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To cite this article: Yuzhuo Huang *et al* 2025 *Environ. Res. Commun.* **7** 015010

IOP Publishing   *Environ. Res. Commun.* **7** (2025) 015010   https://doi.org/10.1088/2515-7620/ad9e89

Environmental Research Communications

OPEN ACCESS

RECEIVED
8 October 2024

REVISED
2 December 2024

ACCEPTED FOR PUBLICATION
12 December 2024

PUBLISHED
13 January 2025

PAPER

Evaluating the environmental effects of Japan's tourism: insights into pandemic-induced changes and driving forces

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Keywords: carbon footprint, pandemic, domestic tourism, inbound tourism, driving force

Supplementary material for this article is available online

Abstract

The intersection of the COVID-19 pandemic and tourism has significantly influenced emissions from supply chains, highlighting a complex dynamic between tourism and climate change. Although the pandemic represents a unique event within a specific timeframe, analyzing its impact on tourism provides valuable insights into the characteristics of tourism carbon footprints (TCF) in the context of sudden public health crises. Accordingly, we used the latest data available from the global multi-regional input–output table of EXIOBASE3 and Japan's tourist consumption statistics to estimate the TCF from all tourist sources in Japan based on the global economic system, and we visualized the carbon flow caused by population mobility. The decomposition of the environmental impact of the pandemic response further identified the driving forces of TCF changes. The main findings suggested that substantial differences exist in the emission levels and sectoral distributions of TCF between inbound and domestic tourism in Japan. Domestic TCF accounted for the majority of the overall TCF, and it also showed a stronger ability to withstand the pandemic impact, accounting for over 90% of Japan's TCF during the pandemic. The pandemic greatly reduced the TCF and further exacerbated the driving differences. Prior to the pandemic, Japan's TCF had diverse driving forces; however, pandemic-induced restrictions magnified the volume effect, especially in the inbound TCF, whereas other effects remained substantial for the domestic TCF.

1. Introduction

Tourism, as a crucial economic component in the service industry, activates the intrinsic value of nature and culture while also generating enormous economic value through, for example, tourism-related industry chains (Webster & Ivanov 2014). Global tourism expenditure in 2016 reached USD 1.2 trillion, accounting for approximately 7% of global exports in goods and services (United Nations World Tourism Organization 2017). Besides, the impact of tourism on global warming has been recognized as an important issue in the 21st century (Sun *et al* 2020). In 2013, the global tourism carbon footprint (TCF) was 4.5 $GtCO_2e$, accounting for approximately 8% of global greenhouse gas (GHG) emissions, and this number continues to increase steadily every year (Lenzen *et al* 2018).

Tourism is influenced by natural conditions (e.g., temperature), but it is also closely related to social conditions (e.g., pandemics) (Sigala 2020). The COVID-19 pandemic profoundly impacted global health systems and economic interactions, with epidemic prevention measures such as national border closures and travel restrictions severely hindering the tourism development. As a sector highly dependent on population mobility and consumer demand, tourism experienced substantial constraints on its growth due to the pandemic effects (Osorio *et al* 2023). Prolonged restrictions on international travel resulted in losses of USD 4.5 trillion for the tourism in 2020 and a 49.1% decline in its global contribution to gross domestic product (GDP) compared to 2019 (World Travel & Tourism Council 2021).

Japan, recognized for its cultural heritage and advanced infrastructure, has been an important tourism country. In 2019, tourism accounted for 7.3% of Japan's GDP and supported 5.8 million jobs (World Travel & Tourism Council 2022). However, the COVID-19 pandemic severely disrupted both inbound and domestic tourism. In 2020, Japan's government classified COVID-19 as Category 2[4] and implemented entry restrictions, initially targeting China and later extending globally (Ministry of Internal Affairs and Communications 2020). Besides, between 2020 and 2021, four states of emergency were declared, with restrictions gradually expanded nationwide (Coronavirus Infectious Disease Control Headquarters 2021). Although these measures effectively curbed the pandemic, they resulted in a sharp decline in tourism activity.

Explorations of the relationship between tourism and CO_2 emissions at the regional level is often accompanied by more significant environmental impacts. Peeters and Dubois (2010), who quantified global TCF, projected that these emissions would grow at an average rate of 3.2% per year up to 2035. Studies on tourism at the sectoral level enables a more accurate capture of the TCF characteristics. An evaluation of the average TCF of an overnight stay in a Spanish coastland hotel by Puig *et al* (2017) identified electricity and fuel consumption as the main potential hotspots for the TCF. Kitamura (2020) calculated Japan's TCF in 2017 and demonstrated that transport and souvenirs are important sources of CO_2 emissions. Many studies have focused on the changes in the tourism economy and TCF during the COVID-19 pandemic. Gössling *et al* (2020) compared the impacts of COVID-19 to previous pandemics and explored how the pandemic changed tourism. A calculation of the TCF in Spain in 2019 and 2020 under different recovery pathways by Osorio *et al* (2023) led to the proposal that the pandemic greatly reduced the TCF and that new tourists' consumption patterns resulting from the pandemic were no longer sufficient to ensure tourism sustainability. Despite the economic shock created by the pandemic, the pandemic conditions provided a unique opportunity for the ecological restoration of tourist attractions. Chen *et al* (2023) pointed out that the pandemic greatly reduced CO_2 emissions from China's tourism in 2020, and that the estimated ecological compensation for tourism amounted to approximately CNY 6.9 billion.

Continuous monitoring and analysis of tourism GHG emissions, as impacted by the pandemic, are becoming much more pressing. Given these issues, the aim of this study was to evaluate the TCF from Japan's tourism (i.e., inbound, and domestic tourism) during the epidemic stages[5] in 2018–2022. We used the latest data available from the global multiregional input–output (MRIO) table of EXIOBASE3 and Japan's tourist consumption statistics to inquire into the differences in sectoral characteristics of TCF and to visualize the carbon flow caused by population mobility. We also used structural decomposition analysis (SDA) to further explore the driving forces of the environmental impact of pandemic response.

To the best of our knowledge, existing studies have rarely provided a systematic quantification of TCF during the pandemic across all tourist sources in Japan, nor have they thoroughly identified the key influencing factors. This study addresses these gaps through several innovative approaches. First, it offers a comprehensive temporal analysis of the COVID-19 pandemic's impact on Japan's tourism, covering both domestic and inbound tourism—a perspective not commonly addressed in previous research. Moreover, by employing EXIOBASE3, a global MRIO database, this study provides a novel empirical evaluation of how the pandemic reshaped economic linkages between Japan and other global regions. Finally, the study pioneers in decomposing changes in Japan's TCF during the pandemic, visualizing its dynamic trends through the integration of key influencing factors closely tied to the tourism sector. These contributions collectively advance the understanding of the pandemic's far-reaching effects on tourism and its implications for emission reduction. In the long run, the pandemic is a special event over a period of time. However, understanding its tourism impact can assist policymakers in comprehending the characteristics of TCF within the context of abrupt public health changes, while simultaneously considering strategies for climate change mitigation and the tourism recovery.

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

2. Methodology and data

2.1. The accounting method used to determine the indirect TCF

The MRIO model is an economic method for tracking financial flows between major economic sectors in various regions, and it further breaks down national footprint data into more specific consumption- and industry-related components (Sato 2014). The basic structure of the MRIO model is as follows:

[4] Based on the severity of contagiousness and disease, Japan's government divided the overall risk level into Category 1, 2, 3, 4, 5 from high to low.

[5] Before the pandemic: 2018–2019; during the pandemic: 2020–2021 (early-stage pandemic: 2020; mid-stage pandemic: 2021); post pandemic: 2022.

