184	2.28	93	136	1.47	173	320	1.85
TWN	161	522	3.23	65	142	2.18	227	664	2.93
USA	2664	2632	0.99	2901	4741	1.63	5565	7373	1.32
Average	315	383	1.22	264	404	1.53	579	787	1.36
Low-income countries									
BGR	8	11	1.41	3	7	2.39	11	19	1.68
BRA	304	354	1.17	194	302	1.55	498	656	1.32
CHN	851	4705	5.53	204	711	3.49	1055	5416	5.13
HUN	23	28	1.23	14	16	1.17	36	44	1.21
IDN	137	201	1.46	42	107	2.55	180	308	1.72
IND	265	541	2.04	59	168	2.84	324	709	2.19
MEX	131	192	1.47	60	92	1.55	190	284	1.49
ROU	28	41	1.45	8	20	2.61	35	60	1.70
TUR	98	374	3.81	37	117	3.15	135	491	3.63
Average	205	716	3.49	69	171	2.48	274	887	3.24
Country average	290	458	1.58	220	351	1.60	510	809	1.59

I defined $\mathbf{d}_c\mathbf{L}_c^d\mathbf{f}_c^d / \mathbf{d}_c\mathbf{f}_c^d$ as the CO_2 multiplier effect for an entire supply chain. Specifically, this index indicates the degree to which direct CO_2 emissions are amplified by the domestic production system (through Leontief inverse matrix $\mathbf{L}_c^d$). In other words, this multiplier effect represents how "*direct emissions*", by which I mean the emissions embodied in goods and services consumed by households, are amplified by going through the domestic production system. The black dotted and solid lines in Figure 4.1 show the average multiplier effects of 40 countries and regions in 1995 and 2008, respectively. The average multiplier effect of the 40 countries and regions decreased from 2.00 to 1.94 during the study period. This indicates that production systems of countries tended to become slightly less emission-intensive.

In 2008, the largest multiplier effect was 3.87, for China; the second largest was for Russia, 3.78. The multiplier effects of both countries grew substantially during 1995 to 2008, which means these countries shifted to more emission-intensive economies. The country whose production system had the least impact on domestic CO_2 emissions was Luxembourg. In Luxembourg, input to domestic services accounted for approximately 90% of total input to the domestic production system, so the supply chain effect is very small in the case of Luxembourg in 2008. In this way, Figure 4.1 reveals that the impact of a production system on CO_2 emissions is peculiar to the characteristics of the individual country.

It is important to note that Russia has a very large emission multiplier, whereas the input structure in Table 4.2 shows that its total input is lower than the world average. Conversely, despite having the highest total input, the emission multiplier of the U.S. is only 1.63, below the world average (Figure 4.1). This means that it is not just the inputs themselves that impact emissions associated with the domestic supply chain through the domestic production system.

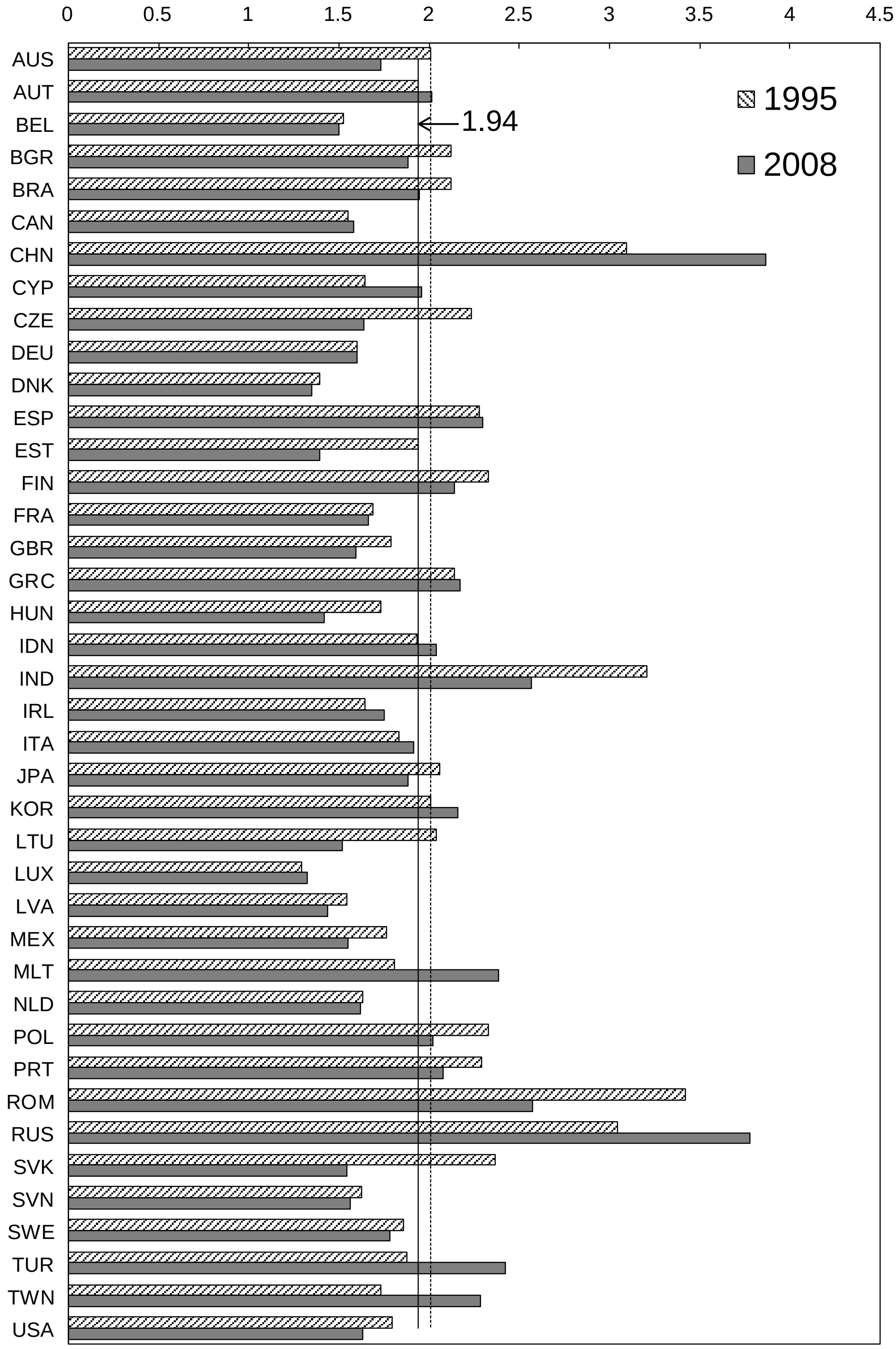

Figure 4.1. Multiplier effects of the entire supply chain for 40 countries and regions in 1995 and 2008.

