Household carbon footprint and embodied carbon flow of domestic trade in Japan

February 2023

Graduate School of Fisheries and Environmental Sciences
Nagasaki University

Yuzhuo Huang

Abstract:

The world's third-largest economy, Japan, is also the fifth-largest greenhouse gas and carbon dioxide (CO_2) emitter globally: therefore, Japan's policies on climate change hold significant implications for mitigating global climate change. After 2013, Japan's CO_2 emissions show a downward trend as a whole, and its reduction rate of CO_2 emissions in the G7 is second only to that of the United Kingdom, which itself heavily intervenes in Japan's active emission reduction policy. However, from the perspective of sustainable development in a long-term, there are still potentials for Japan to cut the CO_2 emissions. Consumer demand drives production-related CO_2 emissions; in developed countries such as Japan, consumption-based accounting covers more CO_2 emissions than production-based accounting, and household consumption and domestic trade have become important carbon sources in consumption-based emission. Moreover, goal setting for sustainable development should consider not only the relationship between economic activities and CO_2 emissions but also carbon inequality. Justice and fairness in the process of emission reduction are important factors that affect the efficiency of policy implementation. The carbon inequality of the household sector is obviously affected by the distribution of CO_2 emissions by household type and income level within each prefecture. The characteristics (e.g., amount and structure) of domestic trade bring the differences in traded CO_2 emissions across prefectures, which intensified the inter-regional carbon inequality. Meanwhile, by the end of 2021, 47 prefectures in Japan had issued statements supporting carbon neutrality. Therefore, scientifically dividing the reduction responsibility of each prefecture, while considering social equality under different economic conditions, is important for Japan to effectively promote overall emission cuts.

Accordingly, evaluating the household carbon footprint (HCF) through demographic shifts and carbon inequality and visualizing embodied carbon flow of domestic trade in Japan have become the main research objective. To achieve the research objective more scientifically, we conducted specific studies from the following three aspects. First, we shed light on structural changes in HCF by age groups at national-level detailing both direct and indirect energy-related CO_2 emissions in 1990-2005, and uncovered insights for mitigating HCF with respect to both supply and demand factors and demographics, notably an aging, shrinking society by index and structural decomposition analysis. Second, we identified the detailed structures of HCF of multi- and single-person households by income level across 47 prefectures based on the 2005 multi-regional input-output table of Japan. Meanwhile, carbon inequality of HCF across prefectures were elucidated through the carbon footprint Gini coefficients of the aforementioned households. Lastly, we evaluated the CO_2 emissions embodied in Japan's domestic imports and exports to visualize the carbon transfer paths between prefectures according to the attributes of production and consumption, and identified the influencing factor of net export CO_2 emissions by log-mean Divisia index decomposition approach.

The main findings from our research are as follows. Household consumption and domestic trade have obviously promoted the growth of Japan's CO_2 emissions. The steady growth of household consumption has accelerated the domestic trade between prefectures, and the differences in trade scale and commodity structure also expand the gap in HCF across prefectures. Among the HCF, indirect CO_2 emissions were higher than direct CO_2 emissions in both the total emissions and change in emission levels. Under the deepening of aging, shrinking society in Japan, the distribution of CO_2 emissions by age groups of the highest income earner in the household will change, and the indirect CO_2 emissions will increase regarding the contributions from related drivers. Substantial differences in HCF exist among prefectures, thus contributing to variances in carbon inequality levels. Multi-person households are currently the main contributors to Japan’s HCF, but the contribution of single-person households has considerable potential to grow. Income level has the most direct influence on HCF, which considerably determines the amount and structure of household consumption. Changes in carbon inequality among prefectures indicate that the aggravation of income inequality widens the HCF gap among income groups—a situation inconducive to the reduction of per-household carbon footprint during climate mitigation. The CO_2 emissions embodied in domestic trade across prefectures are significantly affected by the consumption inside and outside the prefecture. The consumer prefectures not only drive the production-related CO_2 emissions of manufacturing prefectures, but also export sizable CO_2 emissions through the service sector which widely seen as a low-carbon emitter.

Key words: household consumption, domestic trade, carbon footprint, aging society, carbon inequality, income level, household type, Japan

Contents

List of Figures and Tables

Chapter 1. Introduction

During the economic globalization, climate change has become a critical environmental issue in the 21st century, exerting a profound impact on the sustainable development of all countries. Globally, more than 65% of greenhouse gas (GHG) emissions are due to household activities, which are influenced by lifestyle (Ivanova et al., 2016). GHG emissions associated with household consumption —that is, household carbon footprint (HCF)—represents the direct carbon dioxide (CO_2) emissions generated by fuel combustion in boilers, furnaces, and vehicles, and the indirect CO_2 emissions generated in the industrial sectors producing non-energy commodities demanded by the households (Munksgaard et al., 2000). In the context of climate change, goal setting for sustainable development should consider not only the relationship between economic activities and CO_2 emissions but also carbon inequality. HCF inequality is defined as the disparity in per capita CO_2 emissions among households (Xu et al., 2016), and its stems primarily from the HCF differences caused by income levels within region (Hailemariam et al., 2020). Moreover, the economic disparity across regions have resulted in regional carbon inequality, and domestic trade is one of the important aspects reflecting the economic differences across regions. Besides, since the 21st century, CO_2 emissions embodied in inter-regional trade have gradually increased and become an important growth point for CO_2 emissions (Jiang et al., 2015). Household consumption includes domestic products and foreign products, and domestic products can be further divided into local products and other regional products. Household consumption of domestic products is involved in inter-regional trade, meantime, the domestic imports and exports of every region are also affected by household consumption. Therefore, the difference in the structure of trade flows between regions leads to the different CO_2 emissions being embodied in domestic imports and exports, which in turn intensifies the regional carbon inequality.

The origin of carbon footprint can be traced back to a subset of "ecological footprint", which was proposed by Wackernagel and Rees (1996). The ecological footprint measures human demand on natural capital, that is, the biologically productive land and sea area required to sustain a given human population. Accordingly, the carbon footprint denotes the land area required to assimilate the entire CO_2 from human activity during its lifetime. Besides, carbon footprint is also a subset of Lifecycle assessment (LCA), it systematically evaluates carbon impacts of a product, activity, or process over the entire life cycle (Weidema et al., 2008). At the beginning of 21st century, the carbon footprint has become a popularity, mainly because the impact of climate change has gradually attracted the attention of all countries, and consensus has been reached at important international conferences, such as the Kyoto Protocol (Reay et al., 2007). However, most of the definitions of carbon footprint at that time were based on publications from "grey" (public) rather than scientific literature (East, 2008). Therefore, Wiedmann and Minx (2007) put forward a formal definition of carbon footprint, that is a measure of the exclusive total amount of CO_2 emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product. The carbon footprint includes two types of CO_2 emissions: direct CO_2 emissions (scope 1[1]) (i.e., emissions that generated by direct energy use) and indirect CO_2 emissions (scopes 2[2] and 3[3]) (i.e., emissions from the generation of purchased electricity, steam, and heating/cooling, and emissions from goods and services that are finally consumed through the supply chain).

At the end of the 20th century, there was an upsurge of discussion on the principles of producer and consumer in the research on the impact of economy on environment (Gupta and Bhandari, 1999; Munksgaard and Pedersen, 2001; Princen, 1999). About the first decade of the 21st century, the consumption-based accounting of GHGs has become increasingly relevant for policy and decision making, which raised the awareness of indirect CO_2 emissions in government and business (Wiedmann, 2009). After then, the carbon footprint of households has become a hot point in many top-down studies that analyze the environmental pressure caused by products and consumption activities (Hertwich, 2011). Consumer demand drives production-related CO_2 emissions; in developed countries such as Japan, consumption-based accounting covers more CO_2 emissions than production-based accounting (Nansai et al., 2012). Consumption-based accounting (Davis and Caldeira, 2010; Peters, 2008) quantifies not only direct or territorial emissions due to fuel combustion but also indirect emissions generated through the supply chains of goods and services, allowing for the consideration of broader abatement options from both the demand and supply sides (Wiedmann, 2009). This is known as a “cradle-to-gate” (i.e., from raw material extraction to final consumption) assessment. From this point of view, household consumption has been highlighted as playing a dominant role in cradle-to-gate GHG emissions, as measured through national carbon footprint (Wiedenhofer et al., 2018; Zhang et al., 2015).

---

[1] Scope 1 emissions come directly from sources that are owned or controlled by the reporting entity.

[2] Scope 2 emissions physically occur at the facility where electricity, steam, and cooling/heating are generated, however, as a user of the energy, the consumer is still responsible for the GHG emissions that are being created.

[3] Scope 3 emissions are the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly affects in its value chain. It is caused by vendors within supply chain, outsourced activities, and employee travel and commute.

The world's third-largest economy, Japan, is also the fifth-largest GHG and CO_2 emitter globally (Crippa et al., 2019): therefore, Japan's policies on climate change hold significant implications for mitigating global climate change. After 2013, Japan's CO_2 emissions show a downward trend as a whole, and its reduction rate of CO_2 emissions in the G7 is second only to that of the United Kingdom (UK) (Climate Change Convention, 2019), which itself heavily intervenes in Japan's active emission reduction policy. In the 2015 Paris Agreement, Japan had set a target of reducing GHG emissions by 46% in 2030 compared with 2013; based on the agreement, Japan has made several deepening extensions to the target in recent years (Ministry of the Environment Goverment of Japan, 2021). Moreover, in 2020, the Japanese government announced its goal of achieving carbon neutrality and pledged to cut GHG emissions to net-zero by 2050. Japan's CO_2 emissions are mainly concentrated in seven sectors, including industrial sector, transport sector, business and other sector, household sector, energy conversion sector, industry process and waste. From the sectoral distribution of CO_2 emissions after electric/heat distribution in Japan during 2000-2020 (Greenhouse Gas Inventory Office, 2022), the CO_2 emissions of industrial and transport sectors showed a downward trend, and compared with the 2000 level, they decreased by 25% and 28% in 2020, respectively. The CO_2 emissions of the energy conversion sector, industry process and waste generally showed a stable state. However, the CO_2 emissions of the household sector have been obviously increasing since 2000, and the growth rate was the highest in 2013 compared with 2000 level, reaching 30%. This greatly reveals the possibility of further emission reduction in household sector.

With the development of Japan's economy, household consumption under aging society has become one of the important sources of CO_2 emissions (Shigetomi et al., 2018). Therefore, it is necessary for Japan to implement effective measures with respect to technological innovation and envisaged demographic shifts to reduce the impact that household consumption have on overall emission levels (Shigetomi et al., 2018). Between 1990 and 2018, Japan's aging rate increased from 12.1% to 28.2%, while the birth rate fell from 10.0% to 7.4% (Ministry of Internal Affairs and Communications, 2020). The change of population structure has a significant impact on household consumption, which lead to the differences in the characteristics of HCF by age group. Therefore, taking demographic trends as a demand driver of changes in HCF due to an aging, shrinking population is of great significance for developed countries (e.g., Japan) with population issue to achieve mitigation target (Long et al., 2019; Shigetomi et al., 2014; Sovacool et al., 2018)

Household consumption differs by household type, leading to varying HCF levels. Households can generally be divided into single- and multi-person households. In Japan, the number of single-person households continues to increase given low marriage rates. From 2000 to 2018, the proportion of single-person households increased from 27.6% to 35.2%—figures that are expected to further rise in the future (National Institute of Population and Social Security Research, 2018). Correspondingly, exploring HCF on the basis of household type will not only advance the intuitive comparison of differences in HCF between single- and multi-person households across prefectures but will also enable a comprehensive understanding of HCF characteristics under the increasing influence of household consumption on CO_2 emissions in Japan.

Justice and fairness in the process of emission reduction are important factors that affect the efficiency of policy implementation; thus, carbon inequality has been increasingly concerned during the climate mitigation in recent years. Under the influence of economy, there are CO_2 emission gap between different level of wealth accumulation, resulting in uneven distribution of CO_2 emissions. Overall, carbon inequality can be observed from two dimensions, namely, the intra- and inter-regional carbon inequality. The intra-regional carbon inequality is profoundly impacted by the regionality, such as the income level and household type. Specifically, the majority of HCF can be attributed to high-income emitters, which constitute a small part of a population, whereas very little HCF is produced by low-income emitters, which make up a considerable proportion of a population (Hubacek et al., 2017). The characteristics (e.g., amount and structure) of domestic trade bring the differences in traded CO_2 emissions across prefectures, which intensified the inter-regional carbon inequality. Besides, by the end of 2021, 47 prefectures in Japan had issued statements supporting carbon neutrality (Ministry of the Environment Government Japan, 2021). Therefore, scientifically dividing the reduction responsibility of each prefecture, while considering social equality, is important for Japan to effectively promote overall emission cuts. Furthermore, actively dealing with carbon inequality aligns with the objectives of addressing climate change and reducing income inequality in the United Nations' (2015) Sustainable Development Goals.

Against the background of the decrease in overseas market demand, Japan has committed to expanding domestic consumption in recent years to stimulate economic growth, which has promoted an increasing amount of trade between prefectures (Ministry of Economy, Trade and Industry, 2015). In recent years, the financial situation of the central and local governments in Japan has remained grim, and regional economic development can no longer rely on financial support (Cabinet Office of Japanese government, 2011). To stabilize the economy, Japan has further expanded domestic trade by developing circular economies, which have also greatly enhanced the economic links between prefectures. Net domestic exports accounted for a relatively high proportion of the gross regional product (GRP) in most prefectures of Japan, especially in economically advanced prefectures such as Tokyo (Cabinet Office of Japanese government., 2015). Meanwhile, to adapt to the expanding domestic market, the commodity structure of inter-prefectural trade is also changing, thus impacting industrial production in every prefecture of Japan, Therefore, it is necessary to further understand the CO_2 emissions embodied in domestic trade across prefectures to expand the potential for Japan's emission reduction.

There are differences in the degree of dependence on domestic trade among industry sectors. The manufacturing industry plays a leading role in both domestic imports and exports. In Japan's heavy industry base, located in prefectures like Chiba and Kanagawa, the domestic exports accounted for more than 60% of the GRP contributed by the chemical industry in 2011. Meanwhile, the service industry is also an important part of Japan's domestic exports. In Tokyo and Osaka, Japanese megacities with concentrated populations, the commercial sector accounted for 29% and 30% of domestic exports, respectively. The economic driving forces of each prefecture differ with economic development. Manufacturing prefectures use the manufacturing industry as an economic growth point, whereas consumer prefectures use consumption to support their economic foundations. The difference in the structure of trade flows between prefectures leads to different CO_2 emissions being embodied in domestic imports and exports. Besides, with the decentralization of the Japanese government, whether Japan's emissions reduction targets can be achieved depend largely on the effectiveness of the measures in every prefecture (Furukawa, 2010).

Japan's active emission reduction policies have made great effort for the climate change mitigation. However, from the perspective of sustainable development in a long-term, there are still potentials for Japan to cut the CO_2 emissions. Under this occasion, household consumption and domestic trade have become effective ways to further promote the mitigation and achieve carbon neutrality in Japan. Therefore, exploring the structure of HCF under the influence of demographic shifts, household type and income level, and visualizing the carbon flow structure of domestic trade have become main research objective, which is conductive to comprehensively understand the consumption-based emissions in Japan. To reflect the research novelty, we added the visual diagram in Fig. 1-1 to show the relevant details. HCF in Japan has been extensively explored. Precedential research focused more on exploring HCF at the national-level from demographics, consumption and behavior without considering the time trend, carbon inequality and regionality. In this case, this study examined time trends of HCF or the crucial supply-demand drivers considering demographic trends, and elucidated carbon inequality across prefectures through detailed structure of HCF by income level and household type. Meanwhile, there is a considerable amount of research on CO_2 emissions stemming from Japan's trade, however, most research focused on the impact of international trade. Accordingly, this study systematically evaluated the CO_2 emissions embodied in Japan's domestic trade at the prefectural level and identified the influencing factors. Furthermore, we flexibly linked the household consumption and domestic trade through carbon inequality (i.e., intra- and inter-regional carbon inequality), which is conductive to scientifically understand the consumption-based emissions in Japan, and this is also the novelty which is not consisted in the previous research.

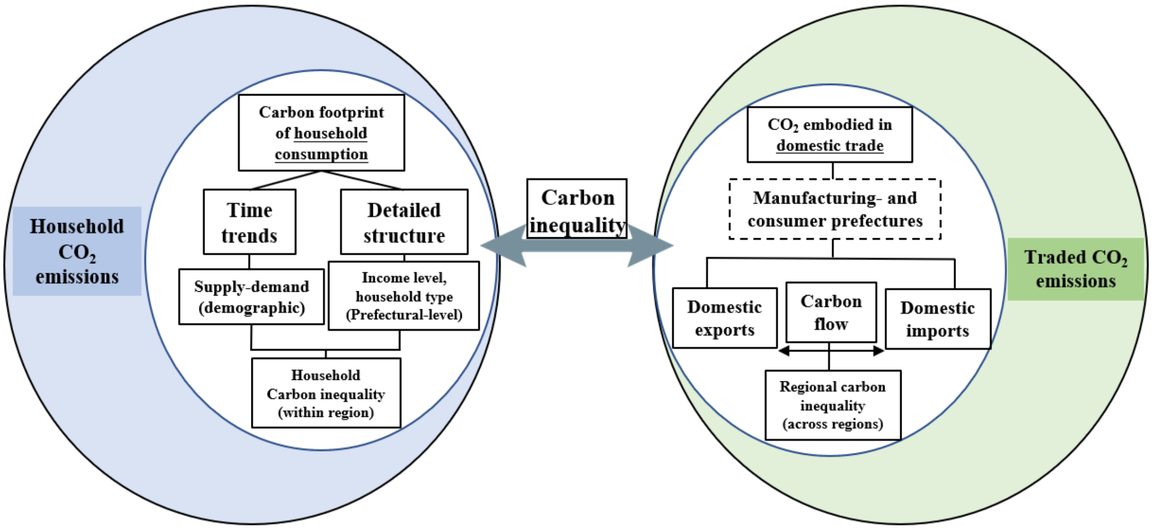


Fig. 1-1 Visual diagram of the research novelty.

To achieve the research objective more scientifically, we conducted three specific studies from the following aspects in Chapters 3–5, which are shown in Fig. 1-2. First, in Chapter 3, we aimed to quantify the impact of demographic shifts on the HCF in Japan's aging, shrinking society. We shed light on structural changes in HCF by age groups at national-level detailing both direct and indirect energy-related CO_2 emissions, and uncovered insights for mitigating HCF with respect to both supply-demand factors and demographics by index decomposition analysis (IDA) and structural decomposition analysis (SDA). Second, in Chapter 4, our purpose was to evaluate carbon inequality by household type and income level across prefectures in

Japan. We quantified detailed structures of HCF across single- and multi-person households of different income levels in 47 prefectures and elucidated carbon inequality by prefecture through the carbon footprint Gini (CF-Gini) coefficients of the aforementioned households. Finally, in Chapter 5, we focused to visualize the carbon transfer paths between prefectures in Japan's domestic trade according to the attributes of production and consumption. We estimated the CO_2 emissions embodied in domestic imports and exports by prefectures using input–output (IO) analysis, followed by the log-mean Divisia index (LMDI) decomposition approach which was used to quantify the influencing factor of net export CO_2 emissions across prefectures.

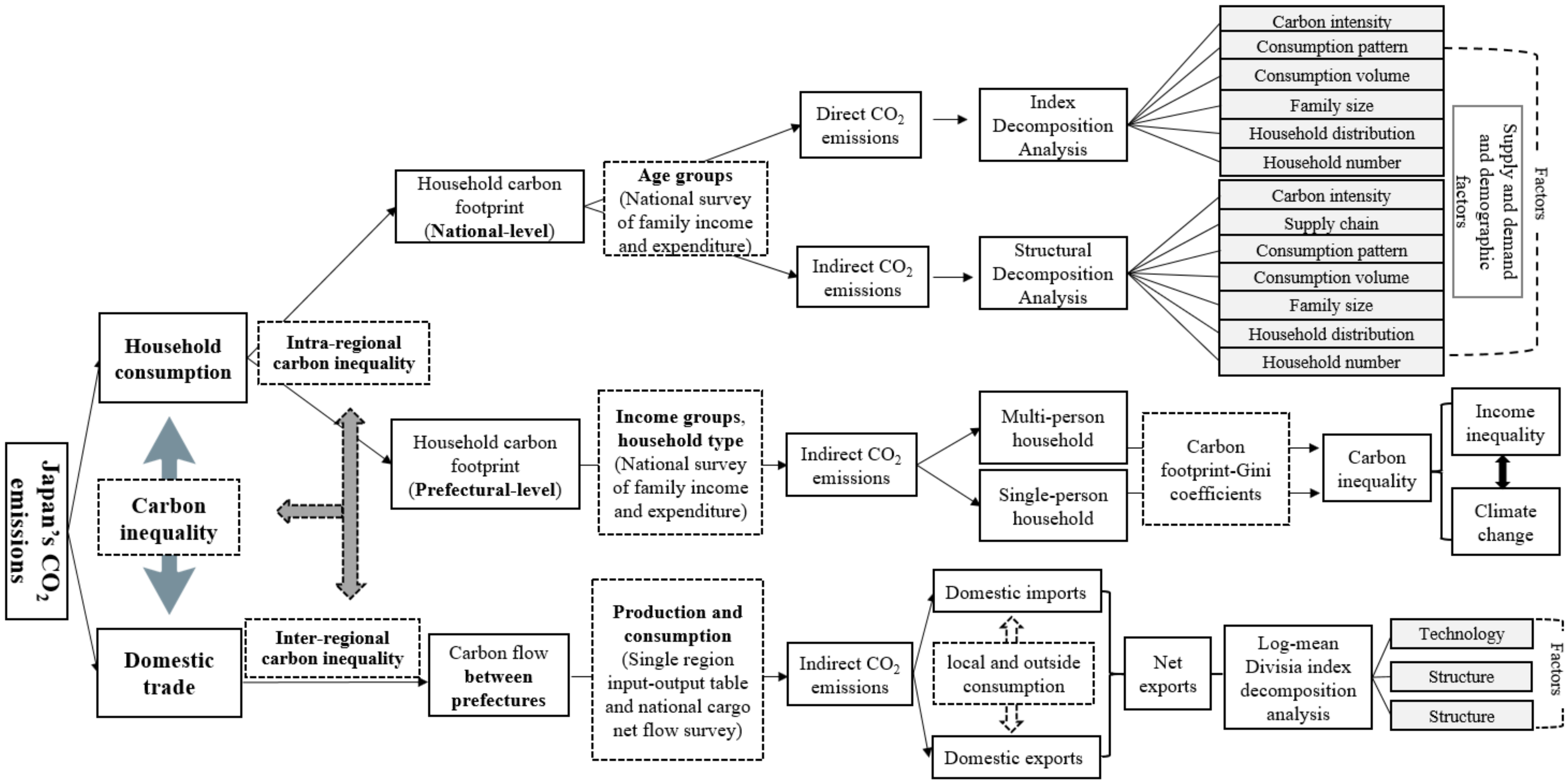


Fig. 1-2 Structure of the research subjective.

Household consumption and domestic trade interact with each other, and they have become important emissions sources in Japan, considering both the household consumption and domestic trade is conductive to comprehensively explore the consumption-based emissions in Japan. Besides, a scientific understanding of Japan's carbon inequality will help ensure the efficiency of climate mitigation measures. Through the evaluation of HCF and visualization of carbon flow embodied in domestic trade in Japan, we can have a multi-dimensional understanding of Japan's CO_2 emissions, which can not only make specific policy implications for emission reduction in a short-term, but also provide a theoretical basis for direction of emission mitigation in a long-term. To promote Japan's carbon neutrality under sustainable development goals, a more scientific and reasonable understanding of its HCF can help in applying targeted measures to reduce emissions by considering demographic trends and crucial supply-demand drivers. Systematically evaluating the carbon inequality by household type across prefectures is helpful to policymakers to deal with the relationship between income inequality and climate change based on regional differences. Besides, visualizing the carbon transfer paths and identifying the influencing factor is useful to coordinate inter-prefectural trade between production and consumption to promote prefectural cooperation of emission reduction. Furthermore, clarifying regional differences in household carbon inequality and traded CO_2 emissions in Japan also has important reference value for research on consumption-based mitigation in other countries. The remainder of this thesis is organized as follows. Chapter 2 presents the literature review; Chapters 3–5 shows the methods and results of three specific studies; Chapter 6 discusses the main findings; Chapter 7 presents the conclusions and policy implications.

Chapter 2. Literature review

In this chapter, we first reviewed the research related to Japan's CO_2 emissions, subsequently provided detailed summaries of research from the perspective of household consumption, trade, and carbon inequality, and finally summarized the relevant literature on the main research methods (i.e., IO analysis).

2.1 CO_2 emissions of Japan

From 2010 to 2016, the average annual growth rate of CO_2 emissions remained at 2.5%, and it was slower than the gross domestic product (GDP) growth rate of Japan (Javid and Khan, 2020). Destek et al. (2020) used the time-varying cointegration and bootstrap-rolling window estimation approach to identify the long-term impacts of economy and CO_2 emissions in G7 countries, and proposed that the nexus between economic growth and CO_2 emission is inverted M-shape in Japan, which is associated with economic and political preferences of countries for foreign direct investment. Adebayo (2021) explored the long-run and causal effects of CO_2 emissions, globalization energy usage, trade openness, and urbanization on economic growth in Japan by employing new econometric techniques. They proposed that urbanization, CO_2 emissions, globalization, and energy usage trigger economic growth, meantime, there is a one-way causality from CO_2 emissions and energy usage to economic growth.

Considering biomass and carbon-free energy sources along with fossil fuels, past and present energy transitions have evidently affected CO_2 emissions. Okushima and Tamura (2007) applied multiple calibration decomposition analysis to identify the drivers of changes in energy use and CO_2 emissions in the Japanese economy between 1970-1995, and showed that total CO_2 emissions increased primarily because of the economic growth, which is represented by final demand effects. Using an extended Kaya decomposition, Lu et al. (2016) quantified the long-term dynamic changes of GHG emissions in Japan after World War II, and further clarified the dynamic changes in combination with energy consumption and economic development. They found that Japan benefited both ecologically and economically from importing fossil fuels and the total environmental impacts of GHG emissions measured by energy decreased after 1997. The environment that governs the relationships between energy consumption, CO_2 emissions and GDP changes with the variations in economic growth, regulatory policy and technology. Based on a novel approach to detect causalities, Ajmi et al. (2013) explored the relationships between CO_2 emissions, energy consumption and GDP, and concluded that there is bidirectional causality between GDP and energy consumption for Japan, meantime, there is also significant time-varying causalities running from GDP to CO_2 emissions.

Industry is one of the main emission sources. Shah (2021) studied the metabolic transition of resource use and CO_2 emissions in nine of the largest economies of Asia, and showed that Japan had the lowest material and CO_2 intensities compared to all other countries. Miura et al. (2021) conducted network data envelope analysis to clarify the relationship between the production efficiency and CO_2 emission of sectors within primary, secondary, and tertiary industries in Japan. They found that prefectures with relatively high efficiency are in the three major metropolitan areas (Tokyo, Aichi, and Osaka). Oshiro and Masui (2015) assessed the impact of the diffusion of low emission vehicles in the transportation industry on Japan's emission reduction, and found that the promotion of low emission vehicles will reduce the CO_2 emissions from transport sector in 2050 by approximately 81% compared to the 1990 level. Matsumoto et al. (2019) investigated the factors behind the historical changes in CO_2 emissions of the Japanese manufacturing industry at both national and prefectural level. They put forward that energy intensity, structure, and activity effects were more influential in the changes of CO_2 emissions than the carbon intensity effect. Hata et al. (2022) evaluated capital-embodied material footprints and their induced CO_2 emissions for the 2015 Japanese economy, and showed that the service sector produced an material footprints of 168 million tons and had a high-level carbon intensity.

The occurrence of unexpected events has a profound impact on the national energy consumption and economic operation. Long et al. (2021) explored the national and regional CO_2 emission patterns for the main economic sectors in Japan during 2007-2015, a period shaped by the 2008 financial crisis and the 2011 Tohoku Earthquake. They found that there is a shift in the dominance of different drivers of CO_2 emissions over time, with a stronger initial impact from economic effects after the 2008 financial crisis, followed by energy structure after the 2011 earthquake. Lastly, changes in international politics also have an important impact on Japan's CO_2 emissions. Dai et al. (2017) studied the impacts of U.S. withdrawal from the Paris Agreement on the CO_2 emission space and mitigation cost of Japan, and proposed that under the 2 °C target, Japan's GDP loss will increase by US$4.1–13.5 billion.

2.2 Household consumption

Consumption has emerged as a key priority in research and policymaking related to sustainable development in the 21st century (Fischer et al., 2017). Against the backdrop of increased commodification of human activities, sustainable household consumption has become an important pathway to urban economic development (Elmqvist et al., 2019). Caeiro et al. (2012) suggested that the impact of household consumption patterns on the environment has become progressively obvious, especially in areas with vast human settlements, such as urban centers. Claudelin et al. (2018) conducted a comparative analysis of households with different income levels to show how a change in household behaviors can improve the sustainability of lifestyles. Wang et al. (2019) evaluated the effects of household energy consumption on health burdens and emphasized the importance of improving household consumption in relation to the environment for both current and future generations.

Household consumption has become one of the important sources of GHG emissions. Hertwich and Peters (2009) quantified the GHG emissions associated with the final consumption of 73 nations and found that at the global level, 72% of these emissions are related to household consumption. Druckman and Jackson (2010) explored the CO_2 emissions that arise from consumption in UK households, which account for over three-quarters of the country's total emissions when measured from a consumption perspective. Gu et al. (2013) found that household use and transport are the two main contributors to household CO_2 emissions. Cárdenas-Mamani et al. (2022) quantified household-related energy use and associated GHG emissions in Lima, Peru between 2007 and 2015. The authors reported that liquefied petroleum gas (LPG), rather than electricity, is the primary energy source in low-income households.

The direct CO_2 emissions generated by household energy consumption account for a relatively small proportion in Japan, at about 5% (Ministry of the Environment Government Japan, 2022). Matsuhashi and Ariga (2016) evaluated the potential reduction of CO_2 emissions by passenger vehicles over the long term in Japan, and showed that there is a correlation between population distribution and passenger car CO_2 emissions in 1980-2005. Long et al. (2018) analyzed the energy-related CO_2 emissions in Japan's megacities using established urban database and emission database, and pointed out that the depopulation of cities can result in higher per capital emissions, as they relate to household energy demand. Matsumoto (2022) explored the effect of carbon taxes on household energy source combinations by conducting a microdata analysis of Japanese households. They found that increased carbon tax leads to an increased percentage of households using gas, and reduced percentage of households selecting full electrification or kerosene. Through the pure aging effect, the cohort effect, and the family structure effect, Inoue et al. (2022) studied how population aging affects household energy consumption in Japan.

They found that there is a substantial impact of population aging on household energy consumption.

The impact of indirect CO_2 emissions from household consumption is greater than that of direct CO_2 emissions, thus prompting studies that focus on indirect HCF. Using the consumer LCA approach, Wang and Yang (2014) analyzed indirect CO_2 emissions from household consumption in urban and rural areas of China. For the same country, Liu et al. (2019) combined LCA and IO analyses to estimate the indirect CO_2 emissions of urban households from 2002 to 2012. The authors proposed that an increase in income is expected to effectively reduce indirect CO_2 emissions from household consumption. Hirano et al. (2016) estimated household CO_2 emissions on the basis of daily activities in Japan and showed that given the current consumption patterns in some selected households, there is a greater increase in indirect than direct CO_2 emissions. Long et al. (2017) evaluated indirect HCF on the grounds of source and its relationship with potential influencing attributes through a case study of 49 capital-level cities in Japanese prefectures in 2005. The authors found a spatially unbalanced distribution of indirect HCF by source.

Shigetomi et al. (2014) estimated changes in the carbon footprint of Japanese households by age group on the basis of an aging, shrinking population and predicted that the HCF in 2035 would be 4.2% lower than that in 2005. Shigetomi et al. (2018) examined the extent to which increases in the total fertility rate and the number of double-income households would affect the domestic carbon footprint associated with household consumption in Japan in 2030. Shigetomi et al. (2021) quantified the reduction in HCF for 25 factors associated with individual lifestyle choices and socioeconomic characteristics across prefectures in Japan in 2005. Long et al. (2021) evaluated urban household emissions in 52 major cities in Japan with 500 emission categories as bases and confirmed the impact of urban household consumption on global GHG emissions. However, there remains a lack of systematic and detailed analyses of HCF structure across all prefectural administrative units in Japan,

2.3 CO_2 emissions embodied in trade

Most studies on CO_2 emissions embodied in trade focus on international trade at national level. Wu et al. (2020) showed that CO_2 emissions embodied in international trade comprise approximately 40% of the global direct CO_2 emissions. The trade volume of developed countries accounts for the vast majority of global trade; thus, some studies have focused on the CO_2 emissions embodied in developed countries' trade. Wang and Zhou (2019) calculated the

CO_2 emissions embodied in Japan–US trade from 2000 to 2011. They found that economic losses in the US outweighed the positive effects of carbon transfer between the two countries. Qiang et al. (2019) studied CO_2 emissions embodied in Germany-US trade from 2000 to 2015 and found that the significance of the US in Germany's external trade was greater than that in the US's external trade. Kim and Tromp (2021a) quantified the CO_2 emissions embodied in South Korea's trade from 2000 to 2014, showing a greater trade-off between the environmental costs and economic benefits of trade.