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

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

where $X = (x_i^s)$ is the column vector of total output, and x_i^s is the total output of sector i in regions s. A is the matrix of technical coefficients in the $(nm \times nm)$ dimension; I is the identity matrix and $(I - A)^{-1}$ is the Leontief inverse, for which each column provides the direct and indirect requirements per unit of production intended for final demand; $A = (a_{ij}^{rs})$, is given by $a_{ij}^{rs} = \frac{z_{ij}^{rs}}{x_j^s}$, where z_{ij}^{rs} represents the intersectoral monetary flows from product i in region r to product j in region s. $F = f_i^{rs}$ is the final demand diagonalized by blocks, which represents the product i in region r that is consumed by region s; The superscripts r and s represent the regions, $r, \ s = 1, \cdots, n$; the subscripts i and j represent the products, where $i, j = 1, \cdots, m$.

As a top-down macroeconomic methodology, the MRIO model has been flexibly extended by adding the emission intensity vector and energy consumption to create the environmentally extended multi-regional input-output (EEMRIO) model (He *et al* 2019). The use of the EEMRIO model is appropriate for economic activities such as tourism (Sun *et al* 2020). The basic formula of the EEMRIO model is defined as:

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

$$K = \begin{bmatrix} k^1 & 0 & \cdots & 0 \\ 0 & k^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & k^m \end{bmatrix} \tag{4}$$

where, C^{ind} is the indirect GHG from the final demand generated by tourism consumption and K is a diagonal matrix that denotes the emissions coefficients (i.e., GHG emissions, including CO_2, CH_4, and N_2O, per unit of output).

Tourism involves the cross-border flows of consumers from different regions; therefore, defining the boundaries of TCF calculations becomes more complex. Generally, three main perspectives are considered when defining the carbon inventory of tourism: production, consumption, and destination (Sun *et al* 2020). The destination perspective measures the domestic and inbound GHG emissions produced to support all tourist activities within the geographic territory of an economy (Sun *et al* 2019). Accordingly, the present study relied on destination perspective to evaluate Japan's TCF, and the final EEMRIO model was built using detailed statistical data on tourism accounting for inbound and domestic tourists (Osorio *et al* 2023). Given that tourism consumption is divided into domestic and inbound tourism, the TCF of Japan can be depicted as follows:

$$C^{\mathrm{ind}} = K(I - A)^{-1}(F^{\mathrm{inb}} + F^{\mathrm{dom}}) \tag{5}$$

where F^{inb} and F^{dom} denote the inbound and domestic tourism consumption.

2.2. The accounting method for the direct TCF

The direct TCF of tourism are produced by tourists through their direct use of fuel for lighting, heating, cooking, transportation, and other activities (Kitamura *et al* 2020). The energy consumed directly in tourist expenditures in this study falls mainly into five categories: coal, gasoline, gas/diesel oil[6], kerosene, and liquefied petroleum gas (LPG).

Following the emission inventory method (Arioli *et al* 2020), the calculation formula for direct CO_2 emissions is defined as follows:

$$C^{\mathrm{dir}} = \sum_{l=1}^{n} EXP_l \times P_l$$

$$P_l = NCV_l \times CC_l \times OF_l \times \frac{44}{12} \tag{6}$$

where C^{dir} is the direct CO_2 emissions of inbound and domestic tourism; EXP_l denotes the consumption of energy l by tourist; P_l is the CO_2 emissions coefficient of the energy l; NCV_l is the low calorific value of energy l; CC_l is the carbon content per unit calorific value of fuel l; OF_l is the oxidation rate of energy l; $l = 1 \cdots 4$ is energy types. The related information of energy included in tourist consumption is summarized in table A2.

[6] In EXIOBASE3, gas and diesel oil are unified in the same category of product 'Gas/Diesel Oil'.

2.3. The SDA approach for indirect TCF

Considering the sectoral distribution and impact breadth of TCF (Meng *et al* 2017), SDA was used to further emphasize the influencing factors of indirect TCF. SDA, as an approach based on an input-output model, explores both the direct and indirect impacts by capturing the spillover effect of demand using the Leontief inverse (Hoekstra, van den Bergh 2003).

Since $\boldsymbol{K}$ is an emission coefficient related to energy technology and $\boldsymbol{A}$ is the matrix of technical coefficients related to production technology, we use $\boldsymbol{TEC} = \boldsymbol{K}(\boldsymbol{I} - \boldsymbol{A})^{-1}$, which denotes technological development, in equation (3) to obtain equation (7).

$$C^{\text{ind}} = TEC \times F \tag{7}$$

Tourism demand $(\boldsymbol{F})$ is the main observation target for analyzing the interannual differences in TCF; therefore, it has been further decomposed into tourist volume, tourism consumption expenditure, and tourism consumption pattern, as shown in equation (8).

$$F = TZ \times PE \times TS \tag{8}$$

where $\boldsymbol{TZ}$ is the diagonal matrix of the tourist number; $\boldsymbol{PE}$ is the diagonal matrix of the tourism consumption expenditure; $\boldsymbol{TS}$ is the matrix of the tourism consumption pattern.

We then plugged equation (8) into equation (7) to obtain the following equation:

$$C^{\text{ind}} = TEC \times TZ \times PE \times TS \tag{9}$$

Assuming the base period of 0 and the reporting period of 1, the changes in the indirect TCF are obtained as follows:

$$\Delta C^{\text{ind}} = C_1^{\text{ind}} - C_0^{\text{ind}} = TEC_1 \times TZ_1 \times PE_1 \times TS_1 - TEC_0 \times TZ_0 \times PE_0 \times TS_0 \tag{10}$$

Theoretically, a non-uniqueness problem will exist for the SDA method and will result in n! types of decomposition forms if the number of decomposed factors is n (Fan *et al* 2019). To address this issue, we used a technique called bipolar decomposition, which takes the average of all possible first-order decomposition forms (Zhang *et al* 2015). Accordingly, $\boldsymbol{\Delta C_{ind}}$ can be further expressed as:

$$\begin{aligned} \Delta C^{\text{ind}} &= \frac{\Delta TEC \times TZ_1 \times PE_1 \times TS_1 + \Delta TEC \times TZ_0 \times PE_0 \times TS_0}{2} \\ &+ \frac{TEC_1 \times \Delta TZ \times PE_1 \times TS_1 + TEC_0 \times \Delta TZ \times PE_0 \times TS_0}{2} \\ &+ \frac{TEC_1 \times TZ_1 \times \Delta PE \times TS_1 + TEC_0 \times TZ_0 \times \Delta PE \times TS_0}{2} \\ &+ \frac{TEC_1 \times TZ_1 \times PE_1 \times \Delta TS + TEC_0 \times TZ_0 \times PE_0 \times \Delta TS}{2} \\ &= \Delta TEC + \Delta TZ + \Delta PE + \Delta TS \end{aligned} \tag{11}$$

where $\boldsymbol{\Delta TEC}$, $\boldsymbol{\Delta TZ}$, $\boldsymbol{\Delta PE}$ and $\boldsymbol{\Delta TS}$ refer to the changes in indirect TCF due to the technological effect, tourist volume effect, tourism consumption expenditure effect, and tourism consumption pattern effect, respectively.

2.4. Data

The annual statistics on the travel content of inbound tourists by region were obtained from a consumption trend survey for foreigners visiting Japan (CTSVJ) (Japan Tourism Agency 2023a), and the annual statistics on the travel content of domestic tourists were obtained from a consumption trend survey of travel and tourism (CTSTT) (Japan Tourism Agency 2023b). The conversion of physical quantities for energy consumption is conducted based on the petroleum product price survey published by the Japan Agency for Natural Resources and Energy (2024). The emission coefficients used for direct TCF came from 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG gas inventories (2006).

