

Article

Estimation of CO₂ Emissions Embodied in Domestic Trade and Their Influencing Factors in Japan

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Abstract: CO₂ emissions embodied in domestic trade between Japanese prefectures are gradually increasing and becoming an important growth point in the country's CO₂ emissions. The primary objective of this study is to evaluate the CO₂ 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: also to identify the influencing factors of the carbon flow. This study estimated the CO₂ emissions embodied in domestic imports and exports by prefectures using input–output analysis, followed by the log-mean Divisia index decomposition approach, which is used to quantify the influencing factor of net export CO₂ emissions across prefectures. The results show substantial regional differences in the CO₂ emissions embodied in domestic imports and exports across prefectures. Manufacturing prefectures satisfy most of Japan's domestic demand for industrial products and are the main net exporters of CO₂ emissions. Carbon flow is more obvious in economically advanced regions (such as the Kanto and Kansai regions) and covers more prefectures through carbon transfer. Consumer prefectures import the most CO₂ emissions and export large amounts of CO₂ emissions to other prefectures. Among the three factors influencing net export CO₂ emissions, the technology effect has the most significant impact through the carbon intensity of domestic trade flows. These findings highlight the substantial differences in CO₂ emissions embodied in domestic trade and the influencing factors across prefectures in Japan. The responsibility for emission reduction is attributable to both manufacturing and consumer prefectures.

Keywords: Japan's domestic trade; carbon transfer; manufacturing prefecture; consumer prefecture; influencing factors



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1. Introduction

1.1. Background

Japan is the world's third-largest economy and also the world's fifth-largest emitter of greenhouse gas (GHG) and carbon dioxide (CO₂) emissions [1]: therefore, Japan's emission reduction policies are significant for dealing with climate change. After 2013, Japan's CO₂ emissions showed a downward trend as a whole, and its reduction rate of CO₂ emissions in the G7 was second only to that of the United Kingdom (UK) [2], which itself heavily intervenes in Japan's active emission-reduction policy. In the 2015 Paris Agreement, the Japanese government set a target of reducing GHGs by 26% in 2030 compared with 2013. This target was further expanded to 46% in 2021 following the Japanese government's 2020 announcement of its goal to be carbon neutral by 2050.

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 [3]. To adapt to

the expanding domestic market, the commodity structure of interregional trade is also changing, thus impacting industrial production in every prefecture. Fossil fuels account for a large proportion of Japan's energy structure, resulting in approximately 80% of the country's GHGs being produced by energy-related CO₂ emissions [4]. However, another characteristic of Japan's CO₂ emissions is that total indirect CO₂ emissions are high, which is an obstacle to further emissions reduction. Moreover, in the 21st century, CO₂ emissions embodied in interregional trade have gradually increased and become an important growth point for overall CO₂ emissions [5]. Therefore, it is necessary to further understand the CO₂ emissions embodied in domestic trade across prefectures to expand the potential for Japan's emissions reduction.

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 [6]. To stabilize the economy, Japan has further expanded domestic trade by developing circular economies, which have also greatly enhanced the economic links between prefectures. According to prefectural economic calculations compiled by the Cabinet Office in 2011 [7], 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. Meanwhile, 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 places 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 their manufacturing industry (See Table A4 in the Appendix A for detailed matching between the manufacturing industry and sectors) as an economic growth point, whereas consumer prefectures use consumption to support their economic foundations. Therefore, the difference in the structure of trade flows between prefectures leads to different CO₂ emissions being embodied in domestic imports and exports. Moreover, with the decentralization of the Japanese government, whether Japan's emissions reduction goal can be achieved depends largely on the effectiveness of the measures in every prefecture [8].

There is a considerable amount of research on CO₂ emissions stemming from Japan's trade. To the best of our knowledge, however, no previous researchers have systematically evaluated the CO₂ emissions embodied in Japan's domestic trade at the prefectural level and identified the influencing factors, so here, we conduct a brief review of Japan's CO₂ emissions from trade. For a more detailed literature review on traded CO₂ emissions, please refer to Section 1.2. Wang et al. [9] quantified the CO₂ emissions from the added value in global trade, and proposed that Japan has been favored by global trade from both the economic and environmental perspectives. This global trade is accompanied by the transfer of energy: Jiang et al. [10] analyzed the spatial transfer pattern of Japan's energy flow in global trade from 1995 to 2011; Wang and Zhou [11] evaluated the inequality in US–Japanese trade in 2000–2011 from the perspectives of the economy and CO₂ emissions; Dou et al. [12] examined the potential impact of the trade openness of China, Japan, and South Korea on CO₂ emissions in 1970–2019; Yoon et al. [13] also focused on China, Japan, and South Korea, and further assessed the drivers of changes in manufacturing CO₂ emissions from trade among the three countries. Based on the inter-prefectural trade in Japan, Battuvshin et al. [14] evaluated the impact of forest biomass resources on the energy supply, while Sadayuki and Arimura [15] evaluated the carbon leakage of firms from the perspective of the interregional carbon trading system in Japan. Although the above research systematically analyzed the CO₂ emissions embodied in Japan's trade, there are still certain limitations. On the one hand, most research related to Japan's traded CO₂ emissions has focused on international trade, ignoring the impact of domestic trade

between prefectures. On the other hand, most research has focused on analyzing the process of carbon transfer in trade, but lacks attention to the driving factors of carbon transfer, which could provide a theoretical basis for adjusting the structure of trade flow.

1.2. Literature Review

1.2.1. CO₂ emissions Embodied in Trade

Despite promoting the development of the world economy, global trade also produces CO₂ emissions, and Wu et al. [16] showed that CO₂ emissions embodied in international trade comprise approximately 40% of global direct CO₂ emissions. The trade volume of developed countries accounts for most of the global trade; thus, some studies have focused on the CO₂ emissions embodied in developed countries' trade. Wang and Zhou [11] calculated the CO₂ emissions embodied in trade between Japan and the United States (US) from 2000 to 2011, and found that economic losses in the US outweighed the positive effects of carbon transfer between the two countries (Wang and Zhou, 2019). Qiang et al. [17] studied CO₂ emissions embodied in German–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 [18] quantified the CO₂ 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 CO₂ emissions embodied in the trade of developing countries will surge [19]. Wang and Yang [20] investigated CO₂ emissions embodied in Chinese–Indian trade and proposed that China was a net exporter of CO₂ and a net exporter of trade. Kim and Tromp [21] quantified the CO₂ emissions and added value embodied in Chinese–Brazilian trade, and showed that China's position as a net CO₂ emissions and net value-added exporter 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 [22]. Therefore, intensive studies have evaluated CO₂ emissions embodied in trade between developing and developed countries. Wang et al. [23] calculated the CO₂ 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. [24] evaluated the CO₂ emissions embodied in trade between the largest net exporter among developing countries (China) and the largest net exporter among developed countries (Germany), finding that CO₂ emissions are mainly concentrated in carbon-intensive industrial sectors. Qiang et al. [25] studied the decoupling of CO₂ emissions embodied in Sino–US trade and showed that it is relatively invariable and gradually improving.

1.2.2. Regional Carbon Transfers

Many studies have further analyzed the transfer paths of CO₂ emissions embodied in trade based on trade flow. As trade structure is affected by economic level, developing countries are often net exporters of CO₂ emissions, whereas developed countries are usually net importers [9]. Wu et al. [26] estimated the CO₂ emission flows between China and Japan from 2000 to 2009 and found that China was a net exporter of CO₂ emissions embodied in Chinese–Japanese trade. Zhao et al. [27] also focused on the CO₂ emissions embodied in trade between Japan and China, further extending the research period from 1995 to 2009, and showed that CO₂ emissions embodied in China's exports increased by approximately 100%. Long et al. [28] compared CO₂ emission flows through imports, exports, production, and consumption to analyze the differences between China and Japan. Xu et al. [29] decomposed the CO₂ emission processes embodied in global trade and traced critical carbon transfer paths, finding that most transfer paths in the US end in services, whereas in China, they end in construction. Xu et al. [30] investigated carbon transfers between mainland China and its trade partners to quantify mitigation targets and 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 countries' economies to be heterogeneous, multi-regional, integrated wholes to analyze in-country carbon transfer [31]. Wei et al. [32] investigated the electricity-related CO₂ emissions and added value embodied in China's interprovincial trade from 2007 to 2012, showing that 20–80% of electricity-related CO₂ emissions and 15–70% of the value added to a province's final demand are outsourced to other provinces. Wang and Hu [33] evaluated carbon transfers caused by interprovincial demand and interprovincial exports for China in 2007, 2010, and 2012. Relatively few studies have been conducted on carbon transfer in Japan's interregional trade: Yi et al. [34] combined prefecture-specific emission databases and technology matrices with the interregional trade flows presented by the nine-region multi-regional input–output (MRIO) table to observe the effects of four environmental burdens in Japan; Hasegawa et al. [35] estimated carbon leakage in 47 prefectures and considered the structure of emissions at the regional level from the standpoint of consumer and producer responsibility in Japan in 2005.