With the reduction in regional tariffs, the CO_2 emissions embodied in the trade of developing countries will surge (Tian et al., 2022). Wang and Yang (2020) investigated CO_2 emissions embodied in China–India trade and proposed that China was a net exporter of CO_2 and a net exporter of trade. Kim and Tromp (2021b) quantified CO_2 emissions and value-added embodied in China–Brazil trade and showed that China's position as net CO_2 emissions and net value-added exporters deepened from 2000 to 2014. Developed countries specialize in relatively cleaner products and services with high value-added parts, whereas developing countries are stuck in pollution-intensive links with low-value-added parts (Liu et al., 2020). Therefore, intensive studies have evaluated CO_2 emissions embodied in trade between developing and developed countries. Wang et al. (2019) calculated the CO_2 emissions embodied in trade between China and Australia from 2000 to 2014 and found that the net carbon outflow from China to Australia is concentrated in the textile and heavy manufacturing sectors. Wang et al. (2019) evaluated the CO_2 emissions embodied in trade between the largest net exporter of developing countries (China) and the largest net exporter of developed countries (Germany), and found that CO_2 emissions are mainly concentrated in carbon-intensive industrial sectors. Qiang et al. (2021) studied the decoupling of CO_2 emissions embodied in Sino-US trade and showed that it is relatively invariable and gradually improving.

Many studies have further analyzed the transfer path of CO_2 emissions embodied in trade based on trade flow. As trade structure is affected by economic level, developing countries are often net exporters of CO_2 emissions, whereas developed countries are usually net importers (Wang et al., 2022). Wu et al. (2016) estimated the CO_2 emission flows between China and Japan from 2000 to 2009 and found that China was a net exporter of CO_2 emissions embodied in China–Japan trade. Zhao et al. (2016) also focused on the CO_2 emissions embodied in the China-Japan trade, further extending the research period from 1995 to 2009, and showed that CO_2 emissions embodied in China's exports increased by approximately 100%. Long et al. (2018) compared CO_2 emission flows through imports and exports, production, and consumption to analyze the differences between China and Japan. Xu et al. (2022) decomposed the CO_2 emission processes embodied in global trade and traced critical carbon transfer paths, finding that most transfer paths in the US end in service, whereas in China, they end in construction. Xu et al. (2022) investigated carbon transfers between mainland China and its trade partners to quantify mitigation targets and to allocate responsibilities. They showed that net carbon transfer paths from China driven by trading partners accounted for 87% of the total number of paths.

Moreover, some studies consider a country's economy as a heterogeneous multi-regional integrated whole to analyze in-country carbon transfer (Zhou et al., 2018). Wei et al. (2020) investigated the electricity-related CO_2 emissions and value-added embodied in China's interprovincial trade from 2007 to 2012, and showed that 20–80% of the electricity-related CO_2 emissions and 15-70% of the value added to a province's final demand are outsourced to other provinces. Wang and Hu (2020) evaluated carbon transfers caused by interprovincial demand and interprovincial exports for China in 2007, 2010, and 2012. Yi et al. (2007) combined prefecture-specific emission databases and technology matrices with the interregional trade flows presented by the nine-region MRIO table to observe the effects of four environmental burdens in Japan. However, there is still a lack of research on carbon flow of domestic trade across prefectures in Japan at this stage.

2.4 Carbon inequality

Social income inequality not only affects the sustainable development of society but also gives rise to carbon inequality in the process of climate change. Hubacek et al. (2017) estimated global GHG emissions in 2010 and found that the top 10% of income earners are responsible for approximately 36% of global emissions, whereas the bottom 50% produce only 15% of emissions. Sommer and Kratena (2017) calculated the carbon footprint of household consumption by five income groups in 27 European Union (EU) nations and found that such footprint exhibits a decoupling effect—that is, the share of the top income group in income (45%) is substantially larger than its share in carbon footprint (37%) and vice versa for the bottom income group (6% in income and 8% in carbon footprint). Seriño and Klasen (2015) maintained that income has a significant nonlinear relationship with CO_2 emissions, depicting an inverted U shape with a turning point beyond the current income distribution. In the context of China, Wiedenhofer et al. (2017) reported that HCF is unequally distributed between the rich and the poor because of differences in the scales and patterns of consumption in the country. Ivanova and Wood (2020) used household-level consumption data to shed light on carbon inequality through the relationships between HCF and socially desirable outcomes in 26 EU countries, regions, and social groups.

Most research on HCF inequality focuses on the national level or part of a country instead of covering all administrative units. Representative works are as follows: Jones and Kammen (2011) quantified the HCF of typical US households in 28 cities on the basis of six household sizes and 12 income brackets in 2005. López et al. (2016) studied HCF inequality in Spanish households under the impact of the great recession of the 21st century. Feng et al. (2021) assessed HCF inequality in the US in 2015 by estimating the consumption-based GHG emissions of nine income groups. Yang and Liu (2017) quantified the inequality in household CO_2 emissions and its influencing factors for three cities in China in 2015. Sun et al. (2021) examined carbon inequality resulting from household consumption in the rural areas of five representative provinces in China. Mi et al. (2020) estimated the HCF of 12 income groups in China's 30 provinces and measured household carbon inequality across provinces in 2007 and 2012. At this stage, research on HCF inequality at the subnational level in Japan is still limited.

2.5 IO analysis

There are generally two methods to assess the environmental impact of production and consumption, namely LCA and IO analysis. LCA covers the production, distribution, use and disposal of individual products, and the IO analysis is well suited to address the environmental pressures from average product and consumption baskets; therefore, the IO analysis is widely used in the top-down studies to comprehensively and directly show the environmental impacts (Hertwich, 2011). The IO model describes and explains the level of output of each sector in a given economy in terms of its relationship with the corresponding level of activity in all other sectors (Leontief, 1970). As a top–down macro-economic methodology, the IO model has been flexibly expanded into the environmentally extended input-output (EEIO) model in the modern economy through the addition of energy consumption and an emission intensity vector (He et al., 2019). The EEIO model is a useful framework for modeling the input and output characteristics of environmental factors and monitoring consumer-driven emissions by linking upstream and downstream production in a multi-regional trade network (Song et al., 2019). It enables a new generation of analyses underlain by a consumption-focused, rather than a production-focused, perspective on the causes of climate change and resource use (Kitzes, 2013). It is also widely employed to evaluate the carbon inequality of household consumption (Feng et al., 2021; Mi et al., 2020; Wang and Yuan, 2022). There are three types of IO models:

single-region IO (SRIO), bilateral trade IO (BTIO), and multi-region IO (MRIO) (Sato, 2014). In a SRIO model, it is assumed that the production technology of imported goods and services is the same as that of domestic technology in the same sector (Wiedmann, 2009). The SRIO model takes a region as an object to examine the emissions related to its total consumption (also known as total demand, including household, government and capital investment) (Sato, 2014). For example, Alcántara and Padilla (2009) studied the CO_2 emissions associated to the group of branches of the service sector based on SRIO model in Spanish; Pan et al.(2008) estimated the scale of emissions embodied in China's current trade pattern based on SRIO model. The BTIO is also known as embodied emissions in bilateral trade, which considers CO_2 emissions in relation to a country's total consumption, but breaks down trade by trading partner and applies different emission factors. For example, Nguyen et al. (2020) applied a BTIO model is to analyze how final demand and use of input in the production of China induces output and value added of Vietnam. The domestic technologies and hence emissions intensities of each country (or region) may differ significantly from those of exporting countries (or region); thus, MRIO model has been systematically developed to consider the differences in national (or regional) technology and specific trade patterns (Hertwich, 2011). The Scientific Knowledge for Environmental Protection proposed that MRIO model is a sound and relevant methodology for accounting for trade-related impacts from a consumption perspective (Wiedmann, 2009). For example, Hasegawa et al. (2015) constructed an subnational MRIO table based on interregional shipments among Japan’s 47 prefectures to to estimate the carbon footprint and carbon leakage of every region; Mangır and Şahin (2022) employed the environmentally extended global MRIO model to calculate Turkey’s consumption-based emissions and import-based embodied emissions for the year 2015.

Chapter 3. Drivers of HCF in an aging, shrinking society of Japan

3.1 Background

In order to meet climate change mitigation goals, nations such as Japan need to consider strategies to reduce the impact that lifestyles have on overall emission levels. In line with Japan's declaration of carbon neutrality in 2021, GHG emissions need to be reduced to net-carbon zero by 2050. To achieve this target, it is necessary to take the demographic shifts as a breakthrough to further understand the distribution characteristics of HCF across age groups. Therefore, we have examined time trends of HCF by considering the supply-demand drivers and demographics in aging, shrinking society of Japan.

3.2 Methodology and data

Here the methodology and data are defined, including the quantification and decomposition approaches, the methodological, and data utilized.

3.2.1 Quantification of carbon footprint by household consumption

HCF is defined as the sum of direct CO_2 emissions induced by driving a passenger motor car, cooking and household heating (D), and indirect (embodied) CO_2 emissions generated through the supply chain due to household consumption (S). D is calculated using Eq. (3-1).

$$D = \sum_{k} \sum_{b} e_k^{dir} f_{kb} \tag{3-1}$$

where e_k^{dir} represents the direct CO_2 emissions per consumption expenditure for energy item k. f_{kb} denotes the household's final consumption by attribute b for energy item k.

Next, S is quantified by Eqs. (3-2) and (3-3).

$$S = \sum_{i} \sum_{b} e_i^{ind} f_{ib} \tag{3-2}$$

$$e_i^{ind} = \sum_{j} q_i \, L_{ij} \tag{3-3}$$

where e_i^{ind} represents the upstream CO_2 emissions per consumption expenditure (embodied CO_2 emission intensity) for commodity $i \ni k$. j denotes the commodity sector. It is estimated by using q_i and $L_{ij} = (I - A_{ij})^{-1}$ which denote the vector containing the direct CO_2

emissions per unit production output for commodity i and upstream requirements per unit production, respectively. L_{ij} is an element of the Leontief inverse matrix obtained from the input-output table.

3.2.2 IDA and SDA

In order to analyze the underpinning factors of HCF, this study adopts IDA (Ang and Zhang, 2000)and SDA (Rose and Casler, 1996) on a time-series data set of both direct and indirect CO_2 emissions induced by Japanese households. To date, IDA has been applied mainly to examine the driving forces of energy consumption and its relation to CO_2 emissions by sector (Ang et al., 1998; Xu and Ang, 2013). SDA has clarified the determinants of lifecycle emissions within carbon footprint, utilizing input-output table data (Hoekstra and van den Bergh, 2003; Lenzen, 2016). These two approaches have been utilized to analyze key determinants of home energy-related CO_2 emissions (Donglan et al., 2010; Xu and Ang, 2014; Zang et al., 2017) and HCF (Feng et al., 2015; Guan et al., 2008; Yuan et al., 2015) respectively, regarding the CO_2 emission intensity, supply chain structure, consumption volume and composition, and population.

To comprehend the contribution of various indicators to the changes in HCF by using IDA and SDA, we decomposed both the direct CO_2 emissions derived from home energy and the indirect CO_2 emissions generated through the supply chain of goods and services (commodities) purchased by households as shown in Eqs. (3-4) and (3-5).

$$D = \sum_k \sum_b e_k^{dir} \frac{f_{kb}}{f_b} \frac{f_b}{p_b} \frac{p_b}{H_b} \frac{H_b}{H} H = \sum_k \sum_b e_k^{dir} y_{kb} w_b s_b d_b H \tag{3-4}$$

$$S = \sum_i \sum_b q_i L_{ij} \frac{f_{ib}}{f'_b} \frac{f'_b}{p_b} \frac{p_b}{H_b} \frac{H_b}{H} H = \sum_i \sum_b q_i L_{ij} y_{ib} w'_b s_b d_b H \tag{3-5}$$

where H and p represent the total number of households and population, respectively. Both y_{kb} and y_{ib} refer to consumption patterns (e.g. medical services are more heavily consumed by elderly households than younger households). w_b and w'_b represent the average per-capita consumption volume for energy items and that for all commodities, respectively. s_b represents the average number of members in each household (i.e. household size). d_b describes the distribution of households (i.e. the proportion of younger households to total households). Hence, Eqs. (3-4) and (3-5) are based on Eqs. (3-1) and (3-2) with household final consumption decomposed into the five factors in line with consumption pattern, consumption volume, family size, household distribution, and number of households. Overall, six drivers are considered for direct CO_2 emissions, and seven drivers for indirect CO_2 emissions.

When D and S shift from year t to year $t+1$, there are no unique solutions for how the decomposition should be solved. To quantify the contributions of each factor, this study used the Shapley-Sun decomposition approach (Sun, 1998) for D, and the Dietzenbacher and Los decomposition approach (Dietzenbacher and Los, 1998) for S, cognizant of identical decomposition without any residues and the commonality of results (Hoekstra and van den Bergh, 2003). For example, the total difference of Eq. (3-4) can be represented by Eq. (3-6).

$$\Delta D = \sum_k \sum_b \Delta e_k^{dir} y_{kb} w_b s_b d_b H + e_k^{dir} \Delta y_{kb} w_b s_b d_b H + e_k^{dir} y_{kb} \Delta w_b s_b d_b H + e_k^{dir} y_{kb} w_b \Delta s_b d_b H + e_k^{dir} y_{kb} w_b s_b \Delta d_b H + e_k^{dir} y_{kb} w_b s_b d_b \Delta H \quad (3\text{-}6)$$

where Δ indicates the difference operator.

Eq. 3-6 converts six multiplicative terms in the first term of Eq. (3-4) into six additive terms. Each additive term in Eq. (3-6) denotes the contribution to changes in D induced by a targeted factor while all other factors are constant. For instance, the first term in Eq. (3-6) refers to the effect on direct CO_2 emissions of changes in direct CO_2 emission intensity while consumption patterns, consumption volume, family size, household distribution, and total number of households are constant between t and $t+1$. Each of the contributions were estimated by taking the average of the 6! = 720 decomposition equations possible (Sun, 1998). Here the effects on direct CO_2 emissions that are related to the first, second, third, fourth, fifth, and sixth terms in Eq. (3-6) are referred to as: intensity effect (direct), consumption pattern effect, consumption volume effect, household size effect, household distribution effect, and household number effect, respectively.

In a similar manner, the total difference of Eq. (3-5) can be demonstrated by Eq. (3-7).

$$\Delta S = \sum_i \sum_b \Delta q_i L_{ij} y_{ib} w_b s_b d_b H + q_i \Delta L_{ij} y_{ib} w_b s_b d_b H + q_i L_{ij} \Delta y_{ib} w_b s_b d_b H + q_i L_{ij} y_{ib} \Delta w_b s_b d_b H + q_i L_{ij} y_{ib} w_b \Delta s_b d_b H + q_i L_{ij} y_{ib} w_b s_b \Delta d_b H + q_i L_{ij} y_{ib} w_b s_b d_b \Delta H \quad (3\text{-}7)$$

Finally, each of the contributions were estimated by taking the average of the 7! = 5040 decomposition equations possible (Dietzenbacher and Los, 1998). Here the effects on indirect CO_2 emissions that are related to the first, second, third, fourth, fifth, sixth, and seventh terms are referred to intensity effect (indirect), supply chain effect, consumption pattern effect, consumption volume effect, household size effect, household distribution effect, and household number effect, respectively.

3.2.3 Data

This study used the time-series Japan input-output tables (TJIO) consisting of the economic transaction (L_{ij}) and household final demand structures ($\sum_b f_{ib}$) for 1990, 1995, 2000, and 2005 based on the 2005 price with 397 common commodities. Hence, the data is comparable among periods. Further, we disaggregated the commodities within petroleum products into six detailed commodities including gasoline, light oil, kerosene, LPG, and other petroleum products (i.e. lubricants) by using the Comprehensive Energy Statistics (Agency for Natural Resources and Energy of Japan, 2019). To identify the relationship between HCF and demographic trends, the final household demand from the TJIO were divided into consumption expenditures for six age groups of the highest income earner in the household (29≤, 30–39, 40–49, 50–59, 60–69, ≥70) for each year using the national survey of family income and expenditure (NSFIE) (Ministry of Internal Affairs and Communications, 2017). Then, the consumption share by attribute, summation of each final consumption type by commodity and the difference between producer-based price and consumer-based price were considered as detailed in a previous study (Shigetomi et al., 2016). q_i was calculated by dividing sectoral CO_2 emissions obtained from the 3EID (National Institute for Environmental Studies, 2013) by total output utilizing the TJIO. b denotes the age of the highest income earner (1: ≤29, 2: 30–39, 3: 40–49, 4: 50–59, 5: 60–69, 6: ≥70).

3.3 Results and discussion

The results and discussion are divided into the three sections of overall trends in emissions, changes within sectors and age groups, and decomposition of the driving forces underpinning emissions.

3.3.1 Overall trends of total direct and indirect CO_2 emissions

CO_2 emissions induced by Japanese household consumption from 1990 to 2005 are shown in Table 3-1. Both direct and indirect CO_2 emissions showed a significant growth trend during the analyzed period. In terms of overall emissions, indirect CO_2 emissions remain nearly four times that of direct CO_2 emissions. The annual average increase of direct CO_2 emissions is relatively small and emissions in 2005 are slightly lower than those in the year 2000. However, indirect CO_2 emissions continuously increased, with an annual average increase of 6.6 $MtCO_2$ in 1990–2005. In terms of the growth rate of emissions, that of direct emissions was higher than that of indirect emissions during the studied period (see Table 3-1). These characteristics will be elaborated by observing the trends in direct and indirect CO_2 emissions by sector, presented in the following section.

Table 3-1. Compositions of Japanese household CO_2 emissions in 1990–2005

	Year				**Average annualized increase**	**Growth rate (between 1990 and 2005)**
	1990	1995	2000	2005		
Direct CO_2 emissions ($MtCO_2$)	104	124	144	143	2.6	37.5%
Indirect CO_2 emissions ($MtCO_2$)	474	543	538	572	6.6	20.9%
Total CO_2 emissions ($MtCO_2$)	577	667	682	715	9.2	23.8%

3.3.2 Changes in direct and indirect CO_2 emissions in different sectors and age groups

The total direct and indirect CO_2 emissions are disaggregated into sectors and household age groups to evaluate their impact on CO_2 emissions. Fourteen sectors are considered including “food and non-alcoholic beverages,” “alcoholic beverages and tobacco,” “clothing and footwear,” “housing,” “furnishings,” “medicals,” “private vehicles,” “public transport,” “information and communication,” “recreation and culture,” “education,” “restaurants and hotels,” “consumable goods,” and “margins, religions and other services.” These sectors are determined based on the “Classification of Individual Consumption by Purpose.”

To observe the impact of demographic factors on CO_2 emissions in an aging society in greater detail, we examined the per capita CO_2 emissions as well as the per household emissions across different age groups. Here, we first focus on the per capita emissions, and subsequently interpret the per household emissions with the average household size and composition of households attributed to each age group

Figure 3-1 presents the trends in total direct CO_2 emissions by sector and average direct CO_2 emissions per capita across age groups. Private vehicles and housing are the only two sectors that generate direct CO_2 emissions from households as fossil fuels are used for these activities. For instance, the private vehicles sector includes gasoline and light oil, while the housing sector includes kerosene, LPG, coal products, and city gas (see also Fig. 3-5). As shown in Fig. 3-1a, the private vehicles sector accounts for a large proportion of direct CO_2 emissions throughout the analyzed period, impacting the high growth rate of direct emissions as referred to above. From 1990 to 2005, Japanese car ownership rose from 57.99 million to 78.28 million vehicles, an increase of approximately 35% (Automobile Inspection and Registration Information Association, 2022). With this increase in car ownership, the growth rate of gasoline consumption was much larger than for other fuels. Consequently, direct CO_2 emissions for the private vehicles sector increased significantly compared to those for the housing sector.

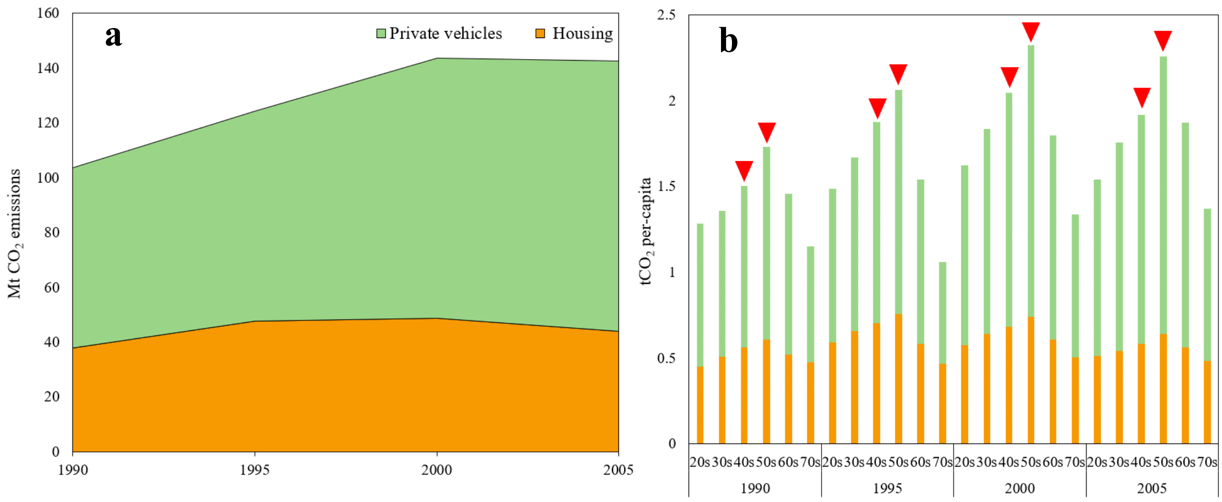


Fig. 3-1. Sectoral composition of direct CO_2 emissions from 1990–2005. (a) total ($MtCO_2$) and (b) per-capita by age group (tCO_2). Inverted triangles denote the noteworthy household age groups as detailed in the main text.

Considering different age groups, direct CO_2 emissions (per-capita) from the private vehicles sector are concentrated within two age groups, the 40s and 50s, as shown in Fig. 3-1b. For those in their 40s, this may be due to work and family needs. With the increase of household savings in these age groups, many families tend to own their own cars and use them frequently. The 50s age group has the highest direct CO_2 emissions across all age groups, possibly because the annual income in the 50s is higher than that of other age groups (Ministry of Internal Affairs and Communications, 2017). In addition, with the increase in household members, the household size has also expanded to a certain extent when compared to others, potentially expanding the demand for private vehicles, particularly large-sized cars. As for the direct CO_2 emissions from the housing sector, these are also concentrated in the 40s and 50s age groups. This may be because more people in their 40s and 50s are married, living with their children and tending to live in relatively large, energy consuming houses. Furthermore, the changes in direct CO_2 emissions in different age groups also showed certain peculiarities, such as CO_2 emissions gradually increasing from householder's 20s, reaching their peak in the 50s and then subsequently declining.

The change in indirect CO_2 emissions in different age groups is similar to that of direct CO_2 emissions (see Figs. 3-1b and 3-2b). Considering the order of growth in sectoral indirect CO_2 emissions, we selected food and non-alcoholic beverages, housing, and public transport sectors for discussion here, as shown in Fig. 3-2a. First, indirect CO_2 emissions generated by the housing sector were mainly concentrated in the three age groups of the 40s, 50s, and 60s as demonstrated by Fig. 3-2b. The reason behind the similarity between direct and indirect CO_2 emissions of those in their 40s and 50s are that residents modify their houses to meet the needs of household life and child-rearing. For the 60s age group, a consideration of the living environment and living conditions for old-age life could increase the cost of housing and lead to the production of more indirect CO_2 emissions.

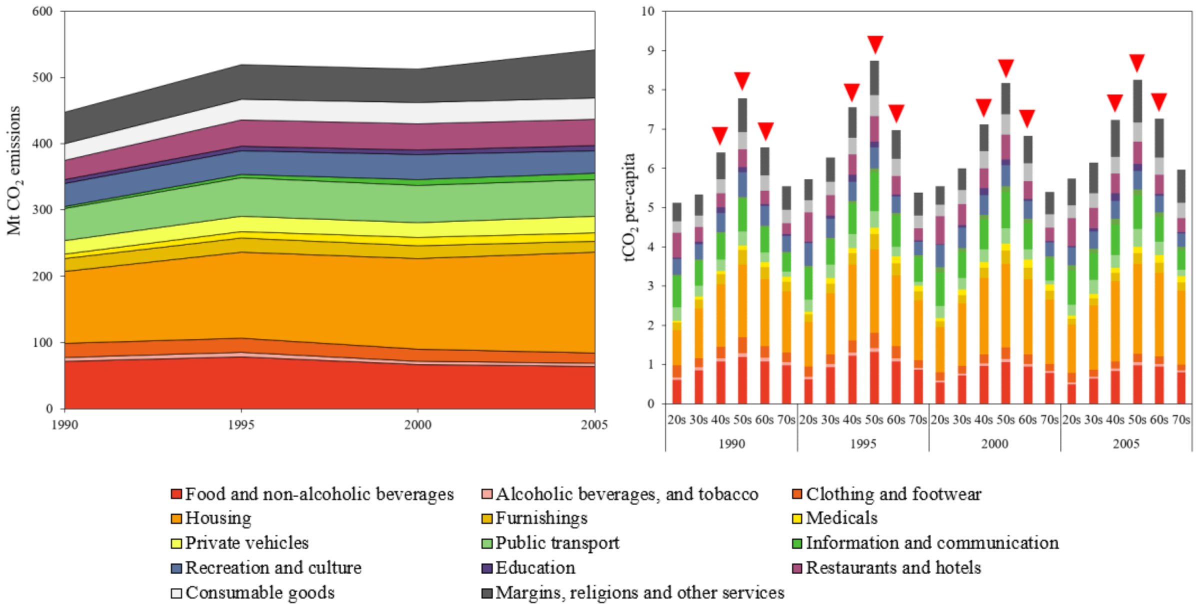


Fig. 3-2. Sectoral composition of indirect CO_2 emissions from 1990–2005. (a) total (Mt CO_2) and (b) per capita by age group (tCO_2). Inverted triangles denote the noteworthy household age groups as detailed in the main text.

Indirect CO_2 emissions from the food and non-alcoholic beverages sector were also concentrated in the 40s, 50s and 60s age groups. In the 40s and 50s age groups, the expansion of household size may lead to an increase in food consumption, which could increase indirect CO_2 emissions. As for the 60s age group, elderly people tend to spend more money on high-quality, expensive food compared to the other age groups. In addition, although the household size is smaller than the 40s and 50s age groups, it is still larger than the age groups of the 20s, 30s, and 70s. These factors combined make the 60s age group the third largest indirect CO_2 emitter on a per capita basis.

Indirect CO_2 emissions from the public transport sector were concentrated in the 20s and 50s age groups. Compared with other age groups, the proportion of private vehicle possession in the 20s age group is relatively low leading to an increased use of public transport, which could increase indirect CO_2 emissions from this sector. People in the 50s' households produced the highest CO_2 emissions from both private vehicles and public transport sectors. Generally, people in the 50s age group have the highest annual income and with the expansion of household size, households are more likely to use private vehicles alongside children of these households using public transport for attending school.

While the overall CO_2 emissions of the public transport sector are increasing, the growth rate is not as fast as that of the private vehicles sector. In addition, there are different trends in indirect CO_2 emissions from the private vehicles and public transport sectors by age group. In 2005, indirect CO_2 emissions for the private vehicles sector for those in their 20s decreased by 21% while those in other age groups, particularly the 30s and 60s, increased by 13-35% compared to 1990. The reasoning for such a decline in the 20s age group is that they were more likely to purchase smaller, less expensive vehicles such as lightweight automobiles (known as kei-cars in Japan) due to financial aspects. On the other hand, because age groups from the 30s to 50s are more likely to be involved in child-raising activities, household life has led to an increased demand for private transport. Furthermore, due to the demographic shift related to an aging, shrinking population leading to a postponement of childbearing age, those in their 60s have also experience an increase in their use of private vehicles.

For public transport, growth trends were evident across all age groups. Among them, the growth is particularly significant for those in their 20s and 40s. In the 20s age group, the reduction in the use of private vehicles led to an increase in public transport demand. As for the 40s age group, their use of public transport also increased, likely due to the expansion of travel needs for work and school as well as an increase in the use of private vehicles, although at a lower rate than for the 30s, 50s, and 60s.

On average, annual income increases from the 20s to the 50s, subsequently declining leading to an increase in consumption and savings, creating upward pressure on CO_2 emissions (Ministry of Internal Affairs and Communications, 2017). Meanwhile, because of the decline in income after the 50s, indirect CO_2 emissions also tend to decline. Further, the household size expands from the 20s to the 50s, while post 50s the household begins to shrink as children become independent and establish their own households, likely linked to the peak in CO_2 emissions observed for the 50s age group.

Figure 3-3 depicts direct and indirect CO_2 emissions per-household during the period 1990-2005. Among age groups, both direct and indirect CO_2 emissions per-household for those in their 50s were estimated to be the largest, followed by those in their 40s during all periods. This is mainly because their average household income and household size were larger than other households' (e.g., in 2005, the average annual household income and household size in their 50s and 40s are 7.8 and 7.3 Million JPY, and 2.9 and 3.2 people/per-household, respectively). While indirect CO_2 emissions for those in their 60s were the third largest for the 15 years investigated, their direct CO_2 emissions were fourth, smaller than for those in their 30s from 1990 to 2000. In 2005, those in their 60s increased to become larger than the 30s'.

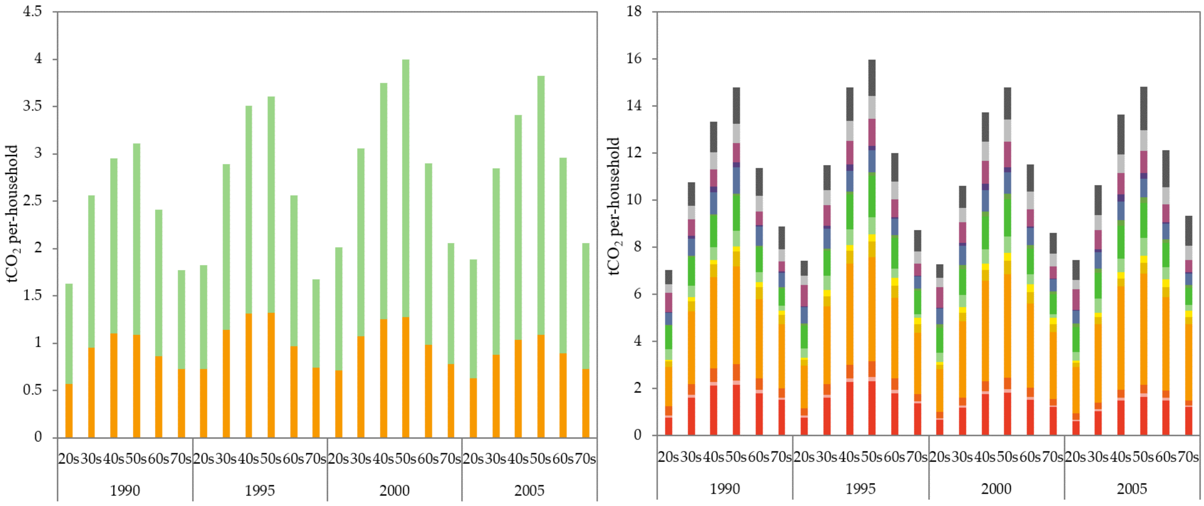


Fig. 3-3. Sectoral composition of per-household CO_2 emissions by age group (tCO_2) from 1990 to 2005. (a) direct and (b) indirect. The color of the legend corresponds to the sectors in Fig. 3-2.

Comparing the per-household results to the per-capita results as presented in Fig. 3-2b and 3-3b, the largest emissions were seen from those in their 50s. However, the orders of magnitude of indirect CO_2 emissions for those in their 40s and 60s differs between per-household and per-capita results, as seen in the emissions levels for 1990 and 2005. This is also observed for direct CO_2 emissions for households aged between their 20s and 70s. These differences between per-household and per-capita are most affected by the average household size and composition of households.

3.3.3 Decomposition Results

3.3.3.1 Driving forces of total direct and indirect CO_2 emissions

Figure 3-4 shows the results of examining the factors affecting direct CO_2 emissions during 1990–2005 using the IDA.