Of the available MRIO databases, EXIOBASE stands out as compatible with the System of Environmental-Economic Accounting due to its high sectorial detail, which is matched with multiple social and environmental satellite accounts (Stadler *et al* 2018). EXIOBASE3 builds upon the previous version of EXIOBASE, and provides the data for 200 products from 49 regions, while the emission satellite accounts record 27 kinds of air pollutants (Zenodo. 2021). Accordingly, relying on the product-by-product EXIOBASE3 in version 3.8.2, we employed MRIO tables and emissions satellite accounts from 2018 to 2022 to conduct our TCF calculation for Japan. We also used CO_2 equivalents provided by the Intergovernmental Panel on Climate Change (2018) to convert the three main types of GHG emissions uniformly into CO_2 to calculate emissions coefficients $(\boldsymbol{K})$.

Before formally running the EEMRIO model, it was necessary to carry out several preprocessing steps on the raw data. First, the CTSVJ and CTSTT statistics for tourist expenditures include 38 and 49 products, respectively, which are recorded based on the purchaser price. By contrast, EXIOBASE3 contains 200 products,

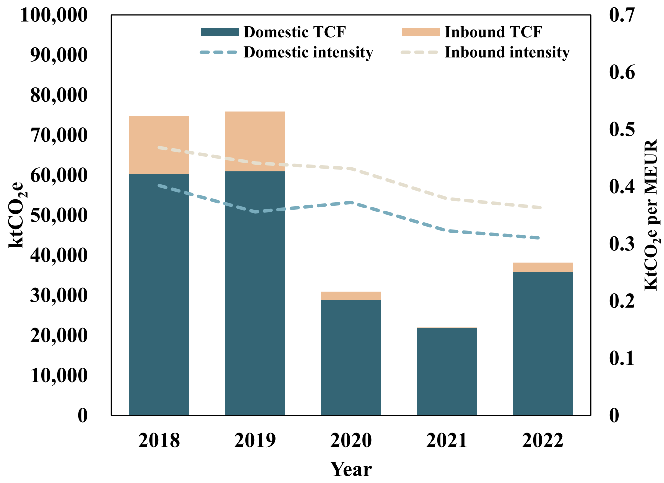

Figure 1. The trends in domestic and inbound TCF, as well as changes in GHG intensity.

which are based on the basic price. Therefore, we followed the methodology of Shigetomi *et al* (2014, 2015) and used an optimization technique to determine tourism expenditure for products listed on EXIOBASE3. Moreover, by also considering the impact of inflation on tourist consumption capacity, this study unified tourism expenditure data into the 2018 price in million euros (MEUR) through the consumer price index (The World Bank 2023).

3. Results and discussion

3.1. The total TCF in Japan

In this study, we introduced the impact of social conditions (i.e., the COVID-19 pandemic) into the analysis of tourism's effects on climate change, revealing the multifaceted characteristics of Japan's TCF. A key innovation of this research lies in its temporal analysis, which captures the dynamic evolution of TCF across a complete time dimension, offering a more robust and nuanced understanding of the pandemic's impacts.

Domestic tourism in Japan played a significant role in the total TCF, with distinct phased characteristics emerging throughout the COVID-19 pandemic (figure 1). Prior to the pandemic, domestic and inbound tourism TCFs in Japan experienced stable growth, increasing modestly by 1% and 4%, respectively. However, in the early stage of the pandemic in 2020, TCFs for both sectors dropped sharply, with inbound tourism experiencing a far steeper decline (86%) compared to domestic tourism (53%). During the mid-stage pandemic in 2021, the downward trend continued, although the decline in domestic TCF eased significantly to 24%, whereas the reduction in inbound TCF worsened to 93%. By 2022, in the post-pandemic era, recovery began, marked by a particularly dramatic resurgence in inbound TCF, which increased 16-fold.

Despite the fluctuations in total TCF from 2018 to 2022, the GHG intensity of Japan's tourism sector consistently showed a downward trend, indicating the effectiveness of Japan's recent carbon reduction measures. Notably, the GHG intensity of inbound tourism was significantly higher than that of domestic tourism. However, the overall GHG intensity for both inbound and domestic tourism in Japan remains relatively higher compared to environmentally advanced countries. For example, a comparison with Spain's tourism sector, as analyzed by Osorio *et al* (2023), reveals important differences. In 2020, the GHG intensity of Japan's inbound and domestic tourism was 0.43 and 0.37 $ktCO_2e$/MEUR, respectively, compared to 0.38 and 0.28 $ktCO_2e$/MEUR in Spain. This discrepancy underscores that, while Japan has made progress in reducing CO_2 emissions, significant potential remains for adopting more aggressive low-carbon strategies. Interestingly, during the COVID-19 pandemic (2019 to 2020), the trends in GHG intensity in Japan exhibited characteristics distinct from those observed in other countries. The GHG intensity of domestic tourism in Japan slightly increased (from 0.36 to 0.37 $ktCO_2e$/MEUR), whereas that of inbound tourism in Japan continued to decline (from 0.45 to 0.43 $ktCO_2e$/MEUR). Conversely, during the same period, the GHG intensity of Spain's domestic tourism exhibited a downward trend, while the GHG intensity of inbound tourism showed a slight increase.

3.2. The direct TCF in Japan

This study utilizes a global MRIO table encompassing 200 product categories, enabling a more comprehensive evaluation of TCF. Most direct CO_2 emissions are generated through transportation during travel, and the direct

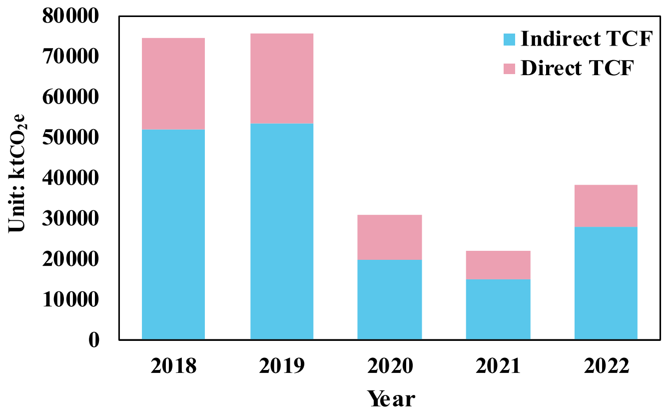

Figure 2. The TCF composition during 2018–2022 in Japan.

Table 1. Direct TCF by energy during 2018–2022 in Japan.

(Unit: ktCO$_2$e)		Gasoline	Gas/diesel oil	Kerosene	LPG
2018	Inbound	32.4	12.8	6.0	3.3
	Domestic	21128.9	842.6	395.3	218.7
2019	Inbound	38.1	15.7	7.2	4.4
	Domestic	20640.3	855.6	394.0	239.3
2020	Inbound	5.1	2.3	1.1	0.7
	Domestic	10338.6	353.3	174.5	101.6
2021	Inbound	0.3	0.1	0.1	0.0
	Domestic	6738.9	209.6	87.9	54.6
2022	Inbound	5.0	2.3	1.0	0.6
	Domestic	9705.5	360.6	151.3	94.0

TCF is derived from the combustion of fuels, which are dominated by gasoline (table 1). The share of direct TCF in Japan's TCF is relatively small, accounting for approximately 27% of the total TCF (figure 2). The direct TCF is much more concentrated in Japan's domestic tourism.

A difference is obvious in the travel modes between inbound and domestic tourists, and this was more evident during the pandemic years. Inbound tourists in Japan mainly choose railway services. Although land transportation is an important expense for inbound tourists, it is more concentrated in buses and taxis. Due to the exchange procedures between international and Japan's driver licenses involved in car rentals, fewer inbound tourists choose self-driving tours, resulting in obviously lower direct TCF. In contrast, the transportation options of domestic tourists are more diverse. Domestic tourists can utilize Japan's efficient public transportation system or they can choose flexible driving plans based on the advantages of resident status. Specifically, domestic tourists can use private vehicles for short-distance travel, while for long-distance travel they can choose to rent vehicles at the destination to further facilitate travel. After the outbreak of the pandemic, driving expenses became more pronounced for domestic tourists. For example, the share of spending on fuel-related petroleum products by domestic tourists increased from 4% to 6% in 2020–2021.

