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Evaluating carbon inequality by household type and income level across prefectures in Japan

Yuzhuo Huang [a,*], Yosuke Shigetomi [a], Ken'ichi Matsumoto [b,c,*]

[a] Graduate School of Fisheries and Environmental Sciences, Nagasaki University, Japan
[b] Faculty of Economics, Toyo University, Japan
[c] Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology, Japan

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ABSTRACT

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. Therefore, it is necessary to explore the carbon footprint of different households on the basis of systematically grouped income levels and evaluate carbon inequality in all prefectures. Using the 2005 multi-regional input–output table of Japan, we identified detailed structures of household carbon footprint (HCF) across single- and multi-person households of different income levels in Japan's 47 prefectures. We elucidated carbon inequality across prefectures through the carbon footprint Gini coefficients of the aforementioned households. The results showed that 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 CF during climate mitigation.

1. Introduction

1.1. Background

Amid economic globalization, climate change has become a critical environmental issue in the 21st century, exerting a profound impact on the sustainable development of countries. Globally, 72% of greenhouse gas (GHG) emissions are caused by household activities, which are influenced by lifestyles (Majid et al., 2014). GHG emissions from production are driven by consumer demand through the supply chain, with a greater proportion of such emissions in developed countries accounted for by consumption-based accounting than production-based accounting (Peters, 2008). On the basis of consumption-based accounting, the indirect GHG emissions associated with household consumption are considerably larger than the direct emissions caused by car driving and gas use in homes (Hertwich, 2011). Indirect consumption-based GHG emissions—that is, household carbon footprint (HCF)—represents the indirect carbon dioxide (CO_2) emissions associated with goods and services that are finally consumed through the supply chain. These issues highlight the imperative to pay attention to HCF to formulate additional emission reduction strategies.

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 it stems primarily from the HCF differences caused by income levels across regions (Hailemariam et al., 2020). For instance, 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). In the process of emission reduction, justice and fairness are essential factors that affect the efficiency of policy implementation. 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.

* Corresponding authors.
E-mail addresses: bb53420006@ms.nagasaki-u.ac.jp (Y. Huang), y-shigetomi@nagasaki-u.ac.jp (Y. Shigetomi), matsumoto1005@toyo.jp (K. Matsumoto).

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The world's third-largest economy, Japan, is also the fifth-largest GHG and CO_2 emitter globally (Crippa et al., 2019). Therefore, its policies on climate change hold significant implications for mitigating global climate change. In the 2015 Paris Agreement, Japan set a target of reducing GHG emissions by 26% in 2030 compared with 2013 levels and used this agreement as basis for further expanding the target to 46% in 2021 (Ministry of Foreign Affairs of Japan, 2021). In 2020, the government of Japan announced its goal of achieving carbon neutrality and pledged to reduce GHG emissions to net zero by 2050 (Ministry of the Environment of Japan, 2021). By the end of 2021, the 47 prefectures of Japan had issued statements supporting carbon neutrality (Ministry of the Evironment of Japan, 2021). Despite these initiatives, however, different levels of economic development mean that the characteristics of household consumption in each prefecture also differ. Therefore, an important measure for Japan to effectively promote carbon neutrality is scientifically distributing responsibility for emission reduction across prefectures while considering social equality.

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 & 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. The succeeding section presents our review of the literature on HCF and carbon inequality.

1.2. Literature review

Consumption has emerged as a key priority in research and policy-making 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., Ramos and Huisingh (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., Leino and Linnanen (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.

Climate change is one of the most formidable obstacles to global sustainable development, and 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., Sun and Wennersten (2013) found that household use and transport are the two main contributors to household CO_2 emissions. Cárdenas-Mamani et al., Kahhat and Vázquez-Rowe (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 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 lifestyle approach (CLA), 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., Wang and Wang (2019) combined CLA and input–output (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.

Given that our study focused on Japan, we also summarized the literature related to HCF in the country. Shigetomi et al., Kagawa and Tohno (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. Hirano et al., Ihara and Yoshida (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., Yoshida and Dong (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., Kagawa and Tohno (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. Huang et al., Chapman and Matsumoto (2019) analyzed the carbon footprint of household consumption in Japan using an index and a structural decomposition analysis of the period 1990 to 2005. The authors discovered that the average annualized increase in indirect HCF is 6.6 Mt-CO_2, which is about 2.5 times that in direct HCF. Shigetomi et al., Yamamoto and Kondo (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.

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., Morenate and Monsalve (2016) studied HCF inequality in Spanish households under the impact of the great recession of the 21st century. Feng et al., Hubacek and Song (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 is still limited.