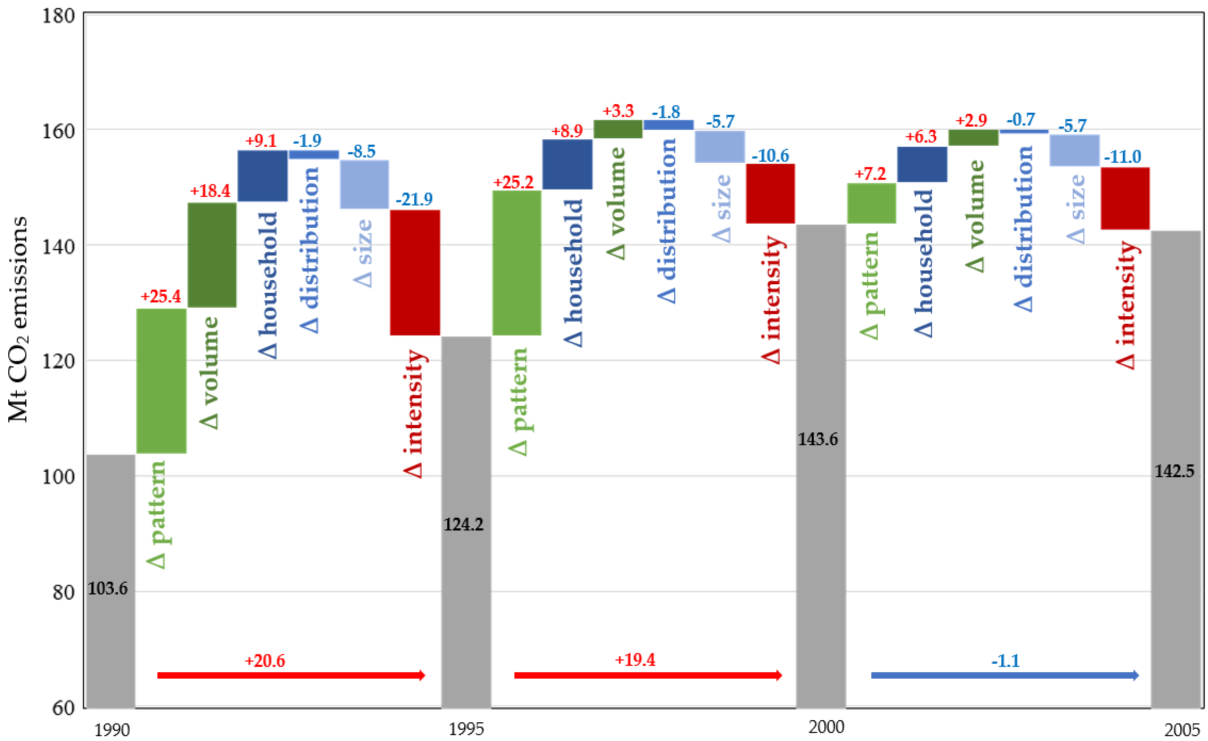


Fig. 3-4. Driving forces of direct household CO_2 emissions in Japan during 1990–2005. Δintensity is the intensity effect, Δpattern is the consumption pattern effect, Δvolume is the consumption volume effect, Δsize is the household size effect, Δdistribution is the household distribution effect, and Δhousehold is the household number effect.

Among factors, the intensity effect was the main driver in reducing direct CO_2 emissions, while the consumption pattern was the main driver which increased emissions. The negative impact of the intensity effect on direct CO_2 emissions has progressed over time, indicating that Japan has made substantial progress in emission reduction technology used in daily life since 1990. Figure 3-5 describes the direct CO_2 emissions by household energy item. The consumption of gasoline increased significantly prior to 2000 which is one of the reasons for the growth of direct CO_2 emissions driven by the consumption pattern during this period. After 2000, along with the slowdown of the growth of gasoline consumption, the positive impact of the consumption pattern has also weakened. In addition, the total number of households in Japan increased from 40.67 million to 49.06 million between 1990 and 2005 (Shigetomi, et al., 2018), promoting a positive impact of the number of households on direct CO_2 emissions. The positive effect of consumption volume on direct CO_2 emissions weakened consistently between 1990 and 2005. This is probably related to the increase of small-scale households which could reduce their energy consumption to a certain extent. Moreover, the negative impact of household size and household distribution on direct CO_2 emissions is gradually increasing, likely due to the influence of recent demographic trends such as an increase in single-person households and a reduction in household size because of an aging society with fewer children.

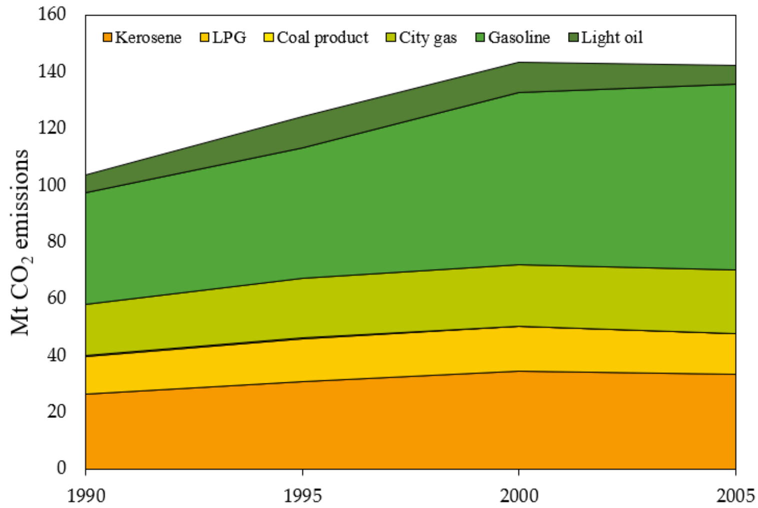


Fig. 3-5. Trend in the direct CO_2 emissions by energy item.

Considering the effects of household size, the number of households and household distribution in 1995, 2000 and 2005, we find that the sum of these effects gradually decreased direct CO_2 emissions. This suggests that if Japan maintains an aging society with a low birth rate, direct CO_2 emissions generated by the household sector will gradually decrease.

Figure 3-6 shows the SDA result for indirect CO_2 emissions in 1990–2005. As for indirect CO_2 emissions, both the total emissions and change in emission levels were higher than for direct CO_2 emissions and the sectoral composition of indirect CO_2 emissions is more diverse. Further, the change in driving forces of indirect CO_2 emissions are relatively complex. Indirect CO_2 emissions grew rapidly from 1990 to 1995 with growth slowing down during 1995–2000, thereafter slightly accelerating. This may be due to the post-bubble economy in which Japan adopted government intervention policies to stimulate the recovery of the economy and increase household consumption, resulting in an increase in indirect CO_2 emissions between 1990 and 1995. With the change in policy direction from economic stimulus to economic constraint (including raising the consumption tax and increasing medical expenses in 1997) (Choi et al., 2017), the growth rate of indirect CO_2 emissions slowed down in 1995–2000. After 2000, due to the effect of the internet bubble in the US (Chan, 2014), Japan was forced to introduce looser monetary policies to stimulate economic development which increased its indirect CO_2 emissions to some extent.

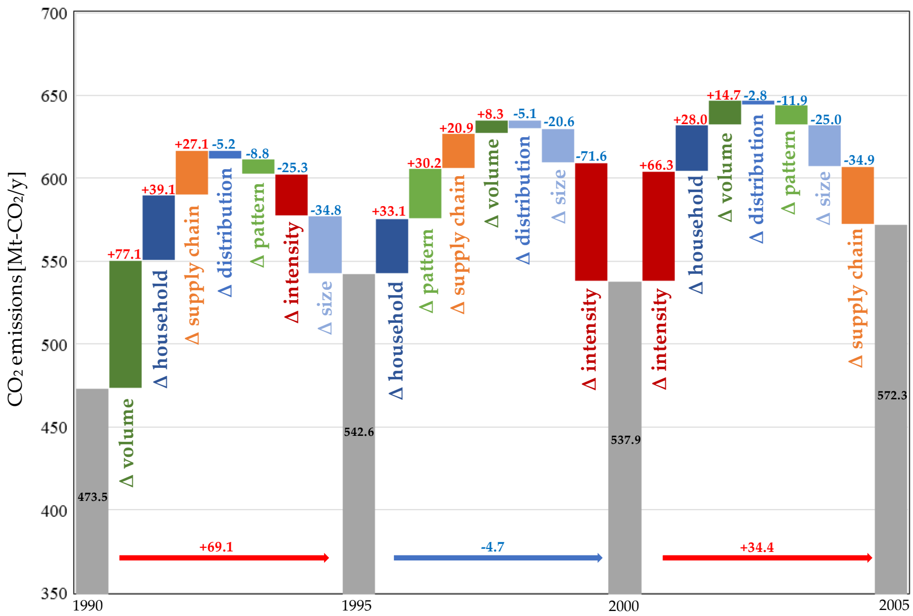
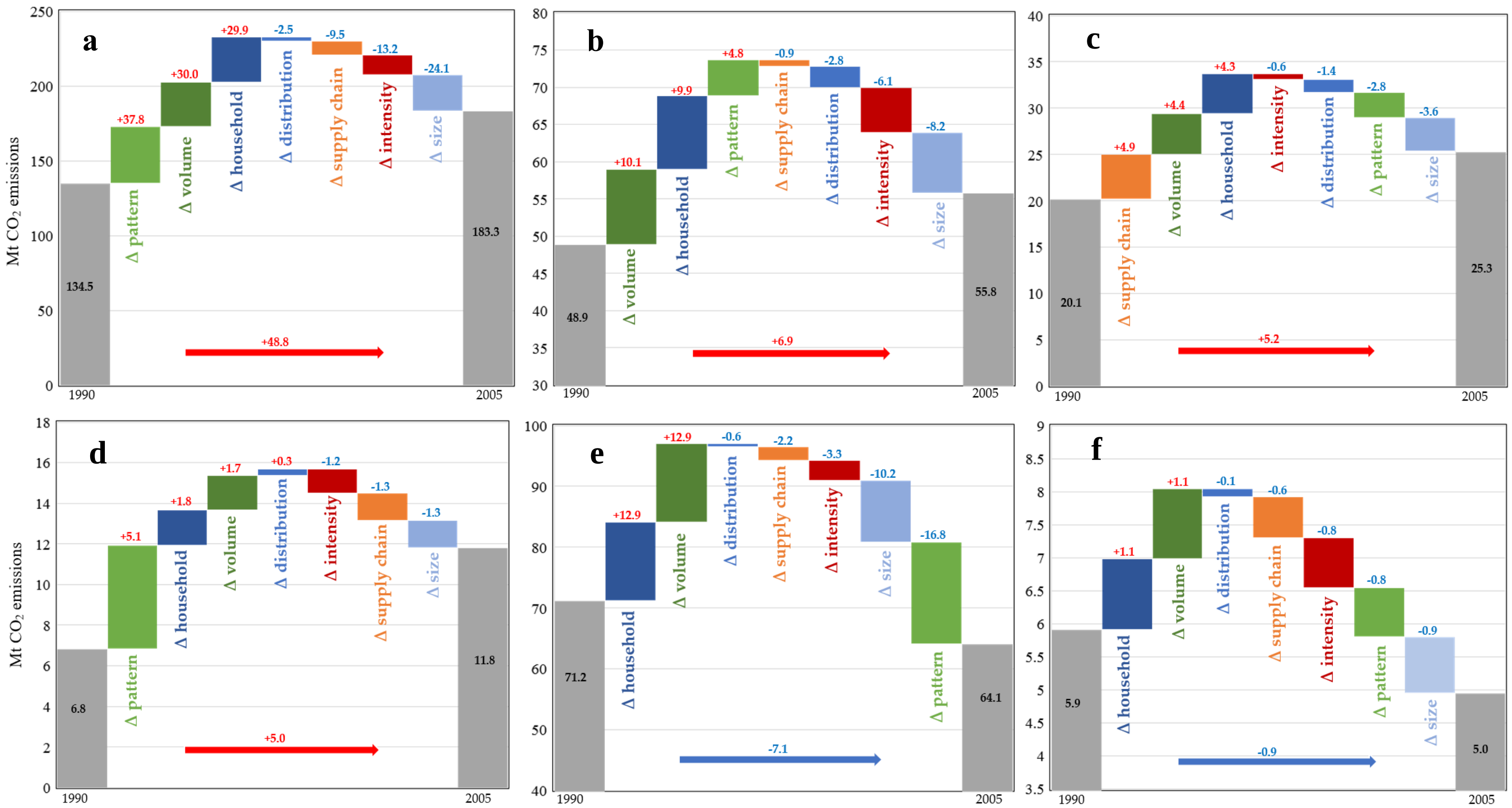


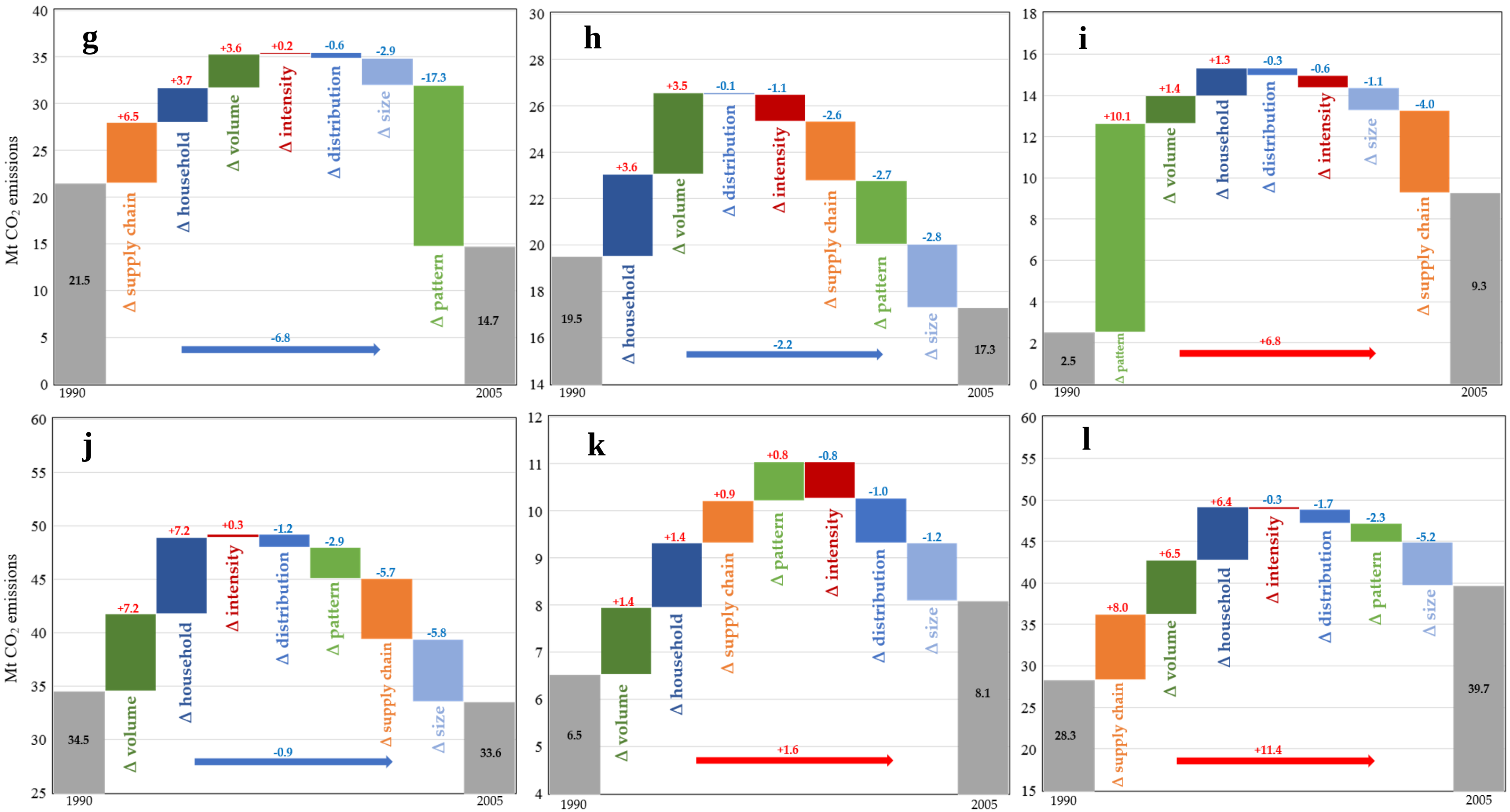
Fig. 3-6. Driving forces of indirect CO_2 emissions during 1990–2005. Δintensity is the intensity effect, Δsupply chain is the supply chain structure effect, Δpattern is the consumption pattern effect, Δvolume is the consumption volume effect, Δsize is the household size effect, Δdistribution is the household distribution effect, and Δhousehold is the household number effect.

With the increase in the number of households, the positive impact of the number of households on indirect CO_2 emissions has gradually increased, becoming one of the main factors promoting indirect CO_2 emissions post-2000. The positive impact of the supply chain structure on indirect CO_2 emissions increased slightly before 2000, shifting to a negative effect after 2000. This may be caused by the transformation and maturing of enterprise, eliminating excess employment, equipment and debt through a severe restructuring process from the late 1990s to the early 2000s. From the 1990s, along with an emphasis on environmental protection and energy saving (e.g., the Kyoto Protocol adopted in 1997), the impact of the supply chain structure toward CO_2 emissions became negative which reflects the great development of low-carbon technology in the whole supply chain. The negative impact of the intensity effect on indirect CO_2 emissions increased from 1990 to 2000 and weakened thereafter. After the bubble economy, economic recovery may be an important reason for the change in intensity effect. The impact of the consumption pattern on indirect CO_2 emissions changed from negative to positive from 1995 to 2000, turning to negative once more, after 2000, although this impact was relatively small. Because of the economic stimulus policy post bubble economy, the choice of consumers tended to be toward high-quality and environment-friendly consumption, causing the consumption pattern to inhibit indirect CO_2 emissions. However, during the period of economic constraint policies, consumers tended to choose goods with high performance and low price, reducing the environmental awareness of consumption, resulting in a positive consumption pattern impact. Summing up the effect of household size, the number of households and household distribution in 1995, 2000 and 2005 and observing the changes, it was identified that the effect is gradually changing toward the positive and increasing. This identifies that if Japan maintains an aging society with a low birth rate, the indirect CO_2 emissions generated by households will continue to grow.

3.3.3.2 Driving forces of indirect CO_2 emissions of key sectors

By observing the changes in indirect CO_2 emissions across sectors in Fig. 3-7, this study identified six sectors with significant growth (amount) in indirect CO_2 emissions from 1990–2005. These are the housing, public transport, private vehicle, medical sectors, information and communication, and clothes and footwear sectors. We have emphasized discussions about the decomposition results for these six sectors because we consider it is essential with regard to the relationship between an aging, shrinking population and increasing household CO_2 emissions.


a
Mt CO_2 emissions
134.5
+37.8
Δ pattern
+30.0
Δ volume
+29.9
Δ household
-2.5
Δ distribution
-9.5
Δ supply chain
-13.2
Δ intensity
-24.1
Δ size
183.3
+48.8
1990
2005
b
48.9
+10.1
Δ volume
+9.9
Δ household
+4.8
Δ pattern
-0.9
Δ supply chain
-2.8
Δ distribution
-6.1
Δ intensity
-8.2
Δ size
55.8
+6.9
1990
2005
c
20.1
+4.9
Δ supply chain
+4.4
Δ volume
+4.3
Δ household
-0.6
Δ intensity
-1.4
Δ distribution
-2.8
Δ pattern
-3.6
Δ size
25.3
+5.2
1990
2005
d
Mt CO_2 emissions
6.8
+5.1
Δ pattern
+1.8
Δ household
+1.7
Δ volume
+0.3
Δ distribution
-1.2
Δ intensity
-1.3
Δ supply chain
-1.3
Δ size
11.8
+5.0
1990
2005
e
71.2
+12.9
Δ household
+12.9
Δ volume
-0.6
Δ distribution
-2.2
Δ supply chain
-3.3
Δ intensity
-10.2
Δ size
-16.8
Δ pattern
64.1
-7.1
1990
2005
f
5.9
+1.1
Δ household
+1.1
Δ volume
-0.1
Δ distribution
-0.6
Δ supply chain
-0.8
Δ intensity
-0.8
Δ pattern
-0.9
Δ size
5.0
-0.9
1990
2005



g
Mt CO2 emissions
1990
21.5
+6.5 Δ supply chain
+3.7 Δ household
+3.6 Δ volume
+0.2 Δ intensity
-0.6 Δ distribution
-2.9 Δ size
-17.3 Δ pattern
14.7
2005
-6.8
h
1990
19.5
+3.6 Δ household
+3.5 Δ volume
-0.1 Δ distribution
-1.1 Δ intensity
-2.6 Δ supply chain
-2.7 Δ pattern
-2.8 Δ size
17.3
2005
-2.2
i
1990
2.5
+10.1 Δ pattern
+1.4 Δ volume
+1.3 Δ household
-0.3 Δ distribution
-0.6 Δ intensity
-1.1 Δ size
-4.0 Δ supply chain
9.3
2005
+6.8
j
Mt CO2 emissions
1990
34.5
+7.2 Δ volume
+7.2 Δ household
+0.3 Δ intensity
-1.2 Δ distribution
-2.9 Δ pattern
-5.7 Δ supply chain
-5.8 Δ size
33.6
2005
-0.9
k
1990
6.5
+1.4 Δ volume
+1.4 Δ household
+0.9 Δ supply chain
+0.8 Δ pattern
-0.8 Δ intensity
-1.0 Δ distribution
-1.2 Δ size
8.1
2005
+1.6
l
1990
28.3
+8.0 Δ supply chain
+6.5 Δ volume
+6.4 Δ household
-0.3 Δ intensity
-1.7 Δ distribution
-2.3 Δ pattern
-5.2 Δ size
39.7
2005
+11.4

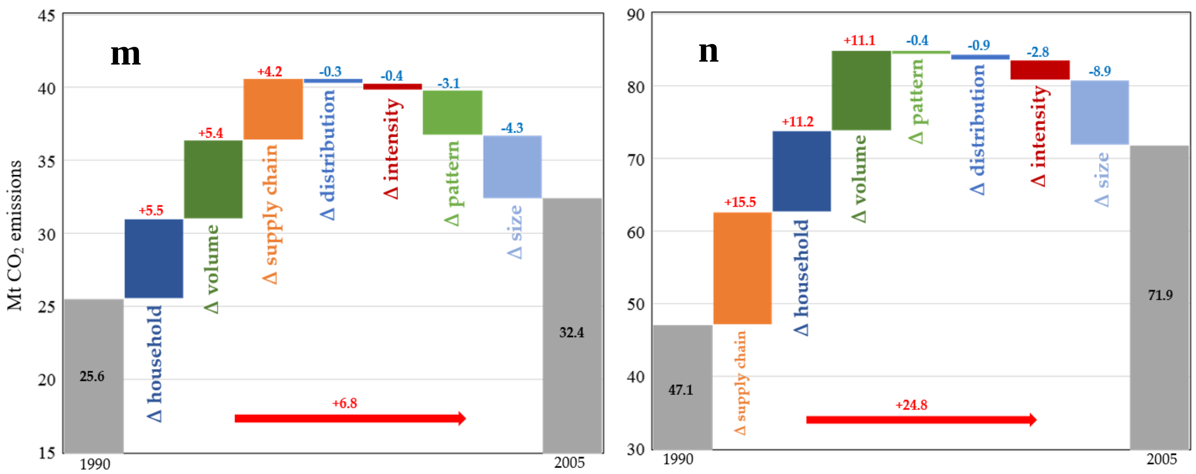


Fig. 3-7. SDA results for indirect CO_2 emissions between 1990 and 2005 for 14 sectors. Δintensity is intensity effect, Δsupply chain is supply chain structure effect, Δpattern is consumption pattern effect, Δvolume is consumption volume effect, Δsize is household size effect, Δdistribution is household distribution effect, and Δhousehold is the number of households effect. (a) housing sector, (b) public transport, (c) private vehicles, (d) medical sector, (e) food and non-alcoholic beverages, (f) alcoholic beverages and tobacco, (g) clothing and footwear, (h) furnishings, (i) information and communication, (j) recreation and culture, (k) education, (l) restaurants and hotels, (m) consumable goods, and (n) margins, religions and other services.

First, the housing sector (Fig. 3-7a), which produced the largest indirect CO_2 emissions at any time between 1990 and 2005, increased consistently in 1990–2005. The technology and size effects are the main drivers which reduce indirect CO_2 emissions. The rapid development of energy-related technologies has greatly reduced the indirect CO_2 emissions from housing. Meanwhile, with the growth of single-person households, the proportion of small-scale households has gradually increased (Ministry of Health Labour and Welfare, 2018). Compared with average-sized households, small-scale households utilize a lower number of consumables and appliances (e.g. air-conditioners etc.), leading to a lower level of indirect CO_2 emissions. The number of households, consumption volume, and consumption pattern were the main drivers of CO_2 emissions growth. From 1990 to 2005, the number of households in Japan expanded. Meanwhile, the increase in single-person households have increased the demand for housing, further expanding consumption volumes. Therefore, the positive impact of the number of households and consumption volume on indirect CO_2 emissions increased. As for the consumption pattern, residents seeking a better quality of life tend to invest in quality of life outcomes, leading to an increase in indirect CO_2 emissions.

For the public transport sector, it is the second largest indirect CO_2 emitter among the four sectors. As shown in Fig. 3-7b, changes in consumption volume and the number of households were the main drivers which promoted growth of indirect CO_2 emissions in this sector. The number of households in Japan continued to grow from 1990 to 2005 increasing the positive effect, while, due to economic situation changes, households might choose public transport in order to reduce living costs. An increase in environmental awareness has also prompted people to use more public transport. In addition, indirect CO_2 emissions have been restricted to a large extent by the household size and household distribution effects. The reason may be that small-scale households may prefer to travel by lower cost public transport when compared to private transport, with the same trend shown by the elderly. Moreover, the development of low-carbon technologies has also greatly reduced the CO_2 emissions associated with the public transport sector.

The private vehicle sector is one of the main sources of direct CO_2 emissions from households (see Fig. 3-1), while this sector also has a strong impact on indirect CO_2 emissions. With the increasing number of households in Japan (Ministry of Health Labour and Welfare, 2018), the demand for private cars is also expanding, causing the number of households and consumption volume effects to become important drivers in promoting indirect CO_2 emissions in this sector as shown in Fig. 3-7c. The supply chain effect has increased indirect CO_2 emissions, likely due to economic globalization, causing the production and manufacture of automobiles to be regionally diversified, whereby technological differences in production and transport between regions may place upward pressure on indirect CO_2 emissions. The consumption pattern has become the main driver restricting indirect CO_2 emissions perhaps because people have become more likely to use public transport due to abovementioned reasons, although many households still have a need for a private vehicle. With increasing awareness of environmental protection, households are willing to consider the purchase of environmentally friendly automobile models. Meanwhile, with the development of automobile manufacturing technology, consumers are more willing to buy fuel-efficient vehicles. Household size and household distribution effects had a stable, inhibitory effect on indirect CO_2 emissions, mainly because an aging society and increase in households with less members reduced the consumption of private vehicles.

Although the medical sector has lower indirect CO_2 emissions among the selected sectors, it has a high growth rate, at 73% (Fig. 3-7d). Considering the current situation of Japan's aging society, the medical sector has a great impact on the lives of elderly people. Therefore, it is of great practical significance to analyze the influencing factors of indirect CO_2 emissions in the medical sector. Consumption pattern and consumption volume have strongly contributed to the increase in indirect CO_2 emissions as elderly households increase. In the context of an aging society, Japan's elderly population continues to grow, leading to continued expansion of national medical expenditure. Furthermore, the proportion of imported drugs has been gradually increasing (Statistics Bureau, 2019), also the main reason for the decreasing impact of supply chain structure on indirect CO_2 emissions. Though the impact of technology on indirect CO_2 emissions changed during 1990–2005, it has always been negative. This is probably due to the continuous development of medical manufacturing technologies which are more environmentally aware. Finally, the household size also plays an important role in inhibiting indirect CO_2 emissions. The decrease in household size (i.e., a relative increase in the share of small-scale households in the total households) has greatly reduced household consumption of medicine and consequently reduced indirect CO_2 emissions to a certain extent.

Note that the highest and lowest growth rates of indirect CO_2 emissions were shown in the clothing and footwear, and information and communication sectors, respectively. In the clothing and footwear sector, the pattern effect was also the main factor responsible for reducing indirect CO_2 emissions (Fig. 3-7g). During the studied period, outsourcing of production in this sector to developing Asian countries reduced production costs[4]. At the same time, fast fashion became popular (Uniqlo etc.). These complementary phenomena resulted in lower consumption of apparel and lead to a reduction in indirect CO_2 emissions.

The growth rate in the information and communication sector was 267%, while that in the clothing and footwear sector was -31% during the studied period. The reasons behind these changes can be explained as follows. In the information and communication sector, the pattern effect was the major factor underpinning an increase in emissions (Fig. 3-7i). From the end of the 20th century, the world, including Japan, began to enter into the information technology age, and computers and the internet began to spread. Meanwhile, mobile phones also became more common. This means that information and communication technology penetrated into daily life and consumption of such technologies has rapidly increased, having a commensurate effect on indirect CO_2 emissions.

3.3.4 Limitations of the study

The approach used in this study has several limitations with regard to the data and methodology employed. First, to conduct SDA it is necessary to prepare time-series data on both household consumption expenditures and environmental burden intensities that are consistent with the IO table and to deflate according to the base year price information. In this regard, this study used the TJIO covering the periods 1990–1995–2000–2005. We recognize that the latest year analyzed in this study is more than 10 years in the past, however, it is currently impossible to prepare more recent deflated data for consumption expenditure and embodied CO_2 emissions intensity. The latest domestic IO table describes the economic transactions accounting for household consumption expenditures in 2011, and the embodied CO_2 emission intensity values for 2011 have already been published. However, it is relatively difficult to deflate consumption expenditures and intensities due to the disconnection between commodity sectors and their definitions.

[4] As a result of outsourcing abroad, the supply chain effect became positive during this period.

Chapter 4. Carbon inequality by household type and income level across prefectures in Japan

4.1 Background

Affected by income level, household type, and other socioeconomic factors, carbon inequality among households substantially differs across prefectures in Japan, thereby profoundly affecting the country's sustainable development. Besides, assessing carbon inequality among households in Japan necessitates a comprehensive understanding of the relationship between HCF and income level across prefectures. Therefore, it is important to explore the carbon footprint of different household type on the basis of systematically grouped income levels in all prefectural administrative units. In consideration of these issues, we have quantified HCF between single- and multi-person households of different incomes in Japan's 47 prefectures, and elucidated household carbon inequality through the CF-Gini coefficients.

4.2 Methodology and data

Here the methodology and data are defined, including the quantification of HCF, carbon footprint-Gini coefficients, the methodological and data utilized.

4.2.1 Quantification of HCF by household type

To achieve the goals of this study—visualizing the connection between household consumption and CO_2 emission by household type and income level and rectifying carbon inequality during the climate mitigation process—we selected the EEIO model based on Japan's subnational MRIO.

The basic structure of an MRIO model can be expressed as follows (Peters and Hertwich, 2008):

$$X = (I - A)^{-1}F \tag{4-1}$$

$$X = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix}, A = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix}, F = \begin{bmatrix} F^{11} & F^{12} & \cdots & F^{1n} \\ F^{21} & F^{22} & \cdots & F^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ F^{n1} & F^{n2} & \cdots & F^{nn} \end{bmatrix} \tag{4-2}$$

where X is the vector of total output, I denotes the identity matrix, A refers to the technical coefficient matrix, and F is the final demand matrix. The technical coefficient submatrix, $A^{rs} = (a_{ij}^{rs})$, is given by $a_{ij}^{rs} = \frac{z_{ij}^{rs}}{x_j^s}$, where z_{ij}^{rs} represents the intersectoral monetary flows from sector i in prefecture r to sector j in prefecture s, and x_j^s is the total output of sector

j in prefecture s. $F^{rs} = f_i^{rs}$ is the final demand of prefecture s for the goods of sector i imported from prefecture r. As we employed Japan's MRIO table for the 47 prefectures (Hasegawa et al., 2015), i and $j = 1 \cdots 80$ represent all economic sectors, while r and $s = 1 \cdots 47$ represent all the prefectures (Fig. 4-1). The currency used in the MRIO table is Japanese yen (JPY), which was therefore used to measure all monetary amounts in this study.

Through CO_2 emission intensity (i.e., CO_2 emissions per unit of economic output), indirect carbon footprint is calculated thus (Sun et al., 2020):

$$C_{\mathrm{ind}} = K(I - A)^{-1}F \tag{4-3}$$

where C is the total carbon footprint and K is a vector of the carbon intensity for all economic sectors in all prefectures.

Final demand (F) can be divided into consumption outside a household, household consumption, central and local government consumption, the gross domestic fixed capital formation of public/private sectors, and the increase in stocks. Given the lack of international import-related household consumption data by prefecture in the MRIO table, we considered only household consumption in Japan's domestic market. Accordingly, the HCF in Japan can be calculated as follows:

$$C_{\mathrm{h}} = K(I - A)^{-1}H_{\mathrm{ce}} \tag{4-4}$$

where C_h denotes the HCF that represents the indirect CO_2 emissions associated with goods and services, including electricity, which are finally consumed through the supply chain, and H_{ce} is the household consumption expenditure.