4.2. Decomposition of CO_2 emission multipliers for 40 countries and regions

Using the method described in Section 2, I calculated the emission multiplier effect of each production system segment by decomposing the whole of the production system into four supply chain segments (supply chain of material goods input to material goods, supply chain of material goods input to services, supply chain of services input into material goods, and supply chain of services input to services). Figure 4.2 and 4.3 show the CO_2 multiplier effect $\overline{q}_{kl}$ of the segments' supply chain in the domestic production system associated with household consumption for four years in the study period: 1995, 2000, 2005, and 2008. In the figures, $\overline{q}_{kl}$ represents the CO_2 multiplier effect of the segment consisting of inputs from group *k* to group *l* (*k, l* = 1 indicate the group of industries for material goods; *k, l* = 2 indicate the group for services). The heights of the boxes in Figures 2 and 3 represent the interquartile range (IQR; i.e., the range between the 25 and 75 percentiles, the bottom and top edges of the box, respectively). The horizontal line and × symbol inside each box respectively represent the median and mean of decomposition multipliers of countries and regions. From Figure 4.2 and 4.3, I can compare the amplification powers of the CO_2 emissions resulting from the supply chain of each production system segment by year. It should be noted that multiplier effects estimated by Eq. (3) do not depend on the magnitude of household consumption considered in this study.

Figure 4.2 shows that, between 1995 and 2008, the mean value of the CO_2 multiplier effect $\overline{q}_{11}$ regarding material goods input to material goods fell from 1.44 to 1.35. The average production structure related to this segment has steadily contributed to suppressing CO_2 emissions. A detailed look by country from the WIOD database shows that between 1995 and 2008, for many developed countries such as the U.S.A. and Japan, the trend was downward and fell below the world average. For example, in 2008, the country with the lowest value of $\bar{q}_{11}$, 1.06, was Belgium. A look at the input structure of Belgium shows that total input related to a segment between material goods in 2008 fell to approximately 80% of the 1995 input value. Note in particular that between 1995 and 2008 intermediate demand in the segment for Agriculture, Hunting, Forestry and Fishing (−3.0 billion $), Electricity, Gas and Water Supply (−2.1 billion $), and Basic Metals and Fabricated Metal (−2.0 billion $) shrunk substantially. Thus, Belgium has arrived at a more environmentally friendly production structure through a reduction of the demand of high emission-intensive goods in the producing sectors during the 15 years.

At the same time, the $\bar{q}_{11}$ values of developing countries such as China, Rumania, and India greatly exceeded the world average. It is striking that China, unlike many other developing countries, saw rapid growth in the emissions effect of production systems associated with supply chains for material goods, with a remarkable +113% growth rate between 1995 and 2008. According to the WIOD, domestic inputs of material goods to material goods in the supply chain segment in China were 6 times higher in 2008 than in 1995. There was a large increase in demand in every material goods sector of China over this period, but growth was most dramatic in Electrical and Optical Equipment (+619 billion $) and Basic Metals and Fabricated Metal (+542 billion $). The most significant sectors driving demand in these two sectors were also Electrical and Optical Equipment and Basic Metals and Fabricated Metal, respectively, suggesting that intermediate inputs between the same industrial sectors is an important factor in boosting emission multiplier effect $\overline{q}_{11}$. Although I expected that structural changes of the countries have slowly occurred in the *long* term, the above result shows that there occurred a significant structural change of the country in the *medium* term from 1995 to 2008 and it contributed to climate change.

The country with the second highest $\overline{q}_{11}$ in 2008 was India, a country whose domestic industrial structure features a high proportion of tertiary industry. This suggests that there may be something strange about these $\overline{q}_{11}$ results. However, a look at the input structure of India shows that total input between 1995 and 2008 doubled (see Figure 4.1), and intermediate demand in the materials goods sectors of Electricity, Gas and Water Supply, Other Non-Metallic Mineral, and Basic Metals and Fabricated Metal grew by 23 billion \$, 18 billion \$, and 17 billion \$, respectively. Although the production amount of India's material goods sectors is relatively small compared to its service sectors, supply chain segments in the country's production systems featuring input from one material goods sector to another were found to have the effect of potentially increasing CO_2 emissions in the country.

Here, I estimated $\overline{q}_{12}$ showing the degree to which emissions are amplified by supply chain segments in which inputs flow from material goods sectors to service sectors. Fi 4.2 shows that $\overline{q}_{12}$ is less widely dispersed than $\overline{q}_{11}$. From 1995 to 2008, the mean value of $\overline{q}_{12}$ for the 40 countries and regions remained almost unchanged, only rising from 1.25 to 1.26. Over the same period, however, 15 of the 40 countries and regions show increases in $\bar{q}_{12}$; in particular, Russia showed the highest value of $\bar{q}_{12} = 2.16$ in 2008 and increased 1.4-fold during 1995 to 2008. Behind the rise in Russia's $\bar{q}_{12}$ value is growing demand in Construction and Electricity, Gas and Water Supply in the service sector. Based on the WIOD, the service sector with the highest demand for these material goods inputs was Real Estate Activities. Hertwich and Peters (2009) also demonstrated the importance of shelter in Russia's carbon footprint, and the results here reconfirm that real estate activities in the Russian economy have a large impact on the country's domestic CO_2 emissions. While the biggest emission multiplier effect in most countries tends to be $\bar{q}_{11}$, in the case of Russia, the emission multiplier effect associated with supply chains between material goods sectors $\bar{q}_{12}$ is the largest (in 2008, 2.16). This value is quite large compared to a $\bar{q}_{11}$ value of 1.45 in Russia. This suggests that, for the CO_2 emissions induced in Russia's domestic supply chains, the consumption of material goods and energy necessary to produce services is more important than the consumption of material goods and energy to produce material goods. In other words, Russia needs to pay attention to inputs from material goods sectors to service sectors, especially production systems for real estate and housing services. From these results, I can confirm that, for the CO_2 emissions induced in domestic supply chains, the consumption of material goods and energy necessary to produce services is more important than the consumption of material goods to produce material goods.

Figure 4.3 shows the changes in the CO_2 multiplier effects $\bar{q}_{21}$ and $\bar{q}_{22}$ of the segments' supply chain in the domestic production structures related to the service inputs to material goods sectors and to service sectors associated with household consumption for four years in the study period: 1995, 2000, 2005, and 2008. From Figure 4.3, I found that the services input to material goods tended to contribute to increasing CO_2 emissions through its production segment during 1995 to 2008 (see left-hand side of Figure 4.3). On the other hand, the multiplier effects in terms of the services input to services have not changed during the study period (right-hand side of Figure 4.3). Compared with the $\bar{q}_{11}$ and $\bar{q}_{12}$, the CO_2 multiplier effect $\bar{q}_{21}$ had smaller values and not so much impact on the domestic CO_2 emissions for the study period. However, in some countries, such as Belgium and Canada, the multiplier effects regarding the segment of the input of services to material goods exceeded that of the input of material goods to services. This result shows that the 40 countries and regions focused on in this study have tended to accelerate climate change more through producing services necessary for our material society than through producing material goods.

