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A Spatial Structural Decomposition Analysis of the Carbon Footprint of Household Consumption for Japanese Regions

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Abstract

Focusing on the increasing concern of local governments about global warming, this study analyzes carbon footprints at the regional (subnational) level in Japan by using a multi-regional input-output (MRIO) table and decomposition technique. Specifically, we estimate production- and consumption-based emissions at the regional level by using the 2005 MRIO table consisting of all regions (47 prefectures) in Japan and its 80 industrial sectors. In calculating the carbon footprint, we improve our consideration of spatial variations of emission intensities by constructing the dataset of emission coefficients of industries at the regional level corresponding to the district of our MRIO table. Furthermore, we apply a decomposition analysis to the regional differences in carbon footprint of per capita household consumption to elucidate what factors generate these differences. The results reveal net exporters and net importers of emissions via a quantitative identification of carbon leakage among regions and the factors contributing to increasing or decreasing carbon footprints embodied in regional consumer behavior.

Keywords: carbon footprint, multi-regional input-output table, decomposition analysis, Japan

1. Introduction

In 1998, the Japanese government enacted the Law Concerning the Promotion of Measures to Cope with Global Warming and encouraged municipalities to voluntarily seek solutions toward reducing greenhouse gas (GHG) emissions and disclosing information on GHG emission inventories. As a result, climate policies increasingly tend to be discussed at the regional level as well as the national and international level. When we consider developing more effective climate policies, we inevitably need regional analyses of global warming.

Moreover, when considering the scope of carbon dioxide or CO_2 emissions (one of the GHGs) emitted by a region, we can identify regional emissions from two viewpoints. The first concerns “production-based” emissions, which refers to the CO_2 actually emitted from industries in a region as the

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result of production activities. The other concerns “consumption-based” emissions, which refers to the CO_2 emitted to satisfy the final demands of goods and services and the CO_2 emitted directly by households via the use of private automobiles and household heating.

In order to establish effective GHG reduction policies at the regional (subnational) level, it is essential to address consumption-based emissions. This is significant because emissions from Japan’s residential sector have been increasing in recent years, and moreover, local governments can exercise relatively more discretion in framing and implementing environmental policies related to this sector.

However, in contrast to production-based emissions, it is difficult to calculate consumption-based emissions, because it is necessary to consider both direct and indirect emissions. Consumption-based emissions other than direct emissions from households are frequently referred to as the “carbon footprint.” A carbon footprint is not consistent with the direct emissions of a region due to various regional characteristics such as the locations of industries and housing, patterns of inter-regional transactions, and division of labor. A carbon footprint generated outside a region is frequently referred to as “carbon leakage.[4]” The increase in the carbon leakage has resulted from the advanced division of labor and growing transactions among regions. A large carbon leakage makes it difficult to estimate the carbon footprint accurately. Therefore, it is important to quantitatively estimate the carbon leakage among regions and industries. An input-output (IO) model, especially a multi-regional input-output (MRIO) model, is useful for carbon footprint analysis.

Focusing on the CO_2 emissions influenced by regional consumer behavior and their spatial variations, this study investigates the carbon footprint at the regional level using an MRIO table consisting of all regions (47 prefectures) in Japan. In calculating the carbon footprint, we improve our consideration of spatial variations of emission intensities by constructing the dataset of emission coefficients of industries at the regional level corresponding to the district of our MRIO table. Furthermore, based on the methodologies in Kagawa and Inamura (2004) and Zhou and Imura (2011), we apply a spatial decomposition analysis across Japanese regions to investigate the main factors generating spatial variations in the carbon footprint.

The rest of this paper is organized as follows. The second section explains the structure of the MRIO table used in this study, the MRIO model of the carbon footprint, and the method of decomposition analysis. The third section examines the results. Finally, we summarize the conclusions and discuss policy implications in the fourth section.

2. Multi-regional input-output model of the carbon footprint

2.1 Structure of our multi-regional input-output table

We use the MRIO table constructed by Hasegawa et al. (2011), which consists of 80 industrial sectors

[4] Generally speaking, carbon leakage often indicates the phenomenon whereby overseas emission (especially in countries with less environmental restriction) is increased due to emission restriction in one country. However, not only emission reduction but the phenomenon whereby certain economic activity of one country (region) leads to induced emissions in another country (region) through international division of labor and trade is also regarded as carbon leakage here.

and 47 regions (all prefectures) in Japan in 2005. Appendix 1 shows the names and locations of the prefectures, and Appendix 2 shows the industrial classification.