On the grounds of household type, household consumption can be subdivided into single- and multi-person household consumption. Correspondingly, the HCF of each prefecture can be indicated as:

$$C_{\mathrm{h}} = K(I - A)^{-1}\left(H_{\mathrm{ce}}^{\mathrm{single}} + H_{\mathrm{ce}}^{\mathrm{multi}}\right) \tag{4-5}$$

where H_{ce}^{single} and H_{ce}^{multi} are the household consumption expenditure of single- and multi-person households, respectively.

We assumed that household consumption gradually increases with improvements in income, resulting in greater HCF. Therefore, combining the MRIO table with data from the NSFIE (Ministry of Internal Affairs and Communications, 2015b), we further divided the indirect HCF of single- and multi-person households on the basis of income group. This yielded 10 annual income groups of multi-person households (0–200, 200–300, 300–400, 400–500, 500–600, 600–700, 700–800, 800–1000, 1000–1500, 1500–; unit: JPY 10000) and 10 income groups of single-person households (0–200, 200–250, 250–300, 300–350, 350–400, 400–450, 450–500, 500–550, 550–600, 600–; unit: JPY 10000).

The NSFIE data were recorded on the basis of purchaser price, while the MRIO table for the 47 prefectures was based on producer price. Because of inconsistencies among economic sectors, we used the optimization technique to determine household type-based consumption for the sectors listed on the MRIO table. This determination began with an addressing of inconsistencies (i.e., price accounting and sector) between the MRIO table and the NSFIE data (Shigetomi et al., 2014, 2015). In addition, the NSFIE survey is held every five years, so the 2004 NSFIE data were used to complement the 2005 Japan MRIO table.

Note that the NSFIE consumption data of multi-person households were available at both the national and prefectural levels, whereas those of single-person households were available only at the national level. Considering that the consumption structures and population proportions of single- and multi-person households in Japan did not change significantly in 2005, we assumed that the consumption proportions of these households were equal at the national and prefectural levels. Therefore, the single-person household consumption of each prefecture was calculated on the basis of the ratio of multi-person household consumption to single-person household consumption at the national level.

4.2.2 Calculation of carbon inequality: CF-Gini coefficients

The conventional Gini coefficient, which was proposed by Corrado Gini (Dalton, 1920), is an effective tool for quantifying inequality in income distribution across regions. Generally, using the Gini index involves assigning a real number between 0 and 1 to each non-negative income vector, which represents inequality level (Mirzaei et al., 2017).

With the basic formula of the Gini coefficient as basis, the CF-Gini coefficient used in this work is calculated in the following manner (Mi et al., 2020):

$$G_{\mathrm{CF}} = \sum_{ig=1}^{v} HD_{ig}CF_{ig} + 2\sum_{ig=1}^{v} HD_{ig}(1 - T_{ig}) - 1 \tag{4-6}$$

where G_{CF} is the CF-Gini coefficients, HD_{ig} and CF_{ig} are the proportion of households and carbon footprints of each income group, respectively. T_{ig} refers to the cumulative proportion of the carbon footprint of each income group, and $ig = 1 \cdots v$ refers to the number of income groups. Since we employed the NSFIE, $ig = 1 \cdots 10$ in this study.

4.2.3 Data

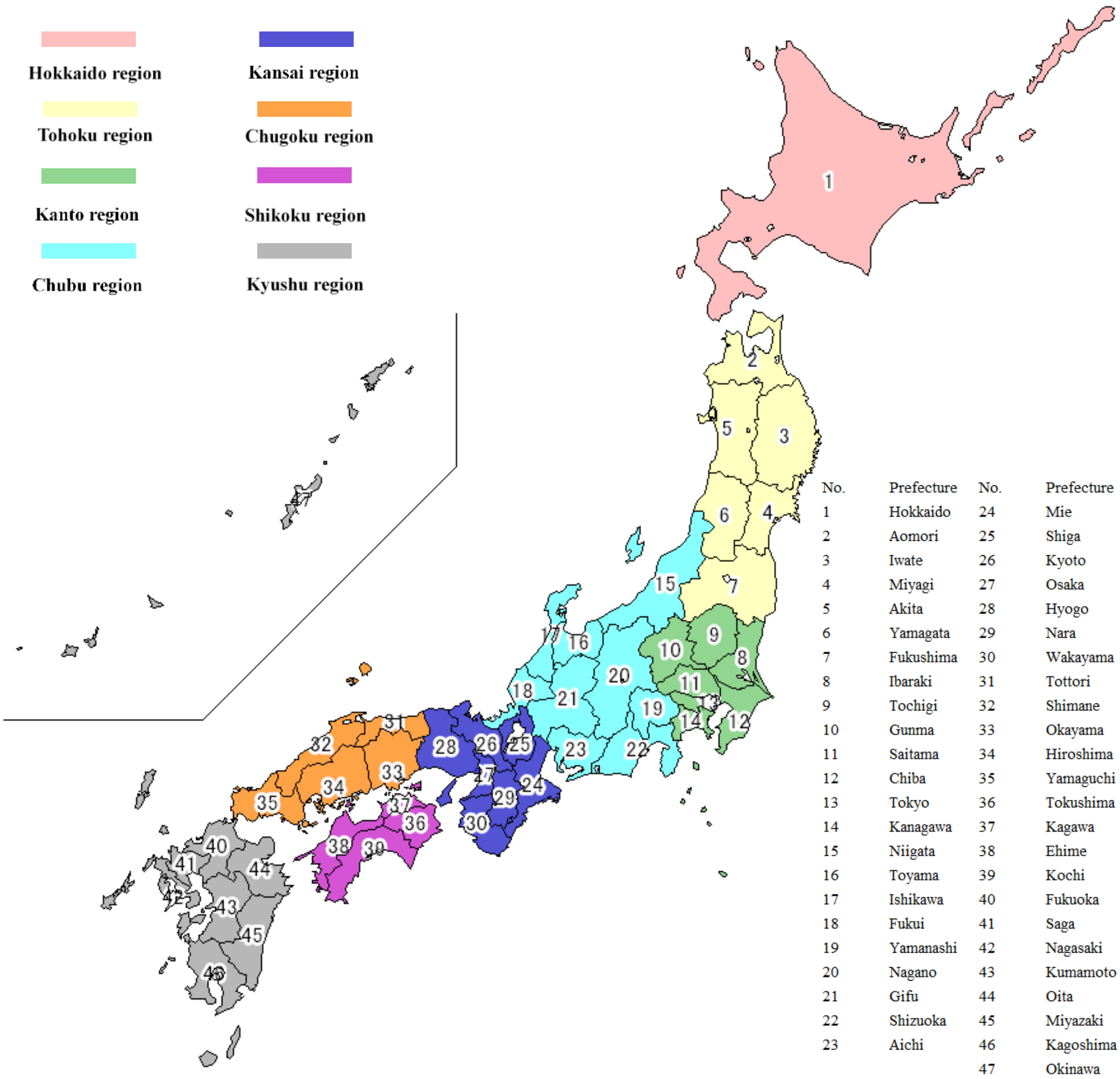
Household consumption data were derived from the 2005 Japan MRIO table (Hasegawa et al., 2015) and the NSFIE (Ministry of Internal Affairs and Communications, 2015b). The 2005 emission factors used to calculate the HCF of the 47 prefectures were obtained from Comprehensive Energy Statistics (Agency for Natural Resources and Energy of Japan, 2021). The sector classification of Comprehensive Energy Statistics and the 2005 Japan MRIO table differed. Correspondingly, when calculating carbon intensity K, we first determined correspondence between Comprehensive Energy Statistics and the 2005 Japan MRIO table among sectors (Table 4-1). Given that social background is one of the important influencing factors for carbon intensity in economic sectors, HCF levels in different years have varying characteristics. Note that the change in power structure owing to the 2011 Great East Japan Earthquake could have led to a significant alteration in HCF. From 2011 to 2019 in Japan, the proportion of nuclear power out of the total power composition of the country decreased from 31.4% to 6.2%, and that of thermal power increased from 63.1% to 75.7% (Ministry of Economy Trade and Industry Agency for Natural Resources and Energy, 2021). The geographical locations of the research area in Japan are shown in Fig. 4-1.

Table 4-1. The correspondence of sectors between Comprehensive Energy Statistics and the 2005 Japan MRIO table

No.	Sector of Comprehensive Energy Statistics	No.	Sector of the 2005 Japan MRIO table
1	Agriculture, Forestry and Fishery	1	Agriculture, forestry, and fishery
2	Mining, Quarrying of Stone, and Gravel	2	Metallic ores
		3	Non-metallic ores
		4	Coal mining, crude petroleum and natural gas
3	Manufacture of Food, Beverages, Tobacco and Feed	5	Food and tobacco
		6	Beverage
4	Manufacture of Textile Mill Products	7	Textile products
		8	Wearing apparel and other textile products
5	Manufacture of Lumber, Wood Products, Furniture and Fixtures	9	Timber and wooden products
		10	Furniture and fixtures
6	Manufacture of Pulp, Paper and Paper Products	11	Pulp, paper, paperboard, and building paper
		12	Paper products
7	Printing and Allied Industries	13	Publishing, printing
8	Manufacture of Chemical and Allied Products, Oil and Coal Products	14	Chemical fertilizer
		15	Basic inorganic chemical products
		16	Basic organic chemical products
		17	Organic chemical products
		18	Synthetic resins
		19	Synthetic fibers
		20	Final chemical products
		21	Medicaments
		22	Petroleum refinery products
		23	Coal products
9	Manufacture of Plastic Products, Rubber Products and Leather Products	24	Plastic products
		25	Rubber products
10	Manufacture of Ceramic, Stone and Clay Products	26	Glass and glass products
		27	Cement and cement products
		28	Pottery, china, and earthenware
		29	Other ceramic, stone and clay products

11	Manufacture of Iron and Steel	30	Pig iron and crude steel
		31	Steel products
		32	Cast and forged steel products
		33	Other iron or steel products
		34	Non-ferrous metals
		35	Non-ferrous metal products
		36	Metal products for construction and architecture
		37	Other metal products
12	Manufacture of Machinery	38	General industrial machinery
		39	Special industrial machinery
		40	Other general machines
		41	Machinery for office and service industry
		42	Industrial electric equipment
		43	Applied electric equipment and electric measuring instruments
		44	Other electric equipment
		45	Household electric and electric applications
		46	Communication equipment
		47	Electric computing equipment and accessory equipment
		48	Semiconductor devices and integrated circuits
		49	Other electrical equipment
		50	Passenger motor cars
		51	Other cars
		52	Motor vehicle parts and accessories
		53	Other transportation equipment
		54	Precision instruments
13	Miscellaneous Manufacturing Industry	55	Miscellaneous manufacturing products
		56	Reuse and recycling
14	Construction Work Industry	57	Building construction and repair of construction
		58	Public construction
		59	Other civil engineering and construction

15	Electricity, Gas, Heat Supply and Water	60	Electricity
		61	Gas supply and heat supply
		62	Water supply and waste management services
16	Wholesale and Retail Trade	63	Commerce
17	Finance and Insurance	64	Financial and insurance
18	Real Estate and Goods Rental and Leasing	65	Real estate agencies and rental services
		66	House rent
		67	Goods rental and leasing services
19	Transport and Postal Activities	68	Transport
20	Information and Communications	69	Communication
		70	Broadcasting
		71	Information services
		72	Internet based services
		73	Image information production and distribution industry
		74	Advertising and survey
21	Government	75	Public administration
22	Education, Learning Support	76	Education and research
23	Scientific Research, Professional and Technical Services		
24	Medical, Health Care and Welfare	77	Medical service, health and social security and nursing care
25	Compound Services	78	Other business services
26	Miscellaneous Services		
27	Accommodations, Eating and Drinking Services	79	Personal services
28	Living Related and Personal Services and Amusement Services		
29	Unable to Classify	80	Activities not elsewhere classified



No.	Prefecture	No.	Prefecture
1	Hokkaido	24	Mie
2	Aomori	25	Shiga
3	Iwate	26	Kyoto
4	Miyagi	27	Osaka
5	Akita	28	Hyogo
6	Yamagata	29	Nara
7	Fukushima	30	Wakayama
8	Ibaraki	31	Tottori
9	Tochigi	32	Shimane
10	Gunma	33	Okayama
11	Saitama	34	Hiroshima
12	Chiba	35	Yamaguchi
13	Tokyo	36	Tokushima
14	Kanagawa	37	Kagawa
15	Niigata	38	Ehime
16	Toyama	39	Kochi
17	Ishikawa	40	Fukuoka
18	Fukui	41	Saga
19	Yamanashi	42	Nagasaki
20	Nagano	43	Kumamoto
21	Gifu	44	Oita
22	Shizuoka	45	Miyazaki
23	Aichi	46	Kagoshima
		47	Okinawa

Fig. 4-1 The geographical locations of 47 prefectures and 8 regions in Japan

4.3 Results and discussion

4.3.1 Carbon footprint attributed to households across 47 prefectures

Overall, HCF is more concentrated in high-income prefectures, such as Tokyo, Kanagawa, and Osaka (Fig. 4-2). The HCF of these prefectures is significantly higher than that of the other prefectures, and their GRP in 2005 was among the top three in Japan. As described in Eq. (4-3), final demand encompasses six items, among which household consumption generates the most carbon footprint. Moreover, the share of HCF in the total carbon footprint of final demand considerably varies across prefectures. Generally, prefectures with a high HCF tend to account for a relatively higher share of HCF in the total carbon footprint of final demand. For instance, such share in Tokyo is 58%, whereas that in Fukui is only 45%.

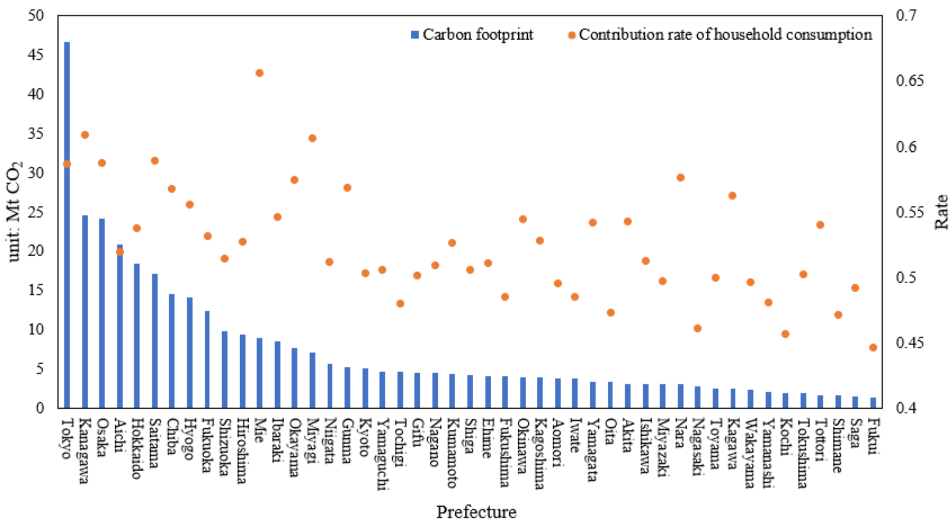


Fig. 4-2. HCF and its share in the total carbon footprint of final demand across prefectures in Japan (2005).

There are clear differences between the total HCF and per-household carbon footprint in the 47 prefectures, confirming that household consumption in every prefecture differs under varying income levels and natural conditions (Figs. 4-2 and 4-3). The per-household carbon footprint is visibly affected by household expenditure. Prefectures with a high per-household carbon footprint typically incur substantial annual per-household expenditure, which is related to high income levels. Although the annual per-household expenditure is high, the per-household carbon footprint is low in some prefectures, such as Tokyo. This finding is attributed to the fact that commerce and service account for a high proportion of household consumption and that the high utilization of public transport reduces the use of private vehicles.

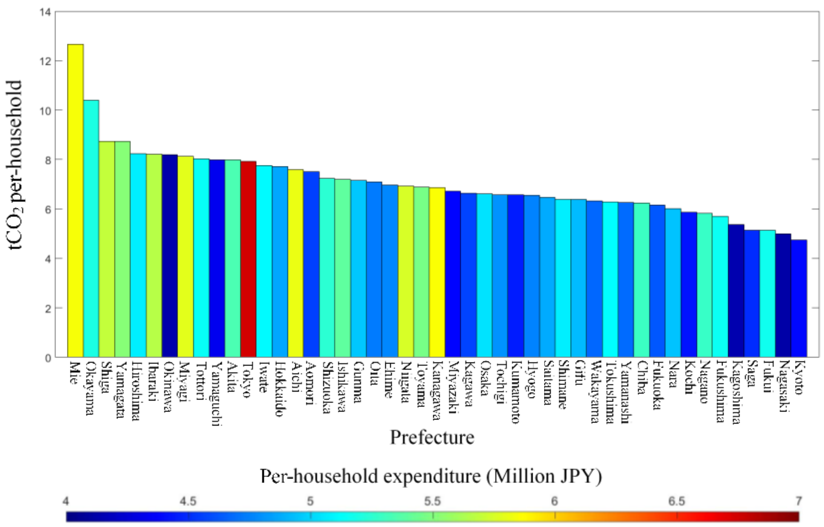


Fig. 4-3 Per-household carbon footprint across prefectures in Japan (2005). The color of the

bar corresponds to the per-household expenditure

4.3.2 HCF structure across 47 prefectures

According to the sectoral classification code compiled by the Ministry of Internal Affairs and Communications (2015a), the 80 sectors of interest in this study were aggregated into 35 to more directly observe the structure of HCF (Fig. 4-4).

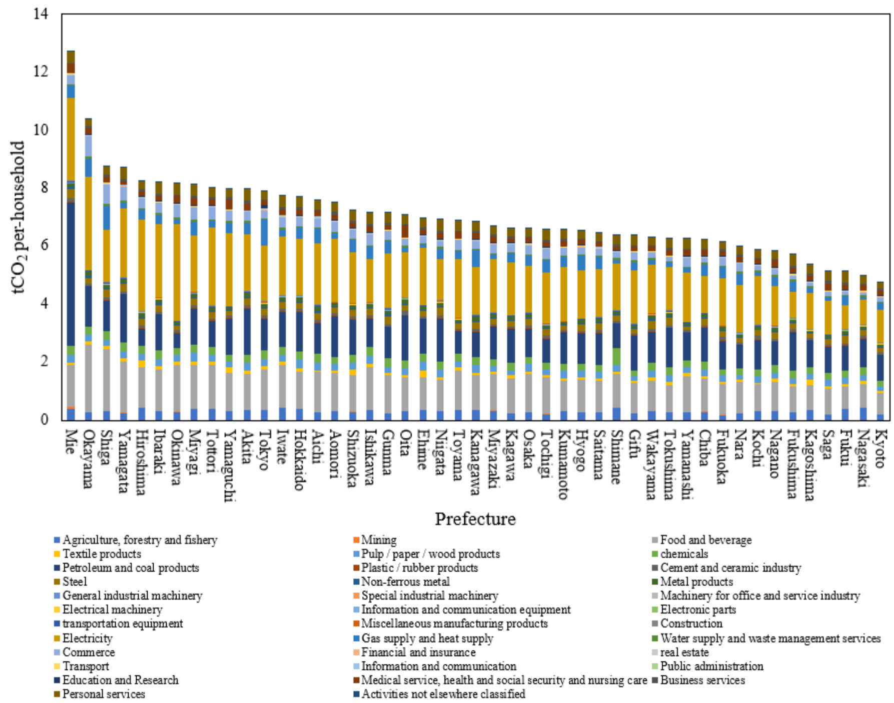


Fig. 4-4. The structure of per-household carbon footprint across prefectures in Japan (2005).

Overall, the food and beverage, petroleum and coal, utility, and service sectors are important sources of HCF. Food and beverages are the most frequently consumed items in households, and their consumption is more easily affected by household wealth than the consumption of other products and services. The HCF of food and beverage is higher in the Kanto region, which includes Tokyo. For example, the per-household carbon footprint of food and beverage in Tokyo is about 1.5 times that in Kochi. The HCF of petroleum and coal products is readily discernible in the Tohoku, Kansai, and Chugoku regions. The HCF of utilities is mostly concentrated in electricity, which is closely related to household appliance usage. Meanwhile, the higher the per-household carbon footprint by prefecture, the greater the carbon footprint of electricity. For example, Mie's per-household carbon footprint of electricity is 1.5 times larger than that of Tokyo. Moreover, the HCF of services is lower in high-income prefectures than their low-income counterparts. For instance, the per-household carbon footprint of personal services in Tokyo is 0.29 tCO_2, whereas that in Fukui is 0.4 tCO_2.

4.3.3 HCF by household type and income level across 47 prefectures

In this section, we first discuss differences in HCF by household type and subsequently provide a detailed analysis of HCF by considering both household type and income level.

4.3.3.1 Differences in HCF by household type

Overall, the annual per-household expenditure of multi-person households is visibly higher than that of single-person households (Fig. 4-5). The HCF of the former accounts for 75% of Japan's national HCF, and their national per-household carbon footprint is 7.5 tCO_2, which is 1.3 times that of single-person households (5.7 tCO_2).

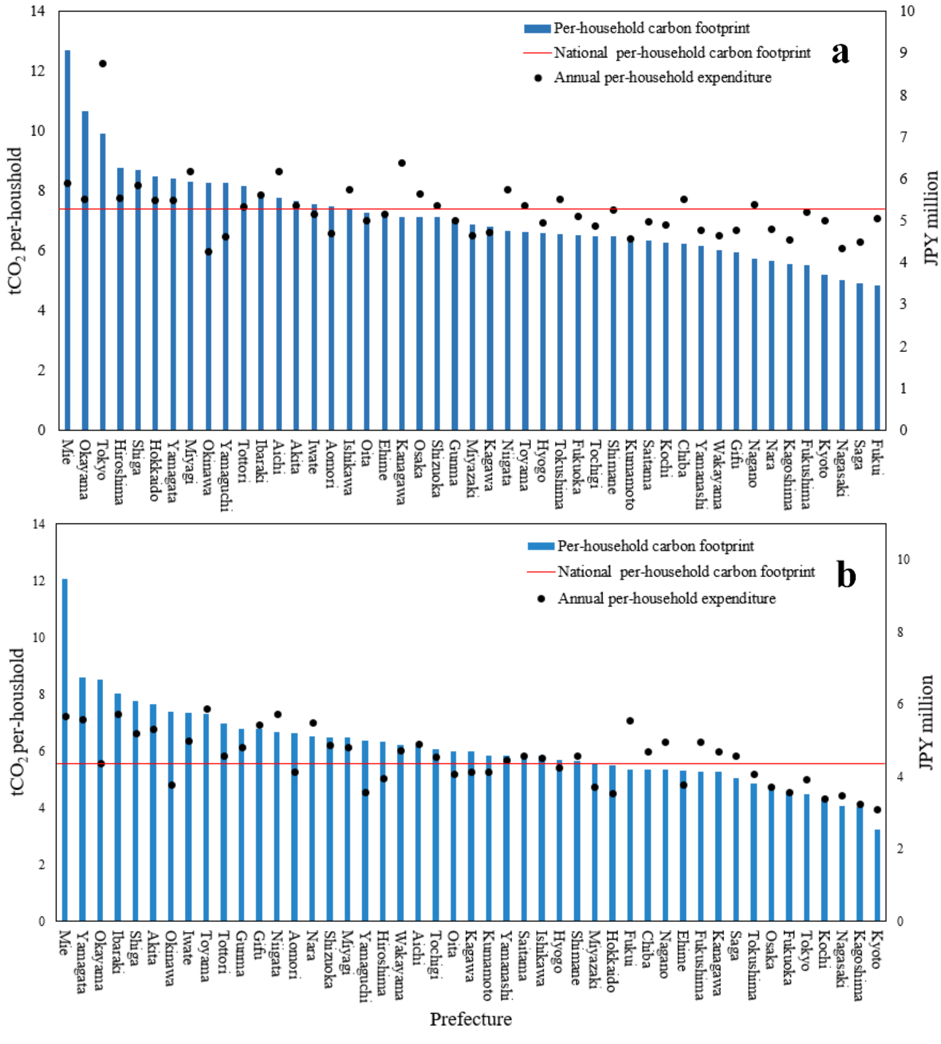


Fig. 4-5 Per-household carbon footprint and annual per-household expenditures of (a) multi-

and (b) single-person households across prefectures in Japan (2005).

The more advanced the economy, the more obvious the gap in per-household carbon footprint between single- and multi-person households. The per-household carbon footprint of multi-person households in Tokyo, which was ranked high in terms of GRP in 2005, is 2.2 times that of single-person households. However, in Okinawa, which had a relatively lagging GRP, the per-household carbon footprint of multi-person households is 1.1 times that of single-person households.

Per-household population is an important factor affecting HCF, highlighting that it is meaningful to further classify multi-person households into subcategories on the basis of household population. Many studies have explored how per-household populations affect HCF at the national level. For example, Jones and Kammen (2011) quantified the HCF of typical US households for six household sizes and found that the size and composition of carbon footprint vary substantially by income and household size. Shigetomi et al. (2018) examined the extent to which increases in the total fertility rate and the number of double-income households affect the domestic carbon footprint associated with household consumption in 2030. In our context, the NSFIE consumption data of multi-person households across prefectures in Japan do not encompass households with different populations. Therefore, it is currently impossible to further evaluate the HCF of multi-person households by adding to the subcategories considered at the prefectural level.

4.3.3.2 HCF based on household type and income level

The HCF in each prefecture was quantified by considering household type and income level (Fig. 4-6).

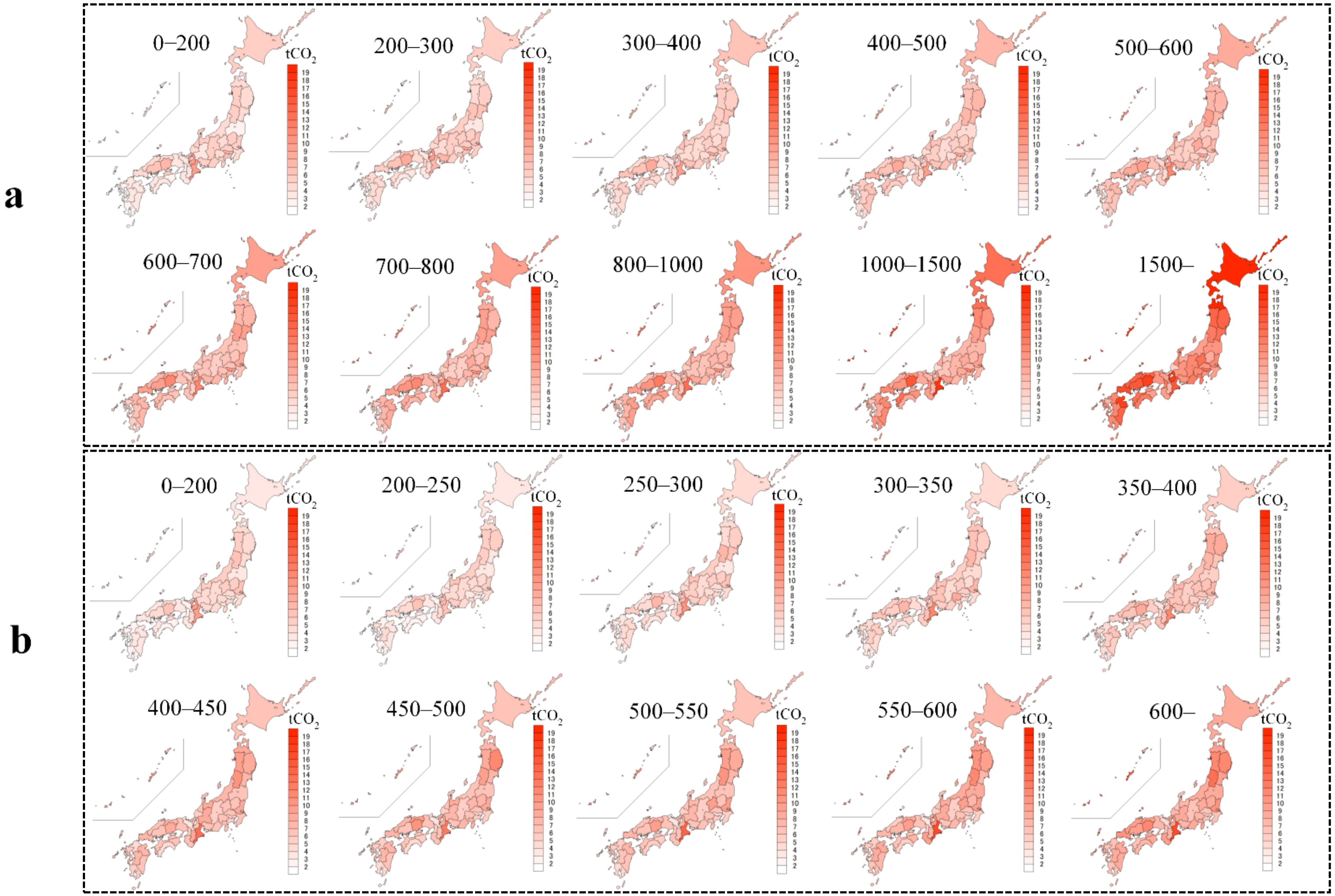


Fig. 4-6. Per-household carbon footprint (unit: tCO_2) of (a) multi- and (b) single-person households by income group (unit: JPY 10000) across prefectures in Japan (2005).

On the whole, the HCF of multi-person households increases with income (Fig. 4-6a). High-GRP prefectures (i.e., prefectures with a high GRP per household[5]) have an overall high HCF, which exhibits uniform growth among income groups. This phenomenon occurs mainly in the Kanto and Chubu regions, such as Tokyo. Electricity is the major CO_2-emitting sector across prefectures (Fig. 4-4), resulting in more pronounced differences in the HCF of electricity across income groups. In Tokyo, the HCF of electricity in households with an annual income of more than JPY 15 million is 1.8 times that of households with an annual income of less than JPY 2 million, while 3.6 times that of Aomori.

The income groups with the highest and lowest HCF are concentrated in low-GRP prefectures, mainly in the Hokkaido, Tohoku, Chugoku, and Kyushu regions. These regions have economic similarities: The GRP of most of the prefectures in these regions is lower than the prefectural average GRP (JPY 11.2 trillion), and the overall degree of household prosperity is low, which is manifested in the fact that the annual per-household expenditure in these localities is less than JPY 5 million. Furthermore, per-capita expenditure is an important factor influencing the income groups with the highest and lowest HCF across the prefectures (Fig. 4-7).

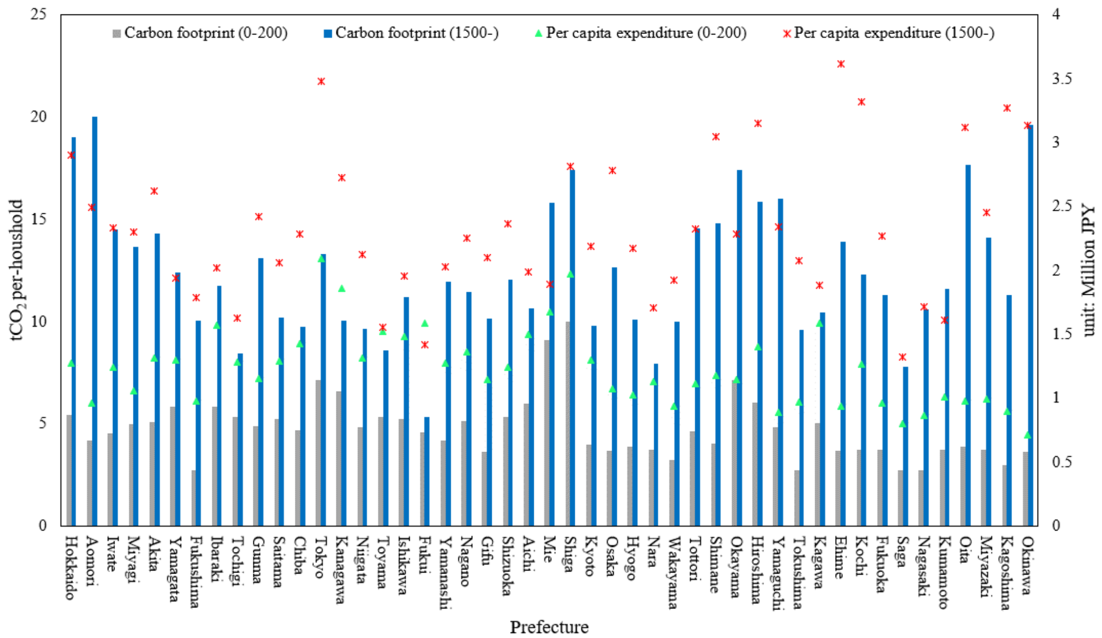


Fig. 4-7. Per-household carbon footprint and per-capita expenditures of multi-person households with less than JPY 2 million (0–200) and more than JPY 15 million (1500–) across prefectures in Japan (2005).