1.3. Research Objective

Trade accelerates the transfer of CO₂ emissions between producers and consumers; it also intensifies climate change, so a systematic assessment of CO₂ emissions from domestic trade is significant for elucidating methods for the reduction of Japan's emissions. Therefore, the objective of this study is to visualize carbon transfer paths by estimating the CO₂ emissions embodied in domestic imports and exports across prefectures based on input–output analysis (IOA), and to identify the influencing factor of carbon flow through the log-mean Divisia index (LMDI) decomposition approach.

1.4. Research Significance

Through this study, the characteristics of CO₂ emissions embodied in domestic trade can be specified for each sector in every prefecture. The carbon reduction responsibilities of each prefecture under different economic modes can be further distinguished through the visualization of carbon flows to formulate more targeted carbon reduction measures in Japan. Furthermore, the results of the study can provide insights with international applicability for reducing CO₂ emissions, as evaluating the CO₂ emissions from domestic trade is conducive to longer-term carbon reduction in each country and 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 CO₂ emissions embodied in domestic trade. Finally, our research is helpful for balancing the supply–demand relationship between regions within each country and for avoiding carbon inequality in the process of carbon reduction.

The remainder of this paper is organized as follows: Section 2 discusses the methodology and data; Section 3 presents the results and discusses the main findings; and Section 4 presents the conclusions and policy implications.

2. Methodology and Data

Combining the single-regional input–output (SRIO) table of each prefecture and the National Cargo Net Flow Survey (NCNFS) from 2010, we first provide an assessment of the CO₂ emissions embodied in Japan's domestic trade. We subsequently applied the LMDI decomposition approach to quantitatively evaluate the factors influencing net export CO₂ emissions.

2.1. CO₂ Emissions Assessment Framework with Input–Output Model

IOA is one of the main methods used to evaluate CO₂ emissions embodied in trade [36], and its basic principle comes from the technique of representing the complex interdependence between economic sectors [37]. Owing to the lack of domestic trade data in the IO tables (IOTs) of some prefectures, 30 prefectures (See Figure A1, Figure A2 in the Appendix A for the geographical coverage of the study) were studied in this research.

The basic equation for the assessment of CO₂ emissions can be expressed as follows [38]:

$$C = K(I - A)^{-1}Y \quad (1)$$

$$A = \begin{bmatrix} \left(\begin{array}{ccc} a^{11} & \dots & a^{1n} \\ \vdots & \ddots & \vdots \\ a^{n1} & \dots & a^{nn} \end{array} \right) \end{bmatrix}$$

where A is the technical coefficient matrix, Y is the final demand vector, K is the CO₂ emission intensity vector, referring to sectoral CO₂ emissions per monetary unit, C is the total embodied CO₂ emissions driven by final demand Y , and n is the number of economic sectors.

Based on Equation (1), the CO₂ emissions embodied in the domestic exports of each prefecture can be expressed as

$$C_j^{EX} = K(I - A)^{-1}Y_j^{EX} \quad (2)$$

where C_j^{EX} is the CO₂ emissions embodied in domestic exports in sector j and Y_j^{EX} is a vector of the amount of domestic exports in sector j .

Considering the differences in the technical coefficients of the corresponding exporters, the CO₂ emissions embodied in the domestic imports of each prefecture can be expressed as follows:

$$C_j^{IM} = \sum_{r=1}^{29} k_r (I - A_r)^{-1} Y_{r,j}^{IM} \quad (3)$$

where C_j^{IM} is the CO₂ emissions embodied in domestic imports in sector j and $Y_{r,j}^{IM}$ is a vector of the volume of domestic imports from prefecture r in sector j .

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

$$Y_{r,j}^{IM} = Y_j^{IM} \times \frac{Z_{r,j}^{IM}}{\sum Z_{r,j}^{IM}} \quad (4)$$

where Y_j^{IM} is the total amount of domestic imports in the sector j , and $Z_{r,j}^{IM}$ refers to the import amounts from prefecture r in sector j .

2.2. Evaluation of Influencing Factors Using the LMDI Decomposition Approach

Typically, IOA is combined with structural decomposition analysis to evaluate the factors influencing changes in CO₂ emissions. However, the research object is the influencing factors of net export CO₂ emissions generated by domestic imports and exports in each prefecture, and changes in panel data are not involved. Therefore, the LMDI decomposition approach was used in this study.

The CO₂ emissions embodied in domestic imports and exports can be decomposed based on the Kaya identity as follows:

$$C^{EX} = \sum_{j=1} C_j^{EX} = \sum_{j=1} \frac{C_j^{EX}}{Y_j^{EX}} \times \frac{Y_j^{EX}}{TOT^{EX}} \times TOT^{EX} = \sum_{j=1} TEC_j^{EX} \times STR_j^{EX} \times TOT^{EX} \quad (5)$$

$$C^{IM} = \sum_{j=1} C_j^{IM} = \sum_{j=1} \frac{C_j^{IM}}{Y_j^{IM}} \times \frac{Y_j^{IM}}{TOT^{IM}} \times TOT^{IM} = \sum_{j=1} TEC_j^{IM} \times STR_j^{IM} \times TOT^{IM} \quad (6)$$

where TEC_j^{EX} and TEC_j^{IM} refer to the carbon intensity of the domestic imports and exports in sector j , STR_j^{EX} and STR_j^{IM} refer to the share of sector j in total domestic imports and exports, and TOT^{EX} and TOT^{IM} refer to the total trade amount of domestic imports and exports.

The total effect on net export CO₂ emissions can be expressed as follows:

$$\begin{aligned} \Delta C &= C^{EX} - C^{IM} = \\ \Delta C_{TEC} + \Delta C_{STR} + \Delta C_{TOT} &= \sum_{j=1} W_j \times \ln \frac{TEC_j^{EX}}{TEC_j^{IM}} + \sum_{j=1} W_j \times \ln \frac{STR_j^{EX}}{STR_j^{IM}} + \sum_{j=1} W_j \times \ln \frac{TOT^{EX}}{TOT^{IM}} \\ W_j &= \begin{cases} \frac{C_j^{EX} - C_j^{IM}}{\ln C_j^{EX} - \ln C_j^{IM}}, C_j^{EX} \neq C_j^{IM} \\ C_j^{EX}, C_j^{EX} = C_j^{IM} \end{cases} \end{aligned} \quad (7)$$

where ΔC_{TEC} denotes the technology effect, ΔC_{STR} denotes the structure effect, and ΔC_{TOT} denotes the scale effect.

2.3. Data

Each prefecture produces its own IOTs, so the IOTs of the 30 prefectures were retrieved via each prefecture's official website (The official websites of each prefecture's IOT are listed in Table A1, Table A2 in the Appendix A). This study focused on 2011 IOTs with the best data available [39]. Emission factors were obtained from the Agency for Natural Resources and Energy [40]. Regional trade data were collected from the 2010 (The NCNFS is held every five years, with the last three times being in 2015, 2010 and 2005. To cooperate with the 2011 SRIO table, the NCNFS in 2010 was used in this study) NCNFS between prefectures [41].