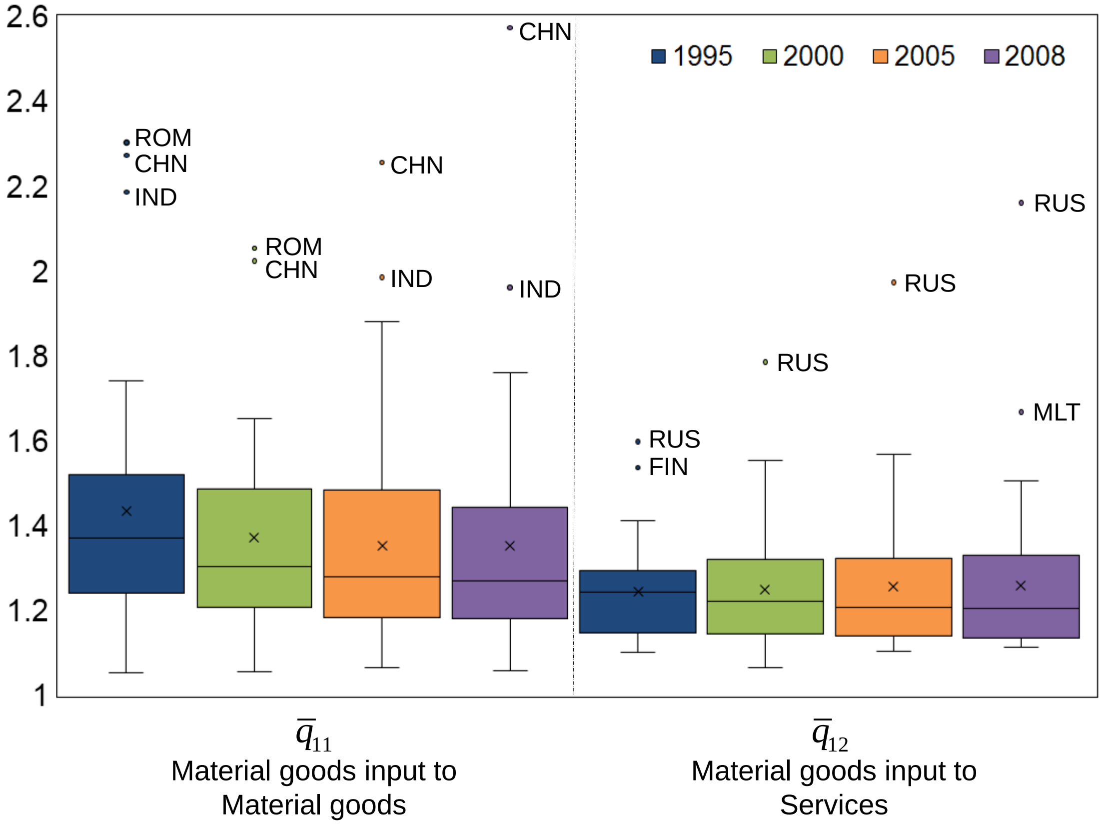

Figure 4.2. CO_2 multiplier effect $\bar{q}_{kl}$ of the segments' supply chain in the domestic production system associated with household consumption for four years in the study period: 1995, 2000, 2005, and 2008.

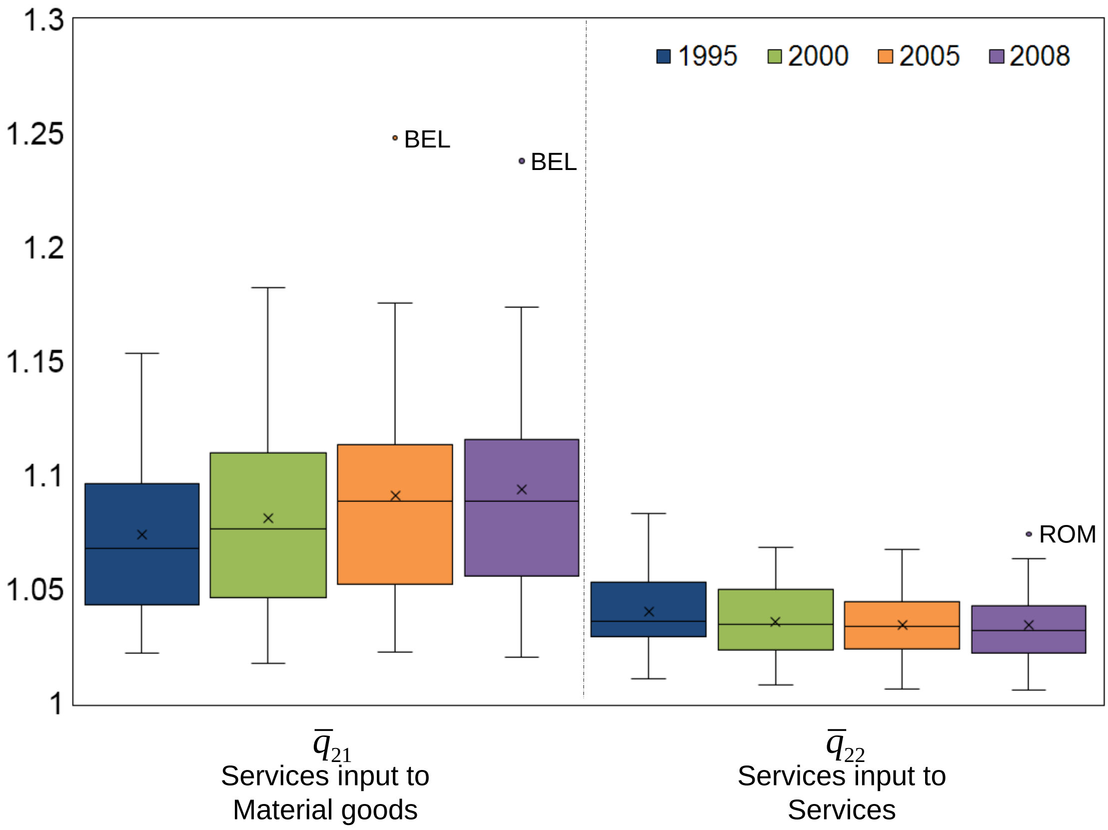

Figure 4.3. CO_2 multiplier effects of the segments' supply chain in the domestic production structures related to the service inputs to material goods sectors and to service sectors associated with household consumption for four years in the study period: 1995, 2000, 2005, and 2008.