---

[5] Data related to GRP per household are shown in Table A2.

Income groups with high HCF in low-GRP prefectures generally have considerable per-capita expenditures, equal to or even higher than those of income groups in some high-GRP prefectures. For example, the HCF of households with an annual income of more than JPY 15 million in Okinawa is 19.6 tCO_2, while the per-capita expenditures of households with the same income level in Okinawa is JPY 3.1 million—figures that are close to those of Tokyo (JPY 3.5 million). Although the per-capita expenditures are close, the HCF levels of high-income groups in Okinawa and Tokyo are markedly different. In Okinawa, the need for private vehicles and cooling vastly increases the HCF of high-income groups. Income groups with low HCF in low-GRP prefectures generally incur low per-capita expenditures. For instance, the HCF of households with an annual income of less than JPY 2 million in Oita is 3.9 tCO_2 compared with 7.1 tCO_2 in Tokyo, and the per-capita expenditure of households with the same income level in Oita is JPY 0.98 million, which is significantly lower than that of Tokyo (JPY 2.09 million).

In single-person households, income groups with the highest and lowest HCF are relatively concentrated in low-GRP prefectures, as is the case with multi-person households (Fig. 4-6b). However, there are substantial differences in HCF across income groups between single- and multi-person households in high-GRP prefectures, such as Tokyo. In these prefectures, the HCF of multi-person households is high among income groups overall, whereas the HCF of single-person households is visibly low. These findings are closely related to the demographic structure, income pattern, and cost of living in high-GRP prefectures.

The structure of population age has a profound impact on the HCF of single-person households in high-GRP prefectures. The proportion of older adults (over 65 years old) in single-person households is high (Cabinet Office of Japanese government, 2019). Generally, high-GRP prefectures with low HCF (e.g., Tokyo) have a low aging rate (Fig. 4-8). Because of the concentration of a young labor force in Tokyo, its aging rate (18.3%) is manifestly low (Ministry of Internal Affairs and Communications, 2006). Moreover, young people spend about half as much time at home as older adults (Statistics Bureau, 2017), thereby tremendously reducing the HCF of electricity in single-person households. For example, the annual per-household electricity expenditures of single-person households in Tokyo are 54% of those in Yamagata.

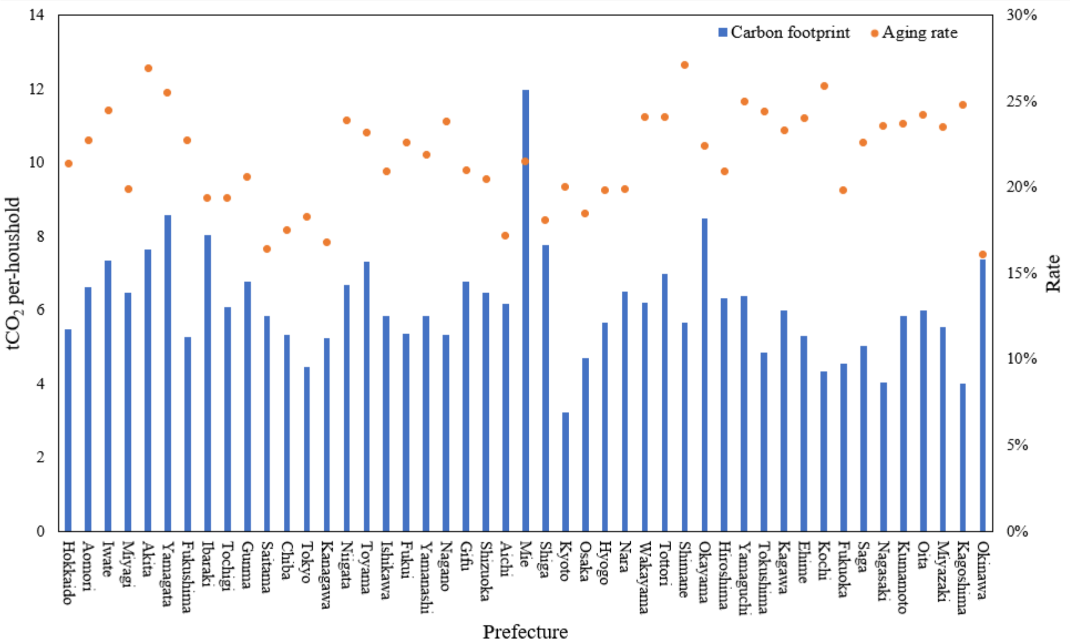


Fig. 4-8. Per-household carbon footprint of single-person households and aging rates across prefectures in Japan (2005).

Compared with multi-core income households, single-person households have markedly low overall income. Although income in high-GRP prefectures is relatively high, the high cost of living reduces the selective consumption of single-person households. For example, out of the annual per-household expenditure in Tokyo, real estate expenditure is JPY 0.31 million—2.6 times that of Yamagata (JPY 0.12 million); meanwhile, the annual per-household expenditure of Yamagata is JPY 5.6 million—1.4 times that of Tokyo (Fig. 4-13). Moreover, the public transport utilization rate of single-person households in high-GRP prefectures is high, which reduces not only the use of private vehicles but also the HCF of all income groups. The public transport utilization rates of Tokyo and Yamagata are 59% and 5%, respectively (Statistics Bureau, 2011).

4.3.4 Carbon inequality

Household carbon inequality across the 47 prefectures was measured by calculating the CF-Gini coefficients (Fig. 4-9). At the national level, the CF-Gini coefficients of multi-person households are higher than those of single-person households. At the prefectural level, the gap in CF-Gini coefficients between single- and multi-person households becomes more obvious in low-GRP prefectures. Meanwhile, the CF-Gini coefficients of both single- and multi-person households show a decreasing trend from low-GRP prefectures to high-GRP prefectures. The specific trends are as follows: The CF-Gini coefficients of the Hokkaido, Tohoku, Chugoku, and Kyushu regions are significantly higher than those of the other prefectures; those of the Kansai and Shikoku regions show a state of intermediate transition; and the CF-Gini coefficients of the Kanto and Chubu regions are visibly lower than those of the other prefectures.

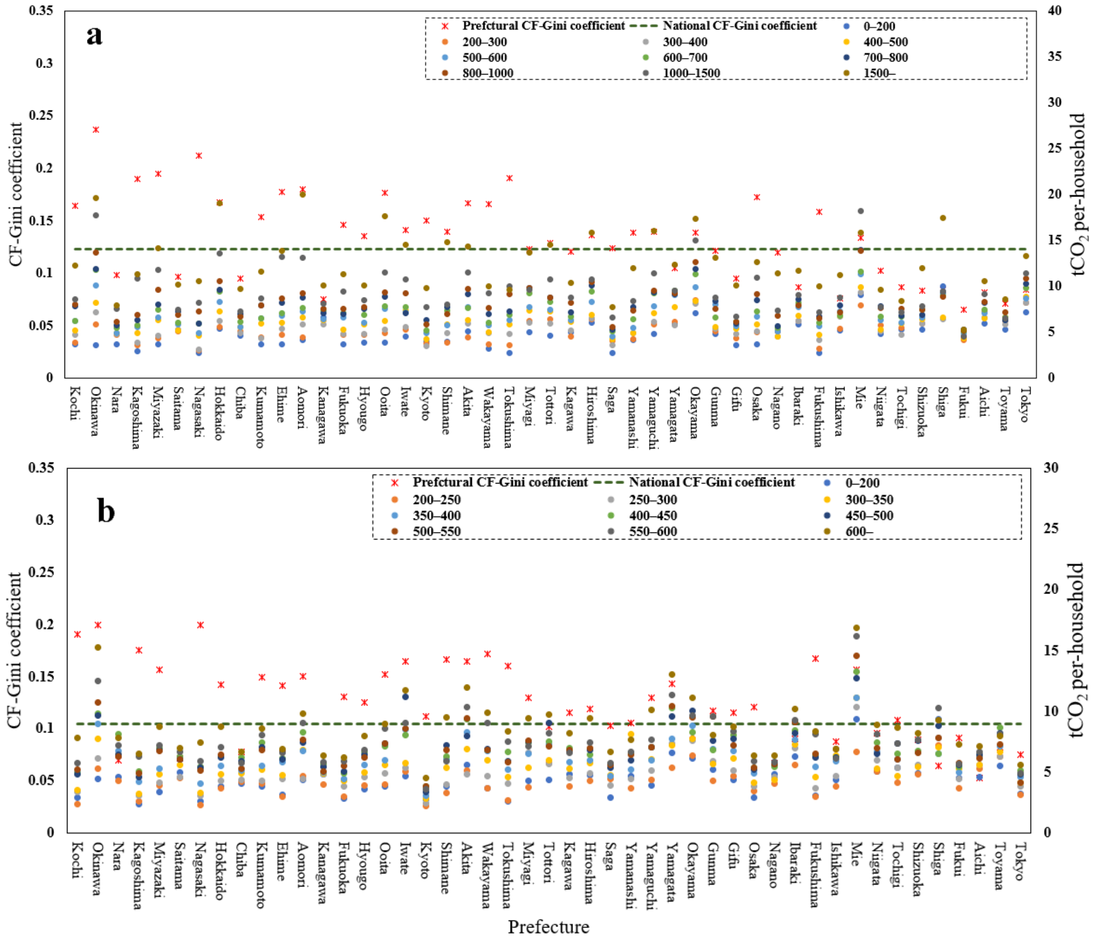


Fig. 4-9. CF-Gini coefficients and per-household carbon footprint by income group (unit: JPY 10000) of (a) multi- and (b) single-person households across prefectures in Japan (2005). All prefectures are arranged on the basis of GRP per household: The prefecture with the lowest GRP per household is on the left (Kochi), and the prefecture with the highest GRP per household is on the right (Tokyo).

In prefectures with high CF-Gini coefficients, high-income households, which constitute a low proportion of the population, make up a large share of HCF. However, in prefectures with low CF-Gini coefficients, the proportions of population and HCF across income groups are generally balanced. For example, a multi-person household with an annual income of over JPY

10 million, accounting for 8% of the population, induces 17% of the HCF in Kagoshima, whereas a multi-person household with the same income level in Toyama, making up 24% of the population, contributes to 26% of the HCF.

According to the sector classification of Shigetomi et al. (2014), we aggregated HCF into 13 sectors. Combined with the proportions of households and HCF by income group in the eight regions of Japan, the CF-Gini coefficients were quantified using Eq. (4-6), which allowed the intuitive observation of carbon inequality in various sectors via a consideration of regionality and household type (Fig. 4-10).

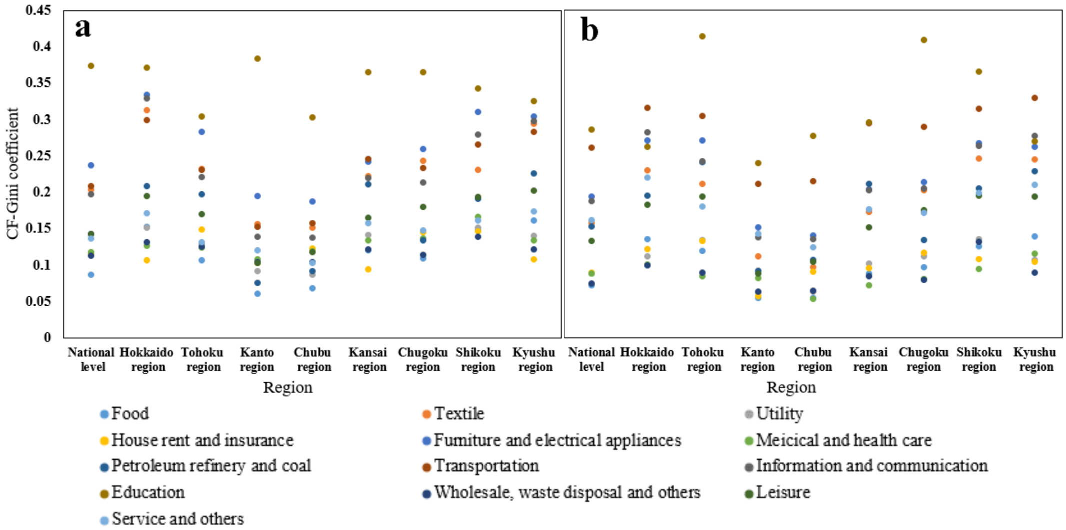


Fig. 4-10. The CF-Gini coefficients of 13 household expenditure categories of (a) multi- and (b) single-person households for eight regions of Japan (2005).

From the perspective of household type, the CF-Gini coefficients of multi-person households in most of the sectors are generally higher than those of single-person households. However, in the transportation, petroleum refining and coal, and service sectors, the CF-Gini coefficients of multi-person households are lower than those of single-person households. These findings reflect that households with multi-core income are more likely to expand the consumption gap among income groups, which in turn exacerbates carbon inequality.

At the national level, the CF-Gini coefficients of food, medical and healthcare, house rent and insurance, and utilities are low, whereas those of education, transportation, and furniture and electrical appliances are noticeably higher. This discrepancy indicates that in Japan, households of different income levels have relatively small differences in basic consumption. With increasing income, however, selective consumption creates a growing gap between high- and low-income groups, which eventually leads to greater carbon inequality.

The CF-Gini coefficients are low in regions with high income levels, and even within the same region, there are differences in coefficients between single- and multi-person households across sectors. The CF-Gini coefficient of education in multi-person households in the Kanto region is higher than those in the other regions, whereas that in single-person households is low. High-income households in high-GRP prefectures spend more on education and further expand the consumption gap with low-income households, resulting in higher CF-Gini coefficients of education in multi-person households. Generally, most of the educational expenditure of single-person households are attributed to young people. Under the influence of intense employment competition in high-GRP prefectures, most young individuals tend to pursue higher education, which is also in line with the fact that the overall college-going rate in the Kanto region is significantly higher than that in other regions (Statistics Bureau, 2015). Because a minimal income gap exists among young adults at the school stage, the CF-Gini coefficient of education in single-person households is low.

4.3.5 Limitations of the study

There are three principal data-related limitations in this study. First, the research covered only indirect HCF. Although the direct energy consumption of households (e.g., the consumption of gasoline and LPG) is reflected in Comprehensive Energy Statistics, it would be excessively coarse to combine energy consumption data with the 2005 Japan MRIO table (Hasegawa et al., 2015) because data on the corresponding sectors for energy consumption are of low resolution. For example, the petroleum refinery product sector is not divided into industries providing gasoline, LPG, kerosene, diesel, and other petroleum products. It is thus difficult to accurately calculate direct HCF at the subnational level in Japan. Second, it is currently impossible to compare HCF levels across prefectures and years. Although we could have determined changes in the carbon intensity of sectors involved in household consumption in different years on the basis of Comprehensive Energy Statistics, an MRIO table with more recent data is presently unavailable. Lastly, due to data limitations, this study only covers the domestic products of household consumption without considering the imported products. For developed countries like Japan, imported products play an important role in the country's indirect CO_2 emissions. Globally, about one fifth of CO_2 emissions are traded internationally, primarily as exports from China and other emerging markets to consumers in developed countries (Davis and Caldeira, 2010). Specifically, in developed countries, such as Britain and France, more than 30% of consumption-based emissions came from imported products in 2004. Analyzing the household consumption of imported products in Japan is not only helpful to understand the international carbon leakage, but also helpful to further divide the responsibility of emission reduction from the perspective of producers and consumers, so as to promote international cooperation on climate mitigation. Therefore, further systematically understanding the HCF characteristics in Japan by exploring the CO_2 emissions of imported products has become one of the important contents in our following research.

Chapter 5. CO_2 emissions embodied in domestic trade and their influencing factors in Japan

5.1 Background

Countries are paying more attention to domestic demand in the 21st century, which has promoted domestic inter-regional trade to become an important carbon source. With the increasingly expanding of domestic consumption to stimulate economic growth, the impact of domestic trade across prefectures on Japan's overall CO_2 emissions has become more important. Besides, trade accelerates the transfer of CO_2 emissions between producers and consumers; it also intensifies climate change, so a systematic assessment of CO_2 emissions from domestic trade is significant for elucidating methods for the reduction of Japan's emissions. Therefore, we have visualized carbon transfer path of domestic imports and exports, and identified its influencing factor.

5.2 Methodology and data

Here the methodology and data are defined, including the quantification of CO_2 emission embodied in domestic trade, decomposition approaches, the methodological, and data utilized.

5.2.1 CO_2 emissions assessment framework with IO analysis

IO analysis is one of the main methods used to evaluate CO_2 emissions embodied in trade (Lin and Xie, 2016). Its basic principle comes from the technique of representing the complex interdependence between economic sectors (Leontief, 1970). The IO analysis quantifies environmental problems through the exchange of materials between economic sectors in production (Wei et al., 2017). Owing to the lack of domestic trade data in the IO tables (IOTs) of some prefectures, 30 prefectures[6] were studied in this research.

The basic equation for the assessment of CO_2 emissions can be expressed as follows:

$$C = p(I - A)^{-1}Y \tag{5-1}$$

$$A = \left[\begin{pmatrix} a^{11} & \cdots & a^{1n} \\ \vdots & \ddots & \vdots \\ a^{n1} & \cdots & a^{nn} \end{pmatrix}\right] \tag{5-2}$$

where C denotes upstream CO_2 emissions per consumption expenditure (embodied CO_2

[6] See Fig. A1 in the Appendix for the geographical coverage of the study.

emission intensity) driven by final demand Y, p is a vector containing the direct CO_2 emissions per unit production output for all commodity sectors, A refers to the technical coefficient matrix, and n is the number of economic sectors.

Based on Eq. 5-1, the CO_2 emissions embodied in the domestic exports of each prefecture can be expressed as

$$C_i^{\mathrm{EX}} = \sum_j p_i L_{ij} Y_i^{\mathrm{EX}} \tag{5-3}$$

where C_i^{EX} represents the CO_2 emissions embodied in domestic exports for commodity i. j denotes the commodity sector. $L_{ij} = (I - A_{ij})^{-1}$ denotes upstream requirements per unit production, and L_{ij} is an element of the Leontief inverse matrix obtained from the input-output table. Y_i^{EX} denotes the household's final consumption by attribute i.

The domestic imports of each prefecture come from other prefectures in Japan. Thus, it is necessary to consider the differences in the technical coefficients (A) of the corresponding exporters. The CO_2 emissions embodied in domestic imports of each prefecture can be expressed as follows:

$$C_i^{\mathrm{IM}} = \sum_{r=1}^{29} p_r (I - A_r)^{-1} Y_{r,i}^{\mathrm{IM}} \tag{5-4}$$

where C_i^{IM} is the CO_2 emissions embodied in domestic imports in commodity i and $Y_{r,i}^{\mathrm{IM}}$ is a vector of the amount of domestic imports from prefecture r in commodity i.

Since the subnational MRIO table of Japan after 2010 is not currently available for use, we could not directly obtain the data for $Y_{r,i}^{\mathrm{IM}}$. Therefore, we use Japan's National Cargo Net Flow Survey (NCNFS) to estimate the trade flow of each prefecture from the other 29 prefectures. Domestic import matrices can be disaggregated as follows:

$$Y_{r,i}^{\mathrm{IM}} = Y_i^{\mathrm{IM}} \times \frac{Q_{r,i}^{\mathrm{IM}}}{\sum Q_i^{\mathrm{IM}}} \tag{5-5}$$

where Y_i^{IM} is the total amount of domestic imports in commodity i. $Q_{r,i}^{\mathrm{IM}}$ refer to the import amounts from prefecture r in commodity i. $\sum Q_i^{\mathrm{IM}}$ refer to the total import amounts in commodity i.

5.2.2 Evaluation of influencing factors using the LMDI approach

Typically, IO analysis is combined with SDA to evaluate the factors influencing the changes in CO_2 emissions. However, the research object is the influencing factors of net export CO_2 emissions generated by domestic import and export in each prefecture, and changes in panel data are not involved. Therefore, the LMDI decomposition approach was used in this study. The advantage of the LMDI decomposition approach is that it can be completely decomposed compared to other decomposition methods, and the results are more accurate and convincing (Quan et al., 2020).

To obtain the net export CO_2 emissions, we first decomposed the CO_2 emissions embodied in domestic imports and exports based on the Kaya identity as follows:

$$C^{\mathrm{EX}} = \sum_{i=1} C_i^{\mathrm{EX}} = \sum_{i=1} \frac{C_i^{\mathrm{EX}}}{Y_i^{\mathrm{EX}}} \times \frac{Y_i^{\mathrm{EX}}}{TOT^{\mathrm{EX}}} \times TOT^{\mathrm{EX}} = \sum_{i=1} TEC_i^{\mathrm{EX}} \times STR_i^{\mathrm{EX}} \times TOT^{\mathrm{EX}} \tag{5-6}$$

$$C^{\mathrm{IM}} = \sum_{i=1} C_i^{\mathrm{IM}} = \sum_{i=1} \frac{C_i^{\mathrm{IM}}}{Y_i^{\mathrm{IM}}} \times \frac{Y_i^{\mathrm{IM}}}{TOT^{\mathrm{IM}}} \times TOT^{\mathrm{IM}} = \sum_{i=1} TEC_i^{\mathrm{IM}} \times STR_i^{\mathrm{IM}} \times TOT^{\mathrm{IM}} \tag{5-7}$$

where and TEC_i^{EX} and TEC_i^{IM} refer to the carbon intensity of the domestic exports and imports in commodity i; STR_i^{EX} and STR_i^{IM} refer to the share of commodity i in total domestic exports and imports; TOT^{EX} and TOT^{IM} refer to the total trade amount of domestic exports and imports.

The total effect on net export CO_2 emissions can be expressed as:

$$\Delta C = C^{\mathrm{EX}} - C^{\mathrm{IM}} =$$

$$\Delta C_{\mathrm{TEC}} + \Delta C_{\mathrm{STR}} + \Delta C_{\mathrm{TOT}} = \sum_{i=1} W_i \times \ln \frac{TEC_i^{\mathrm{EX}}}{TEC_i^{\mathrm{IM}}} + \sum_{i=1} W_i \times \ln \frac{STR_i^{\mathrm{EX}}}{STR_i^{\mathrm{IM}}} + \sum_{i=1} W_i \times \ln \frac{TOT^{\mathrm{EX}}}{TOT^{\mathrm{IM}}} \tag{5-8}$$

$$W_i = \begin{cases} \dfrac{C_i^{\mathrm{EX}} - C_i^{\mathrm{IM}}}{\ln C_i^{\mathrm{EX}} - \ln C_i^{\mathrm{IM}}}, C_i^{\mathrm{EX}} \neq C_i^{\mathrm{IM}} \\ C_i^{\mathrm{EX}}, C_i^{\mathrm{EX}} = C_i^{\mathrm{IM}} \end{cases} \tag{5-9}$$

The three influencing factors of net export CO_2 emissions are as follows:

Technology effect:

$$\Delta C_{\mathrm{TEC}} = \sum_{i=1} W_i \times \ln\left(\frac{TEC_i^{\mathrm{EX}}}{TEC_i^{\mathrm{IM}}}\right) \tag{5-10}$$

Structure effect:

$$\Delta C_{\mathrm{STR}} = \sum_{i=1} W_i \times \ln(\frac{STR_i^{\mathrm{EX}}}{STR_i^{\mathrm{IM}}}) \tag{5-11}$$

Scale effect:

$$\Delta C_{\mathrm{TOT}} = \sum_{i=1} W_i \times \ln(\frac{TOT^{\mathrm{EX}}}{TOT^{\mathrm{IM}}}) \tag{5-12}$$

5.2.3 Data

Each prefecture produces its SRIO table; thus, the IOTs of the 30 prefectures were retrieved via each prefecture's official website[7]. This study focused on 2011 IOTs, with the best data available (Wakiyama et al., 2020). Emission factors were obtained from the Agency for Natural Resources and Energy of Japan (2021). Regional trade data were collected from the 2010[8] NCNFS between prefectures (Ministry of Land Infrastructure Transport and Tourism, 2016). Based on sector classification of Comprehensive Energy Statistics, we aggregated the IOT's sectors to form 28 sectors (Table 5-1. The sectoral correspondence between NCNFS and IOTs is also shown in Table 5-1 The geographical locations of the research area in Japan are shown in Fig. 5-1.

Table 5-1 Matching table between sectors of NCNFS and IOTs

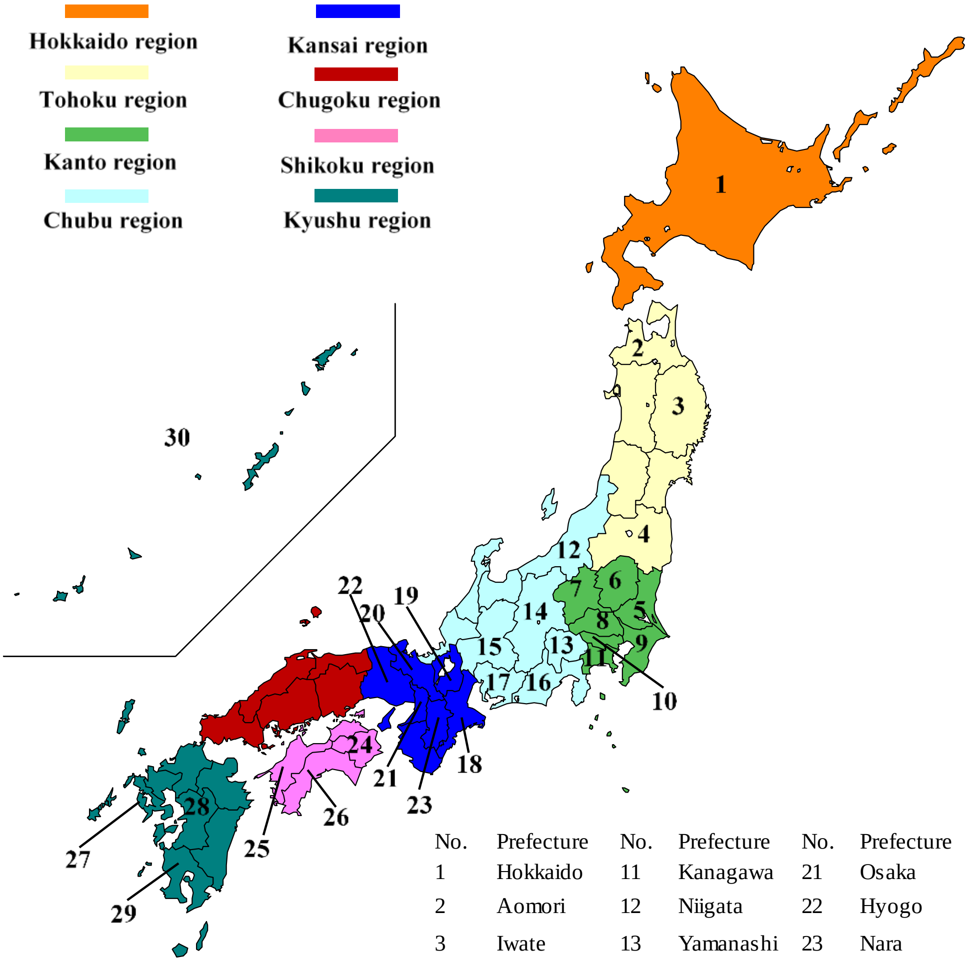
NCNFS	No.	IOTs	NCNFS	No.	IOTs
Agricultural, marine, and forest products	1	Agriculture, forestry, and fisheries	Special product	15	Electricity, gas, heat, and water supply
Mining products	2	Mining industry		16	Business
Light industrial products	3	Food and beverage industry		17	Finance and Insurance industry
	4	Textile industry		18	Real estate industry
	5	Wood products, furniture, and other		19	Transportation and postal business

[7] The official websites of each prefecture's IOT are put in Table A2 in Appendix.

[8] NCNFS is held every five years, with the last three times being in 2015, 2010, 2005. In order to cooperate with the 2011 SRIO table, the NCNFS in 2010 was used in this study.

		industry			
	6	Pulp, paper, paper processed product industry		20	Information and communication industry
	7	Printing, plate making, bookbinding industry		21	Official business
	8	Plastic, rubber, leather product industry		22	Education and learning support industry
	9	Ceramic industry		23	Medical, welfare
Chemical products	10	Chemical industry (including petroleum and coal products)		24	Complex service business
Metal machinery products	11	Steel industry		25	Professional, technical service industry
	12	Machine industry		26	Accommodation, restaurant service industry
Industrial waste	13	Recycling and processing of renewable resources		27	Life-related service industry, entertainment industry
Miscellaneous manufactured products	14	Construction industry		28	Activities not elsewhere classified

Note: The manufacturing industry includes the sector marked in orange, and the service industry includes the sector marked in green.



No.	Prefecture	No.	Prefecture	No.	Prefecture
1	Hokkaido	11	Kanagawa	21	Osaka
2	Aomori	12	Niigata	22	Hyogo
3	Iwate	13	Yamanashi	23	Nara
4	Fukushima	14	Nagano	24	Tokushima
5	Ibaraki	15	Gifu	25	Ehime
6	Tochigi	16	Shizuoka	26	Kochi
7	Gunma	17	Aichi	27	Nagasaki
8	Saitama	18	Mie	28	Kumamoto
9	Chiba	19	Shiga	29	Kagoshima
10	Tokyo	20	Kyoto	30	Okinawa

Fig. 5-1. The geographical locations of 30 prefectures and eight regions in Japan

To check the effectiveness of domestic imports data for every prefecture, we calculated the proportion of import volume from the other 29 prefectures in the total domestic imports of each prefecture (Table 5-2). Generally, 22 prefectures had a proportion more than 70%, with a weighted average of 92.9%, which confirms that the study area could show the characteristics of CO_2 emissions embodied in Japan's domestic trade.

Table 5-2. The proportion of import volume from the other 29 prefectures in the total domestic imports of each prefecture

Prefecture	Percentage	Prefecture	Percentage
Hokkaido	89.57%	Shizuoka	95.82%
Aomori	82.14%	Aichi	88.11%
Iwate	37.67%	Mie	95.51%
Fukushima	61.05%	Shiga	94.01%
Ibaraki	97.58%	Kyoto	93.30%
Tochigi	96.79%	Osaka	85.88%
Gunma	98.13%	Hyogo	74.60%
Saitama	97.71%	Nara	92.43%
Chiba	98.54%	Tokushima	48.46%
Tokyo	98.29%	Ehime	27.62%
Kanagawa	97.71%	Kochi	71.14%
Niigata	86.54%	Nagasaki	30.26%
Yamanashi	96.84%	Kumamoto	15.57%
Nagano	94.33%	Kagoshima	19.86%
Gifu	95.52%	Okinawa	45.97%
Weighted average: 92.98%			

5.3 Results and discussion

5.3.1 The CO_2 emissions embodied in Japan's domestic trade

The total CO_2 emissions embodied in the domestic trade of 30 prefectures are approximately 486 Mt CO_2, accounting for 41% of Japan's total indirect CO_2 emissions in 2011 (Japan Center for Climate Change Actions, 2021). Moreover, referring to the currently available data on consumption-based emissions in Japan in 2005 (Hasegawa et al., 2015), the proportion of CO_2 emissions embodied in domestic trade across prefectures is higher than 30%. Generally, CO_2 emissions embodied in domestic imports and exports across prefectures show substantial regional differences (Fig. 5-2). A few prefectures produce the majority of CO_2 emissions through domestic trade, and these prefectures are mainly in the Kanto, Chubu, and Kansai regions, such as Tokyo, Aichi, and Osaka. In addition, those prefectures are economically similar in that they boast a high GRP and domestic trade. An active economy stimulates domestic trade between producers and consumers, which obviously promotes the transfer of CO_2 emissions.