The CO₂ emissions statistics table for each prefecture includes 28 sectors (see Table A3), and based on the sector classification of this table we combined the IOT's sectors to form 28 sectors (Table A4). The names of the sectors in the IOT and CO₂ emissions statistics table are different, and we adopt the IOT naming method. The sectoral correspondence between the NCNFS and IOTs is also shown in Table A4.

To check the effectiveness of domestic import 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 A1). Generally, 22 prefectures had more than 70% domestic imports, with a weighted average of 92.9%, which confirms that the study area could show the characteristics of CO₂ emissions embodied in Japan's domestic trade.

3. Results and Discussion

3.1. The CO₂ Emissions Embodied in Japan's Domestic Trade

The total CO₂ emissions embodied in the domestic trade of 30 prefectures were approximately 486 MtCO₂, accounting for 41% of Japan's total indirect CO₂ emissions in 2011 [42]. Moreover, referring to the currently available data on consumption-based emissions in Japan in 2005 [35], the proportion of CO₂ emissions embodied in domestic trade across prefectures was higher than 30%. Generally, CO₂ emissions embodied in

domestic imports and exports across prefectures show substantial regional differences (Figure 1). A few prefectures produce the most CO₂ emissions through domestic trade, and these prefectures are mainly in the Kanto, Chubu, and Kansai regions, which include Tokyo, Aichi, and Osaka. In addition, these 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 CO₂ emissions.

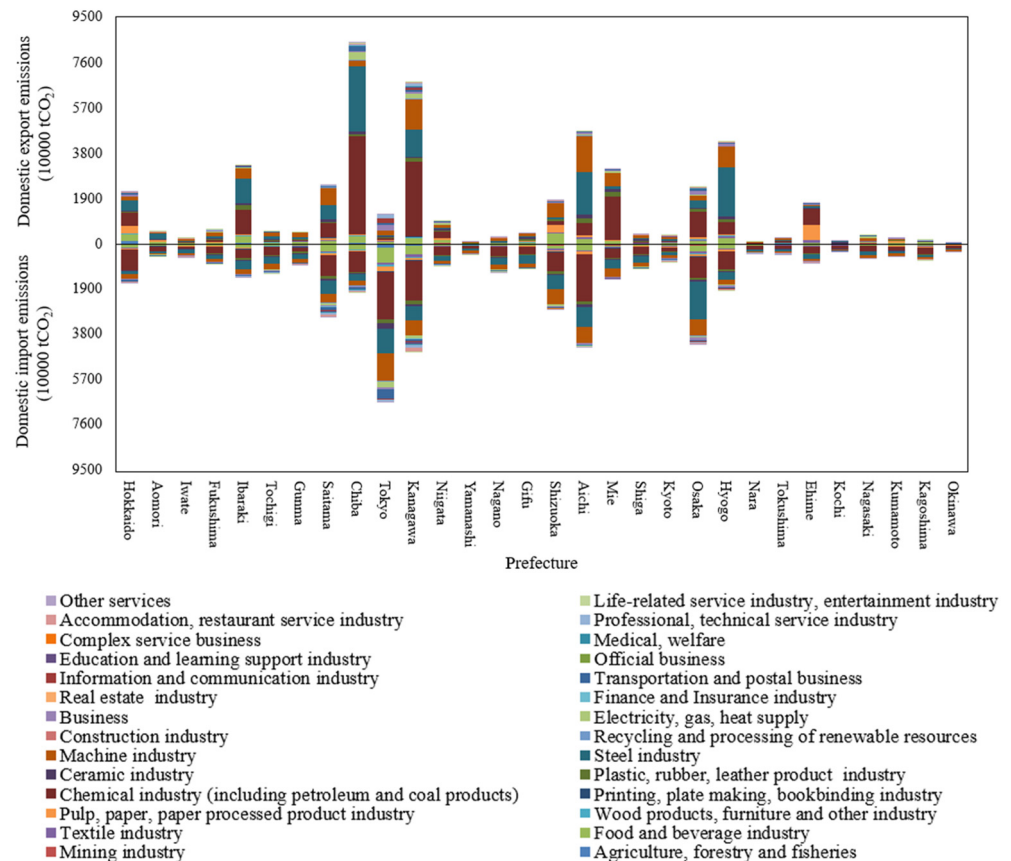


Figure 1. The CO₂ emissions embodied in Japan's domestic imports and exports across prefectures in 2011.

CO₂ emissions embodied in domestic exports are concentrated in manufacturing prefectures: in contrast, the CO₂ emissions embodied in domestic imports are concentrated in consumer prefectures. Chiba, Kanagawa, Aichi, and Hyogo, the four prefectures with a high proportion of the manufacturing industry in the GRP, account for 31% of the amount of total domestic exports in Japan (Figure 2). This reflects how a few manufacturing prefectures satisfy most of Japan's domestic demand for industrial products, thus becoming the leading net exporters of CO₂ emissions. The raw materials needed for production promote the expansion of domestic imports; thus, some manufacturing prefectures also have a significant amount of CO₂ emissions embodied in domestic imports, such as Kanagawa and Aichi. Compared with domestic exports, the CO₂ emissions embodied in the domestic imports of most prefectures, excluding manufacturing prefectures, are relatively high, especially in consumer prefectures such as Tokyo and Osaka.

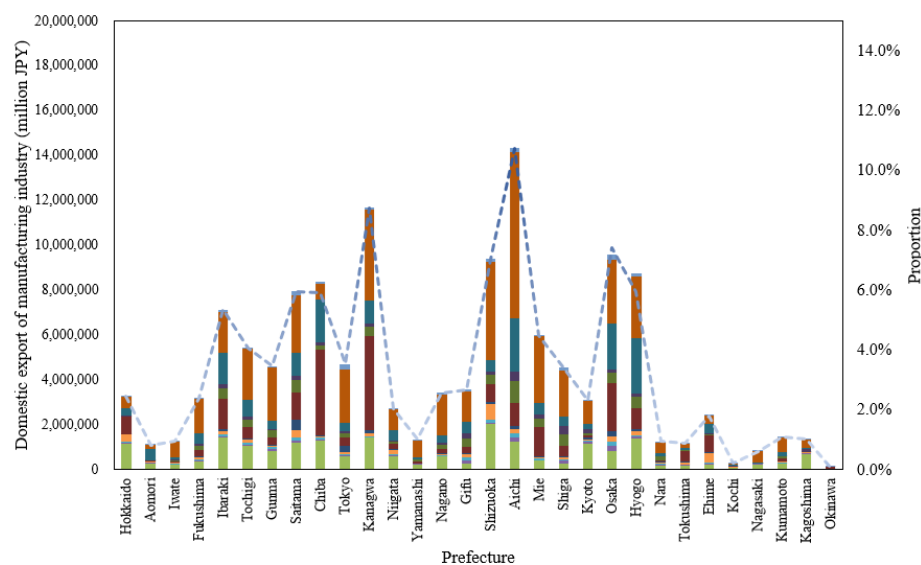


Figure 2. Domestic exports of the manufacturing industry by prefecture, and their shares of Japan’s total manufacturing domestic exports (indicated by a light blue dotted line) in 2011. The color of the legend corresponds to the sectors in Figure 1.

In Japan’s domestic exports, the chemical, steel, and machine industries account for a high proportion of CO₂ emissions in heavy-industry prefectures, mainly in the Kanto and Chubu regions. The economies of these prefectures are clearly export oriented; therefore, the manufacturing industry is more dependent on the external market. In addition, the CO₂ 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 CO₂ emissions from domestic exports. Therefore, we selected these three prefectures as case studies to further discuss the CO₂ emissions embodied in domestic exports with industrial structures.

CO₂ emissions from the chemical and steel industries account for a large proportion of the domestic exports from 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 industries in Japan [43]. 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 CO₂ 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 CO₂ emissions embodied in Aichi’s domestic exports came 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 CO₂ emissions embodied in domestic exports are relatively low.