Figure 1 shows the structure of the MRIO table used in this study. The MRIO table counts import (**m**) in a lump sum along the column direction independently from the intermediate input (**A**) and the final demand (**f**).

		Intermediate input	Final demand	Export	Total output
		Hokkaido (1) ········ Okinawa (47)	Hokkaido (1) ········ Okinawa (47)		
Intermediate input	Hokkaido (1) ········ Okinawa (47)	A	f	e	x
Import		m	m		
Value-added		v			
Total output		x			

Figure 1 Structure of the MRIO table used in this study

2.2 Input-output model of the carbon footprint

We explain the MRIO model for estimating the carbon footprint. The balance equation of output to row direction is expressed as Equation (1), because domestic export and import is endogenous in the MRIO table.

$$\underbrace{\begin{bmatrix}\mathbf{x_1}\\ \mathbf{x_2}\\ \vdots\\ \mathbf{x_R}\end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix}\mathbf{A_{11}} & \mathbf{A_{12}} & \cdots & \mathbf{A_{1R}}\\ \mathbf{A_{21}} & \mathbf{A_{22}} & \cdots & \mathbf{A_{2R}}\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{A_{R1}} & \mathbf{A_{R2}} & \cdots & \mathbf{A_{RR}}\end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix}\mathbf{x_1}\\ \mathbf{x_2}\\ \vdots\\ \mathbf{x_R}\end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix}\mathbf{f_{11}}\\ \mathbf{f_{21}}\\ \vdots\\ \mathbf{f_{R1}}\end{bmatrix}}_{\mathbf{f_1}} + \cdots + \underbrace{\begin{bmatrix}\mathbf{f_{1R}}\\ \mathbf{f_{2R}}\\ \vdots\\ \mathbf{f_{RR}}\end{bmatrix}}_{\mathbf{f_R}} + \underbrace{\begin{bmatrix}\mathbf{e_1}\\ \mathbf{e_2}\\ \vdots\\ \mathbf{e_R}\end{bmatrix}}_{\mathbf{e}} \qquad (1)$$

where $\mathbf{x}$, $\mathbf{A}$, $\mathbf{f_r}$, and $\mathbf{e}$ are the output vector, input coefficient matrix, regional final demand vector, and export vector, respectively.

As shown in Figure 1, the MRIO table excludes import (**m**) in the endogenous and final demand sectors by deducting it from the column direction as a lump sum. Therefore, the import vector is originally excluded in Equation (1). Then, we develop Equation (1) as Equation (2).

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}(\mathbf{f_1} + \cdots + \mathbf{f_R} + \mathbf{e}) \qquad (2)$$

Next, we estimate both production-based emissions ($\mathbf{q}_{\mathbf{r}}^{\mathbf{P}}$) and consumption-based emissions ($\mathbf{q}_{\mathbf{r}}^{\mathbf{C}}$) by linking the dataset of emission coefficients in industries (**d**) with Equation (2).

$$\mathbf{q}_{\mathbf{r}}^{\mathbf{P}} = \mathbf{D}_{\mathbf{r}}\mathbf{x}_{\mathbf{r}} \tag{3}$$

$$\mathbf{q}_{\mathbf{r}}^{\mathbf{C}} = \mathbf{D}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{f}_{\mathbf{r}} \tag{4}$$

In Equations (3) and (4), **D** is a diagonal matrix with emission coefficient **d**. Equation (3) denotes production-based emissions, namely CO_2 emitted to produce domestic final demand goods and exports. On the other hand, Equation (4) denotes consumption-based emissions generated indirectly to satisfy regional final demand, which is frequently referred to as the carbon footprint. Therefore, Equation (4) does not include consumption-based emissions such as direct emissions of households generated by use of private automobiles and household heating.

Equation (4) does not include the carbon footprints generated in foreign countries to produce Japan's imports, because we use the MRIO table shown in Figure 1. Therefore, this study confines itself to domestic emissions while analyzing the carbon footprint and leakage.

2.3 Spatial decomposition analysis

To identify how the carbon footprint is influenced by consumer behavior at the regional level, we apply spatial decomposition analysis to regional differences in the carbon footprint induced by per capita household consumption. In the decomposition analysis, we decompose the difference in carbon footprint between a prefecture and the national average.