3.3. The indirect TCF in Japan

Although Japan's indirect TCF varied across sectors between inbound and domestic tourism, the main sectors were chemical products, accommodation/food services, and transportation. The domestic TCF accounted for the majority of the overall indirect TCF, and this proportion was particularly evident during the pandemic (figure 3(b)). This phenomenon is closely related to the economic composition of Japan's tourism. In 2019, as the last year for the normal development of Japan's tourism before the pandemic, the consumption of domestic tourism was JPY 22 trillion, accounting for 78.5% of the overall tourism revenue. During 2018–2019, although slight changes occurred in the sectoral distribution of the inbound and domestic TCF, the overall indirect TCF steadily increased. This rise in indirect TCF was mainly affected by policy supports, such as a basic plan for national tourism promotion (The Small and Medium Enterprise Agency 2014). Between 2020 and 2021, the indirect TCF drastically declined, and the reduction was much greater for the inbound TCF than for the

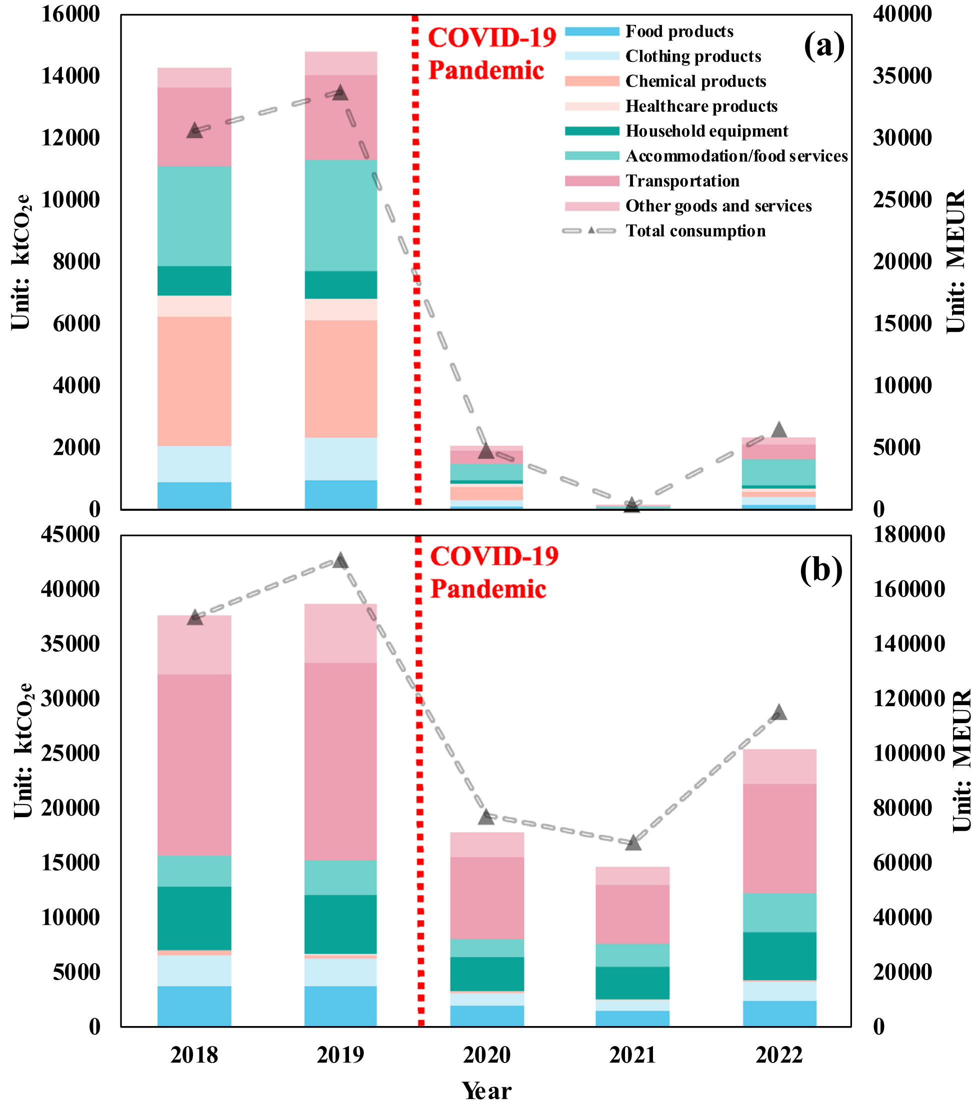

Figure 3. The indirect TCF of inbound (a) and domestic (b) tourism in Japan (the gray dashed line represents tourism consumption).

domestic TCF. In 2020, the domestic TCF decreased to 46% of the 2019 level, while the inbound TCF decreased to 13.8% of the 2019 level. In 2021, the inbound TCF continued to drop, reaching a five-year low that accounted for only 1% of the 2019 level (figure 3(a)). However, during the pandemic, Japan's domestic tourism still maintained a certain level of development. Against the backdrop of domestic epidemic stabilization, Japan's government implemented an incentive policy called 'Go To Travel[7]' from August 2020 to actively promote domestic tourism through preferential measures (Japan Tourism Agency 2020). With the global step into the post pandemic stage, the recovery of international tourists and the expansion of domestic tourism have greatly promoted Japan's tourism consumption (Ministry of Economy Trade and Industry 2023). Both the domestic and inbound TCF in 2022 showed an obvious rebound but remained below the TCF level in 2019.

Combining detailed sectoral classification and tourist expenditures in figure 3 reveals that the domestic TCF structure in Japan is complex, and tourism consumption is diversified. In comparison, the inbound TCF and expenditures are concentrated in chemical products and accommodation/food services.

The domestic TCF of manufacturing products remained stable at around 30% but underwent certain changes with the effects of the pandemic (figure 4(c)). For example, the proportion of beverage products (including alcoholic drinks) in the domestic TCF in 2020 was 4.4%, representing an increase of 25% compared to the 2019 level. The proportion of accommodation/food services was lower for the domestic TCF than for inbound tourism. However, this proportion has been rising with its increasing share in domestic tourist expenditures since 2020 (figure 4(d)). Among the transportation options, the domestic TCF in aviation was high,

[7] Go To Travel is a campaign by the Japan's government that offers large discounts on travel inside Japan.