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 (Figure 3). Carbon flow is more obvious in economically advanced regions (e.g., the Kanto and Kansai regions) and covers more prefectures through carbon transfer. For example, Tokyo’s CO₂ emissions account for 14% of Japan’s CO₂ emissions embodied in domestic imports, and the emission sources extend from the Tohoku to Kanto regions (Ibaraki, Saitama, Chiba, etc.). However, the CO₂ emissions of economically backward regions are lower and concentrated in neighboring manufacturing prefectures.

For instance, Gifu accounts for only approximately 2% of the total CO₂ emissions, mainly from neighboring Aichi. Furthermore, consumer prefectures import major CO₂ emissions and export substantial amounts of CO₂ 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.

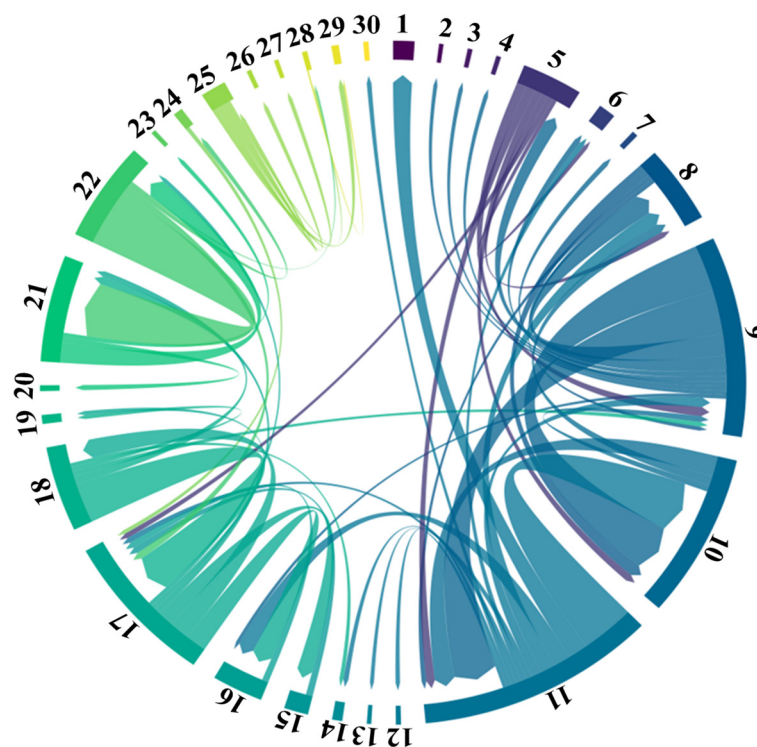


Figure 3. Flow chart of the CO₂ emissions embodied in domestic imports between prefectures of Japan in 2011 (unit in 10,000 tCO₂). The numbers in the flowchart correspond to the prefectures, as detailed in Figure A1.

Tokyo is an important consumer prefecture with a high population concentration, whereas Chiba and Kanagawa are the main emission sources of the Hokkaido, Tohoku, Kanto, and Chubu regions in domestic imports. Therefore, we selected those three prefectures as case studies to further discuss regional differences in combination with the sectoral distribution of embodied CO₂ emissions in Japan's domestic imports (Figure 4).

The main sources of CO₂ emissions embodied in Tokyo's domestic imports were Chiba and Kanagawa, and there were specific differences in sectoral distribution (Figure 4a). In contrast, CO₂ 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 CO₂ 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, the 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.

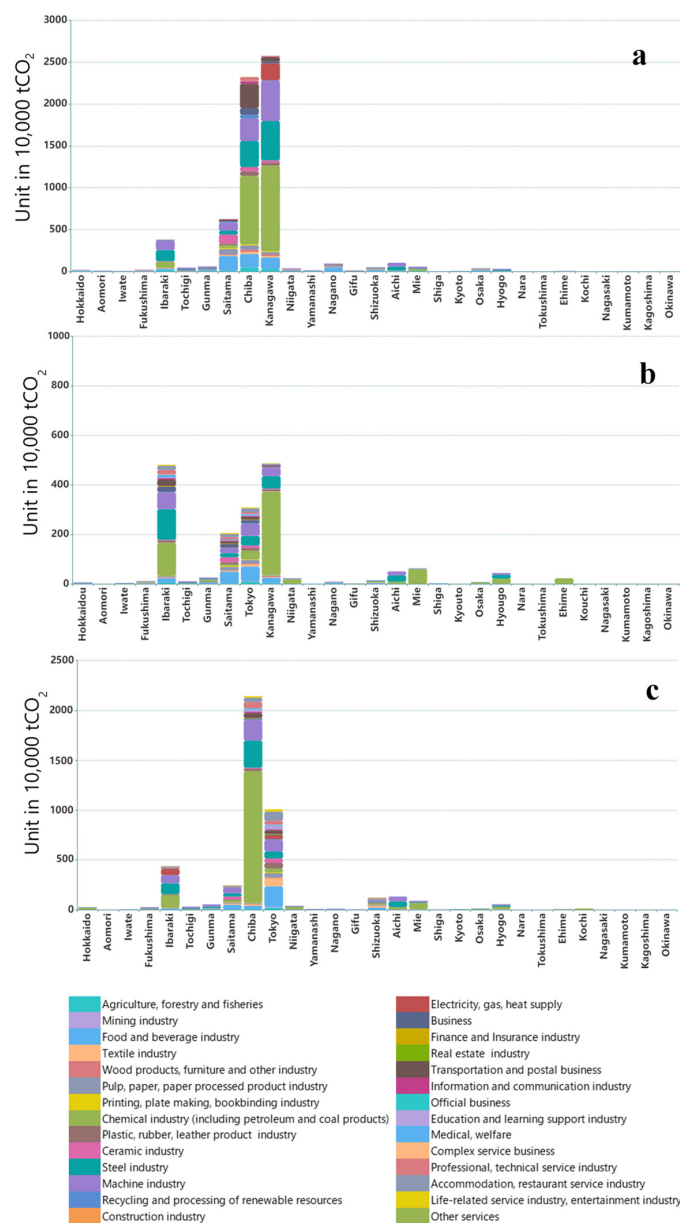


Figure 4. The CO₂ emissions embodied in the domestic imports of Tokyo (a), Chiba (b), and Kanagawa (c) by the exporter in 2011.

Although Chiba and Kanagawa are manufacturing prefectures, there are differences in the sources of CO₂ 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 CO₂ emissions embodied in domestic imports. The emission sources of Chiba, such as Kanagawa, Ibaraki, and Tokyo, were relatively diverse (Figure 4b). In contrast, the emission source of Kanagawa was concentrated in Chiba (Figure 4c). 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 CO₂ emissions from consumer prefectures in domestic imports, such as Tokyo.

3.3. The Influencing Factors of Net Export CO₂ Emissions across Prefectures

Among the 30 prefectures, 20 have negative net export CO₂ emissions, especially consumer prefectures with advanced economies (e.g., Tokyo and Osaka). Prefectures with positive net export CO₂ emissions are mostly manufacturing prefectures and are concentrated in the Kanto and Kansai regions (e.g., Kanagawa, Hyogo). From the impact degrees of the three influencing factors, the technology effect had the most significant impact on net export CO₂ emissions (Figure 5b). 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 CO₂ emissions was relatively weak and was mainly affected by the economic structure within each prefecture (Figure 5c). The scale effect has the least impact on net export CO₂ emissions and has a positive impact, mainly in the Kanto region (Figure 5d).