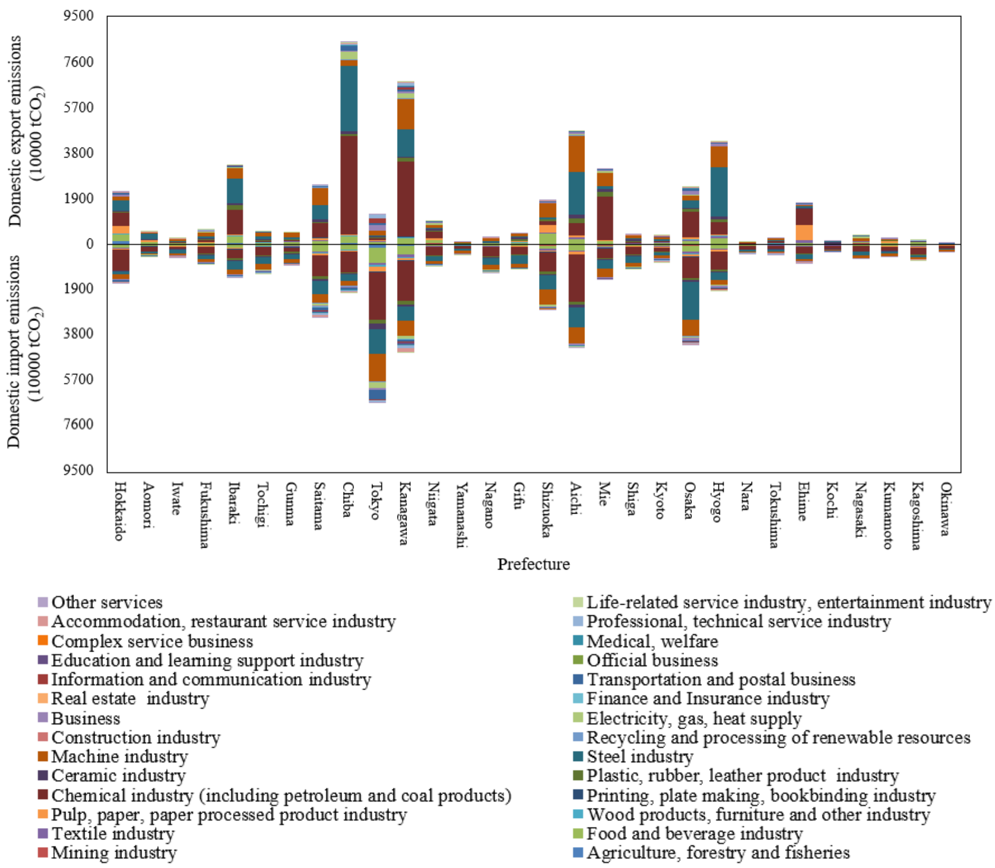


Fig. 5-2. The CO_2 emissions embodied in Japan's domestic imports and exports across prefectures in 2011.

CO_2 emissions embodied in domestic exports are concentrated in manufacturing prefectures (i.e., prefectures where the manufacturing industry is the economic base). By contrast, the CO_2 emissions embodied in domestic imports are concentrated in consumer prefectures (i.e., prefectures where consumption supports the economic foundation). Chiba, Kanagawa, Aichi, and Hyogo, the four prefectures with a high proportion of the manufacturing industry in the GRP, account for 31% of the total domestic exports amount in Japan (Fig. 5-3). This reflects that a few manufacturing prefectures satisfy most of Japan's domestic demand for industrial products, thus becoming the leading net exporters of CO_2 emissions. The raw materials needed for production promote the expansion of domestic imports; thus, some manufacturing prefectures also have a significant amount of CO_2 emissions embodied in domestic imports, such as Kanagawa and Aichi. Compared with domestic exports, the CO_2 emissions embodied in the domestic imports of most prefectures, excluding manufacturing prefectures, were relatively high, especially in consumer prefectures, such as Tokyo and Osaka.

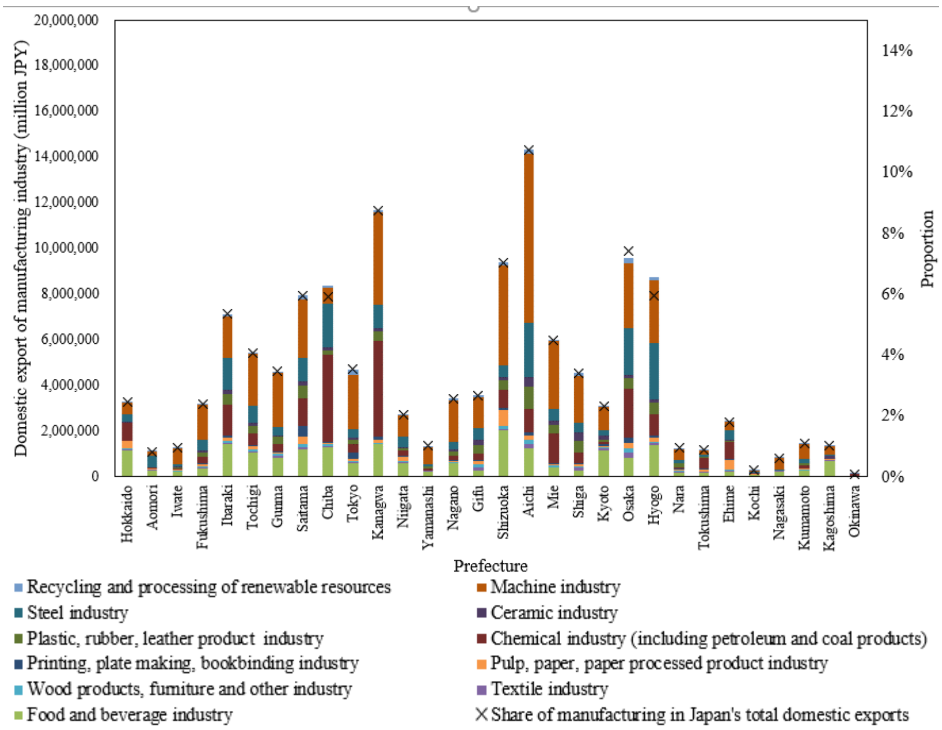


Fig. 5-3 Domestic exports of the manufacturing industry by prefecture, and their shares of Japan's total manufacturing domestic exports in 2011.

In Japan's domestic exports, the chemical, steel, and machine industries account for a high proportion of CO_2 emissions in heavy-industry prefectures, mainly in the Kanto and Chubu regions. The economy of these prefectures is clearly export-oriented; therefore, the manufacturing industry is more dependent on the external market. In addition, the CO_2 emissions embodied in the domestic exports of other prefectures are relatively small and concentrated in light industries, such as the food and beverages. Chiba, Kanagawa, and Aichi are all important manufacturing prefectures in Japan with higher CO_2 emissions from domestic exports. Therefore, we selected these three prefectures as case studies to further discuss the CO_2 emissions embodied in domestic exports with industrial structures.

CO_2 emissions from the chemical and steel industries account for a large proportion of the domestic exports from Chiba. Chiba, which has the Keiyo Rinkai Complex, Japan's largest basic materials industry cluster, and which provides the necessary raw materials and energy for all the industries in Japan (Matsumoto et al., 2019). Chemical, petroleum, and steel products produced in the Keiyo Rinkai Complex account for approximately 60% of Chiba's total manufacturing shipment value. In Kanagawa, the CO_2 emissions embodied in domestic exports are concentrated in the machine and chemical industries, which are also the mainstays of the region's economy. In 2010, the total output of Kanagawa's manufacturing industry ranked second in Japan, with the machine industry accounting for 16.9% of the manufacturing industry. The CO_2 emissions embodied in Aichi's domestic exports were mainly from the machine and steel industries. The transport machinery industry is the traction force of the manufacturing industry, with more than half of the total shipments in Aichi's manufacturing industry. In addition, most mechanical products exported by Aichi focus on precision instruments and high-tech products; thus, the CO_2 emissions embodied in domestic exports are relatively lower.

5.3.2 Carbon transfer path of domestic imports between prefectures

Overall, there were substantial differences in the carbon transfer paths of domestic imports in Japan's 30 prefectures (Fig. 5-4). Carbon flow is more obvious in economically advanced regions (e.g., Kanto and Kansai regions) and covers more prefectures through carbon transfer. For example, Tokyo's CO_2 emissions account for 14% of Japan's CO_2 emissions embodied in domestic imports, and the emission sources extend from Tohoku to Kanto region (Ibaraki, Saitama, Chiba, etc.). However, the CO_2 emissions of economically backward regions are lower and concentrated in neighboring manufacturing prefectures. For instance, Gifu accounts for only approximately 2% of the total CO_2 emissions, mainly from neighboring Aichi. Furthermore, consumer prefectures import major CO_2 emissions and export substantial amounts of CO_2 emissions to other prefectures. For example, Tokyo has a large carbon output for Hokkaido, Ibaraki, Chiba, and Kanagawa, while Osaka is an important emission source for

Aichi, Mie, Shiga, and Nara.

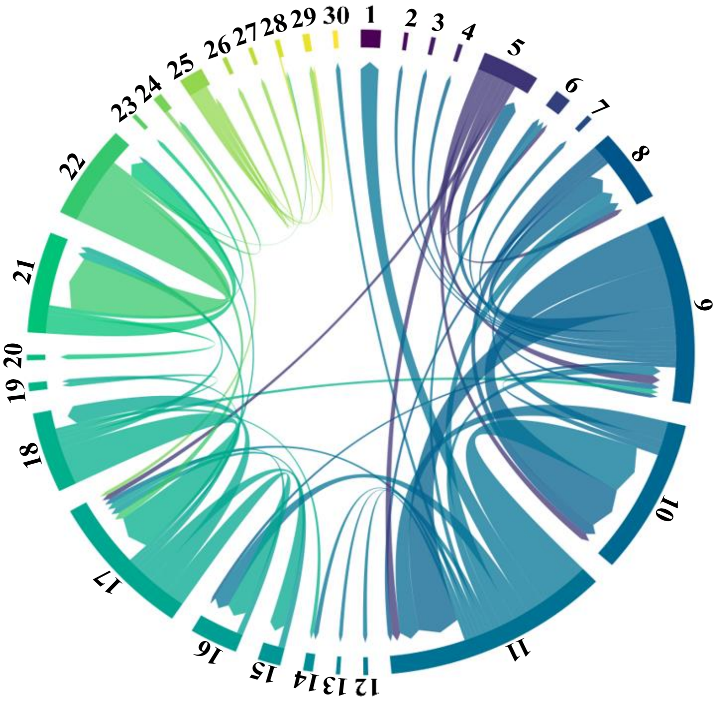


Fig. 5-4. Flow chart of the CO_2 emissions embodied in domestic imports between prefectures of Japan in 2011 (unit in 10,000 tCO_2). The numbers in the flowchart correspond to the prefectures, as detailed in Fig. 5-1.

Tokyo is an important consumer prefecture with a high population concentration, whereas Chiba and Kanagawa are the main emission sources of Hokkaido, Tohoku, Kanto, and Chubu regions in domestic imports. We emphasize discussion about the sectoral distribution of embodied CO_2 emissions for the three prefectures because we consider it is essential with regard to the relationship between regional development and CO_2 emissions, those for the other prefectures are detailed in Fig. A1 in Appendix.

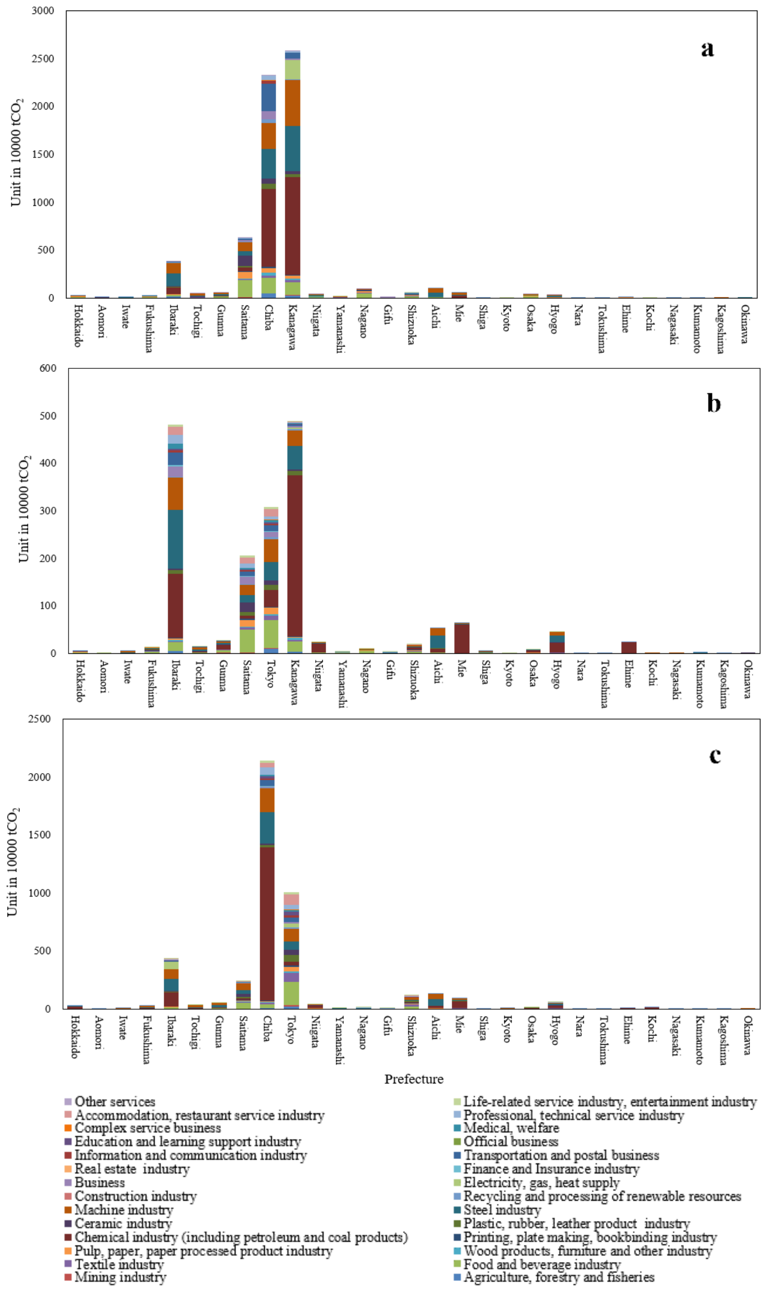


Fig. 5-5. The CO_2 emissions embodied in domestic imports of Tokyo (a), Chiba (b), and Kanagawa (c) by the exporter in 2011.

The main sources of CO_2 emissions embodied in Tokyo's domestic imports were Chiba and Kanagawa, and there were specific differences in sectoral distribution (Fig. 5-5a). In contrast, CO_2 emissions from other prefectures are lower, mainly in light industries. In domestic imports from Kanagawa and Chiba, the food and beverage, chemical, steel, and machine industries were the main sectors contributing to CO_2 emissions. Tokyo is the capital of Japan, so production costs are higher than in other prefectures: thus, the development of heavy industry, which relies on resources and land areas, is limited. As important industrial bases in Japan, neighboring prefectures Chiba and Kanagawa largely undertake the task of exporting heavy industrial products to Tokyo. Urban agriculture in neighboring prefectures (e.g., Saitama and Chiba) is promoted by the huge market demand of Tokyo and has become an important emission source. Although Chiba and Kanagawa are manufacturing prefectures, there are differences in the sources of CO_2 emissions embodied in domestic imports, where these emissions in Chiba were lower than those in Kanagawa. The basic materials industry accounts for a sizable proportion of Chiba's manufacturing industry; thus, the huge demand for raw materials makes Chiba's trade structure more dependent on international imports, which decreases CO_2 emissions embodied in domestic imports. The emission sources of Chiba, such as Kanagawa, Ibaraki, and Tokyo, were relatively diverse (Fig. 5-5b). In contrast, the emission source of Kanagawa was concentrated in Chiba (Fig. 5-5c). As Chiba is Japan's largest basic materials industry cluster, it can provide sufficient production support for the development of heavy industry in Kanagawa. Chiba and Kanagawa also have significant amounts of CO_2 emissions from consumer prefectures in domestic imports, such as Tokyo.

5.3.3 The influencing factors of net export CO_2 emissions across prefectures

Among the 30 prefectures, 20 have negative net export CO_2 emissions, especially consumer prefectures with advanced economies (e.g., Tokyo and Osaka; Fig. 5-6a). Prefectures with positive net export CO_2 emissions are mostly manufacturing prefectures and are concentrated in the Kanto and Kansai regions (e.g., Kanagawa, Hyogo). From the impact degree of the three influencing factors, the technology effect had the most significant impact on net export CO_2 emissions (Fig. 5-6b). The technology effect has an obvious positive impact on manufacturing prefectures while negatively affecting consumer prefectures. The impact of the structure effect on net export CO_2 emissions was relatively weak and was mainly affected by the economic structure within each prefecture (Fig. 5-6c). The scale effect has the least impact on net export CO_2 emissions and has a positive impact, mainly in Kanto region (Fig. 5-6d).

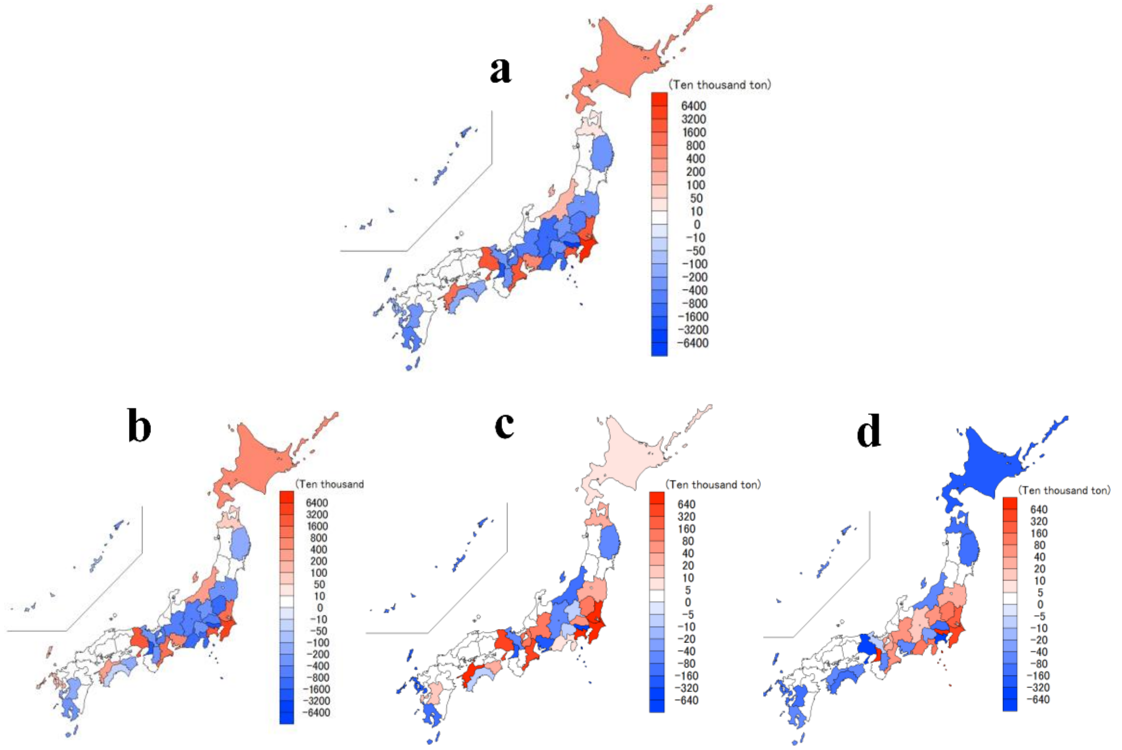


Fig. 5-6. Total net export CO_2 emissions (a) and the impact of three factors on net export CO_2 emissions across prefectures in 2011: technology effect (b), structure effect (c), and scale effect (d).

The impact of the technology effect on net export CO_2 emissions is mainly reflected in carbon intensity based on Eqs. (5-6) and (5-7). Chiba and Kanagawa are the important manufacturing prefectures in the Kanto region. However, the positive impact of the technology effect in Chiba is stronger than that in Kanagawa. The domestic exports of Chiba are dominated by the basic materials industry, including raw materials and energy. By contrast, Kanagawa has a high proportion of domestic exports in the machinery industry, and the added value of these exports in manufacturing industry of Kanagawa (24%) is much higher than that of Chiba (12%). Through the commodity structure of domestic trade, the carbon intensity of Chiba was obviously higher than that of Kanagawa, and therefore, the technology effect had a stronger positive impact on Chiba. The negative impact of the technology effect gradually increases from economically backward prefectures to economically advanced prefectures: this is because economically advanced prefectures can provide a sufficient economic foundation for the development of technology-intensive and service industries and provide a huge consumer market.

The difference in economic structure causes the impact of the structure effect on net export CO_2

emissions to differ between prefectures. In consumer prefectures housing a high proportion of the service industry, such as Tokyo, the structural effect has a significant negative impact. In prefectures where economic traction is shifting from manufacturing to services, such as Shizuoka and Kochi, the structural effect has a relatively weak positive or negative impact. In manufacturing prefectures with export-oriented economies that rely on external markets and resources, such as Chiba and Kanagawa, the structural effect has a strong positive effect.

The impact of the scale effect is determined largely by the volume of domestic imports and exports in each prefecture. When domestic exports are higher than domestic import, the scale effect has a positive effect, as in Chiba. However, the scale effect also has a positive effect in some consumer prefectures with advanced economies, such as Tokyo and Osaka. The main reason is that, in addition to importing industrial products from manufacturing prefectures, consumer prefectures also export large amounts of CO_2 emissions through service industries to other prefectures. This also confirms that although manufacturing prefectures are the main net exporters of CO_2 emissions, consumer prefectures are also important sources of CO_2 emissions embodied in domestic trade.

5.3.4 Limitations of the study

There are mainly three limitations in this study. First, as the subnational MRIO table of Japan after 2010 is not currently available for use, we estimated the domestic trade flows between prefectures based on the SRIO table and NCNFS, and we recognize that the latest year analyzed in this study is more than 10 years in the past; however, it is currently impossible to prepare more recent data on SRIO tables for each prefecture in Japan. Therefore, the domestic trade flow of each prefecture cannot accurately reflect the actual situation. Second, because the SRIO tables for some prefectures do not provide domestic import and export data, the study area was limited to 30 prefectures. Therefore, the conclusions of this study cannot be fully applicable to all prefectures in Japan. Finally, this study does not involve non-combustion CO_2 emissions in the production process, which may underestimate the CO_2 emissions embodied in the domestic trade of each prefecture.

Chapter 6. Discussion

Although Japan’s CO_2 emissions have been decreasing in recent years, with the increasing traction of consumption on the economy, household consumption has become a new driving force of the carbon growth. In the context of Japan's aging and shrinking society, the demographic trend (i.e., age structure and household type) of population is constantly changing, which has also greatly changed the consumption characteristics of household. As the proportion of the elderly population continues to rise, there will be a postponement of the peak of household CO_2 emissions by age in Japan, and the expansion of the small-scale household will also increase the CO_2 emissions from the basic consumption. Japan's carbon inequality is not obvious at the national-level, but shows substantial differences based on regional economy at the prefectural-level. From the perspective of household type, the rapid growth rate of single-person household will further widen the CO_2 emission gap between high-income and low-income households. Domestic imports and exports of each prefecture are significantly affected by the local and outside consumption, and the consumption mainly comes from the household consumption. Therefore, consumer prefectures, especially economically advanced regions, have obvious carbon input in Japan's domestic trade due the huge market demand, and the manufacturing prefectures exports industrial products to most regions in Japan, thus becoming the main net carbon exporters.

Household consumption shows an increasingly important impact on CO_2 emissions in Japan, which is in line with the previous research in developed countries, and this has been verified at both national level (Chapter 3) and prefectural level (Chapter 4). During 1990-2005, the share of household consumption in Japan's total CO_2 emissions rose from 49% to 55%, and the average share of household consumption in CO_2 emissions of 47 prefectures is 51% in 2005. In addition, indirect CO_2 emissions of household consumption have a more profound impact on Japan's emission reduction. There are great differences between direct and indirect energy consumption in household consumption structure; thus, the characteristics of direct and indirect CO_2 emissions from household consumption are also different. Indirect CO_2 emissions were higher than direct CO_2 emissions in both the total emissions and change in emission levels, and the change in driving forces of indirect CO_2 emissions are more complex.

Although, the impact of demographics on Japan's CO_2 emissions has been extensively explored in the precedential research, there is a lack of focus on demographic trends as a demand driver of changes in HCF. The CO_2 emissions of household consumption in Japan are significantly affected by demographic factors. Under Japan's aging society, the age composition of population has changed, which is reflected in the increase of the elderly population. Generally, the HCF increase with the age, and reach the peak at 50s. However, the deepening of aging society will gradually shift the peak age of HCF backward. From 1990 to 2005, the HCF over 50s have a sizable increase, with a growth rate of 10%. At this stage, the single-person household accounts for about 30% of Japan's CO_2 emissions. However, considering the growth rate of single-person households under the shrinking society of Japan, the share of CO_2 emissions from single-person households will continue to rise in the future.

Most of the existing research focused on national HCF characteristic in Japan instead of the household carbon inequality considering the income level and regionality. The HCF levels of prefectures show substantial differences, which also contribute to variations in carbon inequality. Income level has the most direct influence on HCF, which considerably determines the amount and structure of household consumption. Overall, HCF generally increases with income, but under the impact of regional economy and household type, special situations arise in the distribution of HCF across income groups. Specifically, the income gap in low-GRP prefectures is visibly large, resulting in the polarization of HCF caused by extremely high or low incomes; the opposite is exhibited by the HCF of high-income single- and multi-person households in high-GRP prefectures. The changes in carbon inequality across prefectures indicate that the aggravation of income inequality widens the gap in HCF between income groups, which is inconducive to the reduction of per-household carbon footprint during climate mitigation.

Previous research focused more on Japan's carbon leakage of international trade, but little attention was paid to the carbon transfer generated by domestic trade. There are substantial differences in CO_2 emissions embodied in domestic trade and the influencing factors across prefectures in Japan (Chapter 5). The CO_2 emissions embodied in domestic imports and exports across prefectures are related to both the production and consumption, and the responsibility of emission reduction is attributable to both manufacturing and consumer prefectures. Consumer demand represented by the household consumption drives the production-related CO_2 emissions, meanwhile, the consumption and production of each prefecture involves local and other regional products, which brings about the transfer of CO_2 emissions from domestic trade. Therefore, the interaction between consumption and production is not only reflected in the differences in total CO_2 emissions between domestic imports and exports, but also the differences in sectoral distribution of CO_2 emissions.

From the perspectives of household consumption and domestic trade, this study confirms that consumption-based emissions have a substantial impact on Japan's overall CO_2 emissions, which also plays a positive role in further exploring the potential of carbon reduction to achieve carbon neutrality in Japan. However, at the present stage, there is still a great space for the development of the research on consumption-based emissions in Japan. Affected by the available data, there are many future expansion contents in this study, such as the CO_2 emission characteristics of household consumption in imported products, the further classification of household types, and the traded emissions across all prefectural administrative units in Japan. Moreover, climate mitigation requires long-term plans and scientific countermeasures, it is necessary to understand the impact of demographics, economy, energy and other factors on CO_2 emissions in a multi-dimensional way. Therefore, in the following research, we will further expand the research width. For example, exploring the carbon rebound effect on HCF under the energy conservation policies in Japan, and investigating the impact of changes in household consumption awareness on HCF during the COVID-19 pandemic.

Chapter 7. Conclusions and policy implications

7.1 Conclusions

A multi-dimensional understanding of Japan's CO_2 emissions can not only help to comprehend the impact of household consumption and domestic trade on CO_2 emissions in a short-term, but also support the consumption-based mitigation with theoretical basis in a long-term. Accordingly, we have evaluated the HCF through demographic shifts, household type, and income level, and compared the household carbon inequality across prefectures to further stress the relationship between income inequality and climate change. Moreover, we have visualized the carbon transfer of domestic imports and exports by prefecture and identified their influencing factors. The main findings are as follows.

1. Household consumption and domestic trade have obviously promoted the growth of Japan's CO_2 emissions. The steady growth of household consumption has accelerated the domestic trade between prefectures, and the differences in trade scale and commodity structure also expand the gap in HCF across prefectures. With the Japanese economy paying more attention to consumption to stimulate domestic demand, the consumption-based emissions play a more important role in Japan's emission mitigation.
2. Among the HCF, indirect CO_2 emissions were higher than direct CO_2 emissions in both the total emissions and change in emission levels. Under the deepening of aging, shrinking society in Japan, the distribution of CO_2 emissions by age groups of the highest income earner in the household will change, and the indirect CO_2 emissions will increase regarding the contributions from related drivers.
3. There are substantial differences in the HCF across prefectures, which are influenced by the regional economy. The income level and household type have profound impact on household carbon inequality within each prefecture. Besides, the rapid growth rate of single-person household will further widen the HCF gap between high-income and low-income households.
4. The difference in CO_2 emissions of domestic trade among prefectures has aggravated regional carbon inequality, and the carbon flow is significantly affected by the consumption inside and outside every prefecture. Besides, the consumer prefectures not only drive the production-related CO_2 emissions of manufacturing prefectures, but also export sizable CO_2 emissions through the service sector which widely seen as a low-carbon emitter.

7.2 Policy implications

Based on the impact of household consumption and domestic trade on Japan's CO_2 emissions, emission reduction measures must be consistent with demographic trends and consumption characteristics. At present, the Japanese Government has formulated specific emission reduction policies from the energy and technology aspects, focusing on the industry, transport and energy conversion sectors. The measures on household sector are mainly about the energy use (Ministry of the Environment Government of Japan, 2022). For example, in response to the carbon neutral target in 2050, the Japanese policy implements the net zero energy house standard[9] (ZEH) for new household buildings. Besides, Japanese government aims to promote the introduction of equipment and devices with high energy conservation performance. Specifically, 100% diffusion of high-efficiency lighting such as LEDs in the stock by 2030, guiding measures for energy conservation in support of septic tank installation. Lastly, Japanese government has introduced home energy management system, smart meters and smart home devices to comprehensively monitor the energy use of household buildings. Although some of the current measures are aimed at household lifestyle, they focus more on the cultivation of climate change and environmental awareness, and lack systematic solutions based on HCF characteristics. For example, the Ministry of Environment Government Japan created and published the video "2100 Future Weather Forecast" and launched COOL CHOICE, which is an initiative to reduce GHG emissions through making various "wise choices" in daily life, such as changing products, using services and choosing a lifestyle that helps create a decarbonized society. Besides, it is worth noting that at this stage, there is no clear policy targeting on CO_2 emissions embodied in domestic trade in Japan. Therefore, systematically considering the impact of household consumption and domestic trade on Japan’s overall emissions can provide Japan with the potential for further emission reduction. Meanwhile, countermeasures against CO_2 emissions must fully consider the impact of intra-regional and inter-regional carbon inequality, so as to avoid social conflicts. Specifically, the following policy implications are proposed based on our findings:

It is necessary to pay more attention to the impact of consumption-based CO_2 emissions on the overall emission reduction, and further comprehend the characteristics of HCF and traded CO_2 emissions on the basis of clarifying the economic development, age structure, household type,

[9] ZEH: On the basis of reducing household energy consumption by more than 20%, Japanese Government will further reduce energy consumption by introducing renewable energy, and finally classify household buildings according to the energy-saving results.

and income level. Household consumption and domestic trade interact with each other, and they both are important parts of the economy across prefectures. The consumption characteristics of each prefecture will be reflected in the domestic imports and exports. Therefore, every prefecture should have an extensive understanding of consumption related conditions, which include consumption trends within and outside the prefecture.

Emission reduction policies must be adapted to the economic level in each prefecture to provide a social basis for sustainable development. The economic situation of low-GRP prefectures with serious carbon inequality can be improved by developing a green economy that generates increased employment opportunities and augments the overall income of households. Although carbon inequality is alleviated in high-GRP prefectures, the overall HCF in these localities is considerable. An essential measure, therefore, is to adjust the household consumption structure in high-GRP prefectures by increasing the market share of low-carbon commodities and reducing the carbon intensity of household consumption through price influence.

Since the aging, shrinking society issue occurs over a very long-time span, emission reduction policies should be continuously adjusted according to the evolution of demographic changes. With the continuous increase in the proportion of elderly people, household-related sectors need to pay more attention to the CO_2 emissions from consumption by household over 50s. Based on the regional gap in HCF caused by household types, the responsibilities must be further distributed to reduce carbon inequality. For high-GRP prefectures, multi-person households can reduce the HCF of overall income groups by adjusting the household consumption base and promoting low-carbon, energy-efficient household consumption. For low-GRP prefectures, the emission reduction of both multi- and single-person households can consider carbon inequality as the point of penetration, which can not only narrow the social income gap but also reduce the polarization of HCF caused by extremely high or low incomes.

The premise of emission reduction is to maintain the normal supply–demand relationship of Japan's domestic trade. The responsibility for emission reduction is attributable to both manufacturing and consumer prefectures; thus, it is necessary to focus on the net export CO_2 emissions of manufacturing prefectures while paying attention to the carbon output of consumer prefectures. The Japanese government can enhance the synergy between producers and consumers. For the main carbon net exporters of manufacturing prefectures, it can improve the proportion of high-end products in the raw material processing industry in the industrial chain and promote the upgrading of the overall industrial structure while driving enterprises to adjust production. Consumer prefectures share responsibility for emissions, given that their demand induces emissions from production. Consumer prefectures can increase their market shares of low-carbon products through financial support, and by adjusting market demand to promote a low-carbon production structure. Moreover, for the service sector in consumer prefectures, emphasis should be placed on improving energy efficiency and promoting innovation in energy technologies to reduce energy consumption in the production process.

Finally, in addition to the domestic perspective in Japan, this research can provide insights with international applicability for climate mitigation. Achieving the goal of emission mitigation under the constraints of an aging society and household consumption has important practical significance for many countries. Although the aging society is a serious issue in Japan, this issue is also emerging in the other developed countries, even for developing countries, like China. Meanwhile, clarifying regional differences in HCF and carbon inequality in Japan also has important reference value for research on consumption-based mitigation in other countries. Evaluating the CO_2 emissions from domestic trade is conducive to longer-term emission reduction, which is helpful to balance the supply-demand relationship between regions for every country. Both domestic and international trade are important supports for each country's economy. However, there is a certain degree of instability in international trade because of the changing international political situation. Meanwhile, expanding domestic demand to form new economic growth points is an important way of sustaining economic development in the 21st century. Therefore, it can be predicted that additional countries and regions will pay attention to domestic consumption, which will increase the CO_2 emissions embodied in domestic trade.