1.3. Purpose of the study

Household consumption levels in Japanese prefectures differ given the influence of income level, household type, social infrastructure, natural conditions, and other factors. HCF in the country has been extensively explored, but to the best of our knowledge, no study has evaluated it on the basis of different households with different income levels across prefectural administrative units. Assessing carbon inequality among households in Japan necessitates a systematic understanding of the relationship between HCF and income level in these prefectures. Clarifying regional differences in HCF and carbon inequality in the country also has important reference value for research on consumption-based mitigation in other countries. In consideration of these issues, the current work was aimed at quantifying HCF-induced carbon inequality between single- and multi-person households of different incomes in Japan's 47 prefectures. With the country's 2005 subnational multi-regional input–output (MRIO) table as reference, this study inquired into differences in HCF across the prefectures on the basis of household type. We also calculated the Gini coefficients of carbon footprint (CF-Gini coefficients hereafter) in the aforementioned households to measure carbon inequality by prefecture. To promote carbon neutrality under Japan's sustainable development goals, a more scientific and reasonable understanding of its HCF can advance the application of targeted measures for reducing emissions across prefectures on the grounds of consumption differences due to household type. Meanwhile, a more comprehensive understanding of carbon inequality in each prefecture can not only alleviate social contradictions but also provide a theoretical basis for policymakers to deal with the relationship between income inequality and climate change.

The remainder of the paper is organized as follows. Section 2 describes the methodology and data used in this work, and Section 3 presents the results and discussion. Section 4 concludes the paper with policy implications.

2. Methodology and data

2.1. Quantification of HCF by household type

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 & Yuan, 2022). There are three types of IO models: single-region IO, bilateral trade IO, and MRIO (Sato, 2014). 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 & Hertwich, 2008):

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

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

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. A1). 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):

$$C = K(I - A)^{-1}F \tag{3}$$

where C is the indirect carbon footprint, and K is a vector of carbon intensity for all economic sectors in all the 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:

$$C_h = K(I - A)^{-1}H \tag{4}$$

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 represents household consumption.

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

$$C_h = K(I - A)^{-1}(H_m + H_s) \tag{5}$$

where H_s and H_m are the household consumption levels 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 National Survey of Family Income and Expenditure (NSFIE) (Ministry of Internal Affairs & 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 10,000) 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 10, 000).

The NSFIE data were recorded on the basis of purchaser price, while

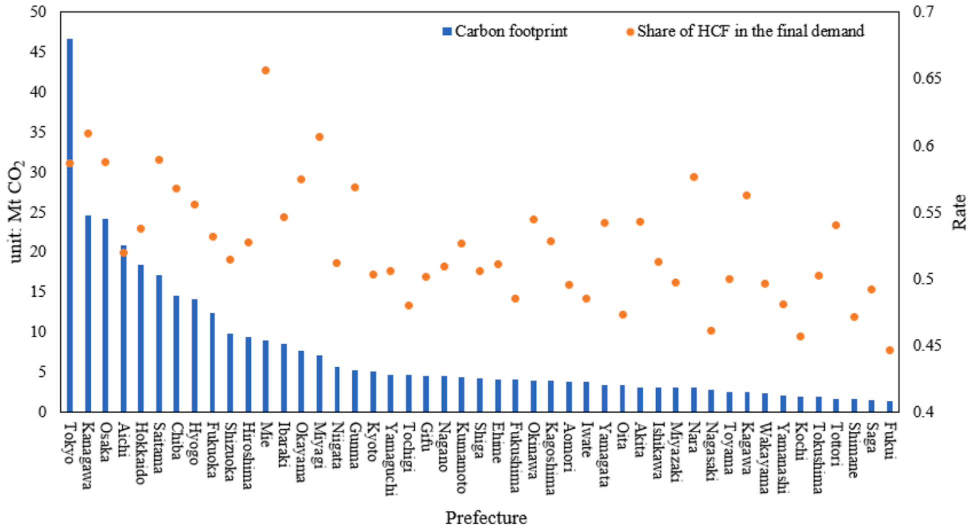

Fig. 1. HCF and its share in the total carbon footprint of final demand across prefectures in Japan (2005).

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.

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):

$$G_{CF} = \sum_{b=1}^{k} D_b Y_b + 2\sum_{b=1}^{k} D_b (1 - T_b) - 1 \tag{6}$$

where G_{CF} is the CF-Gini coefficient; D_b and Y_b are the proportion of households and HCF of each income group b, respectively; T_b refers to the cumulative proportion of the HCF of each income group b; and b denotes the number of income groups. Because we employed the