The decomposition equation is developed as follows.

$$\begin{aligned}
\Delta\mathbf{c} &= \mathbf{c}_r - \mathbf{c}_{na} \\
&= \mathbf{D}_r(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_r h_r - \mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_{na} h_{na} \\
&= (\mathbf{D}_r - \mathbf{D}_{na})(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_r h_r + \mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_r h_r - \mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_{na} h_{na} \\
&= \Delta\mathbf{D}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_r h_r + \mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}(\mathbf{s}_r - \mathbf{s}_{na})h_r + \mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_{na} h_r - \mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_{na} h_{na} \\
&= \Delta\mathbf{D}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_r h_r + \mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}\Delta\mathbf{s} h_r + \mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_{na}(h_r - h_{na}) \\
&= \underbrace{\Delta\mathbf{D}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_r h_r}_{\mathbf{D}\text{-factor}} + \underbrace{\mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}\Delta\mathbf{s} h_r}_{\mathbf{s}\text{-factor}} + \underbrace{\mathbf{D}_{na}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_{na}\Delta h}_{h\text{-factor}} \qquad (5)
\end{aligned}$$

where $\Delta\mathbf{D} = \mathbf{D}_r - \mathbf{D}_{na}$, $\Delta\mathbf{s} = \mathbf{s}_r - \mathbf{s}_{na}$, $\Delta h = h_r - h_{na}$

In Equation (5), **c** is the vector of the carbon footprint of per capita household consumption. **s** is the composition vector denoting the share of expenditure on each commodity of household consumption. Therefore, the summation of all elements in **s** is equal to one. *h* is the scalar denoting total expenditure of per capita household consumption. The subscripts *r* and *na* denote each region (shown in Appendix 1) and national average, respectively.

We also construct another decomposition equation.

$$\Delta \mathbf{c} = \Delta \mathbf{D}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_{na}h_{na} + \mathbf{D}_r(\mathbf{I}-\mathbf{A})^{-1}\Delta \mathbf{s}h_{na} + \mathbf{D}_r(\mathbf{I}-\mathbf{A})^{-1}\mathbf{s}_r \Delta h \qquad (6)$$

The weight between each region (r) and the national average (na) in each term in Equation (5) are diametrical to the corresponding terms in Equation (6). Equations (5) and (6) are called "polar decomposition" equations. Although there can be decompositions other than those seen in these two equations, we take the average of the two polar decomposition equations based on Equations (5) and (6), because Dietzenbacher and Los (1998) showed that the average of two polar decomposition equations is approximately equivalent to the average of all decomposition equations.

Using Equations (5) and (6), we decompose the total differences ($\Delta \mathbf{c}$) to three factors (**D**-factor, **s**-factor, and h-factor). The **D**-factor denotes the carbon footprint influenced by regional differences in the emission intensities of production activities. The **s**-factor and h-factor explain the effect of consumer behaviors. The former is based on differences in the consumption patterns, and the latter is based on the differences in the expenditure scales.

2.4 Emission data

The National Institute for Environmental Studies in Japan publishes various national emissions datasets. The "3EID," developed by Nansai and Moriguchi (2012), is one such dataset, which compiles CO_2 emissions in Japan by industry and energy types. Notably, the industrial classification is based on Japan's IO table. Therefore, we obtain the data of emission coefficients (**d**) at the national level from Nansai and Moriguchi (2012).

Based on the "3EID," we estimate emission coefficients at the regional level corresponding to the district of our MRIO table using regression analysis. In the regression analysis, we use the data of industrial emissions and intermediate inputs at the national level and construct the multiple regression equation without the constant term, wherein the explained variables are direct emissions from each industry, and the explanatory variables are intermediate inputs for each industry in terms of coal, crude petroleum, and natural gas (4); petroleum refinery products (22); coal products (23); and gas, steam, and hot water supply (61). We choose these four intermediate inputs as explanatory variables, because these are related to direct energy consumptions or fuel input. However, several industries use these inputs not as fuel input but as material input. Therefore, we regard the value of explanatory variables as zero for these industries (Table 1).