Acknowledgement:
First of all, I am grateful to my family for their unflinching support for my study abroad. The warmth of my parents, like a lighthouse, give me the courage to move forward, even in the face of all the unknown storms, I can start at ease.

I would like to express my deepest appreciations and gratitude to Professor Ken'ichi Matsumoto for his direction, instruction, perseverance, acumen and inspirations throughout my doctoral studies. Every time I was confused, Professor Matsumoto helped me and gave me his learning experience, which to a large extent strengthened my confidence in the future research.

I would like to thank my supervisor Professor Kensuke Katayama, for his meticulous help to my study and life, which contributed to the smooth progress of my research. Meanwhile, in the process of getting along with Professor Katayama, I greatly admire his professional ability and understanding of student.

I would like to thank my subadvisor Professor Yosuke Shigetomi. It is precisely because of the guidance and help of Professor Shigetomi that my doctoral research continued to have staged breakthroughs and achievements. Moreover, the patience and enthusiasm of Professor Shigetomi made me feel the warmth between teachers and students.

I would also like to express thanks to Professor Sunhee Suk. Every time I participate in Professor Suk's class, I feel not only the professional quality, but also the harmonious atmosphere between teacher and students. Meanwhile, I sincerely thank Professor Suk for taking the time and effort to provide me with insightful guidance of doctoral thesis.

I also extend my best gratitude to my love Yuting Zheng for her endless support whenever I called for. Thank you for sharing all my life and feelings.

Last but not least I would also like to thank my alma mater, Nagasaki University, especially the Graduate School of Fisheries and Environmental Sciences. Thank my alma mater for giving me the opportunity to further my studies and making me a better person. Meanwhile, thank all the staff who diligently provide education support assistance for students, you all have become an important part of my doctoral study.

Reference

Adebayo, T. S. (2021). Do CO_2 emissions, energy consumption and globalization promote economic growth? Empirical evidence from Japan. *Environmental Science and Pollution Research*, *28*(26), 34714–34729. https://doi.org/10.1007/s11356-021-12495-8

Agency for Natural Resources and Energy of Japan. (2019). *Comprehensive Energy Statistics*. https://www.enecho.meti.go.jp/statistics/total_energy/results.html (Accessed July 10, 2022).

Agency for Natural Resources and Energy of Japan. (2021). *Comprehensive Energy Statistics*. https://www.enecho.meti.go.jp/statistics/total_energy/results.html (Accessed October 27, 2021).

Ajmi, A. N., Hammoudeh, S., Nguyen, D. K., & Sato, J. R. (2013). On the relationships between CO_2 emissions, energy consumption and income: The importance of time variation. *Energy Economics*, *49*, 629–638. https://doi.org/10.1016/j.eneco.2015.02.007

Alcántara, V., & Padilla, E. (2009). Input-output subsystems and pollution: An application to the service sector and CO_2 emissions in Spain. *Ecological Economics*, *68*(3), 905–914. https://doi.org/10.1016/j.ecolecon.2008.07.010

Ang, B., Zhang, F., & Choi, K. H. (1998). Factorizing changes in energy and environmental indicators through decomposition. *Energy*, *23*(6), 489–495. https://doi.org/10.1016/S0360-5442(98)00016-4

Ang, B. W., & Zhang, F. Q. (2000). A survey of index decomposition analysis in energy and environmental studies. *Energy*, *25*(12), 1149–1176. https://doi.org/10.1016/S0360-5442(00)00039-6

Automobile Inspection and Registration Information Association. (2022). *Motor Vehicles Owned by Kind (F.Y.1966-2022).* https://www.airia.or.jp/publish/statistics/number.html (Accessed October 20, 2019).

Cabinet Office of Japanese government. (2019). *2019 White Paper on the Aging Society*. https://www8.cao.go.jp/kourei/whitepaper/index-w.html (Accessed August 27, 2022).

Cabinet Office of Japanese government. (2011). *The regional economy of 2011*. https://www5.cao.go.jp/j-j/cr/cr11/cr11.html (Accessed October 20, 2022).

Cabinet Office of Japanese government. (2015). *Prefectural economic calculation*. https://www.esri.cao.go.jp/jp/sna/sonota/kenmin/kenmin_top.html (Accessed October 20, 2022).

Caeiro, S., Ramos, T. B., & Huisingh, D. (2012). Procedures and criteria to develop and evaluate household sustainable consumption indicators. *Journal of Cleaner Production*, *27*, 72–91. https://doi.org/10.1016/j.jclepro.2011.12.026

Cárdenas-Mamani, Ú., Kahhat, R., & Vázquez-Rowe, I. (2022). District-level analysis for household-related energy consumption and greenhouse gas emissions: A case study in Lima, Peru. *Sustainable Cities and Society*, *77*, 103572. https://doi.org/10.1016/j.scs.2021.103572

Chan, Y. C. (2014). How does retail sentiment affect IPO returns? Evidence from the internet bubble period. *International Review of Economics and Finance*, *29*, 235–248. https://doi.org/10.1016/j.iref.2013.05.016

Choi, Y., Hirata, H., & Kim, S. H. (2017). Tax reform in Japan: Is it welfare-enhancing? *Japan and the World Economy*, *42*, 12–22. https://doi.org/10.1016/j.japwor.2017.07.002

Claudelin, A., Järvelä, S., Uusitalo, V., Leino, M., & Linnanen, L. (2018). The economic potential to support sustainability through household consumption choices. *Sustainability*, *10*(11). https://doi.org/10.3390/su10113961

Climate Change Convention. GHG Time Series Data from UNFCCC 2019. https://di.unfccc.int/time_series (Accessed October 20, 2022).

Crippa, M., Oreggioni, G., Guizzardi, D., Muntean, M., Schaaf, E., Lo Vullo, E., Solazzo, E., Monforti-Ferrario, F., Olivier, J., & Vignati, E. (2019). *Fossil CO_2 &GHG emissions of all world countries*. https://doi.org/10.2760/687800

Dai, H. C., Zhang, H. Bin, & Wang, W. T. (2017). The impacts of U.S. withdrawal from the Paris Agreement on the carbon emission space and mitigation cost of China, EU, and Japan under the constraints of the global carbon emission space. *Advances in Climate Change Research*, *8*(4), 226–234. https://doi.org/10.1016/j.accre.2017.09.003

Dalton, H. (1920). The Measurement of the Inequality of Incomes. *The Economic Journal*, *30*(119), 348. https://doi.org/10.2307/2223525

Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(12), 5687–5692. https://doi.org/10.1073/pnas.0906974107

Destek, M. A., Shahbaz, M., Okumus, I., Hammoudeh, S., & Sinha, A. (2020). The relationship between economic growth and carbon emissions in G-7 countries: evidence from time-varying parameters with a long history. *Environmental Science and Pollution Research*, *27*(23), 29100–29117. https://doi.org/10.1007/s11356-020-09189-y

Dietzenbacher, E., & Los, B. (1998). Structural Decomposition Techniques: Sense and

Sensitivity. *Economic Systems Research*, *10*(4), 307–324. https://doi.org/10.1080/09535319800000023

Donglan, Z., Dequn, Z., & Peng, Z. (2010). Driving forces of residential CO_2 emissions in urban and rural China: An index decomposition analysis. *Energy Policy*, *38*(7), 3377–3383. https://doi.org/10.1016/j.enpol.2010.02.011

Druckman, A., & Jackson, T. (2010). An Exploration Into the Carbon Footprint of UK Households. *Research Group on Lifestyles, Values and Environment*, resolve working paper 02-10. http://www.surrey.ac.uk/resolve/Docs/WorkingPapers/RESOLVE_WP_02-10.pdf

East, A. J. (2008). What is a carbon footprint? An overview of definitions and methodologies. *Vegetable industry carbon footprint scoping study*, discussion papers and workshop, *26*. Sydney: Horticulture Australia Limited.

Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., Takeuchi, K., & Folke, C. (2019). Sustainability and resilience for transformation in the urban century. *Nature Sustainability*, *2*(4), 267–273. https://doi.org/10.1038/s41893-019-0250-1

Feng, K., Davis, S. J., Sun, L., & Hubacek, K. (2015). Drivers of the US CO_2 emissions 1997–2013. *Nature Communications*, *6*, 7714. https://doi.org/10.1038/ncomms8714

Feng, K., Hubacek, K., & Song, K. (2021). Household carbon inequality in the U.S. *Journal of Cleaner Production*, *278*, 123994. https://doi.org/10.1016/j.jclepro.2020.123994

Fischer, D., Stanszus, L., Geiger, S., Grossman, P., & Schrader, U. (2017). Mindfulness and sustainable consumption: A systematic literature review of research approaches and findings. *Journal of Cleaner Production*, *162*, 544–558. https://doi.org/10.1016/j.jclepro.2017.06.007

Furukawa, S. (2010). Local Decentralization in Japan. *Local Government Law Journal*, *10*(3), 35–63. https://doi.org/10.21333/lglj.2010.10.3.002

Greenhouse Gas Inventory Office. (2022). *Japan Greenhouse Gas Inventory Report*. https://www.nies.go.jp/gio/aboutghg/index.html (Accessed December 3, 2022).

Gu, Z. H., Sun, Q., & Wennersten, R. (2013). Impact of urban residences on energy consumption and carbon emissions: An investigation in Nanjing, China. *Sustainable Cities and Society*, *7*, 52–61. https://doi.org/10.1016/j.scs.2012.11.004

Guan, D., Hubacek, K., Weber, C. L., Peters, G. P., & Reiner, D. M. (2008). The drivers of Chinese CO_2 emissions from 1980 to 2030. *Global Environmental Change*, *18*(4), 626–

634. https://doi.org/10.1016/j.gloenvcha.2008.08.001

Gupta, S., & Bhandari, P. M. (1999). An effective allocation criterion for CO_2 emissions. *Energy Policy*, *27*(12), 727–736. https://doi.org/10.1016/S0301-4215(99)00058-0

Hailemariam, A., Dzhumashev, R., & Shahbaz, M. (2020). Carbon emissions, income inequality and economic development. *Empirical Economics*, *59*(3), 1139–1159. https://doi.org/10.1007/s00181-019-01664-x

Hasegawa, R., Kagawa, S., & Tsukui, M. (2015). Carbon footprint analysis through constructing a multi-region input–output table: a case study of Japan. *Journal of Economic Structures*, *4*(1). https://doi.org/10.1186/s40008-015-0015-6

Hata, S., Nansai, K., & Nakajima, K. (2022). Fixed-capital formation for services in Japan incurs substantial carbon-intensive material consumption. *Resources, Conservation and Recycling*, *182,* 106334. https://doi.org/10.1016/j.resconrec.2022.106334

He, H., Reynolds, C. J., Li, L., & Boland, J. (2019). Assessing net energy consumption of Australian economy from 2004–05 to 2014–15: Environmentally-extended input-output analysis, structural decomposition analysis, and linkage analysis. *Applied Energy*, *240,* 766–777. https://doi.org/10.1016/j.apenergy.2019.02.081

Hertwich, E. G. (2011). The Life Cycle Environmental Impacts Of Consumption. *Economic Systems Research*, *23*(1), 27–47. https://doi.org/10.1080/09535314.2010.536905

Hertwich, E. G., & Peters, G. P. (2009). Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science and Technology*, *43*(16), 6414–6420. https://doi.org/10.1021/es803496a

Hirano, Y., Ihara, T., & Yoshida, Y. (2016). Estimating residential CO_2 emissions based on daily activities and consideration of methods to reduce emissions. *Building and Environment*, *103*, 1–8. https://doi.org/10.1016/j.buildenv.2016.02.021

Hoekstra, R., & van den Bergh, J. C. J. M. (2003). Comparing structural decomposition analysis and index. *Energy Economics*, *25*(1), 39–64. https://doi.org/10.1016/S0140-9883(02)00059-2

Hubacek, K., Baiocchi, G., Feng, K., Muñoz Castillo, R., Sun, L., & Xue, J. (2017). Global carbon inequality. *Energy, Ecology and Environment*, *2*(6), 361–369. https://doi.org/10.1007/s40974-017-0072-9

Hubacek, K., Baiocchi, G., Feng, K., & Patwardhan, A. (2017). Poverty eradication in a carbon constrained world. *Nature Communications*, *8*(1), 1–8. https://doi.org/10.1038/s41467-017-00919-4

Inoue, N., Matsumoto, S., & Mayumi, K. (2022). Household energy consumption pattern changes in an aging society: the case of Japan between 1989 and 2014 in retrospect. *International Journal of Economic Policy Studies*, *16*(1), 67–83. https://doi.org/10.1007/s42495-021-00069-y

Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., & Hertwich, E. G. (2016). Environmental Impact Assessment of Household Consumption. *Journal of Industrial Ecology*, *20*(3), 526–536. https://doi.org/10.1111/jiec.12371

Ivanova, D., & Wood, R. (2020). The unequal distribution of household carbon footprints in Europe and its link to sustainability. *Global Sustainability*, *3*. https://doi.org/10.1017/sus.2020.12

Japan Center for Climate Change Actions. (2021). *Trends in carbon dioxide emissions by sector in Japan (1990-2019)*. https://www.jccca.org/oyakudachi/download-list (Accessed January 27, 2022).

Javid, M., & Khan, M. (2020). Energy efficiency and underlying carbon emission trends. *Environmental Science and Pollution Research*, *27*(3), 3224–3236. https://doi.org/10.1007/s11356-019-07019-4

Jiang, Y., Cai, W., Wan, L., & Wang, C. (2015). An index decomposition analysis of China's interregional embodied carbon flows. *Journal of Cleaner Production*, *88*, 289–296. https://doi.org/10.1016/j.jclepro.2014.04.075

Jones, C. M., & Kammen, D. M. (2011). Quantifying carbon footprint reduction opportunities for U.S. households and communities. *Environmental Science and Technology*, *45*(9), 4088–4095. https://doi.org/10.1021/es102221h

Kim, T. J., & Tromp, N. (2021a). Analysis of carbon emissions embodied in South Korea's international trade: Production-based and consumption-based perspectives. *Journal of Cleaner Production*, *320*, 128839. https://doi.org/10.1016/j.jclepro.2021.128839

Kim, T. J., & Tromp, N. (2021b). Carbon emissions embodied in China-Brazil trade: Trends and driving factors. *Journal of Cleaner Production*, *293*, 126206. https://doi.org/10.1016/j.jclepro.2021.126206

Kitzes, J. (2013). An introduction to environmentally-extended input-output analysis. *Resources*, *2*(4), 489–503. https://doi.org/10.3390/resources2040489

Lenzen, M. (2016). Structural analyses of energy use and CO_2 emissions – an overview. *Economic Systems Research*, *28*(2), 119–132. https://doi.org/10.1080/09535314.2016.1170991

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics*, *52*(3), 262. https://doi.org/10.2307/1926294

Lin, B., & Xie, X. (2016). CO_2 emissions of China's food industry: An input-output approach. *Journal of Cleaner Production*, *112*, 1410–1421. https://doi.org/10.1016/j.jclepro.2015.06.119

Liu, H., Zong, Z., Hynes, K., & De Bruyne, K. (2020). Can China reduce the carbon emissions of its manufacturing exports by moving up the global value chain? *Research in International Business and Finance*, *51*, 101101. https://doi.org/10.1016/j.ribaf.2019.101101

Liu, X., Wang, X., Song, J., Wang, H., & Wang, S. (2019). Indirect carbon emissions of urban households in China: Patterns, determinants and inequality. *Journal of Cleaner Production*, *241*(2019), 118335. https://doi.org/10.1016/j.jclepro.2019.118335

Long, R., Li, J., Chen, H., Zhang, L., & Li, Q. (2018). Embodied carbon dioxideflow in international trade: A comparative analysis based on China and Japan. *Journal of Environmental Management*, *209*, 371–381. https://doi.org/10.1016/j.jenvman.2017.12.067

Long, Y., Dong, L., Yoshida, Y., & Li, Z. (2018). Evaluation of energy-related household carbon footprints in metropolitan areas of Japan. *Ecological Modelling*, *377*, 16–25. https://doi.org/10.1016/j.ecolmodel.2018.03.008

Long, Y., Jiang, Y., Chen, P., Yoshida, Y., Sharifi, A., Gasparatos, A., Wu, Y., Kanemoto, K., Shigetomi, Y., & Guan, D. (2021). Monthly direct and indirect greenhouse gases emissions from household consumption in the major Japanese cities. *Scientific Data*, *8*(1), 1–11. https://doi.org/10.1038/s41597-021-01086-4

Long, Y., Yoshida, Y., & Dong, L. (2017). Exploring the indirect household carbon emissions by source: Analysis on 49 Japanese cities. *Journal of Cleaner Production*, *167*, 571–581. https://doi.org/10.1016/j.jclepro.2017.08.159

Long, Y., Yoshida, Y., Liu, Q., Guan, D., Zheng, H., Li, Y., & Gasparatos, A. (2021). Japanese carbon emissions patterns shifted following the 2008 financial crisis and the 2011 Tohoku earthquake. *Communications Earth & Environment*, *2*(1), 1–12. https://doi.org/10.1038/s43247-021-00194-8

Long, Y., Yoshida, Y., Meng, J., Guan, D., Yao, L., & Zhang, H. (2019). Unequal age-based household emission and its monthly variation embodied in energy consumption – A case study of Tokyo, Japan. *Applied Energy*, *247*, 350–362. https://doi.org/10.1016/j.apenergy.2019.04.019

López, L. A., Arce, G., Morenate, M., & Monsalve, F. (2016). Assessing the Inequality of Spanish Households through the Carbon Footprint: The 21st Century Great Recession Effect. *Journal of Industrial Ecology*, *20*(3), 571–581. https://doi.org/10.1111/jiec.12466

Lu, H. F., Lin, B. Le, Campbell, D. E., Sagisaka, M., & Ren, H. (2016). Interactions among energy consumption, economic development and greenhouse gas emissions in Japan after World War II. *Renewable and Sustainable Energy Reviews*, *54*, 1060–1072. https://doi.org/10.1016/j.rser.2015.10.062

Mangır, N., & Şahin, Ü. A. (2022). An environmentally extended global multi-regional input–output analysis of consumption-based and embodied import-based carbon emissions of Turkey. *Environmental Science and Pollution Research*, *29*(36), 54813–54826. https://doi.org/10.1007/s11356-022-19290-z

Matsuhashi, K., & Ariga, T. (2016). Estimation of passenger car CO_2 emissions with urban population density scenarios for low carbon transportation in Japan. *IATSS Research*, *39*(2), 117–120. https://doi.org/10.1016/j.iatssr.2016.01.002

Matsumoto, K., Shigetomi, Y., Shiraki, H., Ochi, Y., Ogawa, Y., & Ehara, T. (2019). Addressing key drivers of regional CO_2 emissions of the manufacturing industry in Japan. *The Energy Journal*, *40*(01), 3–8. https://doi.org/10.5547/01956574.40.si1.kmat

Matsumoto, S. (2022). How will a carbon tax affect household energy source combination? *Energy Strategy Reviews*, *40*, 100823. https://doi.org/10.1016/j.esr.2022.100823

Ministry of Health Labour and Welfare. (2018). *National Livelihood Survey*. https://www.e-stat.go.jp/stat-search/files?page=1&toukei=00450061 (Accessed October 20, 2022).

Mi, Z., Zheng, J., Meng, J., Ou, J., Hubacek, K., Liu, Z., Coffman, D. M., Stern, N., Liang, S., & Wei, Y. M. (2020). Economic development and converging household carbon footprints in China. *Nature Sustainability*, *3*(7), 529–537. https://doi.org/10.1038/s41893-020-0504-y

Ministry of Economy Trade and Industry Agency for Natural Resources and Energy. (2021). *Energy White Paper 2021*. https://www.enecho.meti.go.jp/about/whitepaper/2021/pdf/. (Accessed August 24, 2022).

Ministry of the Environment Government of Japan. (2021). *Global Warming Countermeasure Plan of Japan*. https://www.env.go.jp/earth/ondanka/keikaku/211022.html (Accessed October 20, 2022).

Ministry of the Environment Government of Japan. (2021). *What is carbon neutrality*. https://ondankataisaku.env.go.jp/carbon_neutral/about/ (Accessed October 20, 2022).

Ministry of the Environment Government of Japan. (2022). *Global Warming Countermeasures Plan*. https://www.env.go.jp/earth/ondanka/keikaku/211022.html (Accessed October 20, 2022).

Ministry of Economy, Trade and Industry. (2015). *White paper on manufacturing infra-structure*. https://www.meti.go.jp/report/whitepaper/index_mono.html (Accessed August 24, 2022).

Ministry of Internal Affairs and Communications. (2006). *National census (2005)*. https://www.e-stat.go.jp/stat-search/files?page=1&toukei=00200521 (Accessed August 16, 2022).

Ministry of Internal Affairs and Communications. (2015a). *Input-output table of Japan (2015)*. https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00200603&tstat=000001130583&cycle=0&year=20150&month=0. (Accessed January 27, 2022).

Ministry of Internal Affairs and Communications. (2015b). *National survey of family income and expenditure in 2004*. https://www.stat.go.jp/data/zensho/2004/index.html (Accessed October 27, 2021).

Ministry of Internal Affairs and Communications. (2017). *NSFIE; National Survey of Family Income and Expenditure*. https://www.e-stat.go.jp/stat-search/files?page=1&toukei=00200564&tstat=000000640002. (Accessed October 20, 2022).

Ministry of Internal Affairs and Communications. (2020). *National census (2020)*. https://www.e-stat.go.jp/stat-search/files?page=1&toukei=00200521&tstat=000001136464. (Accessed June 15, 2022).

Ministry of Land Infrastructure Transport and Tourism. (2016). *National cargo netflow survey*. https://www.mlit.go.jp/sogoseisaku/transport/butsuryu06100.html (Accessed October 20, 2022).

Ministry of the Environment of Japan. (2021). *Status of 2050 carbon neutrality statement by local governments*. https://www.env.go.jp/policy/zerocarbon.html (Accessed October 20, 2022).

Mirzaei, S., Borzadaran, G. R. M., Amini, M., & Jabbari, H. (2017). A comparative study of the Gini coefficient estimators based on the regression approach. *Communications for Statistical Applications and Methods*, *24*(4), 339–351. https://doi.org/10.5351/CSAM.

2017.24.4.339

Miura, T., Tamaki, T., Kii, M., & Kajitani, Y. (2021). Efficiency by sectors in areas considering CO_2 emissions: The case of Japan. *Economic Analysis and Policy*, *70*, 514–528. https://doi.org/10.1016/j.eap.2021.04.004

Munksgaard, J., & Pedersen, K. A. (2001). CO_2 accounts for open economies: Producer or consumer responsibility? *Energy Policy*, *29*(4), 327–334. https://doi.org/10.1016/S0301-4215(00)00120-8

Munksgaard, J., Pedersen, K. A., & Wien, M. (2000). Impact of household consumption on CO_2 emissions. *Energy Economics*, *22*(4), 423–440. https://doi.org/10.1016/S0140-9883(99)00033-X

Nansai, K., Kagawa, S., Kondo, Y., Suh, S., Nakajima, K., Inaba, R., Oshita, Y., Morimoto, T., Kawashima, K., Terakawa, T., & Tohno, S. (2012). Characterization of economic requirements for a "carbon-debt-free country." *Environmental Science and Technology*, *46*(1), 155–163. https://doi.org/10.1021/es202007b

National Institute for Environmental Studies. (2013). *Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables*. https://www.cger.nies.go.jp/publications/report/d031/jpn/datafile/index.htm (Accessed January 10, 2019).

Nguyen, Q. T., Trinh, B., Ngo, T. L., & Tran, M. D. (2020). Analysis of bilateral input-output trading between Vietnam and China. *Journal of Asian Finance, Economics and Business*, *7*(6), 157–172. https://doi.org/10.13106/JAFEB.2020.VOL7.NO6.157

National Institute of Population and Social Security Research. (2018). *Future estimation of the number of Japanese households (national estimation)*. https://www.ipss.go.jp/pp-ajsetai/j/HPRJ2018/t-page.asp (Accessed October 20, 2022).

Okushima, S., & Tamura, M. (2007). Multiple calibration decomposition analysis: Energy use and carbon dioxide emissions in the Japanese economy, 1970-1995. *Energy Policy*, *35*(10), 5156–5170. https://doi.org/10.1016/j.enpol.2007.04.001

Oshiro, K., & Masui, T. (2015). Diffusion of low emission vehicles and their impact on CO_2 emission reduction in Japan. *Energy Policy*, *81*, 215–225. https://doi.org/10.1016/j.enpol.2014.09.010

Pan, J., Phillips, J., & Chen, Y. (2008). China's balance of emissions embodied in trade: Approaches to measurement and allocating international responsibility. *Oxford Review of Economic Policy*, *24*(2), 354–376. https://doi.org/10.1093/oxrep/grn016

Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics*, *65*(1), 13–23. https://doi.org/10.1016/j.ecolecon.2007.10.014

Peters, G. P., & Hertwich, E. G. (2008). CO_2 embodied in international trade with implications for global climate policy. *Environmental Science and Technology*, *42*(5), 1401–1407. https://doi.org/10.1021/es072023k

Princen, T. (1999). Consumption and environment: Some conceptual issues. *Ecological Economics*, *31*(3), 347–363. https://doi.org/10.1016/S0921-8009(99)00039-7

Quan, C., Cheng, X., Yu, S., & Ye, X. (2020). Analysis on the influencing factors of carbon emission in China's logistics industry based on LMDI method. *Science of the Total Environment*, *734*, 138473. https://doi.org/10.1016/j.scitotenv.2020.138473

Rose, A., & Casler, S. (1996). Input-output structural decomposition analysis: a critical appraisal. *Economic Systems Research*, *8*(1), 33–62. https://doi.org/10.1080/09535319600000003

Sato, M. (2014). Embodied carbon in trade: A survey of the empirical literature. *Journal of Economic Surveys*, *28*(5), 831–861. https://doi.org/10.1111/joes.12027

Seriño, M. N. V., & Klasen, S. (2015). Estimation and determinants of the Philippines' household carbon footprint. *Developing Economies*, *53*(1), 44–62. https://doi.org/10.1111/deve.12065

Shah, I. H. (2021). The metabolic transition of material use and carbon emissions in economically growing Asia: Evidence from 1971 to 2016. *Environmental Science and Pollution Research*, *28*(3), 2707–2718. https://doi.org/10.1007/s11356-020-10662-x

Shigetomi, Y., Kanemoto, K., Yamamoto, Y., & Kondo, Y. (2021). Quantifying the carbon footprint reduction potential of lifestyle choices in Japan. *Environmental Research Letters*, *16*(6). https://doi.org/10.1088/1748-9326/abfc07

Shigetomi, Y., Matsumoto, K., Ogawa, Y., Shiraki, H., Yamamoto, Y., Ochi, Y., & Ehara, T. (2018). Driving forces underlying sub-national carbon dioxide emissions within the household sector and implications for the Paris Agreement targets in Japan. *Applied Energy*, *228*, 2321–2332. https://doi.org/10.1016/j.apenergy.2018.07.057

Shigetomi, Y., Nansai, K., Kagawa, S., & Tohno, S. (2014). Changes in the carbon footprint of Japanese households in an aging society. *Environmental Science and Technology*, *48*(11), 6069–6080. https://doi.org/10.1021/es404939d

Shigetomi, Y., Nansai, K., Kagawa, S., & Tohno, S. (2015). Trends in Japanese households' critical-metals material footprints. *Ecological Economics*, *119*, 118–126.

https://doi.org/10.1016/j.ecolecon.2015.08.010

Shigetomi, Y., Nansai, K., Kagawa, S., & Tohno, S. (2016). Influence of income difference on carbon and material footprints for critical metals: the case of Japanese households. *Journal of Economic Structures*, *5*(1). https://doi.org/10.1186/s40008-015-0033-4

Shigetomi, Y., Nansai, K., Kagawa, S., & Tohno, S. (2018). Fertility-rate recovery and double-income policies require solving the carbon gap under the Paris Agreemen-t. *Resources, Conservation and Recycling*, *133*, 385–394. https://doi.org/10.1016/j.resconrec.2017.11.017

Sommer, M., & Kratena, K. (2017). The Carbon Footprint of European Households and Income Distribution. *Ecological Economics*, *136*, 62–72. https://doi.org/10.1016/j.ecolecon.2016.12.008

Song, K., Qu, S., Taiebat, M., Liang, S., & Xu, M. (2019). Scale, distribution and variations of global greenhouse gas emissions driven by U.S. households. *Environment International*, *133*, 105137. https://doi.org/10.1016/j.envint.2019.105137

Sovacool, B. K., Kester, J., Noel, L., & de Rubens, G. Z. (2018). The demographics of decarbonizing transport: The influence of gender, education, occupation, age, and household size on electric mobility preferences in the Nordic region. *Global Environmental Change*, *52*, 86–100. https://doi.org/10.1016/j.gloenvcha.2018.06.008

Statistics Bureau. (2011). *National Census*. https://www.stat.go.jp/data/kokusei/2010/ (Accessed August 21, 2022).

Statistics Bureau. (2017). *Social life basic survey*. https://www.e-stat.go.jp/stat-search/files?page=1&toukei=00200533&tstat=000000000322 (Accessed January 27, 2022).

Statistics Bureau. (2010). *National Census*. https://www.e-stat.go.jp/stat-search/files?page=1&toukei=00200521&tstat=000001007251&result_page=1 (Accessed October 20, 2022).

Statistics Bureau. (2015). *The Statistics of Japan (2009)*. https://www.stat.go.jp/data/nihon/index2.html (Accessed October 20, 2022).

Sun, J. W. (1998). Changes in energy consumption and energy intensity: A complete decomposition model. *Energy Economics*, *20*(1), 85–100. https://doi.org/10.1016/S0140-9883(97)00012-1

Sun, M., Chen, G., Xu, X., Zhang, L., Hubacek, K., & Wang, Y. (2021). Reducing Carbon Footprint Inequality of Household Consumption in Rural Areas: Analysis from Five Representative Provinces in China. *Environmental Science and Technology*, *55*(17), 11511–11520. https://doi.org/10.1021/acs.est.1c01374

Sun, Y. Y., Cadarso, M. A., & Driml, S. (2020). Tourism carbon footprint inventories: A review of the environmentally extended input-output approach. *Annals of Tourism Research*, *82*, 102928. https://doi.org/10.1016/j.annals.2020.102928

Tian, K., Zhang, Y., Li, Y., Ming, X., Jiang, S., Duan, H., Yang, C., & Wang, S. (2022). Regional trade agreement burdens global carbon emissions mitigation. *Nature Communications*, *13*(1), 1–12. https://doi.org/10.1038/s41467-022-28004-5

United Nations. (2015). *Sustainable Development Goals*. https://www.undp.org/sustainable-development-goals (Accessed January 27, 2022).

Wackernagel, M., & Rees, W. (1998). *Our ecological footprint: reducing human impact on the earth* (Vol. 9). New society publishers.