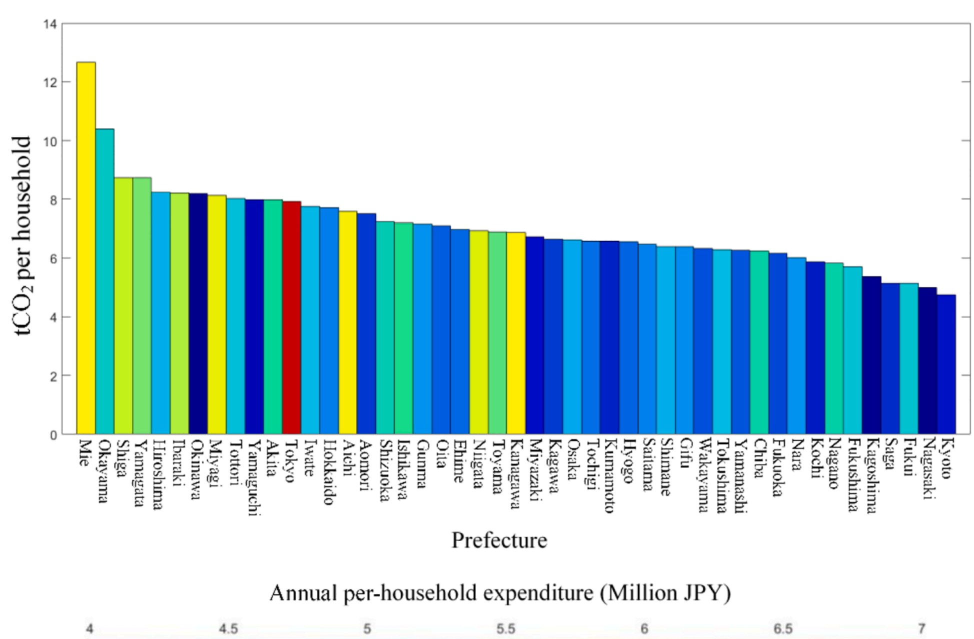

Fig. 2. Per-household carbon footprint across prefectures in Japan (2005). The colored bars correspond to annual per-household expenditures.

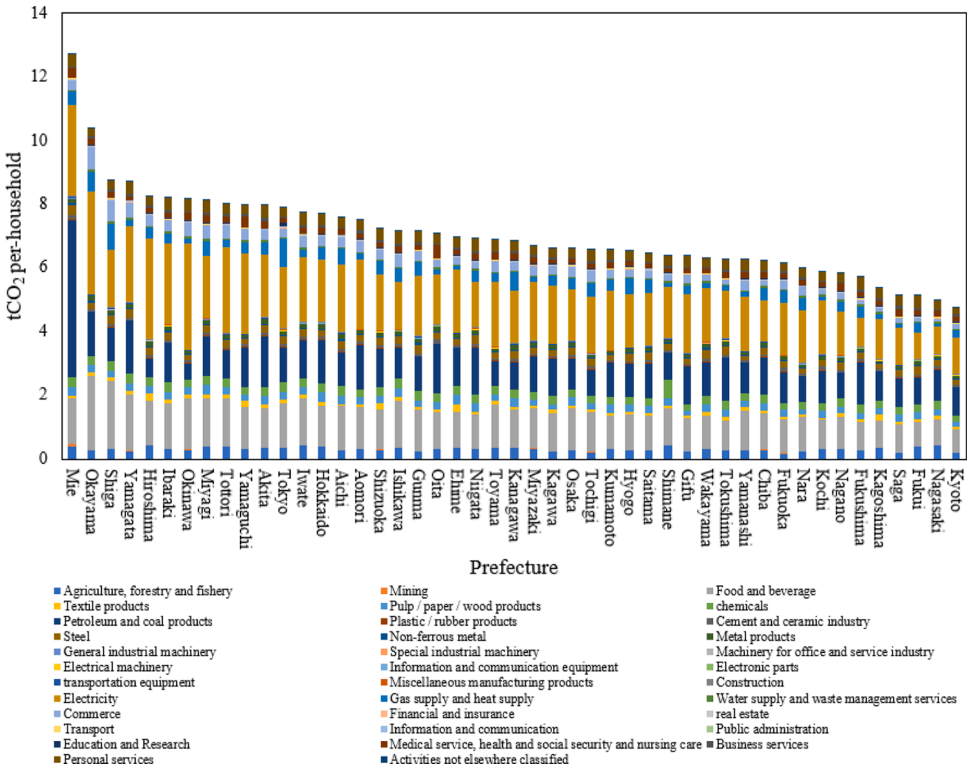

Fig. 3. The structure of per-household carbon footprint across prefectures in Japan (2005).

NSFIE, $b = 1 \cdots 10$ in this study.

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 & Communications, 2015b). The 2005 emission factors used to calculate the HCF of the 47 prefectures were obtained from energy consumption statistics (Agency for Natural Resources & Energy, 2021). The sector classification of the energy consumption statistics and the 2005 Japan MRIO table differed. Correspondingly, when calculating carbon intensity K, we first determined correspondence between the energy consumption statistics and the 2005 Japan MRIO table among sectors (Table A1). 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 & Industry Agency for Natural Resources & Energy, 2021).

3. Results and discussion

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. 1). The HCF of these prefectures is significantly higher than that of the other prefectures, and their gross regional product (GRP) in 2005 was among the top three in Japan. As described in Eq. (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%.