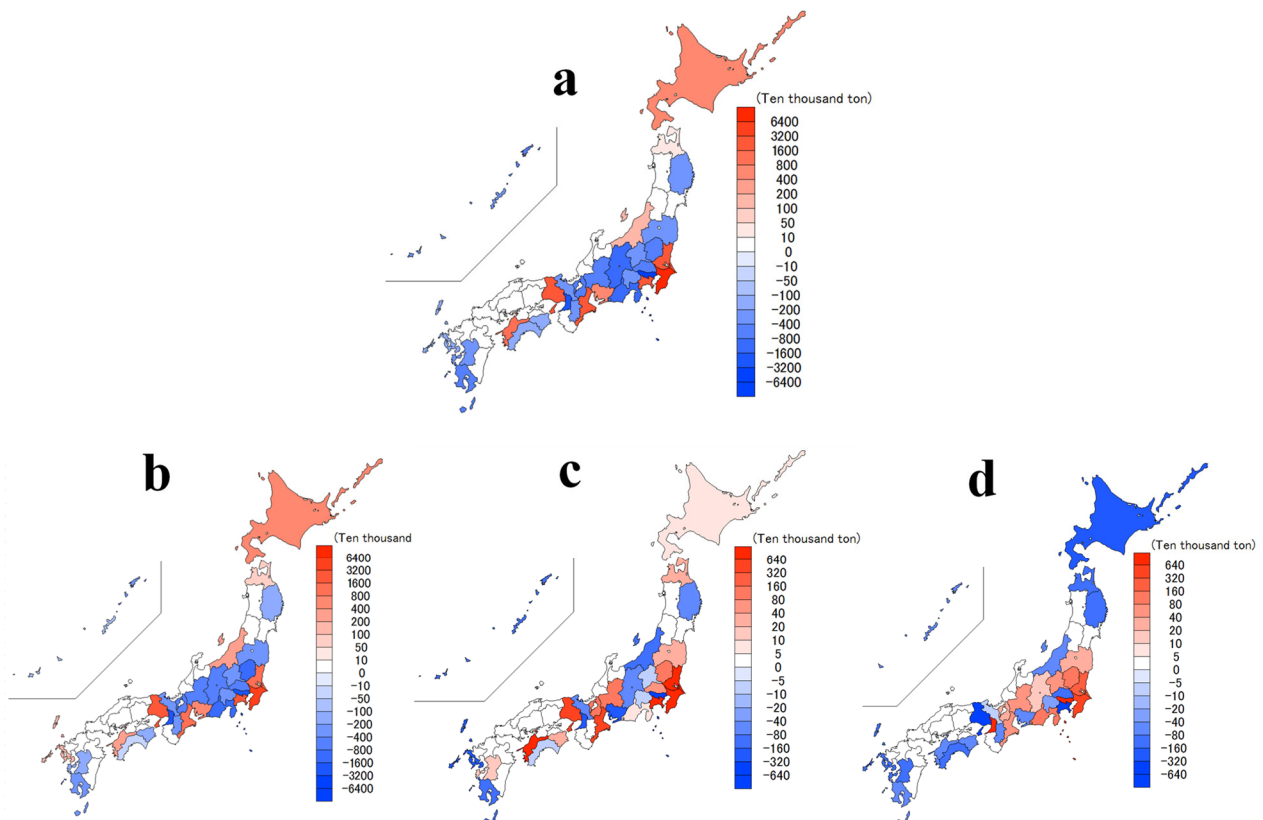


Figure 5. Total net export CO₂ emissions (a) and the impact of three factors on net export CO₂ emissions across prefectures in 2011: technology effect (b), structure effect (c), and scale effect (d).

The impact of the technology effect on net export CO₂ emissions is mainly reflected in carbon intensity (Equations (5) and (6)). Chiba and Kanagawa are the most 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 the 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 (Figure 6), 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.

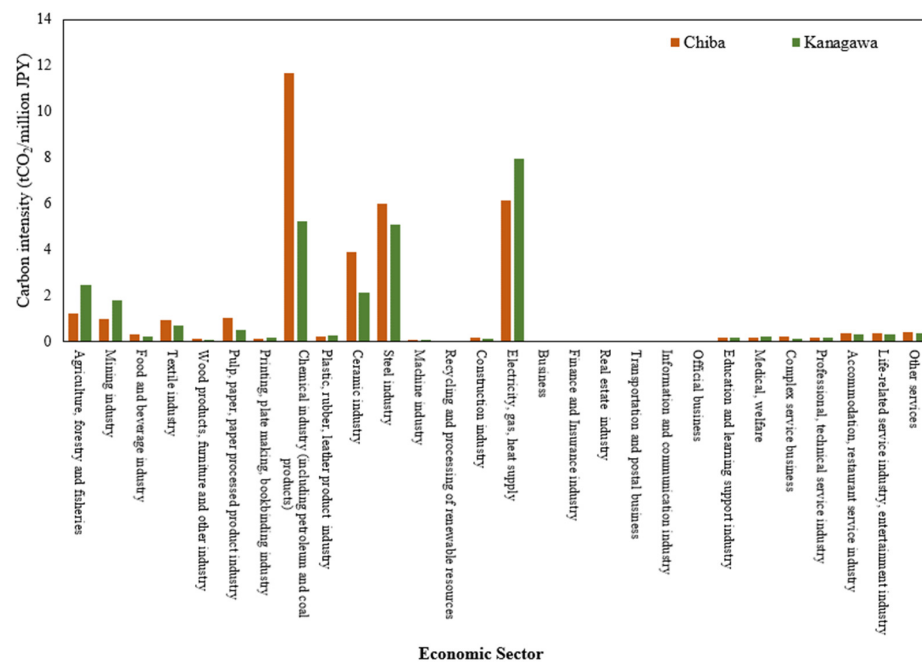


Figure 6. Carbon intensity for 28 economic sectors between Chiba and Kanagawa in 2011.

The differences in economic structure cause the impact of the structural effect on net export CO₂ 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 imports, 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 CO₂ emissions through service industries to other prefectures. This also confirms that, although manufacturing prefectures are the main net exporters of CO₂ emissions, consumer prefectures are also important sources of CO₂ emissions embodied in domestic trade.

3.4. Limitations of the Study

This study has five main limitations. Firstly, 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. Therefore, the domestic trade flow of each prefecture cannot accurately reflect the actual situation. Secondly, the SRIO tables for some prefectures do not provide domestic import and export data, as the study area was limited to 30 prefectures. Therefore, the conclusions of this study cannot be fully applicable to all prefectures in Japan. Thirdly, 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. Because the research data are relatively outdated, the research results may not accurately reflect the current status of CO₂ emissions embodied in Japan's domestic trade. Fourthly, this study does not involve non-combustion CO₂ emissions in the production process, which may reduce the CO₂ emissions embodied in the domestic trade of each prefecture. Finally, to maintain the data integrity of the SRIO, NCNFS, and CO₂ emissions statistics tables during data mapping, we used 28 sectors.

Therefore, the aggregation of sectors may affect the understanding of the CO₂ emissions accounting methods of some sectors, such as petroleum and coal products and chemicals. The limitations of the data could be addressed if the relevant data become available in the future.

4. Conclusions and Policy Implications

The CO₂ emissions embodied in domestic imports and exports differ across prefectures. Generally, CO₂ emissions embodied in Japan's domestic trade are concentrated in economically advanced prefectures, mainly in the Kanto and Kansai regions. Manufacturing prefectures satisfy most of the domestic demand in Japan with industrial products and have become the main net exporters of CO₂ emissions. Carbon flow is more obvious in consumer prefectures and covers more prefectures through carbon transfers. Furthermore, consumer prefectures also export amounts of CO₂ emissions from the service industry to other prefectures.

In terms of the factors influencing net export of CO₂ emissions across prefectures, the technology effect has the most significant impact on the carbon intensity of domestic trade flows. The economic traction of each prefecture is different, which is mainly reflected in the proportion of the manufacturing and service industries in the economic structure. Therefore, the impact of the structural effect on net export CO₂ emissions differs by prefecture. The scale effect of manufacturing prefectures usually positively impacts net export CO₂ emissions, but in consumer prefectures with advanced economies, the scale effect also has a positive impact.

There are substantial differences in CO₂ emissions embodied in domestic trade and the influencing factors across prefectures; thus, emission reduction policies must be formulated flexibly according to local conditions to promote the sustainable development of each prefecture. The results of the analysis suggest policy implications, which are detailed below:

Firstly, it is necessary to adjust the industrial structures of manufacturing prefectures and reduce the carbon intensity of production. The government should promote the diversification of industrial structures in manufacturing prefectures and accelerate innovation in production technology to avoid the high carbon intensity of single production structures. For example, Chiba's basic material industry has the advantage of an industrial cluster under enterprise agglomeration; thus, 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. Meanwhile, in the processing industry of medium- and low-end products, the improvement of energy efficiency and the promotion of environmental protection technologies are key points.