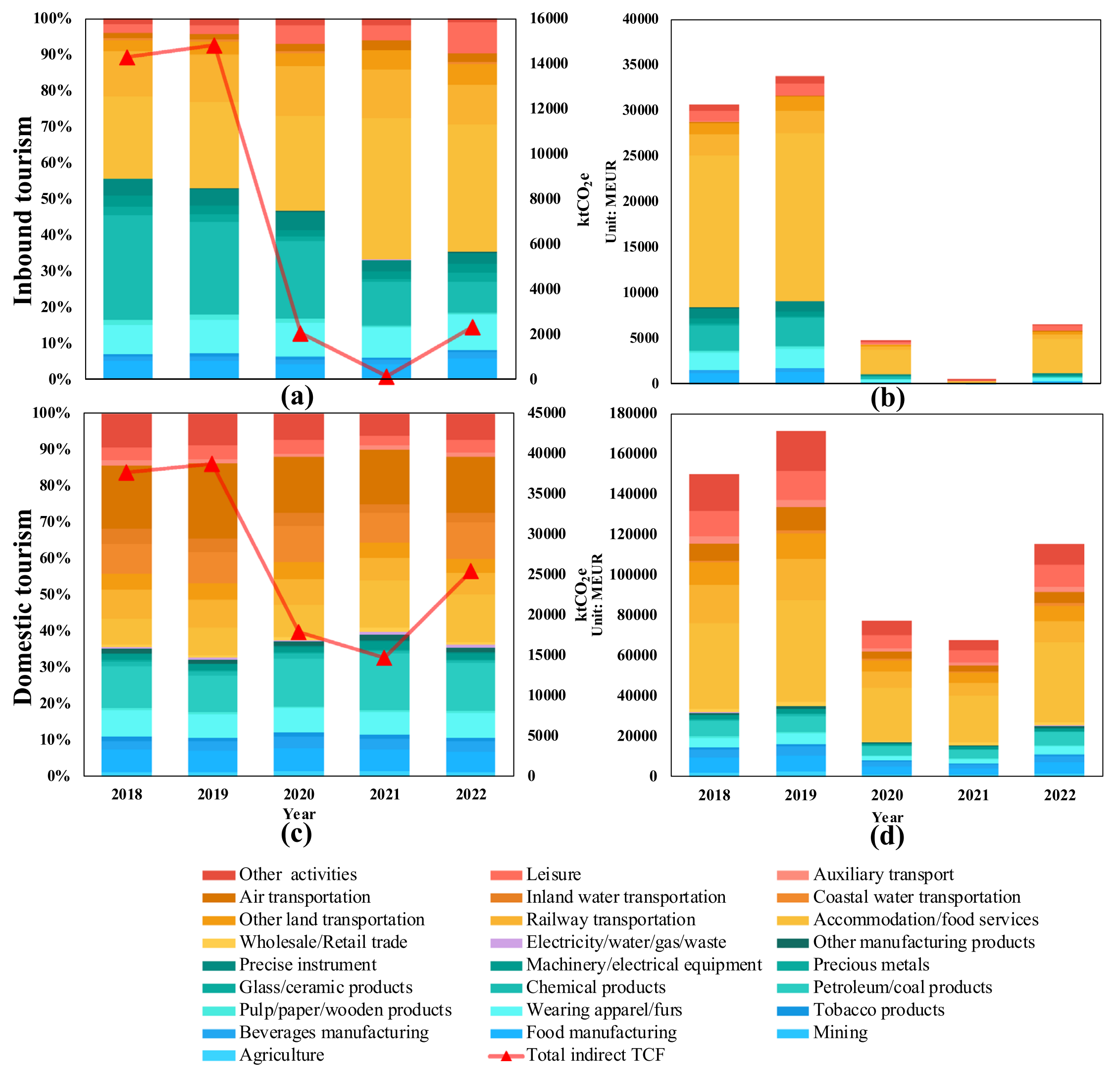

Figure 4. Structure of indirect TCF (a, c) and consumption expenditure (b, d).

while that of railways was low. In addition, an increase occurred in the proportion of domestic TCF from transportation services during the pandemic.

For inbound tourism, the TCF of service sectors (e.g., leisure) has shown an increasing trend since 2018 (figure 4(a)). The inbound TCF in transportation is concentrated more in railways and less in aviation, showing an opposite pattern to the domestic TCF. The reason for this phenomenon is that the price of aviation is higher, while railways have price advantages, as well as more flexible booking methods and times. The destinations of Japan's inbound tourists are predominantly the Kanto, Chubu, Kansai, and Kyushu areas (Japan Tourism Agency 2023a), where efficient railway networks (e.g., Shinkansen) exist within and between these areas.

3.4. Inbound TCF by tourist sources

This study systematically analyzed the carbon transfers between Japan and all its tourist sources, an area that has largely been neglected in previous studies focusing on specific regions or bilateral relationships. For instance, Tsukui *et al* (2017) estimated GHG emissions induced by visitors to Tokyo and Kyoto. In contrast, our study provides a global perspective on carbon flows associated with Japan's tourism sector.

Japan's inbound TCF mainly comes from Asia, Oceania, and North America (figure 5). The inbound TCF for Asia is concentrated in East Asia (e.g., China), and Southeast Asia (e.g., Thailand), while for North America, it is concentrated in the United States (U.S.) and Canada. Regions in Asia have the advantage of being close to Japan in terms of geographical location, resulting in more frequent tourism activities and pronounced inbound TCF. China, as a vital economic component of Asia, accounted for 56% of Japan's total inbound tourists in 2019 (table A1), and generated 64% of the inbound TCF. Japan's pandemic-related entry restrictions in 2020 led to a sharp decline in tourists from China, which was also the main reason for the sudden decrease in inbound TCF.

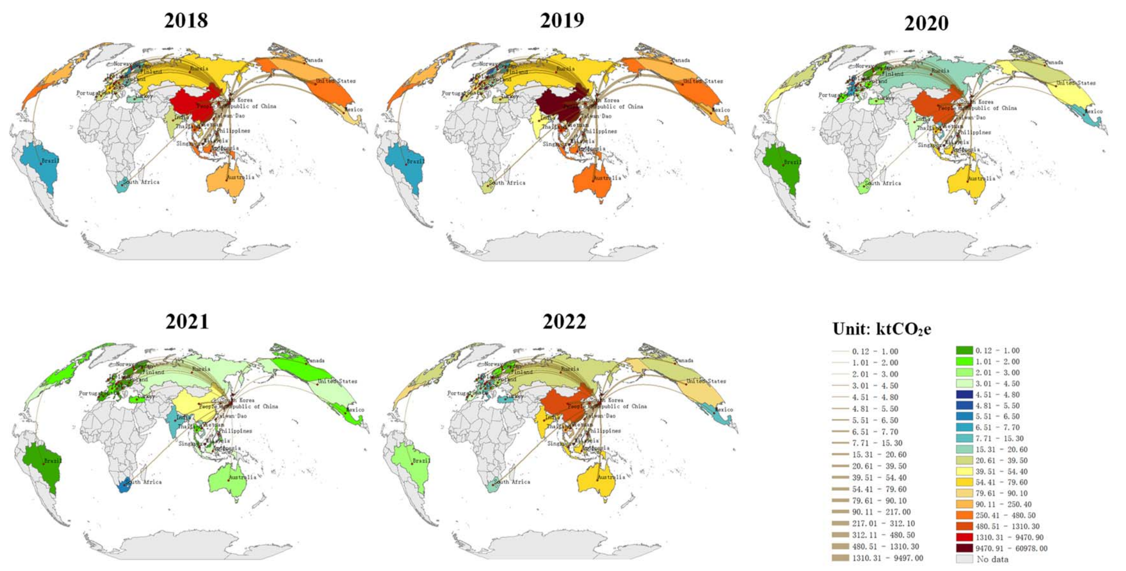

Figure 5. Regional distributions of the inbound TCF for Japan from 2018–2022.

Thailand and Singapore, as major economies in Southeast Asia, are important visa-free regions for Japan. During the pandemic, despite the decrease in the number of Southeast Asian tourists, they still accounted for about 10% of the inbound TCF, and the TCF for Vietnam even showed a slight increase. Although most regions in Europe are important sources of inbound tourists to Japan, the overall number of tourists is small due to the impact of travel distance[8]. Therefore, the overall TCF for European regions is low.

The inbound TCF in Japan varied substantially among tourists by region. The differences are closely related to the tourist consumption structure in each region and present different characteristics depending on the epidemic stage. Based on the main sources of inbound tourists in Japan, we selected 17 regions as typical examples to specifically introduce the differences in per capita TCF (figure 6).

In 2018–2019, an overall increase was observed in the inbound TCF across regions. The per capita TCF in chemical products decreased, while that in accommodation/food services increased. In this period, China's per capita TCF in chemical products decreased from 0.38 to 0.31 tCO_2e, with a decline rate reaching 18%, while that of accommodation/food services increased from 0.13 to 0.15 tCO_2e, with a growth rate of 11%.