There are clear differences between the total HCF and per-household HCF in the 47 prefectures, confirming that household consumption in every prefecture differs under varying income levels and natural conditions (Figs. 1 and 2). 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.

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. 3).

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

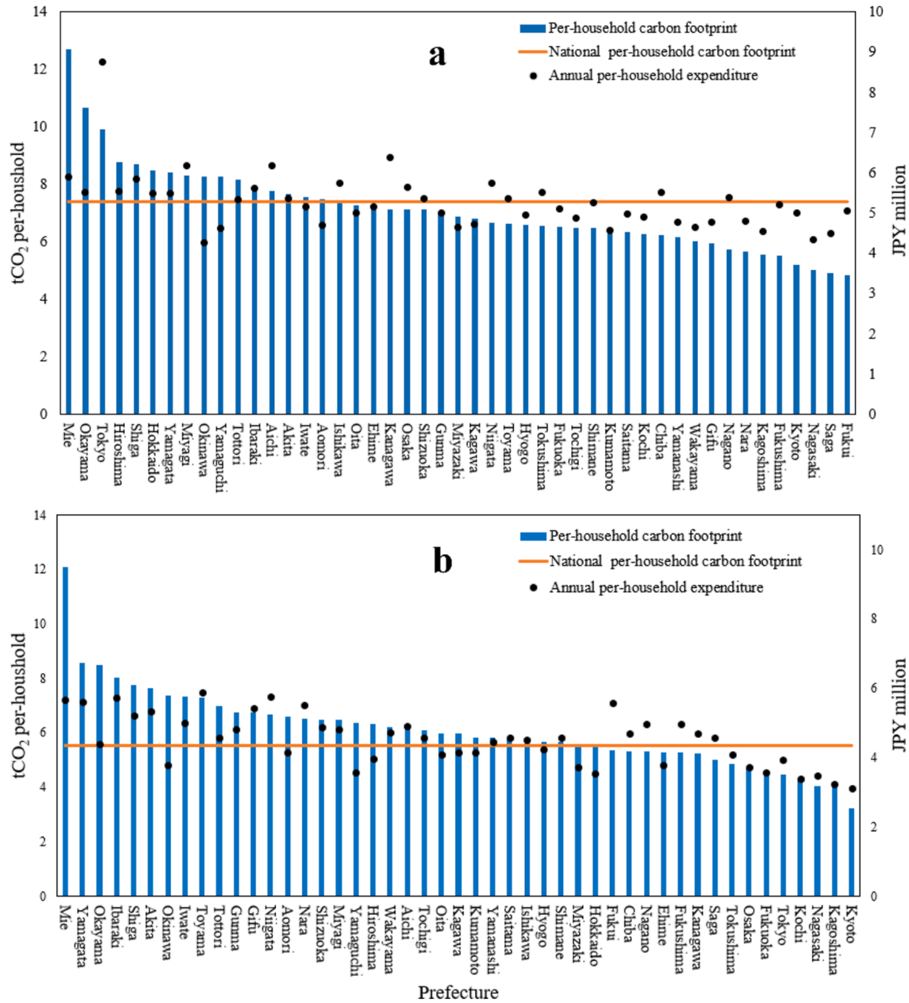

Fig. 4. Per-household carbon footprint and annual per-household expenditures of (a) multi- and (b) single-person households across prefectures in Japan (2005).

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.

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.

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). 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).

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.

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. 5).

On the whole, the HCF of multi-person households increases with income (Fig. 5a). High-GRP prefectures (i.e., prefectures with a high GRP per household[1]) 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. 3), resulting in more pronounced differences in the HCF of electricity across income groups. In Tokyo, the