4.3. Relationship between the main CO_2 multiplier effects and economic growth

Figure 4.4 shows the relationship between GDP per capita and CO_2 emission multiplier effects $\bar{q}_{11}$, $\bar{q}_{12}$, and $\bar{q}_{21}$ in 1995 and 2008. CO_2 emission multiplier effect $\bar{q}_{22}$ was substantially smaller than the other multiplier effects and I did not find a clear relationship between it and economic growth (See Figure S4.1 in the Appendix). CO_2 emission multiplier effects $\bar{q}_{11}$ and $\bar{q}_{12}$, which are related to the material input, tended to decrease with increasing GDP per capita. Some developing countries enlarged their multiplier effects in spite of economic growth, but almost all countries tended to shrink the contribution to CO_2 emissions generated in the segment related to the material inputs during 1995 to 2008. The input structure of Malta, for example, indicates that there was a strong growth in inputs from Electricity, Gas and Water Supply and Pulp, Paper, Printing and Publishing to service sectors. In Korea, as another example, inputs from Food, Beverages and Tobacco and Electrical and Optical Equipment were large. These producing sectors have relatively high emission intensities. In this way, the impact on CO_2 emissions of input structures to service sectors is highly dependent on a country's industrial structure.

Unlike $\bar{q}_{11}$ and $\bar{q}_{12}$, the CO_2 emission multiplier effect associated with the segment of service inputs to material goods, $\bar{q}_{21}$, tended to grow accompanying economic growth. This tendency is especially strong in developed countries; related to this, the demands of Financial Intermediation, Renting of M&Eq and Other Business Activity, and Retail Trade by material goods sectors have increased along with the expansion of the less-material economy implying that the economy tends not to use much material goods. For developing countries, $\bar{q}_{21}$ also increased consistently with economic growth. The demands of Inland Trade, Water Trade, Air Trade, and Wholesale Trade and Commission Trade by material goods sectors have been growing differently from in developed countries. This situation reflects the industrialization occurring in developing countries.

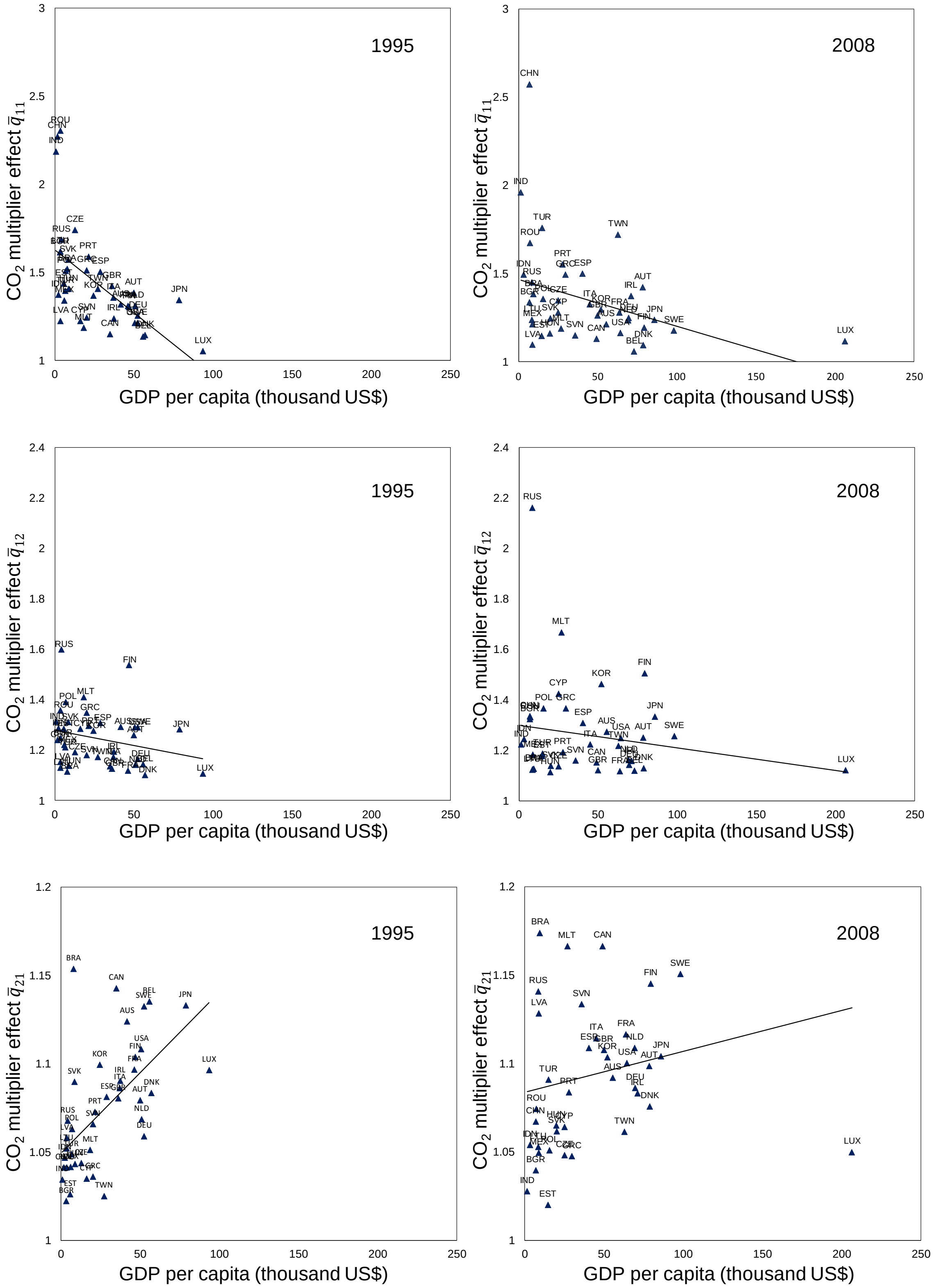

Figure 4.4 Correlation between GDP per capita and the main CO_2 multiplier effects in 1995 and 2008

4.5 Comparison with previous studies

Nansai *et al*. (2009) used the Japan 1990-1995-2000 linked Input-Output Tables and estimated the effect of each of the four supply chain segments related to material goods and services on CO_2 emissions by using a method similar to that in this study. From the results, they reported, "Observing the historical data, although the CO_2 emissions due to the material goods absorbed by material goods rose in 1995, as noted in the previous section, the multiplicative effect of the CO_2 emission by the segment of material goods absorbed by material goods consistently decreased, from 51% ($\overline{q}_{11}$=1.51) in 1990 to 40% (1.40) in 2000." (See page 4243 of Nansai *et al.* (2009).) On the other hand, their study found that the CO_2 multiplier effect regarding material goods input to material goods also has continued to decrease, from 34% ($\overline{q}_{11}$=1.34) in1995 to 23% (1.24) in 2008 (see Table S4.2 in the Appendix). Thus, this study found a similar trend for Japanese production structures that the supply chain segment related to inputs of material goods to material goods sectors reduced its CO_2 intensity.