Secondly, it is important to pay attention to CO₂ emissions from consumer prefectures where the service industry is one of the main sources, although it is widely seen as a low-carbon emitter and therefore regulations to reduce emissions have been neglected. Consequently, for the service sector, emphasis should be placed on improving energy efficiency and promoting innovation in energy technologies to reduce energy consumption in the production process. Moreover, consumer prefectures have a stable and large market, and the government should actively promote the circulation of low-carbon products and guide consumers toward sustainable consumption.

Finally, the responsibility for emission reduction is attributable to both manufacturing and consumer prefectures, because the latter share responsibility for emissions, given that their demand induces emissions from production. The premise of emission reduction is to maintain the normal supply–demand relationship of Japan's domestic trade. Manufacturing prefectures must strive to develop low-carbon economic growth. The government should reduce the utilization of coal for non-power generation, actively develop non-fossil energy and energy storage technologies, and build a new power system with new energy as the main body to reduce the CO₂ emissions generated in the production process. 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, the Japanese government can enhance the synergy between producers and consumers.

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Appendix A

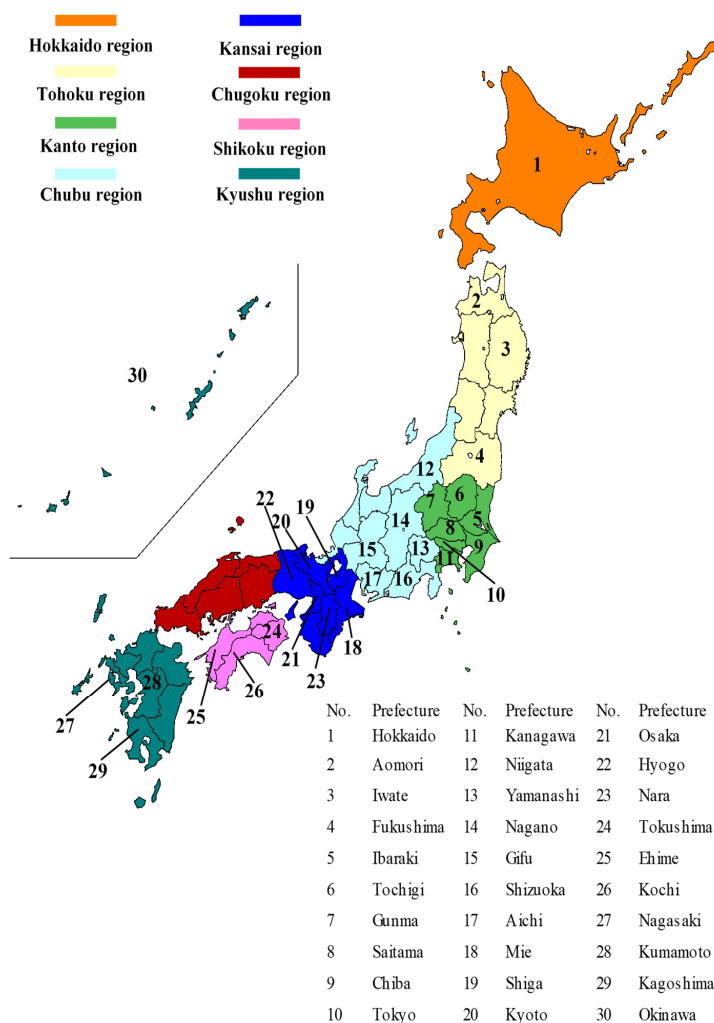


Figure A1. Geographical locations of 30 prefectures and eight regions in Japan.

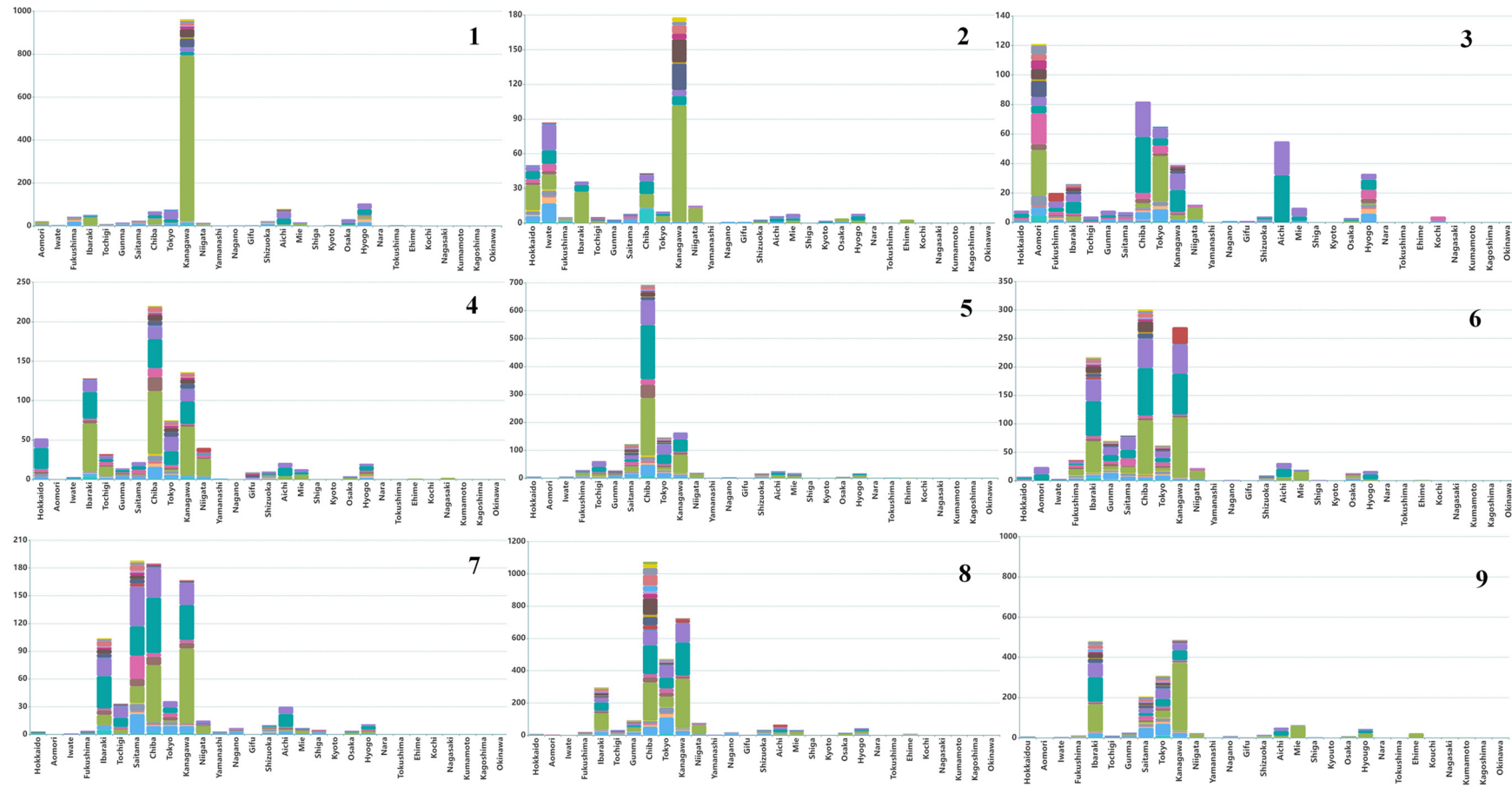


Figure A2. Cont.