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

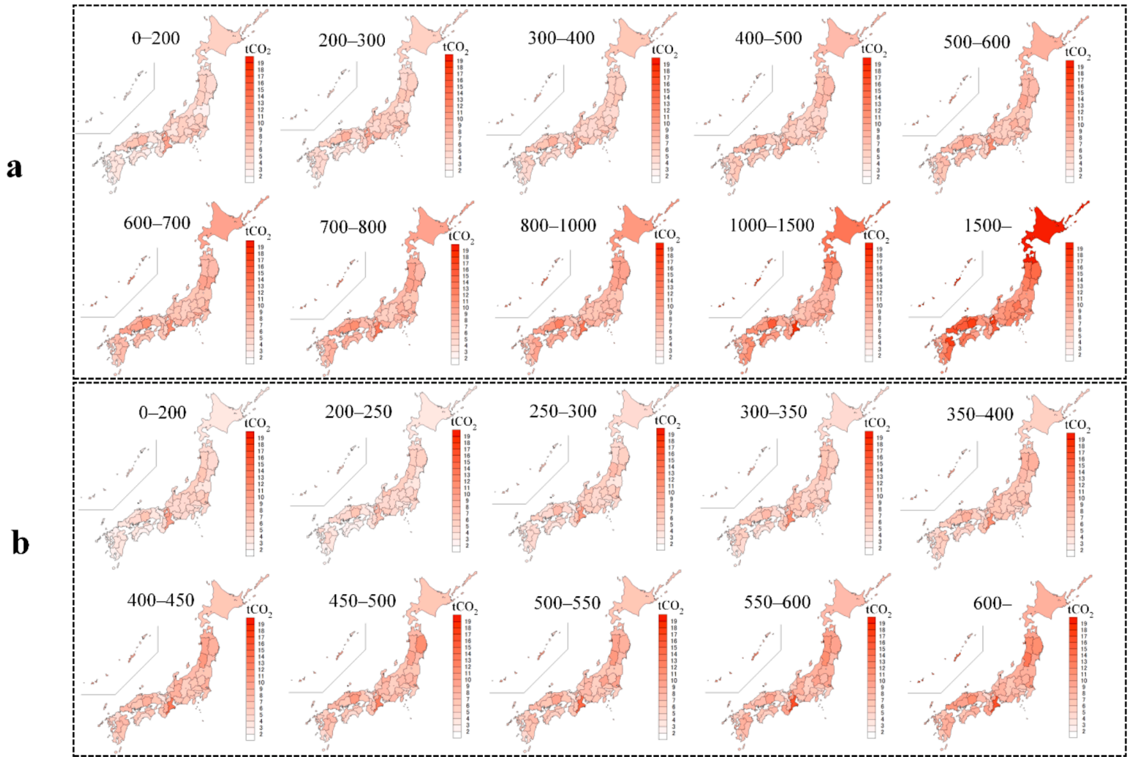

Fig. 5. Per-household carbon footprint (unit: tCO_2) of (a) multi- and (b) single-person households by income group (unit: JPY 10,000) across prefectures in Japan (2005).

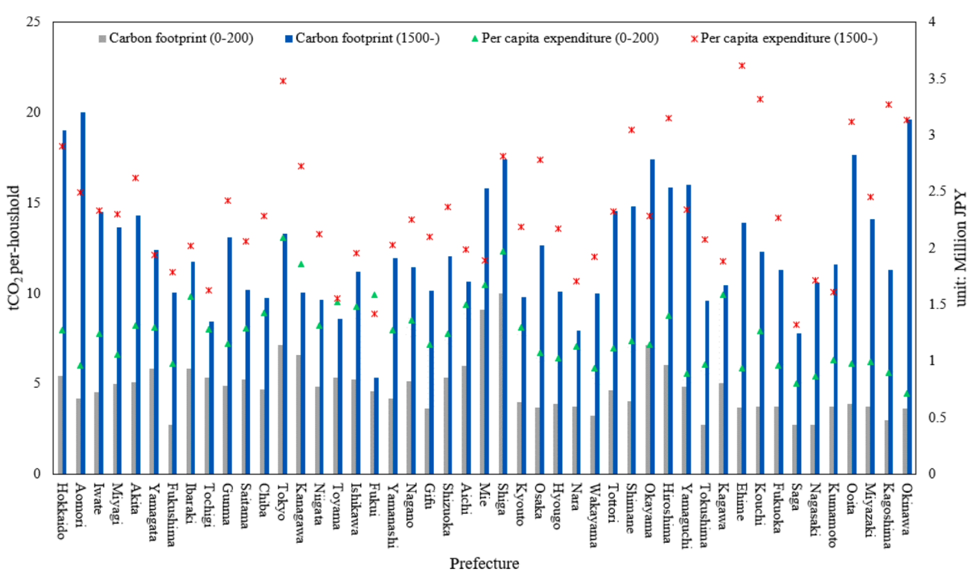

Fig. 6. Per-household carbon footprint and per-capita expenditures of multi-person households with less than JPY 2 million (0–200) and more than JPY 15 million (1500–) across prefectures in Japan (2005).

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 11,186 billion), 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. 6).