Löschel *et al.* (2015) applied IDA to the WIOD in order to identify the factors behind the change in energy intensity of the EU-27 countries between 1995 and 2009, by region and by country, focusing on the change in industrial sector composition and change in sectoral energy intensity. Whereas in this study, I have focused on consumption-based CO_2 emissions, Löschel *et al.* (2015) focused on energy intensity during production. According to Löschel *et al.* (2015), although the aggregate energy emissions intensity of the EU-27 countries between 1995 and 2009 fell by more than 25%, the effect of structural change within the EU countries accounted for approximately 10% of this reduction (see Table 4.2 of Löschel *et al.* (2015)). In addition, an analysis by country discovered and verified that even if all European countries had experienced the same trend of reduction in energy intensity, the factors behind the reduction in intensity would differ markedly from country to country. The results of my study demonstrate not only that the trends in consumption-based CO_2 emission multiplier effects amongst EU countries are substantially heterogeneous (see Figure 4.2 and 4.3, and Table S2) but also, as pointed out by Löschel *et al.* (p.67, 2015), that differences in the economic scales of countries affect production systems (see Figure 4.4).

Minx *et al.* (2011) applied SDA to input-output tables of China in order to specify the drivers of CO_2 emission growth in China between 1992 and 2007. The study showed that although there was a sharp rise in the CO_2 generated within China from 2002 to 2007, the effect of structural change (L) was a major factor contributing to this rise (+108% contribution). Minx *et al.* (2011) further concluded that over this period (2002 to 2007) there was a substantial increase in CO_2 emissions especially induced by capital investment in China and that this driver arises from a shift to a more carbon-intensive structure of the Chinese economy, through increased demand in the construction industry. A look at the estimated CO_2 emission multiplier effects for China in this study shows that the CO_2 emission multiplier effects for supply chain segments related to inputs from material goods sectors to material goods sectors ($\bar{q}_{11}$) over the same period (2002 to 2007) increased 1.3-fold, from 1.97 to 2.59. Since the construction sector is characterized by demand for and production of materials with high CO_2 emission intensities, such as wood, cement, and manufactured parts, I can infer that increased demand for the construction sector in China's domestic economy led to an increase in emissions intensity in the production system, associated with inputs from material goods sectors to material goods sectors. Minx *et al.* (2011) showed that structural change was a major driver of emission growth in China, but the study did not analyze which input segments of the production system require the most focus for reducing emissions. In China, inputs from material goods sectors to material goods sectors are a major factor in driving up emission multipliers (see Figure 4.2 and Table S4.2 in the Appendix).

As mentioned above, the role played by the production structure in CO_2 emissions varies from country to country, so from an economic growth strategy and industrial policy perspective, the important question is how to reduce the emission intensity within the production system of a particular country. Figure 4.2 and 4.3, which show a breakdown of the CO_2 emission multiplier effects obtained in my study, can be useful in developing a country's emission reduction policies.

4.6 Discussion and conclusions

In this study, I divided the production structures of 40 countries and regions into four supply chain segments, focusing on the inputs of goods and services within each country or region, and I estimated the CO_2 emission multiplier effects of each segment. The results clearly showed the role played by the production structure of each country or region in CO_2 emissions. As pointed out by Suh (2006), services are sustained by manufactured goods, so manufactured goods are necessary for the continued growth of service sectors. From the multiplier effects estimated in thischao study, I found that in terms of a global average, segments related to inputs from material goods sectors to service sectors tend to become less emission-intensive. One reason for this may be that the price of manufactured goods has decreased as a result of innovations in manufacturing sectors, as pointed out by Chang (2011) and Rodrik (2015), thereby reducing the cost of the manufactured goods consumed by service sectors.

However, service industries such as Financial Intermediation, Renting of M&Eq, and Other Business Activity in "advanced countries" consume large quantities of material goods, such as Electrical and Optical Equipment, and Electricity, Gas and Water Supply to produce services, and even if the direct emissions of CO_2 from these production activities are low, they nonetheless contribute to increased CO_2 emissions within the country due to inputs of highly emissions-intensive material goods and energy. For a developed country, a large proportion of its GDP is generated by tertiary sector activities, and the role of service sectors in economic growth will further expand. Consequently, for reducing GHG emissions, it is important to understand that service industries are typically supported by large quantities of material goods and energy to produce the services, and therefore to build more environmentally friendly supply chains, focusing on service industries.

In “developing countries”, industrialization is sustained by service sectors such as transport and wholesale sectors (Zhang *et al.*, 2015). Furthermore, the activity of service sectors in developing countries have produced more output than the agriculture and manufacturing sectors. Therefore, the role of service sectors in developing countries is crucial and these sectors are expected to become more important in the near future.

Although policymakers, especially in developed countries, have previously promoted an economic growth strategy included expanding the output of service sectors (Ministry of Economy, Trade and Industry, Japan, 2016; Department of Commerce, the United States, 2013), they should pay more attention to the role of service sectors in climate mitigation and emphasize in their growth strategies that it is important to promote saving energy consumed in the service sectors and reduce the use of highly emission-intensive products in those sectors.

Policymakers need to create policies that simultaneously achieve economic growth and CO_2 emission reductions for their country. Traditionally, the industries most targeted for emission reductions have been electric power generation, heavy industries such as steelmaking and cement, and transportation. Since these industries are vital for sustaining the economic growth of a country, however, it is difficult to limit their production activities. Furthermore, strategies that aim at achieving both economic growth and GHG emission reductions by promoting service industries might appear useful in reducing a country's CO_2 emissions, but if the dependency of service industries on material goods and energy is ignored, there is a risk of increasing the emission intensity of the country's industrial structure. To mitigate this risk, supply chain management is important. However, supply chain management is complicated, requiring an understanding of networks that are often unclear. In contrast, supply chain management of production segments that is focused on transactions of goods and services is simple and easy to understand. Since such supply chain management is also a means for reducing GHG emissions within a country without lowering the level of the country's production activities, it is an approach that is more likely to gain industry consensus.

For the future research, I will reveal the comprehensive roles of the production structure or industrial structure of nations through a more detailed production-level productive efficiency analysis (Dechezleprêtre *et al*., 2013; Dechezleprêtre and Sato, 2017), identifying key structural paths (Lenzen, 2007), and a political analysis that includes, for example, carbon prices (Cramton *et al*., 2017), coal phase-out (UNEP, 2017), and specific national policies.