We estimate the parameters in the regression equation by the least squares method, subject to the summation of the residual error being zero. The regression equation is as follows.

$$y_i = \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \beta_4 x_{i4} + u_i, \qquad i = 1, 2, \ldots, 80 \qquad (7)$$

In Equation (7), y_i denotes direct emissions of industry *i*. Similarly, x_{i1}, x_{i2}, x_{i3}, and x_{i4} denote intermediate inputs from coal, crude petroleum, and natural gas (4); petroleum refinery products (22); coal products (23); and gas, steam, and hot water supply (61), respectively. u_i is the error term, which is expected to occur mainly due to our counting the inputs with the monetary term and the different energy items included in one sector.

Table 1 Energy or fuel inputs regarded as zero in the explanatory variables

	Intermediate input		Industry
(4)	Coal, crude petroleum, and natural gas	(22)	Petroleum refinery products
		(23)	Coal products
		(61)	Gas, steam and hot water supply
(22)	Petroleum refinery products	(16)	Petroleum chemical basic products
(23)	Coal products	(58)	Public construction
		(59)	Other civil engineering and construction

Next, regional emissions from the industrial sector can be estimated by multiplying the estimated parameters by the intermediate inputs used as explanatory variables in each prefecture. We adjust the calculated figures by scaling (using the ratio of the national figure to the summation of the calculated prefectural figures) so that the summation of the calculated regional emissions from industries corresponds to their emissions at the national level.

Finally, we develop the dataset of emission coefficients at the prefectural level by dividing the estimated emissions by monetary output at the prefectural level.

3. Results

3.1 Investigation of spatial variation of emissions

First, we investigate the spatial variation of emissions between regions. Figure 2 plots production and consumption-based emissions[5] at the prefectural level. The emissions are compared per capita to exclude differences due to regional population scales. In Figure 2, the horizontal axis represents production-based emissions, and the vertical axis, consumption-based emissions. The more distant a marker from the 45 degree line in the figure, the larger the difference between the two emissions.

Tokyo (13) has the largest consumption-based emissions of all regions while its production-based emissions are relatively small. On the other hand, Oita (44) has the largest production-based emissions and shows the largest differences between the two emissions. Figure 2 shows that the difference between the two emissions is large in many regions, indicating the importance of investigating carbon footprints at the regional level. In 21 regions, production-based emissions are larger than consumption-based emissions, and the opposite is true of the other 26 regions. The former group can be regarded as net exporters of emissions, and the latter, net importers.

[5] Here, consumption-based emissions include direct emissions from households as well as indirect emissions calculated from Equation (4). Direct emissions from households are calculated by using the regional data of household expenditure and emission coefficients at the national level, based on Nansai and Moriguchi (2012).