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

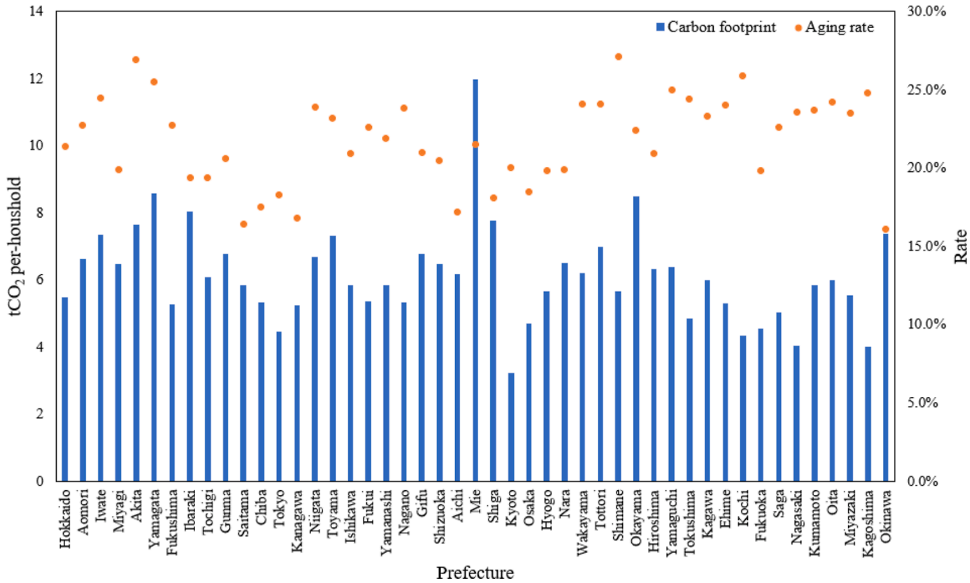

Fig. 7. Per-household carbon footprint and aging rates of single-person households across prefectures in Japan (2005).

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. 5b). However, there are substantial differences in HCF across income groups between single- and multi-person households in high-GRP prefectures, such as Tokyo. In

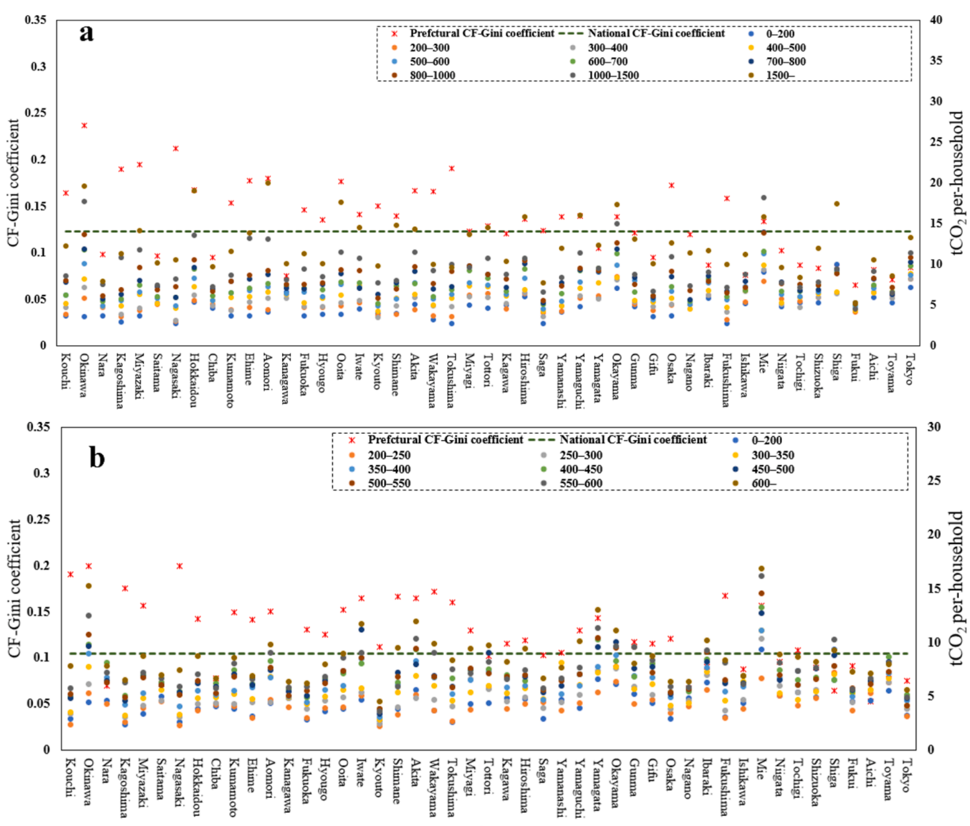

Fig. 8. CF-Gini coefficients and per-household carbon footprint by income group (unit: JPY 10,000) of (a) multi- and (b) single-person households across prefectures in Japan (2005). All prefectures are arranged on the basis of GRP per household: The prefecture with the lowest GRP per household is on the left (Kochi), and the prefecture with the highest GRP per household is on the right (Tokyo).