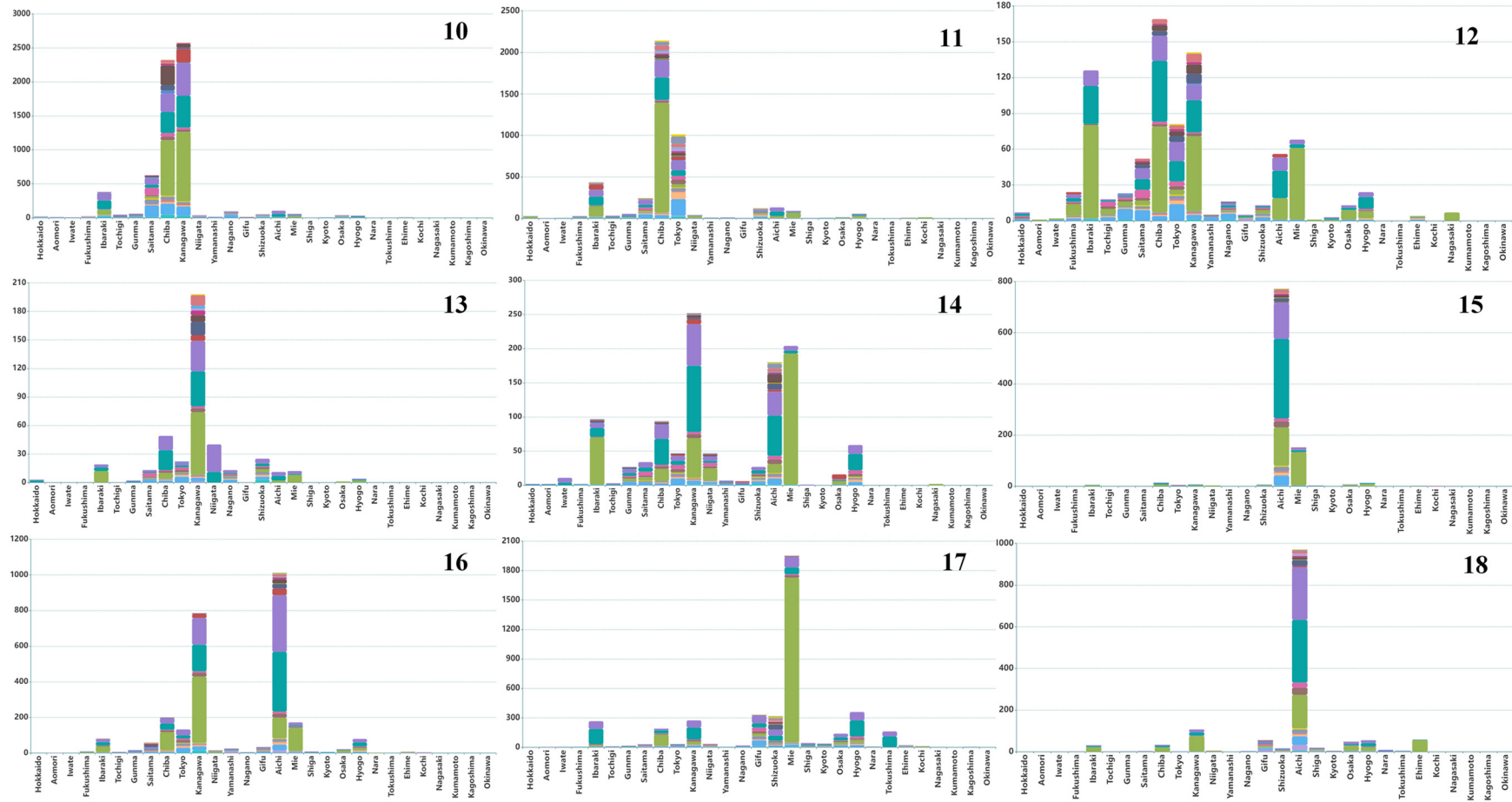


Figure A2. Cont.

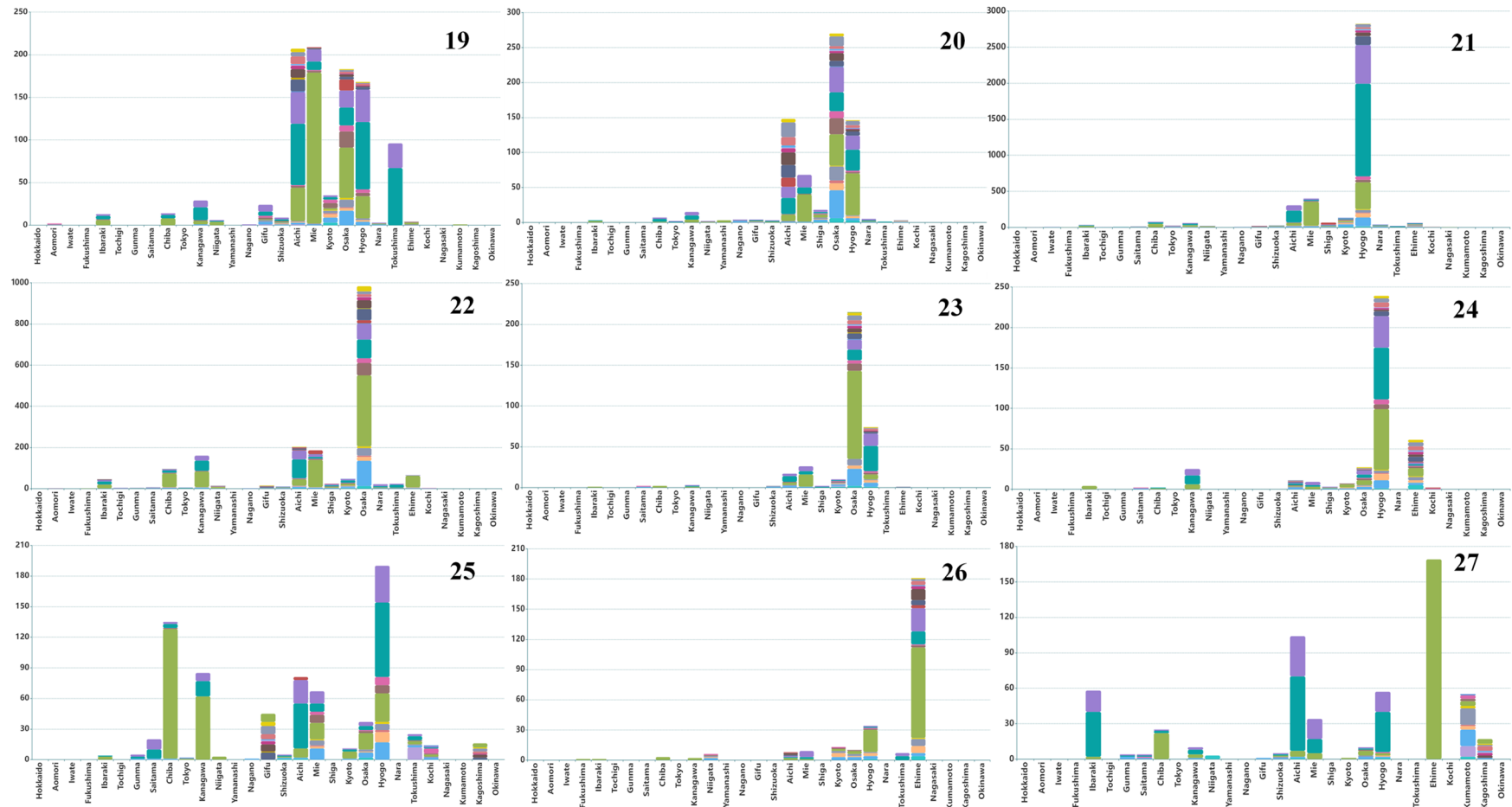


Figure A2. Cont.