Wakiyama, T., Lenzen, M., Geschke, A., Bamba, R., & Nansai, K. (2020). A flexible multiregional input–output database for city-level sustainability footprint analysis in Japan. *Resources, Conservation and Recycling*, *154*, 104588. https://doi.org/10.1016 /j.resconrec.2019.104588

Wang, J., & Yuan, R. (2022). Inequality in urban and rural household CO_2 emissions of China between income groups and across consumption categories. *Environmental Impact Assessment Review*, *94*, 106738. https://doi.org/10.1016/j.eiar.2022.106738

Wang, Q., Liu, Y., & Wang, H. (2019). Determinants of net carbon emissions embodied in Sino-German trade. *Journal of Cleaner Production*, *235*, 1216–1231. https://doi.org/10.1016/j.jclepro.2019.07.011

Wang, Q., & Zhou, Y. (2019). Imbalance of carbon emissions embodied in the US-Japan trade: temporal change and driving factors. *Journal of Cleaner Production*, *237*, 117780. https://doi.org/10.1016/j.jclepro.2019.117780

Wang, Q., & Han, X. (2021). Is decoupling embodied carbon emissions from economic output in Sino-US trade possible? *Technological Forecasting and Social Change*, *169*, 120805. https://doi.org/10.1016/j.techfore.2021.120805

Wang, Q., Kwan, M. P., Zhou, K., Fan, J., Wang, Y., & Zhan, D. (2019). Impacts of residential energy consumption on the health burden of household air pollution: Evidence from 135 countries. *Energy Policy*, *128*, 284–295. https://doi.org/10.1016/j.enpol.2018.12.037

Wang, Q., & Yang, X. (2020). Imbalance of carbon embodied in South-South trade: Evidence from China-India trade. *Science of the Total Environment*, *707*, 134473. https://doi.org/10.1016/j.scitotenv.2019.134473

Wang, Q., & Zhou, Y. (2019). Uncovering embodied CO_2 flows via North-North trade – A case study of US-Germany trade. *Science of the Total Environment*, *691*, 943–959. https://doi.org/10.1016/j.scitotenv.2019.07.171

Wang, S., Zhao, Y., & Wiedmann, T. (2019). Carbon emissions embodied in China–Australia trade: A scenario analysis based on input–output analysis and panel regression models. *Journal of Cleaner Production*, *220*, 721–731. https://doi.org/10.1016/j.jclepro.2019.02.071

Wang, W., & Hu, Y. (2020). The measurement and influencing factors of carbon transfers embodied in inter-provincial trade in China. *Journal of Cleaner Production*, *270*(19), 122460. https://doi.org/10.1016/j.jclepro.2020.122460

Wang, Y., Xiong, S., & Ma, X. (2022). Carbon inequality in global trade: Evidence from the mismatch between embodied carbon emissions and value added. *Ecological Economics*, *195*, 107398. https://doi.org/10.1016/j.ecolecon.2022.107398

Wang, Z., & Yang, L. (2014). Indirect carbon emissions in household consumption: Evidence from the urban and rural area in China. *Journal of Cleaner Production*, *78*, 94–103. https://doi.org/10.1016/j.jclepro.2014.04.041

Wei, J., Huang, K., Yang, S., Li, Y., Hu, T., & Zhang, Y. (2017). Driving forces analysis of energy-related carbon dioxide (CO_2) emissions in Beijing: an input–output structural decomposition analysis. *Journal of Cleaner Production*, *163*, 58–68. https://doi.org/10.1016/j.jclepro.2016.05.086

Wei, W., Hao, S., Yao, M., Chen, W., Wang, S., Wang, Z., Wang, Y., & Zhang, P. (2020). Unbalanced economic benefits and the electricity-related carbon emissions embodied in China's interprovincial trade. *Journal of Environmental Management*, *263*, 110390. https://doi.org/10.1016/j.jenvman.2020.110390

Weidema, B. P., Thrane, M., Christensen, P., Schmidt, J., & Løkke, S. (2008). Carbon footprint: A catalyst for life cycle assessment? *Journal of Industrial Ecology*, *12*(1), 3–6. https://doi.org/10.1111/j.1530-9290.2008.00005.x

Wiedenhofer, D., Guan, D., Liu, Z., Meng, J., Zhang, N., & Wei, Y. M. (2017). Unequal household carbon footprints in China. *Nature Climate Change*, *7*(1), 75–80. https://doi.org/10.1038/nclimate3165

Wiedenhofer, D., Smetschka, B., Akenji, L., Jalas, M., & Haberl, H. (2018). Household time use, carbon footprints, and urban form: a review of the potential contributions of everyday living to the 1.5 °C climate target. *Current Opinion in Environmental Sustainability*, *30*, 7–17. https://doi.org/10.1016/j.cosust.2018.02.007

Wiedmann, T. (2009). A review of recent multi-region input-output models used for consumption-based emission and resource accounting. *Ecological Economics*, *69*(2), 211–222. https://doi.org/10.1016/j.ecolecon.2009.08.026

Wiedmann, T., & Minx, J. (2008). A definition of 'carbon footprint'. *Ecological economics research trends*, 1(2008), 1-11.

Wu, R., Geng, Y., Dong, H., Fujita, T., & Tian, X. (2016). Changes of CO_2 emissions embodied in China-Japan trade: Drivers and implications. *Journal of Cleaner Production*, *112*, 4151–4158. https://doi.org/10.1016/j.jclepro.2015.07.017

Wu, X. D., Guo, J. L., Li, C., Chen, G. Q., & Ji, X. (2020). Carbon emissions embodied in the global supply chain: Intermediate and final trade imbalances. *Science of the Total Environment*, *707*. https://doi.org/10.1016/j.scitotenv.2019.134670

Xu, D., Zhang, Y., Chen, B., Bai, J., Liu, G., & Zhang, B. (2022). Identifying the critical paths and sectors for carbon transfers driven by global consumption in 2015. *Applied Energy*, *306*, 118137. https://doi.org/10.1016/j.apenergy.2021.118137

Xu, D., Zhang, Y., Li, Y., Wang, X., & Yang, Z. (2022). Path analysis for carbon transfers embodied in China's international trade and policy implications for mitigation targets. *Journal of Cleaner Production*, *334*, 130207. https://doi.org/10.1016/j.jclepro.2021.130207

Xu, X., Han, L., & Lv, X. (2016). Household carbon inequality in urban China, its sources and determinants. *Ecological Economics*, *128*, 77–86. https://doi.org/10.1016/j.ecolecon.2016.04.015

Xu, X. Y., & Ang, B. W. (2013). Index decomposition analysis applied to CO_2 emission studies. *Ecological Economics*, *93*, 313–329. https://doi.org/10.1016/j.ecolecon.2013.06.007

Xu, X. Y., & Ang, B. W. (2014). Analysing residential energy consumption usingindex decomposition analysis. *Applied Energy*, *113*, 342–351. https://doi.org/10.1016/j.apenergy.2013.07.052

Yang, T., & Liu, W. (2017). Inequality of household carbon emissions and its influencing factors: Case study of urban China. *Habitat International*, *70*, 61–71. https://doi.org/10.1016/j.habitatint.2017.10.004

Yi, I., Itsubo, N., Inaba, A., & Matsumoto, K. (2007). Development of the interregional I/O based LCA method considering region-specifics of indirect effects in regional evaluation. *International Journal of Life Cycle Assessment*, *12*(6), 353–364. https://doi.org/10.1065/

lca2007.06.339

Yuan, B., Ren, S., & Chen, X. (2015). The effects of urbanization, consumption ratio and consumption structure on residential indirect CO_2 emissions in China: A regional comparative analysis. *Applied Energy*, *140*, 94–106. https://doi.org/10.1016/j.apenergy.2014.11.047

Zang, X., Zhao, T., Wang, J., & Guo, F. (2017). The effects of urbanization and household-related factors on residential direct CO_2 emissions in Shanxi, China from 1995 to 2014: a decomposition analysis. *Atmospheric Pollution Research*, *8*(2), 297–309. https://doi.org/10.1016/j.apr.2016.10.001

Zhang, X., Luo, L., & Skitmore, M. (2015). Household carbon emission research: An analytical review of measurement, influencing factors and mitigation prospects. *Journal of Cleaner Production*, *103*(2015), 873–883. https://doi.org/10.1016/j.jclepro.2015.04.024

Zhao, Y., Wang, S., Yang, J., Zhang, Z., & Liu, Y. (2016). Input-output analysis of carbon emissions embodied in China-Japan trade. *Applied Economics*, *48*(16), 1515–1529. https://doi.org/10.1080/00036846.2015.1102845

Zhou, D., Zhou, X., Xu, Q., Wu, F., Wang, Q., & Zha, D. (2018). Regional embodied carbon emissions and their transfer characteristics in China. *Structural Change and Economic Dynamics*, *46*(2018), 180–193. https://doi.org/10.1016/j.strueco.2018.05.008

Appendix

Table A1. GRP, number of households, and GRP per household across prefectures in Japan (2005)

No.	Prefecture	GRP (unit: billion JPY)	Household (unit: 1000)	GRP per household (unit: million JPY)
1	Hokkaido	19442.2	2380.3	8.2
2	Aomori	4368.4	510.8	8.6
3	Iwate	4496.1	483.9	9.3
4	Miyagi	8429.2	865.2	9.7
5	Akita	3692.4	393.0	9.4
6	Yamagata	3906.7	386.7	10.1
7	Fukushima	7793.9	709.6	11.0
8	Ibaraki	11277.7	1032.5	10.9
9	Tochigi	8217.6	709.3	11.6
10	Gunma	7647.6	726.2	10.5
11	Saitama	20647.0	2650.1	7.8
12	Chiba	19567.8	2325.2	8.4
13	Tokyo	99361.4	5890.8	16.9
14	Kanagawa	31327.3	3591.9	8.7
15	Niigata	9285.2	819.6	11.3
16	Toyama	4835.9	371.8	13.0
17	Ishikawa	4734.0	424.6	11.1
18	Fukui	3409.9	269.6	12.6
19	Yamanashi	3214.8	321.3	10.0
20	Nagano	8423.8	780.2	10.8
21	Gifu	7554.5	713.5	10.6
22	Shizuoka	16919.1	1353.6	12.5
23	Aichi	35609.2	2758.6	12.9
24	Mie	7623.2	675.5	11.3
25	Shiga	6044.2	479.2	12.6
26	Kyoto	10034.9	1079.0	9.3
27	Osaka	39354.8	3654.3	10.8
28	Hyogo	19618.2	2146.5	9.1
29	Nara	3862.1	503.1	7.7
30	Wakayama	3671.6	384.9	9.5
31	Tottori	2042.4	209.5	9.7
32	Shimane	2433.2	260.9	9.3
33	Okayama	7653.8	732.3	10.5
34	Hiroshima	11382.8	1145.6	9.9
35	Yamaguchi	5942.5	591.5	10.0
36	Tokushima	2891.1	298.5	9.7
37	Kagawa	3692.9	377.7	9.8

38	Ehime	4975.0	582.8	8.5
39	Kochi	2405.9	324.4	7.4
40	Fukuoka	18049.1	2009.9	9.0
41	Saga	2874.1	287.4	10.0
42	Nagasaki	4322.7	553.6	7.8
43	Kumamoto	5641.1	667.5	8.5
44	Oita	4331.1	469.3	9.2
45	Miyazaki	3508.1	451.2	7.8
46	Kagoshima	5577.7	725.0	7.7
47	Okinawa	3653.0	488.4	7.5

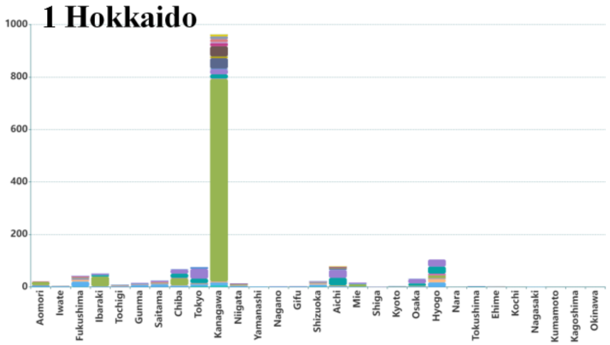
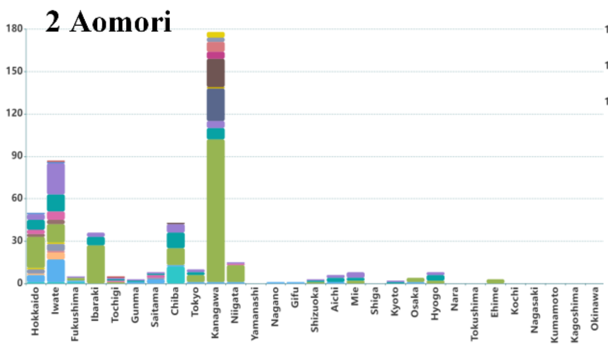
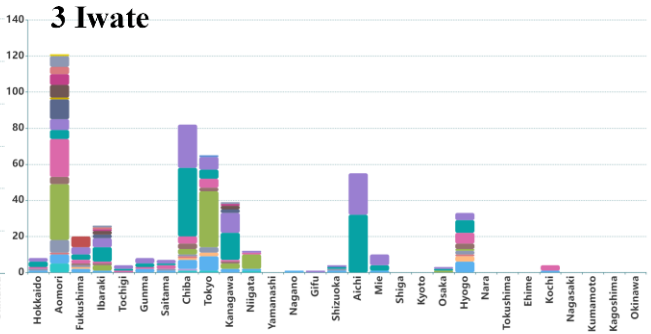
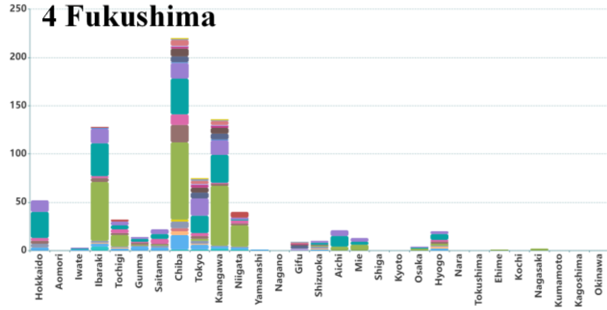
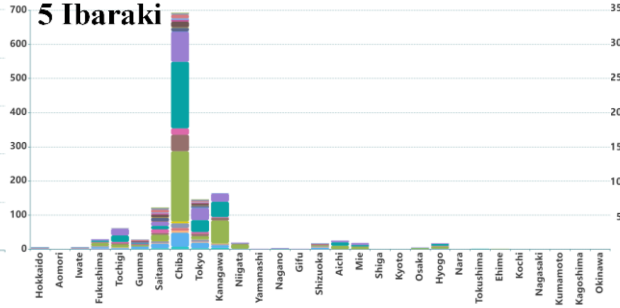
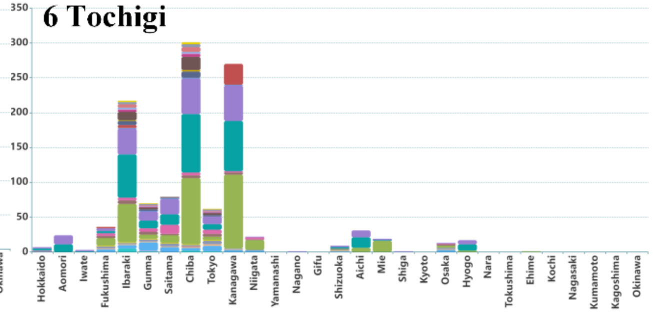
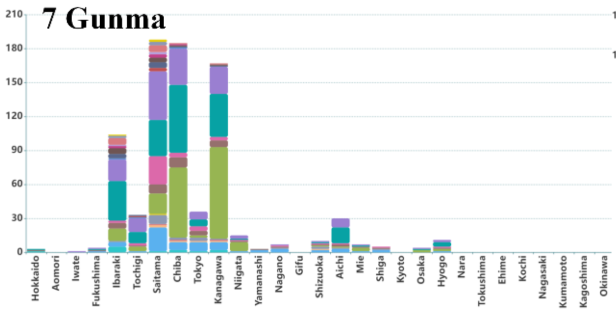
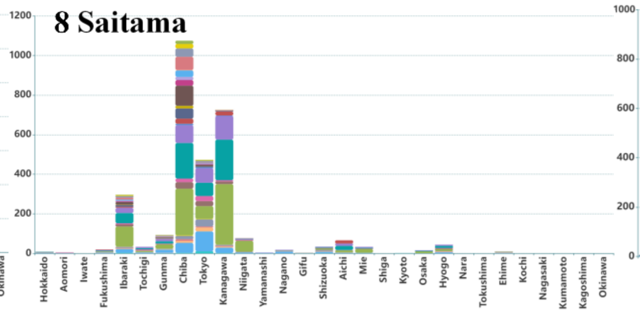
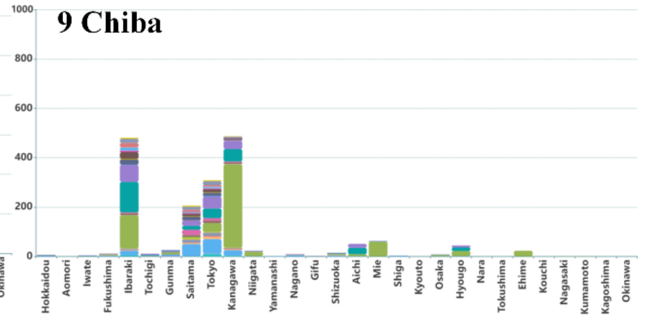
Note: The data for GRP were taken from the Cabinet Office (2021), and the data for households were taken from the Statistics Bureau, Ministry of Internal Affairs and Communications (2010).

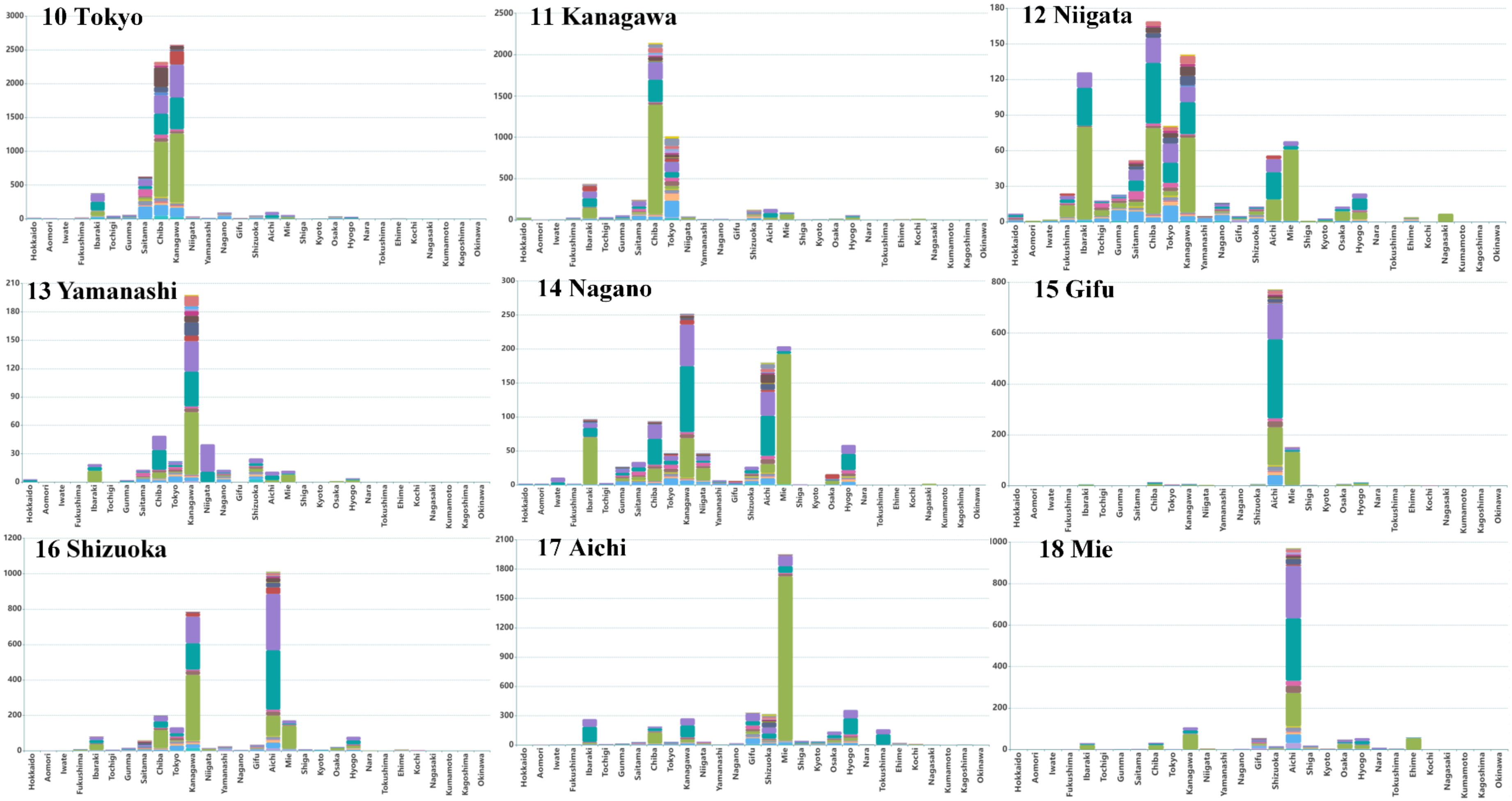
Table A2. Sources of IOTs across prefectures (as of October 20, 2022)

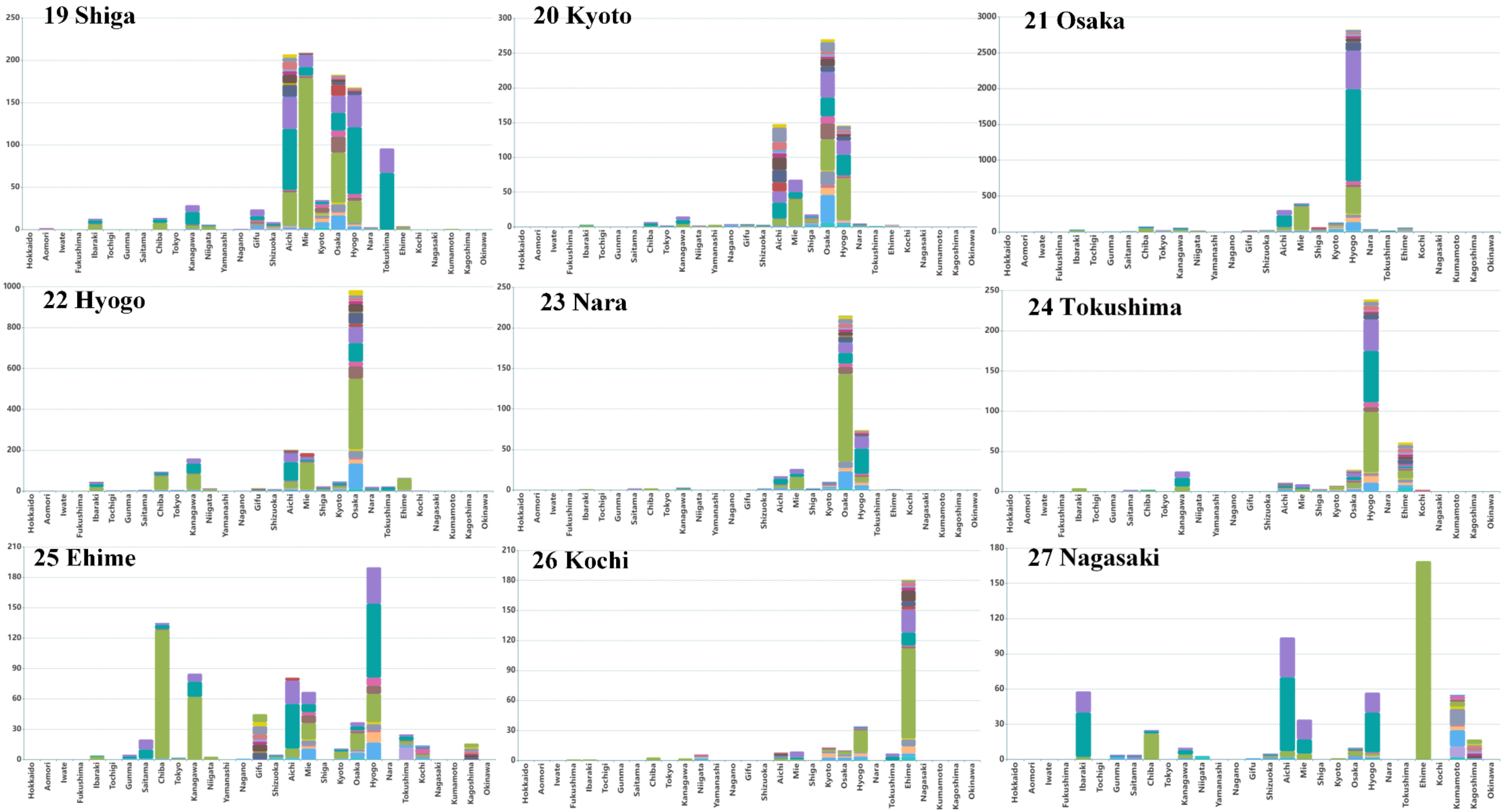
No.	Province	URL
1	Hokkaido	www.hkd.mlit.go.jp/ky/ki/keikaku/u23dsn0000001ma0.html
2	Aomori	opendata.pref.aomori.lg.jp/dataset/dataland/estat27/estat78/
3	Iwate	www3.pref.iwate.jp/webdb/view/outside/s14Tokei/top.html
4	Fukushima	www.pref.fukushima.lg.jp/sec/11045b/17023.html
5	Ibaraki	www.pref.ibaraki.jp/kikaku/tokei/fukyu/tokei/betsu/sangyo/sangyo.html
6	Tochigi	www.pref.tochigi.lg.jp/c04/pref/toukei/toukei/io.html
7	Gunma	www.toukei.pref.gunma.jp/gio/index.html
8	Saitama	www.pref.saitama.lg.jp/a0206/a152/index.html
9	Chiba	www.pref.chiba.lg.jp/toukei/toukeidata/sangyou/index.html
10	Tokyo	www.toukei.metro.tokyo.lg.jp/sanren/sr-index.htm
11	Kanagawa	www.pref.kanagawa.jp/docs/x6z/tc20/sanren/top.html
12	Niigata	www.pref.niigata.lg.jp/site/tokei/0358603.html
13	Yamanashi	www.pref.yamanashi.jp/toukei_2/DB/EDD/dbkeizai06.html
14	Nagano	www.pref.nagano.lg.jp/tokei/tyousa/sangyorenkan.html
15	Gifu	www.pref.gifu.lg.jp/page/14514.html
16	Shizuoka	www.toukei.pref.shizuoka.jp/chosa/15-050/index.html
17	Aichi	www.pref.aichi.jp/soshiki/toukei/io2015.html
18	Mie	www.pref.mie.lg.jp/common/07/ci500002753.htm
19	Shiga	www.pref.shiga.lg.jp/kensei/tokei/sonota/sangyou/317842.html
20	Kyoto	www.pref.kyoto.jp/tokei/cycle/sanren/sanrentop.html
21	Osaka	www.pref.osaka.lg.jp/toukei/sanren/index.html
22	Hyogo	web.pref.hyogo.lg.jp/kk11/ac08_2_000000020.html
23	Nara	www.pref.nara.jp/16376.htm

24	Tokushima	www.pref.tokushima.lg.jp/statistics/year/io/
25	Ehime	www.pref.ehime.jp/toukeibox/datapage/sanren/sanren-p01.html
26	Kochi	www.pref.kochi.lg.jp/soshiki/121901/sanren.html
27	Nagasaki	www.pref.nagasaki.jp/bunrui/kenseijoho/toukeijoho/renkan/
28	Kumamoto	www.pref.kumamoto.jp/soshiki/20/50333.html
29	Kagoshima	www.pref.kagoshima.jp/tokei/bunya/keizai/renkan/
30	Okinawa	www.pref.okinawa.lg.jp/toukeika/io/io_index.html

Note: All data were taken from the official websites of prefectural governments.


1 Hokkaido
0 200 400 600 800 1000
Aomori Iwate Fukushima Ibaraki Tochigi Gunma Saitama Chiba Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyoto Osaka Hyogo Nara Tokushima Ehime Kochi Nagasaki Kumamoto Kagoshima Okinawa

2 Aomori
0 30 60 90 120 150 180
Hokkaido Iwate Fukushima Ibaraki Tochigi Gunma Saitama Chiba Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyoto Osaka Hyogo Nara Tokushima Ehime Kochi Nagasaki Kumamoto Kagoshima Okinawa

3 Iwate
0 20 40 60 80 100 120 140
Hokkaido Aomori Fukushima Ibaraki Tochigi Gunma Saitama Chiba Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyoto Osaka Hyogo Nara Tokushima Ehime Kochi Nagasaki Kumamoto Kagoshima Okinawa

4 Fukushima
0 50 100 150 200 250
Hokkaido Aomori Iwate Ibaraki Tochigi Gunma Saitama Chiba Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyoto Osaka Hyogo Nara Tokushima Ehime Kochi Nagasaki Kumamoto Kagoshima Okinawa

5 Ibaraki
0 100 200 300 400 500 600 700
Hokkaido Aomori Iwate Fukushima Tochigi Gunma Saitama Chiba Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyoto Osaka Hyogo Nara Tokushima Ehime Kochi Nagasaki Kumamoto Kagoshima Okinawa

6 Tochigi
0 50 100 150 200 250 300 350
Hokkaido Aomori Iwate Fukushima Ibaraki Gunma Saitama Chiba Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyoto Osaka Hyogo Nara Tokushima Ehime Kochi Nagasaki Kumamoto Kagoshima Okinawa

7 Gunma
0 30 60 90 120 150 180 210
Hokkaido Aomori Iwate Fukushima Ibaraki Tochigi Saitama Chiba Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyoto Osaka Hyogo Nara Tokushima Ehime Kochi Nagasaki Kumamoto Kagoshima Okinawa

8 Saitama
0 200 400 600 800 1000 1200
Hokkaido Aomori Iwate Fukushima Ibaraki Tochigi Gunma Chiba Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyoto Osaka Hyogo Nara Tokushima Ehime Kochi Nagasaki Kumamoto Kagoshima Okinawa

9 Chiba
0 200 400 600 800 1000
Hokkaidou Aomori Iwate Fukushima Ibaraki Tochigi Gunma Saitama Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyouto Osaka Hyougo Nara Tokushima Ehime Kouchi Nagasaki Kumamoto Kagoshima Okinawa


10 Tokyo
11 Kanagawa
12 Niigata
13 Yamanashi
14 Nagano
15 Gifu
16 Shizuoka
17 Aichi
18 Mie
Hokkaido Aomori Iwate Fukushima Ibaraki Tochigi Gunma Saitama Chiba Tokyo Kanagawa Niigata Yamanashi Nagano Gifu Shizuoka Aichi Mie Shiga Kyoto Osaka Hyogo Nara Tokushima Ehime Kochi Nagasaki Kumamoto Kagoshima Okinawa



19 Shiga
250
200
150
100
50
0
20 Kyoto
300
250
200
150
100
50
0
21 Osaka
3000
2500
2000
1500
1000
500
0
22 Hyogo
1000
800
600
400
200
0
23 Nara
250
200
150
100
50
0
24 Tokushima
250
200
150
100
50
0
25 Ehime
210
180
150
120
90
60
30
0
26 Kochi
210
180
150
120
90
60
30
0
27 Nagasaki
180
150
120
90
60
30
0

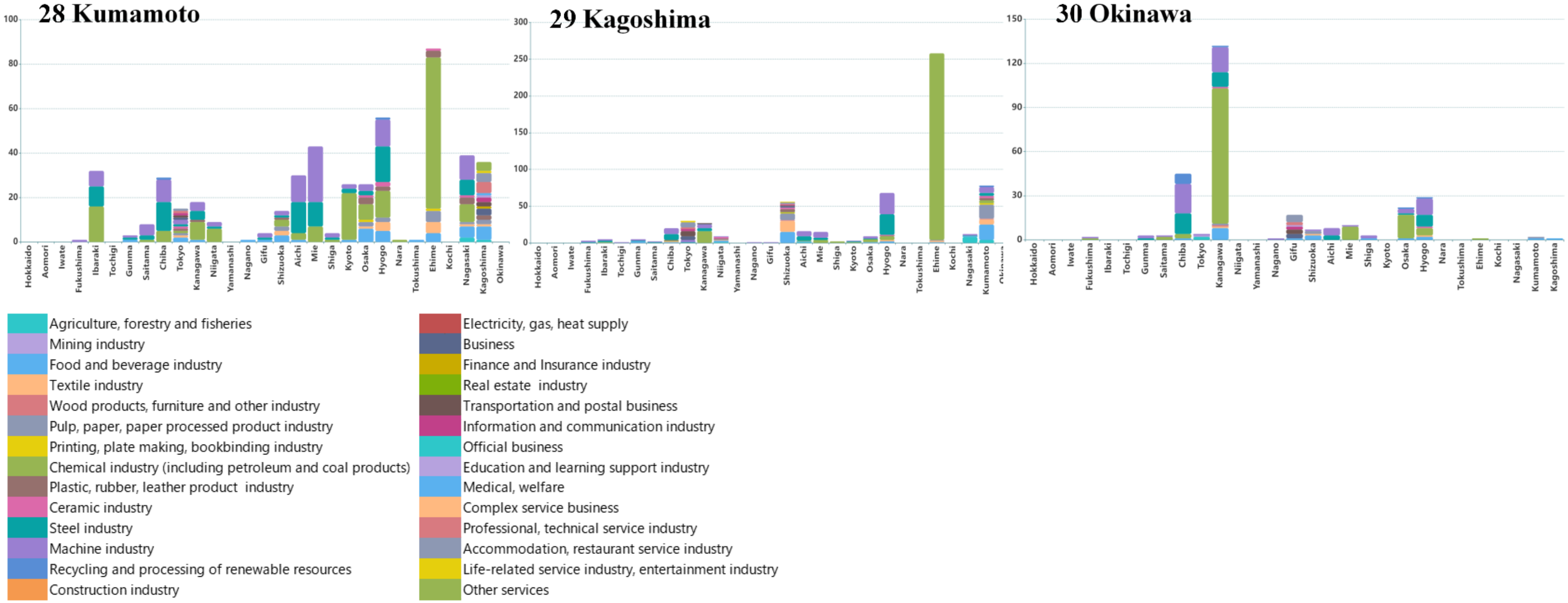


Fig. A1. The CO_2 emissions embodied in the domestic imports of 30 prefectures in Japan by exporters (2011) (unit in 10000 tCO_2). The panel numbers correspond to the numbers in Fig. 5-1.