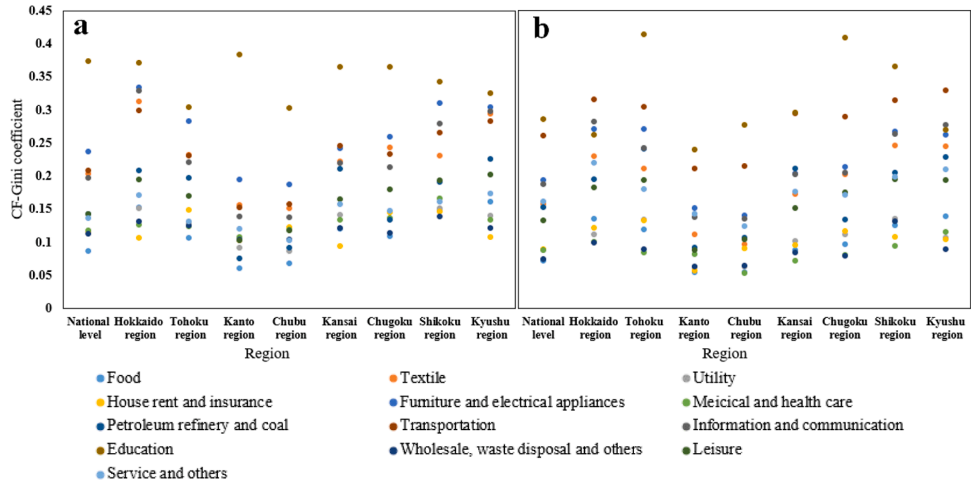

Fig. 9. The CF-Gini coefficients of 13 household expenditure categories of (a) multi- and (b) single-person households for eight regions of Japan in 2005.

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, 2019). Generally, high-GRP prefectures with low HCF (e.g., Tokyo) have a low aging rate (Fig. 7). Because of the concentration of a young labor force in Tokyo, its aging rate (18.3%) is manifestly low (Ministry of Internal Affairs & 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.

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). 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).

3.4. *Carbon inequality*

Household carbon inequality across the 47 prefectures was measured by calculating the CF-Gini coefficients (Fig. 8). 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.

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. (6), which allowed the intuitive observation of carbon inequality in various sectors via a consideration of regionality and household type (Fig. 9).

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.

3.5. Limitations of the study

There are two 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 energy consumption 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 energy consumption statistics, an MRIO table with more recent data is presently unavailable.

4. Conclusion and policy implications

This study inquired into carbon inequality across prefectures through the indirect HCF of single- and multi-person households with different income levels in Japan in 2005. The main findings are as follows.

(1) Economically advanced prefectures have a larger HCF, and the share of HCF out of the total carbon footprint of final demand is high. For example, Tokyo has the highest HCF (46.7 Mt-CO_2), which accounts for 59% of final demand.
(2) At present, multi-person households are the main contributors to Japan's HCF. The national per-household carbon footprint of multi-person households is 7.5 tCO_2, which is 1.3 times that of single-person households (5.7 tCO_2),
(3) In high-GRP prefectures in the Kanto and Chubu regions, the HCF of multi-person households is high and grows in a uniform manner across income groups, whereas the HCF of single-person households is generally lower under the influence of demographic structure, income level, and cost of living.
(4) Household expenditure is the main factor influencing HCF across income groups in low-GRP prefectures. For example, the per-capita expenditures of households with an annual income of more than JPY 15 million in Okinawa (JPY 3.1 million) and Tokyo (JPY 3.5 million) are close, but their HCF levels are noticeably different.
(5) Carbon inequality gradually decreases with improving household wealth, as indicated by the declining CF-Gini coefficients from low-GRP prefectures to high-GRP prefectures. This is evident in the CF-Gini coefficients of multi-person households in Okinawa and Miyagi, which are 0.23 and 0.12, respectively.

Household consumption has become an important source of CO_2 growth in Japan. The HCF levels of prefectures show substantial differences, which also contribute to variations in carbon inequality across these administrative units. 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. Specifically, the results suggest the following policy implications:

First, under Japan's national emission reduction target, each prefecture needs to consider HCF reduction from two dimensions: total and per-household HCF. Although the total HCF in high-GRP prefectures (e.g., Tokyo) is substantial, the per-household carbon footprint is not always prominent. Therefore, when distributing responsibility for emission reduction, it is necessary to comprehensively understand the actual situation of household consumption in each prefecture and consider every household as a unit in formulating an overall emission reduction plan.

Second, 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.

Finally, on the basis of the regional gap in HCF caused by household type, responsibilities must be further distributed to reduce carbon inequality. In high-GRP prefectures, multi-person households can reduce their household consumption base by avoiding wasteful consumption and promoting low-carbon, energy-efficient consumption. In low-GRP prefectures, emission reduction by both single- and multi-person households can be underlain by a consideration of carbon inequality as the point of penetration, which not only narrows the social income gap but also reduces the HCF polarization caused by extremely high or low incomes. Additionally, every prefecture can determine the sectoral focus of emission reduction according to the carbon inequality of different household types in each sector. For example, during emission reduction in multi-person households in high-GRP prefectures, the carbon inequality generated by selective consumption should be strongly considered.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

Data will be made available on request.

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Appendix

See Fig. A1, Tables A1 and A2.