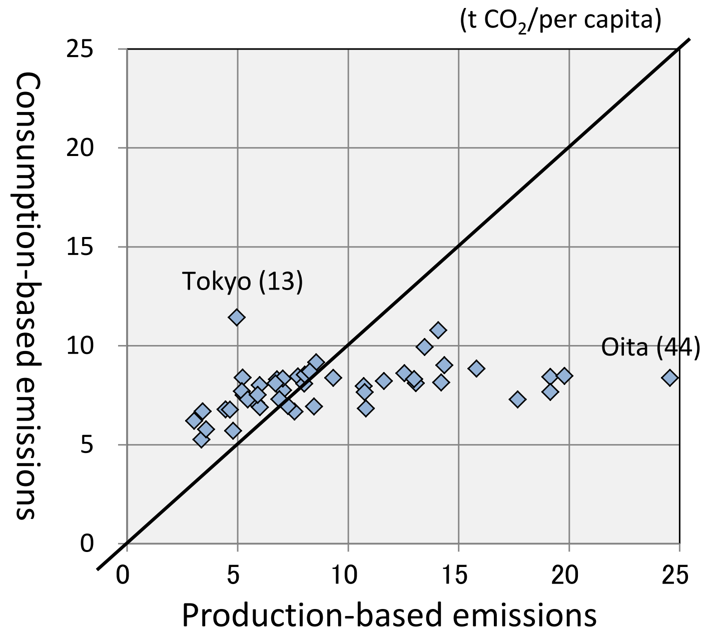

Figure 2 Production and consumption-based per capita emissions for each region

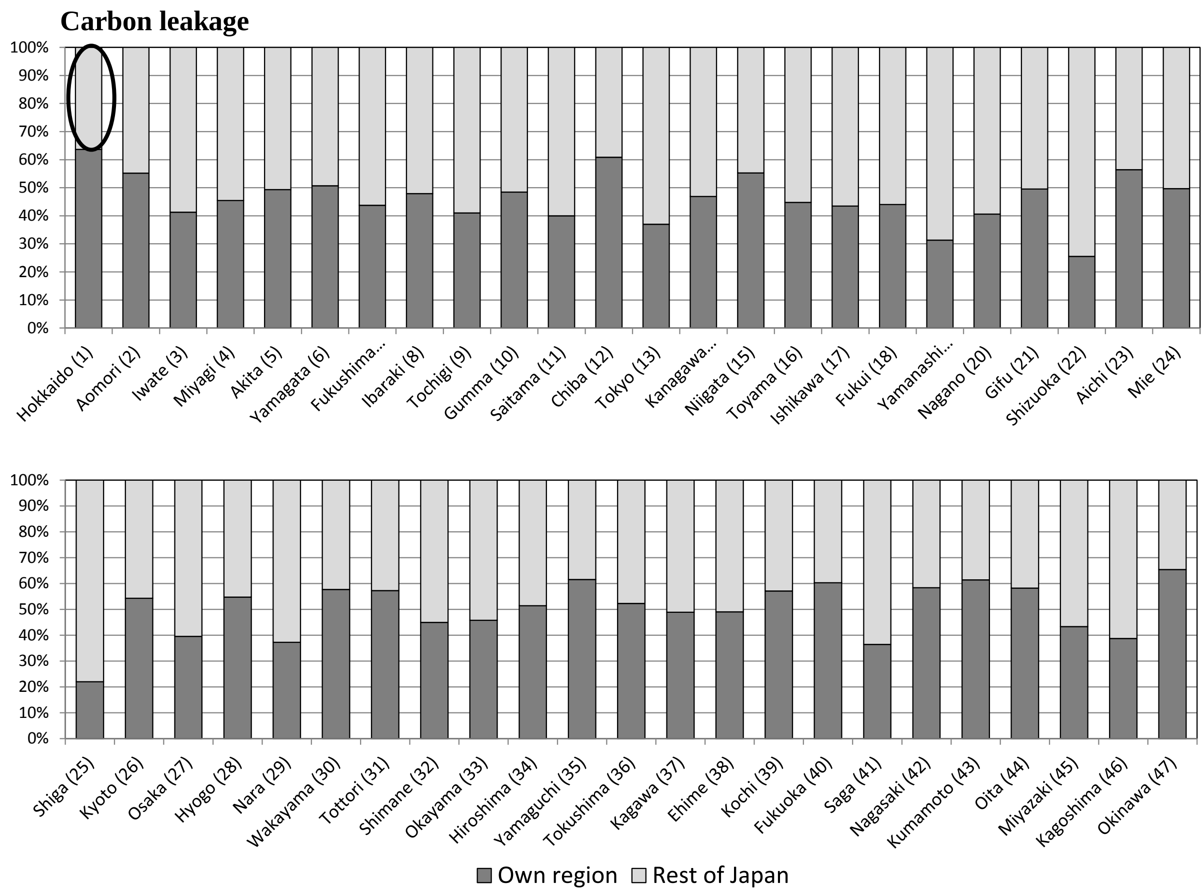

Figure 3 Regional composition of the carbon footprint

Next, we address carbon footprints based on total final demand in each region. As defined in Equation (4), this study regards the carbon footprint as consumption-based emissions excluding direct household emissions. Figure 3 shows a breakup of carbon footprints generated by regions for the prefecture itself and for the rest of Japan. The carbon footprint generated for the rest of Japan is interpreted as carbon leakage. The ratio of carbon leakage to carbon footprint averages 51.8% at the prefectural level, ranging from 34.6% (Okinawa (47)) to 78.0% (Shiga (25)). This reveals that prefectural carbon leakage is relatively large and differs significantly among prefectures, indicating that it is essential to identify carbon leakage more accurately so as to estimate regional carbon footprints.

3.2 Results of the decomposition analysis

Our decomposition analysis derives three factors (**D**-factor, **s**-factor, and *h*-factor), which generate regional differences in the carbon footprint of household consumption.

Figure 4 shows the results of the decomposition analysis by arranging total factors (⊿c), which denotes the actual differences in the carbon footprints between a region and the national average, in descending order. For the three factors, a positive value denotes that the factor contributes to increasing the carbon footprint over the national average, while a negative value denotes the opposite.