The pandemic has substantially affected the tourist consumption structure. During the pandemic, inbound tourists reduced their use of railways and chose aviation instead to reduce travel time and infection risk. Compared to 2019, the per capita TCF for aviation from the United Kingdom in 2020 increased 2.7-fold, while that of railways decreased by 17.1%. The tourists' purchasing capacity during the pandemic greatly weakened, especially in manufacturing products, which depressed the per capita TCF. However, the rising costs of epidemic prevention increased the per capita TCF of service sectors. The reason for the high per capita TCF for Indian tourists in accommodation/food services was that approximately 59% of Indian tourists stay in Japan for more than 7 days, and accommodation and food account for 63% of tourism expenses (Japan Tourism Agency 2023a). Furthermore, India was one of the few regions with positive growth among Japan's inbound tourists during the pandemic (table A1).

Japan reopened inbound tourism in 2022, but the per capita TCF showed different characteristics compared with the pre-pandemic TCF. This demonstrates that despite the potential waning of the pandemic's influence on tourist expenditure, its lasting effects endure. The proportion of per capita TCF in aviation maintained a slight increase, especially in Europe. For Japan's major tourist sources, the service sectors have become the focus of per capita TCF growth, while the per capita TCF of manufacturing products still largely lags behind the 2019 level. For example, China's per capita TCF in leisure services reached 0.29 tCO_2e in 2022, accounting for 16.4% of the total, a value much higher than the proportion before the pandemic. In comparison, in 2019, chemical products accounted for 35.8% of China's per capita TCF, whereas that proportion was only 17.6% in 2022.

[8] The average flight time from Europe to Japan is over 13 h (All Nippon Airways, 2023).

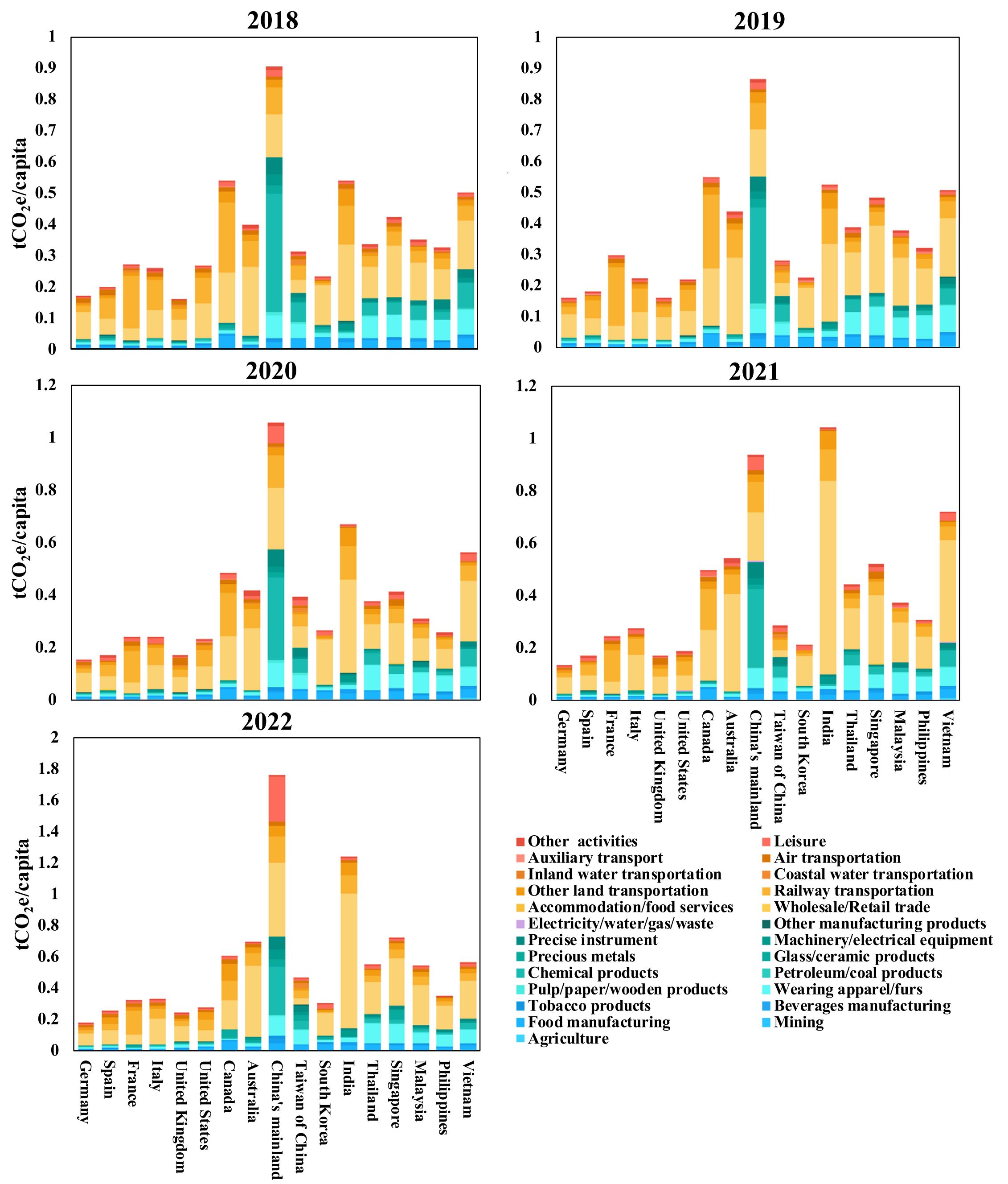

Figure 6. Per capita TCF of inbound tourists from the major tourist sources in Japan.

3.5. The SDA analysis of indirect TCF

Although prior research has primarily concentrated on quantifying CO_2 emissions from tourism, it has often failed to thoroughly investigate the underlying factors driving these changes. Our study bridges this gap by decomposing the changes in Japan's TCF to identify the driving forces behind the environmental impacts of pandemic responses. This systematic and comprehensive approach not only highlights the intricate linkages between Japan's tourism and global supply chains but also uncovers the internal mechanisms behind pandemic-induced changes in tourism's environmental effects, offering novel insights into the intersection of tourism, climate change, and crisis response.

The influencing factors varied depending on inbound and domestic tourism, and differences were evident in the impact level by pandemic stages. Prior to the pandemic, the driving forces of Japan's TCF showed a diversified trend. During the pandemic, the restriction policies greatly affected population mobility. Hence, the volume effect was enhanced, especially in the inbound TCF. Despite the heightened impact of the volume effect on the domestic TCF, the other effects remain substantial.