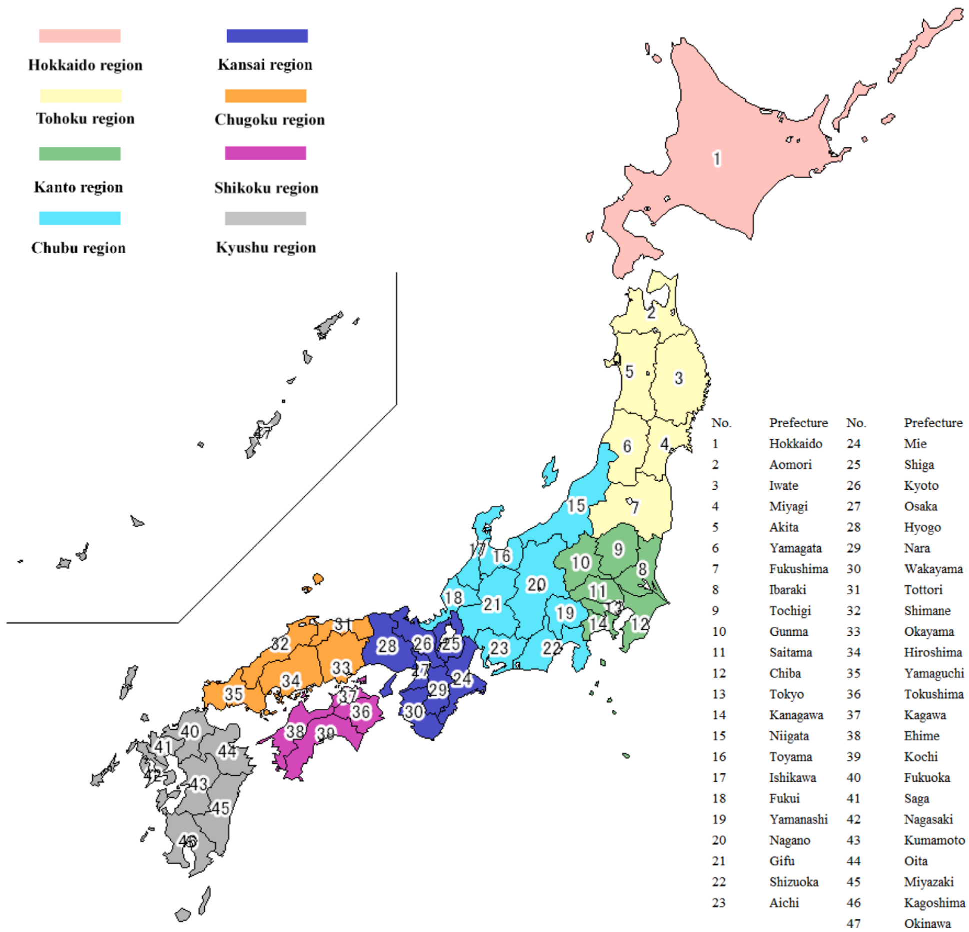

Fig. A1. The geographical locations of 47 prefectures and 8 regions in Japan.

Table A1
The correspondence of sectors between the energy consumption statistics and the 2005 Japan MRIO table.

No.	Sector of energy consumption 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 aparel 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

(continued on next page)

Table A1 (*continued*)

No.	Sector of energy consumption statistics	No.	Sector of the 2005 Japan MRIO table
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 mesuring 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 vheicle 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 enginnering 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	Giids 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 survery
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

Note: The energy consumption statistics is obtained from the Agency for Natural Resources and Energy (2021), and the 2005 Japan MRIO table was compiled by Hasegawa et al. (2015).

Table A2
GRP, number of households, and GRP per household across prefectures in Japan in 2005.

No.	Prefecture	GRP (unit: billion JPY)	Household (unit: 1000)	GRP per household (unit: million JPY)
1	Hokkaido	19,442.2	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	11,277.7	1032.5	10.9
9	Tochigi	8217.6	709.3	11.6
10	Gunma	7647.6	726.2	10.5
11	Saitama	20,647.0	2650.1	7.8
12	Chiba	19,567.8	2325.2	8.4
13	Tokyo	99,361.4	5890.8	16.9

(*continued on next page*)

Table A2 (*continued*)

No.	Prefecture	GRP (unit: billion JPY)	Household (unit: 1000)	GRP per household (unit: million JPY)
14	Kanagawa	31,327.3	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	16,919.1	1353.6	12.5
23	Aichi	35,609.2	2758.6	12.9
24	Mie	7623.2	675.5	11.3
25	Shiga	6044.2	479.2	12.6
26	Kyoto	10,034.9	1079.0	9.3
27	Osaka	39,354.8	3654.3	10.8
28	Hyogo	19,618.2	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	11,382.8	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	18,049.1	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, and the data for households were taken from the Statistics Bureau, Ministry of Internal Affairs and Communications (2010).

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