Both Mie (24) and Tokyo (13) have the largest carbon footprint of all regions, but the factors generating these large emissions differ between them. The **s**-factor for Mie (24) is the largest contributor to increasing the carbon footprint. On the other hand, the largest contributor for Tokyo (13) is the *h*-factor, while the negative **D**-factor and **s**-factor mitigate further increase in the region's carbon footprint. These results imply that the effectiveness of CO_2 reduction policies differ between the two regions.

Although all three factors tend to be mostly negative for regions with small total factors, many regions have both negative and positive factors. Furthermore, the signs of the factors differ between regions, implying it is more effective to consider implementing CO_2 reduction policies at the regional level.

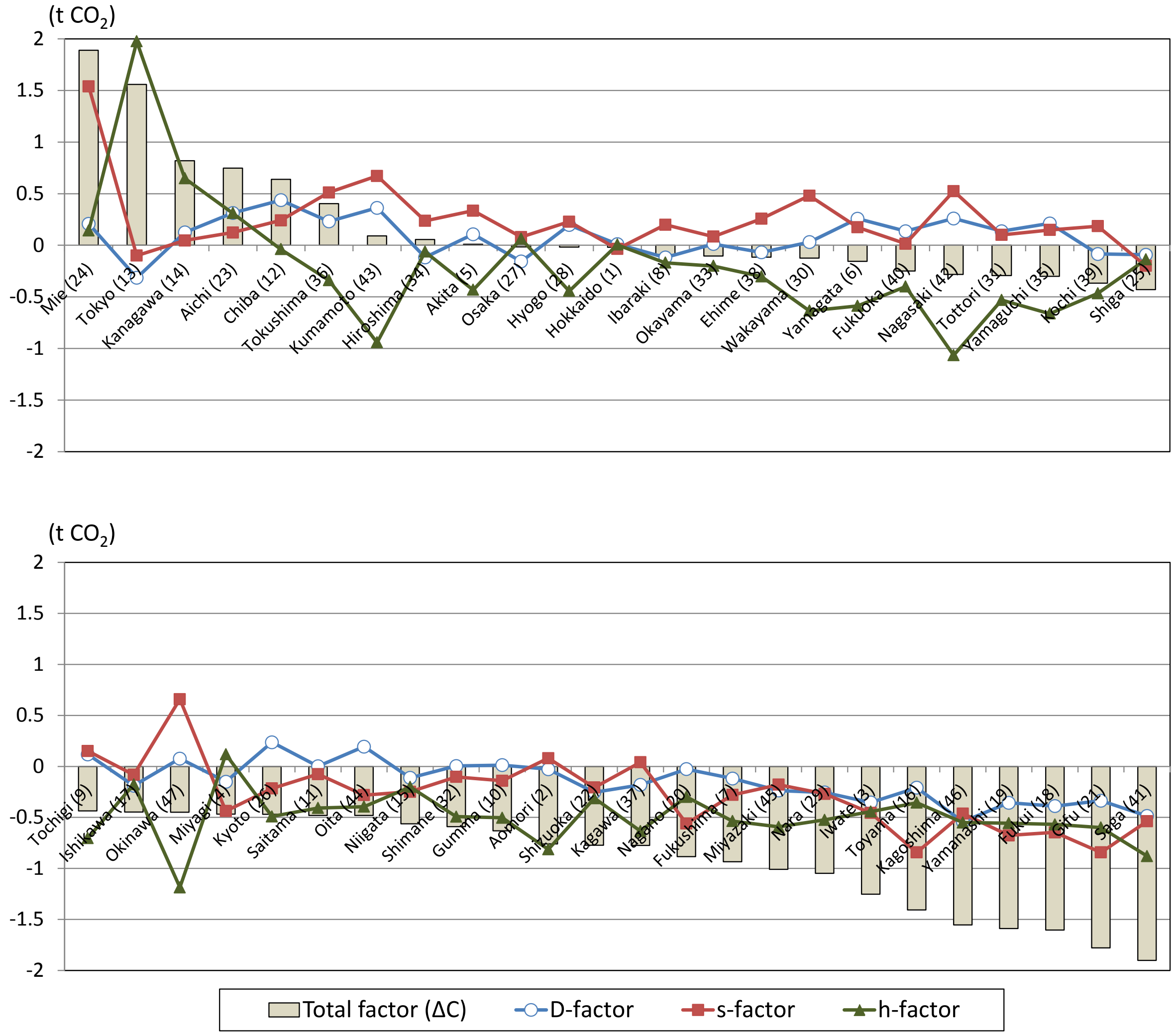

Figure 4 Results of the decomposition analysis of the differences in the carbon footprint between regions and the national average

4. Conclusions

This study focused on the increasing concern of local governments about global warming and analyzed carbon footprints at the regional level by using MRIO tables and the decomposition technique. Specifically, we estimated production- and consumption-based emissions at the regional level by using the 2005 MRIO table consisting of all regions (47 prefectures) in Japan and its 80 industrial sectors. Furthermore, we applied decomposition analysis to the regional differences in the carbon footprint induced by per capita household consumption, to elucidate what factors generate these regional differences.