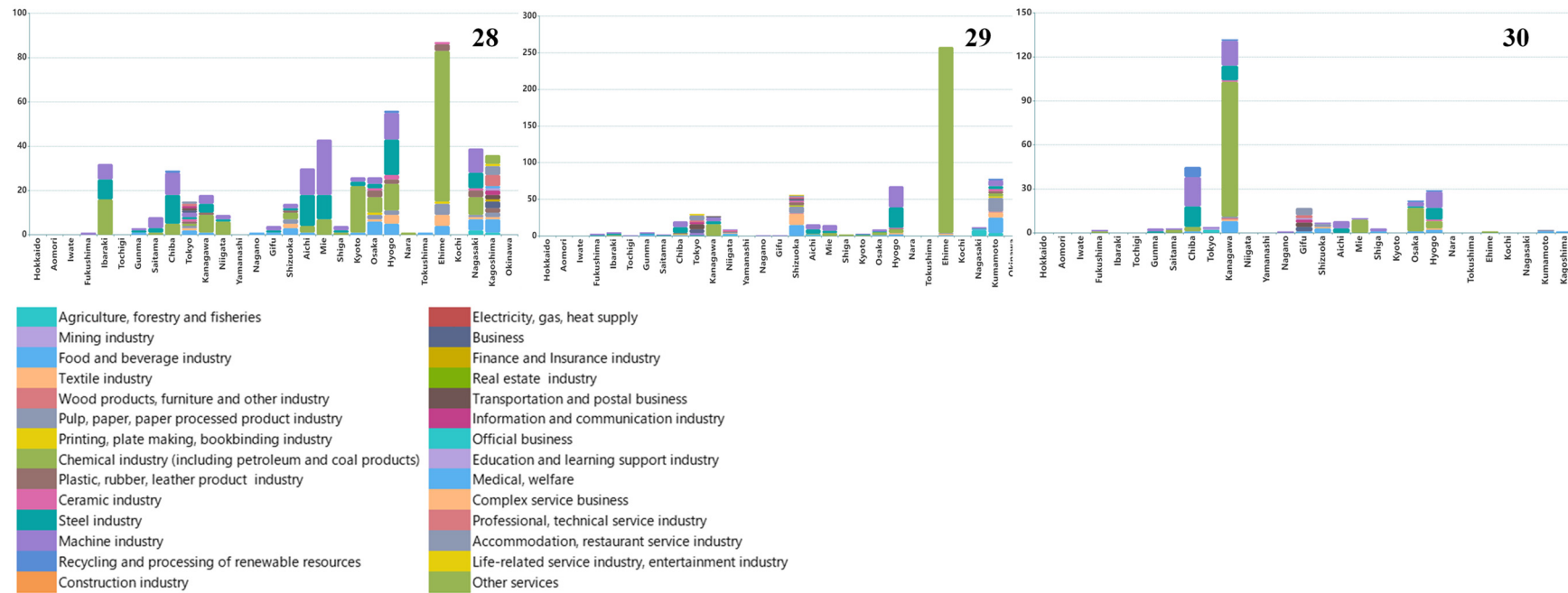


Figure A2. The CO₂ emissions embodied in the domestic imports of 30 prefectures in Japan by exporters in 2011 (units in 10,000 tCO₂). The panel numbers correspond to the numbers in Figure A1.

Table A1. The proportions of import volume from the other 29 prefectures in the total domestic import of each prefecture in 2011.

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%	

Table A2. Sources of IOTs across prefectures (as of 2 April 2022).

No.	Province	URL
1	Hokkaido	http://www.pref.hokkaido.lg.jp/kz/kks/ksk/tgs/renkanhyou2.htm (accessed on 7 June 2021)
2	Aomori	https://opendata.pref.aomori.lg.jp/dataset/dataland/estat27/estat78/ (accessed on 7 June 2021)
3	Iwate	http://www3.pref.iwate.jp/webdb/view/outside/s14Tokei/top.html (accessed on 7 June 2021)
4	Fukushima	http://www.pref.fukushima.lg.jp/sec/11045b/17023.html (accessed on 7 June 2021)
5	Ibaraki	https://www.pref.ibaraki.jp/kikaku/tokei/fukyu/tokei/betsu/sangyo/io23/ (accessed on 10 June 2021)
6	Tochigi	http://www.pref.tochigi.lg.jp/c04/pref/toukei/toukei/io.html (accessed on 10 June 2021)
7	Gunma	https://toukei.pref.gunma.jp/gio/index.html (accessed on 10 June 2021)
8	Saitama	https://www.pref.saitama.lg.jp/a0206/a152/index.html (accessed on 10 June 2021)
9	Chiba	http://www.pref.chiba.lg.jp/toukei/toukeidata/sangyou/index.html (accessed on 10 June 2021)
10	Tokyo	https://www.toukei.metro.tokyo.lg.jp/sanren/sr-index.htm (accessed on 10 June 2021)
11	Kanagawa	http://www.pref.kanagawa.jp/docs/x6z/tc20/sanren/top.html (accessed on 12 June 2021)
12	Niigata	https://www.pref.niigata.lg.jp/site/tokei/0358603.html (accessed on 12 June 2021)
13	Yamanashi	http://www.pref.yamanashi.jp/toukei_2/DB/EDD/dbkeizai06.html (accessed on 12 June 2021)
14	Nagano	https://www.pref.nagano.lg.jp/tokei/tyousa/sangyorenkan.html (accessed on 12 June 2021)
15	Gifu	https://www.pref.gifu.lg.jp/page/14514.html (accessed on 13 June 2021)
16	Shizuoka	http://toukei.pref.shizuoka.jp/chosa/15-050/index.html (accessed on 13 June 2021)
17	Aichi	https://www.pref.aichi.jp/soshiki/toukei/io2015.html (accessed on 13 June 2021)
18	Mie	https://www.pref.mie.lg.jp/common/07/ci500002753.htm (accessed on 13 June 2021)
19	Shiga	https://www.pref.shiga.lg.jp/kensei/tokei/sonota/sangyou/12823.html (accessed on 13 June 2021)
20	Kyoto	http://www.pref.kyoto.jp/tokei/cycle/sanren/sanrentop.html (accessed on 7 June 2021)
21	Osaka	http://www.pref.osaka.lg.jp/toukei/sanren/index.html (accessed on 7 June 2021)
22	Hyogo	https://web.pref.hyogo.lg.jp/kk11/ac08_2_000000020.html (accessed on 7 June 2021)
23	Nara	http://www.pref.nara.jp/16376.htm (accessed on 15 June 2021)
24	Tokushima	https://www.pref.tokushima.lg.jp/statistics/year/io/ (accessed on 7 June 2021)
25	Ehime	https://www.pref.ehime.jp/toukeibox/datapage/sanren/sanren-p01.html (accessed on 5 June 2021)
26	Kochi	https://www.pref.kochi.lg.jp/soshiki/111901/sanren.html (accessed on 15 June 2021)
27	Nagasaki	https://www.pref.nagasaki.jp/bunrui/kenseijoho/toukeijoho/renkan/ (accessed on 15 June 2021)
28	Kumamoto	https://www.pref.kumamoto.jp/soshiki/20/50333.html (accessed on 15 June 2021)
29	Kagoshima	http://www.pref.kagoshima.jp/tokei/bunya/keizai/renkan/ (accessed on 15 June 2021)
30	Okinawa	https://www.pref.okinawa.lg.jp/toukeika/io/io_index.html (accessed on 15 June 2021)

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

Table A3. Sectors of CO₂ emissions statistics table.

No.	Sector	No.	Sector
1	Agriculture, Forestry, and Fishery	15	Electricity, Gas, Heat Supply, and Water
2	Mining, Quarrying of Stone and Gravel	16	Wholesale and Retail Trade
3	Food, Beverages, Tobacco, and Feed	17	Finance and Insurance
4	Textile Mill Products	18	Real Estate and Goods Rental and Leasing
5	Lumber, Wood Products, Furniture, and Fixtures	19	Transport and Postal Activities
6	Pulp, Paper, and Paper Products	20	Information and Communications
7	Printing and Allied Industries	21	Government
8	Chemical and Allied Products, Oil and Coal Products	22	Education, Learning Support
9	Plastic Products, Rubber Products, and Leather Products	23	Medical, Health Care, and Welfare
10	Ceramic, Stone, and Clay Products	24	Compound Services
11	Iron and Steel	25	Scientific Research, Professional and Technical Services
12	Machinery	26	Accommodation, Eating and Drinking Services
13	Miscellaneous Manufacturing Industry	27	Living Related and Personal Services and Amusement Services
14	Construction Work Industry	28	Miscellaneous Services

Table A4. Matching table between sectors of NCNFS and IOTs.

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

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

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