Chapter 5 Conclusion

In this doctoral dissertation, I focused on changes in industrial structures and technology related to supply chains, analyzed the multidirectional and comprehensive world CO_2 emission structure using a multi-regional input-output table from two perspectives, production- and consumption-based CO_2 emissions, and argued how world structural changes have played a role in CO_2 emissions.

Chapter 3 proposed a comprehensive decomposition method to estimate how changes in domestic economic scale, industrial composition, domestic technology, export scale of intermediate products, export composition of intermediate products, export scale of final products, export composition of final products, import scale of intermediate products, import composition of intermediate products, import scale of final products, import composition of final products, and foreign technology affect the volumes of both territorial CO_2 emissions (including emissions induced by producing exports) and extraterritorial CO_2 emissions induced by imports. To conduct this analysis, the sources of the territorial CO_2 emissions of each of 40 nations from 1995 to 2009 were examined using the Environmentally Extended World Input–Output Tables in 2009 prices. From the results on industrial composition effects of countries, I showed that, in contrast to the high-income nations, the middle-income nations heavily industrialized, and the resulting increase in emissions (+111 Mt CO_2) due to industrialization in these middle-income nations exceeded the reduction in emissions (−47 Mt CO_2) due to deindustrialization of the high-income nations. Ultimately, the combined effect from the industrial compositions of the two income groups was positive and the structural changes contributed to increasing CO_2 emissions. The results also showed that the export composition effect was negligibly small in both the high-income and middle-income groups of countries during 1995–2008 and that it has not played an important role in climate change. Furthermore, I categorized 40 countries into 8 groups by pattern of structural changes considering the impact of changes in industrial composition and import composition on emitting CO_2. To design global warming countermeasures from a world perspective, I should consider the differences in the role of structural changes.

Chapter 4 focused on the effects of changes in material and energy input structure on consumption-based CO_2 emissions. Previous studies demonstrated the connection between domestic structural changes including a shift toward a service economy and an increase in the greenhouse gas (GHG) emissions embodied in final demand of a specific country. This chapter covered important follow-up research that examined the environmental effects across countries and evaluated whether the development levels of countries can explain those environmental effects. I employed a multiplicative structural decomposition analysis and decomposed the consumption-based CO_2 emissions of 40 nations into the following four inducement sources: (i) inputs from material goods (including energy) to material goods, (ii) inputs from material goods to services, (iii) inputs from services to material goods, and (iv) inputs from services to services. The results showed that the global average of the CO_2 multiplier effect regarding material goods input to material goods fell from 1.44 to 1.35 between 1995 and 2008. In other words, the average production structure related to this input segment has steadily contributed to suppressing CO_2 emissions. On the other hand, from the global average of another CO_2 multiplier effect, the segment related to inputs from material goods to services did not change toward decreasing CO_2 emissions during the study period but rather made a still higher contribution to CO_2 emissions. It was noted that only the CO_2 multiplier effect of the segment related to inputs from services to material goods tended to increase with economic growth. This situation resulted from the enlargement of demand of service sectors, such as Financial Intermediation, Renting of M&Eq and Other Business Activity, and Retail Trade, in developed countries. We cannot ignore the role of service sectors in developing countries in domestic CO_2 emissions, because the demands of Inland Trade, Water Trade, Air Trade, and Wholesale Trade and Commission Trade by material goods sectors in those countries have been growing, which contributed to making the domestic production structures of the considered supply chain more CO_2 emission intensive. We should pay more attention to the role of service sectors in climate mitigation and emphasize the importance of encouraging service sectors to reduce the amount of energy consumed and to reduce the use of highly emission-intensive products. We also note that it is natural that the role played by the production structure in CO_2 emissions varies from country to country. The results from this chapter provide helpful information for policymakers to identify the target segment of a supply chain in order to reduce domestic CO_2 emissions without lowering the level of the country's production activities.

As I mentioned above, this doctoral dissertation quantitatively evaluated the impacts of changes in industrial structures and production structures considering the supply chain on the global environment from two viewpoints: production-based and consumption-based CO_2 emissions. From the quantitative analyses, I provided a foundation of comprehensive and scientific information as a clue to solving global warming. I could not capture the roles of developing countries such as Southeast Asian and African countries due to the current lack of the relevant datasets. Those countries are now becoming more important in the world as their economies grow, which will result in an expansion of their role in affecting the global environment. Therefore, additional analysis for those countries is needed to grasp an overall picture of world CO_2 emissions, which is future work. In addition, while I demonstrated the impacts of economic structures on the environment from only a macro perspective in this dissertation, the activities of firms and consumers are also very important to mitigate emissions. The method proposed in this dissertation can be applied to micro analysis with more detailed datasets in order to evaluate the role of firms and consumers in CO_2 emissions from a micro perspective. Although this dissertation has limitations as I mentioned above, the findings from this analysis provide crucial information which can guide policymakers in developing countries in their design of effective strategies for both economic growth and CO_2 emission mitigation. In this point, it is expected to be effective to apply the method proposed in this dissertation to a more detailed analysis such as a scenario analysis where the future structure and technology changes are considered.

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Appendix

Chapter 3

Supplementary Tables

Table S3.1. Industry classification

Sector number	Description	Industry group
1	Agriculture, Hunting, Forestry and Fishing	Primary industry
2	Mining and Quarrying	Secondary industry
3	Food, Beverages and Tobacco	
4	Textiles and Textile Products	
5	Leather, Leather and Footwear	
6	Wood and Products of Wood and Cork	
7	Pulp, Paper, Paper , Printing and Publishing	
8	Coke, Refined Petroleum and Nuclear Fuel	
9	Chemicals and Chemical Products	
10	Rubber and Plastics	
11	Other Non-Metallic Mineral	
12	Basic Metals and Fabricated Metal	
13	Machinery, Nec	
14	Electrical and Optical Equipment	
15	Transport Equipment	
16	Manufacturing, Nec; Recycling	
17	Electricity, Gas and Water Supply	
18	Construction	
19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	Tertiary industry
20	Wholesale Trade and Commission Trade, except of Motor Vehicles and Motorcycles	
21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	
22	Hotels and Restaurants	
23	Inland Transport	
24	Water Transport	
25	Air Transport	
26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	
27	Post and Telecommunications	
28	Financial Intermediation	
29	Real Estate Activities	
30	Renting of M&Eq and Other Business Activities	
31	Public Admin and Defence; Compulsory Social Security	
32	Education	
33	Health and Social Work	
34	Other Community, Social and Personal Services	
35	Private Households with Employed Persons	