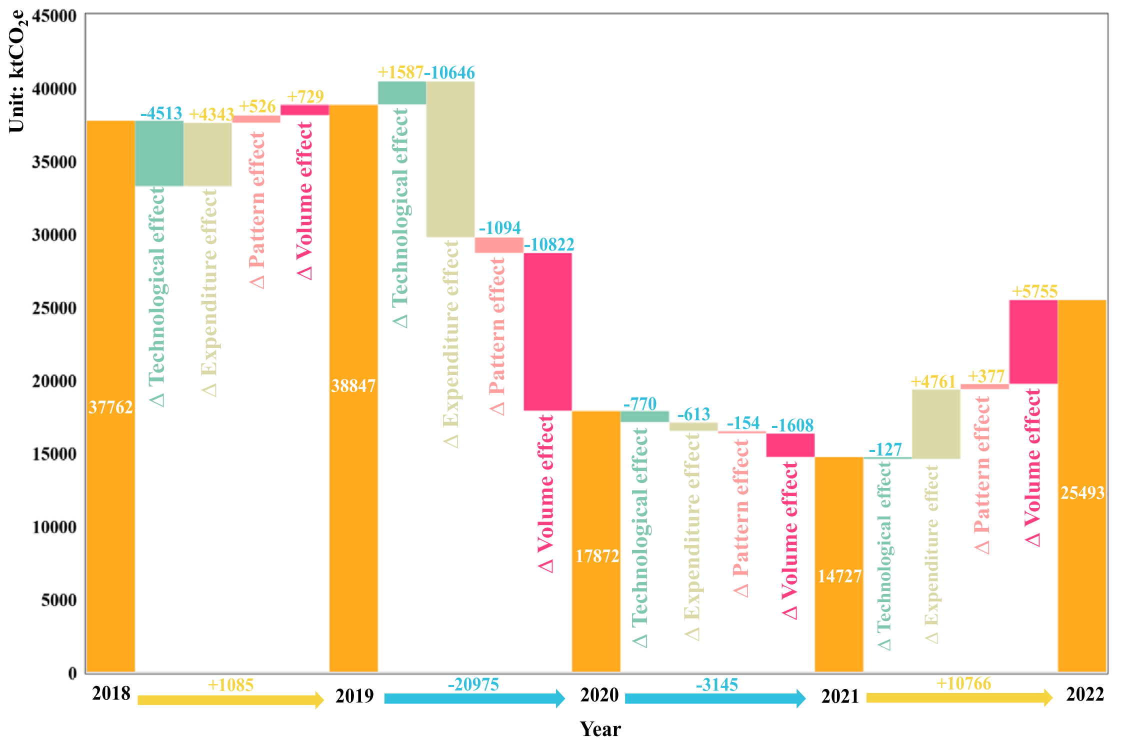

Figure 7. Driving forces of the indirect TCF of domestic tourism. Influencing factors: Δtechnological effect, Δ expenditure effect (tourism consumption expenditure), Δ pattern effect (tourism consumption pattern), and Δvolume effect (tourist volume).

Before the pandemic, technological and expenditure effects were the main driving forces of domestic TCF (figure 7). Since 2014, Japan's economic growth rate has been maintained at around 1%, and stable economic development has provided sufficient financial support for technological progress. Therefore, the technological effect showed an obvious negative impact on inbound TCF. During 2015–2018, Japan's per capita income increased from JPY 4.2 to 4.3 million. Although the consumer price indices slightly increased during the same period, the overall purchasing capacity of residents was strengthened; consequently, the expenditure effect greatly promoted the growth of the domestic TCF.

In the early stage of the pandemic (2020), the volume and expenditure effects evidently affected the domestic TCF. Japan's economic growth rate in 2020 was -4.28%, and the unemployment rate in Japan, after a continuous decline since 2010, showed an upward trend for the first time, reaching 2.8%, and the number of completely unemployed people reached 1.91 million (Statistics Bureau of Japan 2020). The weakening of residents' purchasing capacity led to a strong inhibitory impact of the expenditure effect on domestic TCF. The expansion of the pandemic led to a reduction in travel demand. Compared to 2019, the number of domestic tourists in 2020 decreased by 33%, resulting in a clear negative impact of the volume effect on the domestic TCF. In the mid-stage of the pandemic (2021), Japan's government implemented active industrial support policies, such as subordinated loans for enterprises, to drive economic recovery. Consequently, Japan's economic growth rate in 2021 recovered to 2.15%, which encouraged the recovery of technology investment. The technological effect was transformed into a negative impact during this period. In the post-pandemic stage (2022), the expenditure and volume effects became the main forces of domestic TCF, but showed opposite impacts compared to the early stage. After experiencing four instances of emergency declarations, Japan finally lifted restrictions on population mobility in 2022. Tourism enthusiasm among Japanese residents was further stimulated, leading to an increase in tourism expenditure and promoting the growth of the domestic TCF. The continuously decreasing infection rate and improved tourism support measures resulted in the volume effect showing a strong positive effect on the domestic TCF.

Overall, huge changes arose in the inbound TCF, particularly in 2019–2020 (figure 8). Among the influencing factors, the volume effect is the most important. During 2018–2019, preferential policies for tourism stimulated the growth of inbound tourists, with the number of tourists increasing from 27.7 to 28.17 million. Therefore, the expanding tourist volume promoted an increase in inbound TCF. Since 2019, tourist volume has become the main driving force for the negative growth of inbound TCF. Accompanied by the reopening of

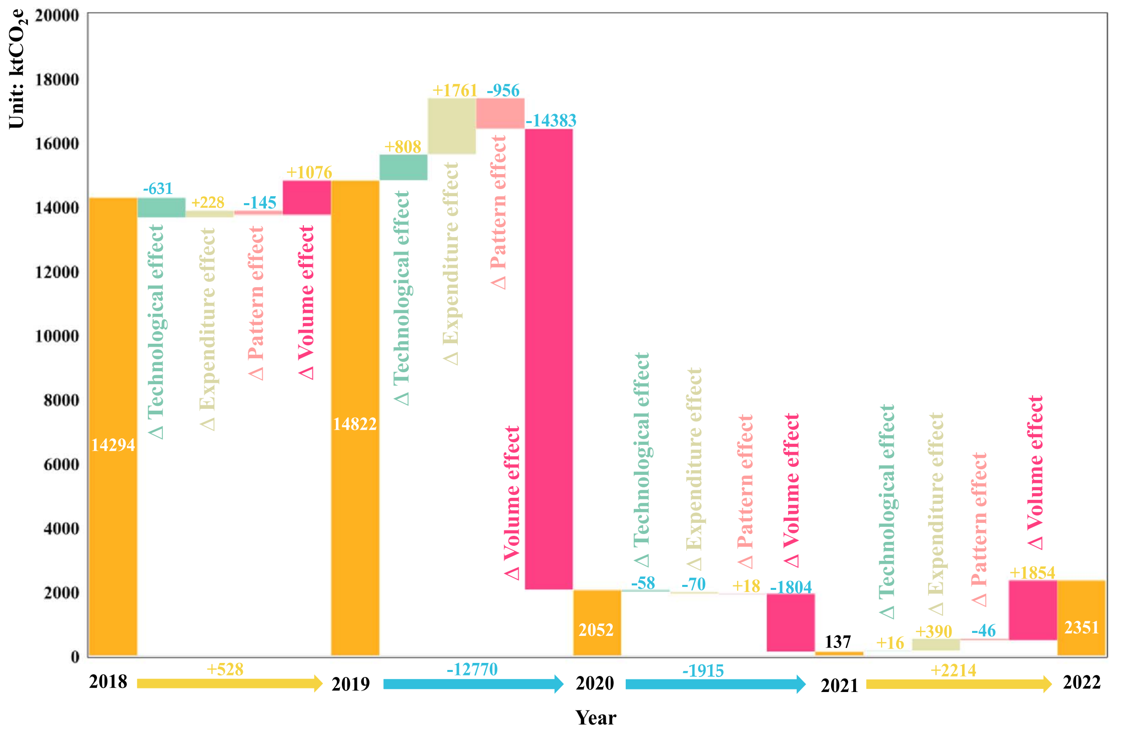

Figure 8. Driving forces of the indirect TCF of inbound tourism. Influencing factors: Δtechnological effect, Δ expenditure effect (tourism consumption expenditure), Δ pattern effect (tourism consumption pattern), and Δvolume effect (tourist volume).

national borders in 2022, the increase in tourism numbers has led the tourist volume to become a great driver of the positive growth of the inbound TCF.

The positive impact of the expenditure effect markedly increased during 2019–2020, indicating that the consumption level of inbound tourists in the early-stage pandemic had not yet declined. The strengthening of entry restriction measures actually stimulated the consumption motivation of inbound tourists. Under the uncertainty of subsequent border measures, inbound tourists tended to have a mentality of concentrated purchases. In 2021–2022, with the attraction brought about by Japan's reopening, the number of inbound tourists greatly rebounded. The U.S. bond interest rate has also risen since 2021, which widened the gap between U.S. and Japan's bond interest rates and exacerbated the depreciation of the Yen. In this context, the consumption demand from inbound tourists was further stimulated, resulting in a positive impact of the expenditure effect on inbound TCF. Within the consumption pattern of inbound tourists, accommodation/food services account for the largest proportion, followed by manufacturing products (concentrated in cosmetics, apparel and furs, and precision instruments). Due to the low-carbon intensity of these products, the consumption pattern generally showed a negative impact on inbound TCF in all periods except 2020–2021.