Analyses using the MRIO table revealed that for many prefectures, production-based emissions differ significantly from consumption-based emissions in terms of volume in the same region and that certain regions are net exporters and others, net importers, of emissions. Furthermore, we found out that the average ratio of carbon leakage to carbon footprint is 51.8% at the prefectural level, ranging from 34.6% (Okinawa) to 78.0% (Shiga). This result implies that it is necessary to clarify the emission sources to be addressed in environmental policies in terms of producer responsibility or consumer responsibility.

Our decomposition analysis found out that factors contributing to increasing or decreasing carbon footprints differ largely at the regional level. It implies that the effectiveness of reduction policies also differs at the regional level. Focusing on regional consumer responsibility, it is important to change consumer behavior, namely to promote environmentally friendly consumer behavior, by informing consumers of regional characteristics affecting the carbon footprint.

In future research, using the methodology and results of this study, we shall determine the carbon footprint embodied in international trade and quantitatively analyze regional policies for global warming.

Appendix 1

Figure A.1 Prefectures in Japan

Appendix 2

Table A.1 Classification of industrial sectors in the MRIO table used in this study

(1)	Agriculture, forestry and fisheries	(21)	Medicaments	(41)	Office machine and machinery for service industry	(61)	Gas, steam and hot water supply
(2)	Metal ores	(22)	Petroleum refinery products	(42)	Household electric and electronic appliances	(62)	Water supply and other sanitary services
(3)	Nonmetal ores	(23)	Coal products	(43)	Electronic computing equipment and accessory equipment	(63)	Trade
(4)	Coal, crude petroleum and natural gas	(24)	Plastic products	(44)	Communication equipment	(64)	Financial service and insurance
(5)	Food and tobacco	(25)	Rubber products	(45)	Applied electronic equipment and Electric measuring instruments	(65)	Real estate agencies, managers and rent
(6)	Drinks	(26)	Glass and glass products	(46)	Semiconductor devices and Integrated circuits	(66)	House rent (imputed house rent)
(7)	Fabric	(27)	Cement and cement products	(47)	Electronic components	(67)	Transport
(8)	Apparel and other ready-made textile products	(28)	Pottery, china and earthenware	(48)	Industrial heavy electrical equipment	(68)	Telecommunication
(9)	Timber and wooden products	(29)	Miscellaneous ceramic, stone and clay products	(49)	Other electrical equipment	(69)	Broadcasting
(10)	Wooden furniture and accessories	(30)	Pig iron and crude steel	(50)	Motor vehicles	(70)	Information service
(11)	Pulp and paper	(31)	Steel	(51)	Other motor vehicles	(71)	Internet services
(12)	Converted paper products	(32)	Cast and forged materials	(52)	Steel ships and repair	(72)	Video and data entry
(13)	Publishing and printing	(33)	Other iron or steel products	(53)	Other transportation equipment and repair	(73)	Advertising services
(14)	Chemical fertilizer	(34)	Nonferrous metals	(54)	Precision machinery	(74)	Public administration
(15)	Industrial inorganic chemicals	(35)	Nonferrous metal products	(55)	Miscellaneous manufacturing products	(75)	Education and research institute
(16)	Petroleum chemical basic products	(36)	Metal products for construction and architecture	(56)	Reuse and recycling	(76)	Medical service, health, social security and nursing care
(17)	Organic chemical products	(37)	Other metal products	(57)	Construction and repair of construction	(77)	Goods renting leasing
(18)	Resin	(38)	General industrial machinery	(58)	Public construction	(78)	Other business services
(19)	Chemical fiber	(39)	Special industrial machinery	(59)	Other civil engineering and construction	(79)	Personal service
(20)	Final chemical products	(40)	Other general machines and parts	(60)	Electric power	(80)	Other

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