Table S3.2. Income classification of countries examined in the study

Country number	Country	Abbreviation	Income group
1	Australia	AUS	High-income group
2	Austria	AUT	
3	Belgium	BEL	
4	Canada	CAN	
5	Cyprus	CYP	
6	Czech Republic	CZE	
7	Germany	DEU	
8	Denmark	DNK	
9	Spain	ESP	
10	Estonia	EST	
11	Finland	FIN	
12	France	FRA	
13	United Kingdom	GBR	
14	Greece	GRC	
15	Ireland	IRL	
16	Italy	ITA	
17	Japan	JPA	
18	Korea	KOR	
19	Lithuania	LTU	
20	Luxembourg	LUX	
21	Latvia	LVA	
22	Malta	MLT	
23	Netherlands	NLD	
24	Poland	POL	
25	Portugal	PRT	
26	Russia	RUS	
27	Slovakia	SVK	
28	Slovenia	SVN	
29	Sweden	SWE	
40	Taiwan	TWN	
30	United States	USA	
31	Bulgaria	BGR	Middle-income group
32	Brazil	BRA	
33	China	CHN	
34	Hungary	HUN	
35	Mexico	MEX	
36	Romania	ROM	
37	Turkey	TUR	
38	Indonesia	IDN	Low-income group
39	India	IND	
41	Rest of World	RoW	-

Table S3.3. Results of decomposing territorial CO_2 emission for exports (Unit: Kt CO_2)

	Intermediate products			Final products			
	Domestic technology effect	Export composition effect	Export scale effect	Domestic technology effect	Export composition effect	Export scale effect	Total
High-income group including U.S.A							
1995-2000	-3046	-0.18	9953	-1259	0.32	2823	8472
2000-2005	-4505	-8.39	6165	-1067	-1.68	1541	2124
2005-2008	-2981	10.96	6875	-1086	6.37	1239	4064
2008-2009	330	9.53	-6016	372	-0.01	-857	-6162
Middle-income group including China							
1995-2000	-7250	114	8463	-6194	43.96	3480	-1342
2000-2005	-4531	-7.75	17755	-2875	0.54	6656	16998
2005-2008	-5300	1.22	24754	-3092	1.45	8661	25026
2008-2009	612	-4.06E-10	-10041	697	8.98E-12	-1533	-10264
Low-income group							
India							
1995-2000	-5606	-172	16519	-1778	-67.79	5022	13917
2000-2005	-1681	-7.64E-06	5240	-2050	-2.45E-06	3934	5443
2005-2008	2605	17.71	12901	1818	6.93	3895	21244
2008-2009	4674	-8.14E-11	-13550	-400	-2.31E-11	98.52	-9178
Indonesia							
1995-2000	3452	-0.02	10168	1244	-1.11E-02	3794	18658
2000-2005	7428	7E-03	5270	975	4.84E-03	-2079	11594
2005-2008	-2893	3E-11	-2198	-572	4.07E-01	-1980	-7643
2008-2009	2284	-3E-11	-821	662	2.37E-12	-508	1617

Chapter 4

Supplementary Figure

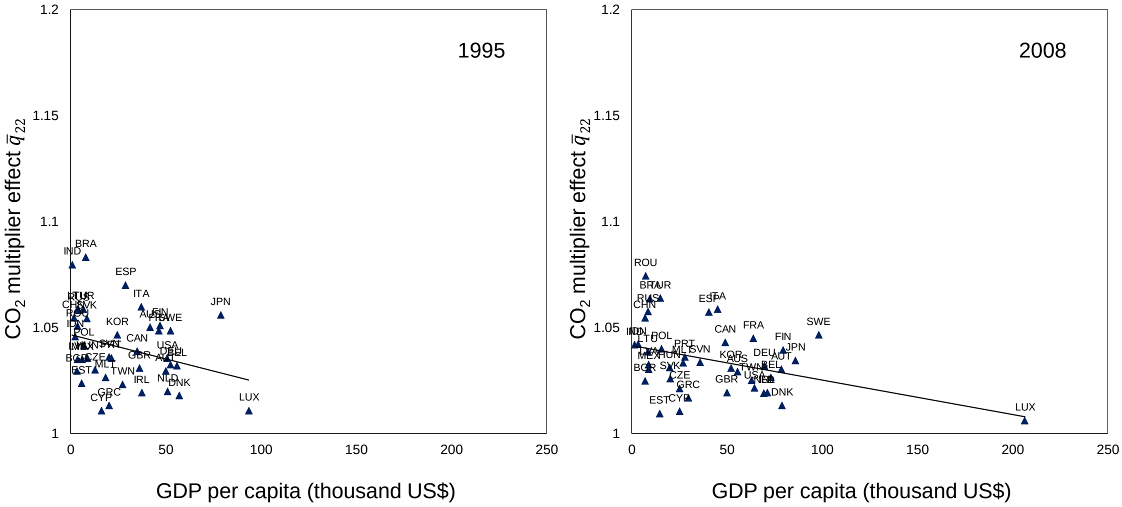

Figure S4.1. Correlation between GDP per capita and CO_2 multiplier effects $\bar{q}_{22}$ in 1995 and 2008

Supplementary Tables

Table S4.1. Industry classification

Sector number	Description	Industry group
1	Agriculture, Hunting, Forestry and Fishing	Material goods and energy
2	Mining and Quarrying	
3	Food, Beverages and Tobacco	
4	Textiles and Textile Products	
5	Leather, Leather and Footwear	
6	Wood and Products of Wood and Cork	
7	Pulp, Paper, Paper , Printing and Publishing	
8	Coke, Refined Petroleum and Nuclear Fuel	
9	Chemicals and Chemical Products	
10	Rubber and Plastics	
11	Other Non-Metallic Mineral	
12	Basic Metals and Fabricated Metal	
13	Machinery, Nec	
14	Electrical and Optical Equipment	
15	Transport Equipment	
16	Manufacturing, Nec; Recycling	
17	Electricity, Gas and Water Supply	
18	Construction	
19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	Service
20	Wholesale Trade and Commission Trade, except of Motor Vehicles and Motorcycles	
21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	
22	Hotels and Restaurants	
23	Inland Transport	
24	Water Transport	
25	Air Transport	
26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	
27	Post and Telecommunications	
28	Financial Intermediation	
29	Real Estate Activities	
30	Renting of M&Eq and Other Business Activities	
31	Public Admin and Defence; Compulsory Social Security	
32	Education	
33	Health and Social Work	
34	Other Community, Social and Personal Services	
35	Private Households with Employed Persons	

Table S4.2The decomposition results for 40 countries in the study period: 1995, 2000, 2005 and 2008

	$\bar{q}_{11}$				$\bar{q}_{12}$				$\bar{q}_{21}$				$\bar{q}_{22}$			
	1995	2000	2005	2008	1995	2000	2005	2008	1995	2000	2005	2008	1995	2000	2005	2008
AUS	1.318	1.267	1.227	1.212	1.292	1.287	1.290	1.273	1.124	1.108	1.099	1.092	1.050	1.040	1.031	1.029
AUT	1.386	1.258	1.360	1.423	1.260	1.228	1.237	1.250	1.079	1.111	1.100	1.099	1.029	1.026	1.024	1.030
BEL	1.138	1.125	1.065	1.058	1.144	1.174	1.105	1.118	1.135	1.145	1.248	1.238	1.032	1.032	1.033	1.026
BGR	1.615	1.415	1.463	1.336	1.248	1.323	1.356	1.322	1.022	1.034	1.047	1.040	1.029	1.030	1.036	1.025
BRA	1.522	1.460	1.439	1.383	1.115	1.117	1.129	1.127	1.154	1.151	1.166	1.174	1.083	1.069	1.067	1.064
CAN	1.151	1.134	1.133	1.130	1.136	1.151	1.152	1.151	1.143	1.158	1.163	1.167	1.039	1.035	1.036	1.043
CHN	2.273	2.053	2.256	2.573	1.240	1.231	1.302	1.335	1.041	1.040	1.052	1.067	1.054	1.059	1.048	1.055
CYP	1.226	1.179	1.215	1.278	1.284	1.346	1.365	1.424	1.035	1.039	1.050	1.064	1.011	1.008	1.009	1.010
CZE	1.742	1.595	1.397	1.348	1.193	1.144	1.124	1.135	1.044	1.040	1.045	1.048	1.030	1.019	1.022	1.021
DEU	1.256	1.230	1.220	1.248	1.165	1.159	1.154	1.142	1.059	1.081	1.085	1.086	1.032	1.037	1.033	1.032
DNK	1.145	1.103	1.107	1.095	1.102	1.106	1.110	1.129	1.083	1.071	1.087	1.076	1.018	1.016	1.017	1.013
ESP	1.505	1.496	1.519	1.498	1.307	1.298	1.323	1.308	1.081	1.081	1.097	1.109	1.070	1.063	1.064	1.057
EST	1.437	1.161	1.157	1.148	1.285	1.185	1.172	1.177	1.026	1.018	1.023	1.020	1.024	1.012	1.013	1.009
FIN	1.306	1.218	1.201	1.195	1.537	1.554	1.568	1.505	1.104	1.141	1.176	1.145	1.051	1.051	1.046	1.039
FRA	1.311	1.268	1.278	1.278	1.118	1.121	1.117	1.116	1.097	1.114	1.114	1.116	1.048	1.048	1.045	1.045
GBR	1.424	1.442	1.295	1.261	1.127	1.140	1.153	1.120	1.080	1.088	1.117	1.108	1.031	1.031	1.024	1.019
GRC	1.513	1.350	1.495	1.494	1.348	1.322	1.406	1.365	1.036	1.028	1.052	1.047	1.013	1.009	1.020	1.017
HUN	1.408	1.218	1.158	1.160	1.137	1.129	1.123	1.114	1.043	1.046	1.071	1.065	1.035	1.026	1.030	1.031
IDN	1.374	1.381	1.490	1.495	1.287	1.250	1.248	1.244	1.047	1.077	1.055	1.054	1.046	1.063	1.044	1.042
IND	2.187	2.024	1.986	1.961	1.313	1.354	1.246	1.222	1.034	1.035	1.028	1.028	1.080	1.052	1.037	1.042
IRL	1.238	1.236	1.233	1.372	1.193	1.167	1.197	1.157	1.090	1.076	1.090	1.083	1.019	1.023	1.023	1.019
ITA	1.358	1.365	1.336	1.326	1.173	1.191	1.202	1.222	1.086	1.100	1.108	1.114	1.060	1.058	1.060	1.058
JPA	1.344	1.322	1.258	1.237	1.282	1.318	1.359	1.333	1.133	1.128	1.118	1.104	1.056	1.047	1.037	1.034
KOR	1.367	1.369	1.339	1.297	1.277	1.292	1.398	1.462	1.099	1.083	1.103	1.104	1.047	1.030	1.036	1.031
LTU	1.620	1.313	1.280	1.238	1.130	1.134	1.123	1.122	1.052	1.045	1.036	1.053	1.059	1.040	1.034	1.038
LUX	1.053	1.055	1.118	1.117	1.108	1.066	1.113	1.122	1.096	1.136	1.054	1.050	1.011	1.010	1.006	1.006
LVA	1.224	1.154	1.125	1.096	1.153	1.129	1.139	1.125	1.058	1.066	1.095	1.128	1.035	1.030	1.028	1.033
MEX	1.342	1.216	1.199	1.214	1.220	1.220	1.201	1.182	1.042	1.047	1.048	1.050	1.035	1.028	1.027	1.030
MLT	1.186	1.159	1.193	1.188	1.411	1.365	1.559	1.668	1.051	1.047	1.135	1.166	1.026	1.020	1.036	1.033
NLD	1.311	1.295	1.222	1.234	1.142	1.141	1.140	1.161	1.068	1.086	1.095	1.109	1.020	1.019	1.019	1.019
POL	1.509	1.564	1.374	1.355	1.392	1.544	1.422	1.365	1.063	1.048	1.049	1.051	1.042	1.035	1.034	1.040
PRT	1.590	1.528	1.571	1.552	1.295	1.223	1.219	1.192	1.073	1.090	1.088	1.084	1.036	1.035	1.035	1.036
ROM	2.304	2.058	1.880	1.674	1.358	1.422	1.324	1.331	1.041	1.064	1.064	1.074	1.051	1.063	1.068	1.074
RUS	1.686	1.652	1.514	1.449	1.599	1.786	1.974	2.161	1.068	1.070	1.111	1.141	1.058	1.051	1.056	1.058
SVK	1.572	1.558	1.328	1.246	1.311	1.155	1.125	1.138	1.090	1.085	1.063	1.062	1.054	1.037	1.027	1.026
SVN	1.245	1.166	1.172	1.150	1.181	1.168	1.153	1.159	1.066	1.075	1.081	1.134	1.036	1.034	1.028	1.033
SWE	1.214	1.204	1.180	1.178	1.291	1.279	1.254	1.256	1.133	1.183	1.154	1.151	1.048	1.055	1.049	1.047
TUR	1.395	1.622	1.640	1.760	1.211	1.181	1.179	1.187	1.049	1.075	1.107	1.091	1.059	1.047	1.058	1.064
TWN	1.407	1.422	1.504	1.722	1.173	1.222	1.214	1.218	1.025	1.026	1.053	1.061	1.023	1.019	1.022	1.025
USA	1.214	1.223	1.163	1.163	1.290	1.356	1.296	1.249	1.108	1.118	1.117	1.100	1.035	1.032	1.024	1.021

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