4. Conclusion and policy implications

This study comprehensively examined the carbon footprint changes in Japan's tourism (i.e., inbound and domestic tourism) by considering the COVID-19 pandemic stages and driving forces. The main findings are as follows:

(1) The TCF in Japan differs significantly between inbound and domestic tourism, with the pandemic amplifying these disparities. Domestic tourism, accounting for over 90% of TCF during the pandemic, showed greater resilience to its impact.

(2) Inbound TCF shows obvious regional differences that are related to the consumption structures of tourists. East Asia (e.g., China and South Korea) and Southeast Asia (e.g., Vietnam) are the main sources of Japan's inbound TCF.

(3) Prior to the pandemic, Japan's TCF had diverse driving forces; however, pandemic-induced restrictions magnified the volume effect, especially in the inbound TCF, while other effects remained substantial in the domestic TCF.

Specifically, the main results suggest the following policy implications:

First, in the post-pandemic era, restoring Japan's tourism sector necessitates a targeted approach that considers the distinct attributes and carbon implications of inbound and domestic tourism. For inbound tourism, while gradually resuming international flights and streamlining visa processes, it is crucial to prioritize environmental sustainability to appeal to international tourists' growing interest in eco-friendly travel. For domestic tourism, reducing its significant TCF requires a focus on transitioning to cleaner energy and advancing low-carbon transportation solutions. Encouraging domestic travelers to adopt sustainable practices can be facilitated by promoting local tourism, which not only reduces the need for long-distance travel but also fosters a deeper appreciation of regional cultures and natural attractions (Kira *et al* 2024). Additionally, as tourism continues to recover, the CO_2 emissions associated with waste treatment attributable to tourists may become a notable factor affecting Japan's efforts to achieve carbon neutrality. Strategies such as offering multilingual environmental guidelines at key tourist hubs to promote environmental awareness and incorporating water-saving technologies in hotels, such as low-flow showerheads, can serve as effective measures to reduce wastewater generation from tourism activities.

Second, tourists from different regions must be guided to reduce TCF through approaches tailored to their consumption patterns. For regions where manufacturing products constitute a significant proportion of consumption expenditure, such as China and Thailand, strategies to encourage tourists to purchase sustainably produced goods could include the targeted promotion of these products at major tourist attractions, offering economic incentives such as discounts or exclusive benefits for purchasing low-carbon certified items, and engaging local tour operators to integrate sustainable shopping opportunities into curated travel itineraries. In regions with a high proportion of service-related consumption, such as France and India, encouraging tourists to select environmentally friendly accommodations can be facilitated through raising awareness on online travel platforms and booking applications, implementing rewards programs that incentivize the choice of certified green accommodations, and launching campaigns that emphasize the environmental benefits of practices. Another meaningful approach is to encourage tourists to adopt a low-carbon diet, such as by scientifically increasing organic vegetarian meals and guiding tourists to reduce food waste (Long *et al* 2024).

Third, targeted measures based on the driving forces of TCF changes are needed to restore tourism. Considering the volume effect, the reduction in tourists under the pandemic has, to some extent, reduced the TCF, but this is not the main factor that suppresses TCF in the long-term development of tourism. Therefore, the orderly restoration of tourist numbers is the basis for ensuring tourism development, as well as one of the important conditions needed to stimulate tourism vitality. Although the impact of consumption patterns is relatively weak, shaping sustainable tourist behaviors holds considerable potential for long-term emission reductions. Japan's government can encourage the comprehensive adoption of environmentally-friendly products and services in tourism-related industries through policy guidance, standard-setting, and technical support. Specifically, it can clearly identify and promote green products, including recyclable materials and low-energy products, both inside and outside tourism destinations. Furthermore, leveraging the cultural heritage of tourist cities to create environmentally sustainable tourism products represents an effective strategy. For example, in Kyoto—renowned for its traditional handicrafts such as washi paper, ceramics, and textiles—the government could support artisans employing renewable materials and eco-friendly techniques by granting them 'green certifications' and incorporating their work into tourism marketing campaigns.

Last but at least, tourism is an important sector for enhancing economic sustainability; therefore, low-carbon tourism is a development issue that each region needs to address. International population mobility constitutes inbound tourism, so the tourism between regions is interrelated. Accordingly, international cooperation and exchanges play a vital role in promoting the development of low-carbon tourism. Regions can share best practices and formulate common standards and guidelines through international organizations such as the United Nations World Tourism Organization. Through these cooperation mechanisms, members can jointly formulate low-carbon tourism development strategies to promote the sustainable development of cross-border tourism activities.

5. Limitations of the study

The limitations of this study are primarily reflected in two aspects: the data and the research design. From the perspective of data, the MRIO tables utilized in this study, covering the period 2012–2022, were estimated by EXIOBASE based on trade and macroeconomic data available up to 2022, including projections from the International Monetary Fund. This reliance on estimated data introduces uncertainties, particularly when analyzing dynamic changes within economic systems. From an environmental efficiency perspective—defined as the relationship between economic output and environmental costs (e.g., CO_2, CH_4)—the environmental extension data in EXIOBASE3 may be outdated or represent averaged values. This static framework limits the model's ability to capture efficiency improvements over time, especially in rapidly evolving sectors like tourism.

From the perspective of research design, while the EEMRIO model effectively captures the carbon footprint of Japan's tourism sector within the global supply chain, it is inherently limited by its reliance on fixed technical coefficients. Besides, we recognize that the specification of influencing factors is crucial for identifying underlying patterns. While this study has meticulously selected influencing factors to align with tourism activities, there remains considerable scope for further refinement and deeper investigation into the identification and understanding of the underlying drivers. Finally, it is undeniable that tourist consumption within Japan's territory also involves embodied CO_2 emissions associated with imports. However, due to data availability constraints, this study does not currently account for the embodied CO_2 emissions from tourist consumption related to imports. To address these limitations, we are committed to improving our approach in future research, aiming to deliver more scientifically robust and accurate results.

Acknowledgments

This study was supported by JSPS KAKENHI (grant number JP23K25071 and JP24K03149).

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of competing interest

The authors declare no conflicts of interest.

Credit authorship contribution

Yuzhuo Huang: Conceptualization, Data curation, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Visualization. **Yosuke Shigetomi**: Validation, Writing - review & editing, Supervision. **Ken'ichi Matsumoto**: Conceptualization, Validation, Writing - review & editing, Supervision, Funding acquisition.

Data availability

Data will be made available on request.

Appendix

Table A1. The number of inbound and domestic tourists by region in Japan.

(Unit: person)		2018	2019	2020	2021	2022
	South Korea	6977812	5036943	391046	18947	1012751
	China's mainland	9689594	10932169	1214687	43545	459769
	Taiwan of China	4544086	4671658	648464	5016	331097
	Thailand	1060402	1246144	203388	2758	198037
	Singapore	396901	450021	49675	857	131969
	Malaysia	426507	458519	67895	1831	74095
	Indonesia	330217	339133	55178	5209	119723
	Philippine	426404	523109	82668	5625	126842
	Vietnam	135963	173936	17296	26586	284113
	India	62207	75558	5406	8831	54314
	England	257391	343122	37778	7294	57496
	France	238905	270660	30824	7024	52782
	Germany	143605	168214	19096	5197	45748
	Germany	120274	132521	9041	3527	23683
Inbound tourist	Russia	66783	88932	15933	3723	10324

Table A1. (Continued.)

(Unit: person)		2018	2019	2020	2021	2022
	Spain	103749	114252	8563	3053	15926
	Sweden	42003	42848	5698	1112	7900
	Netherlands	55689	63205	5837	1860	12064
	Switzerland	43639	45510	4654	1387	8917
	Belgium	25991	30554	2739	1122	6611
	Finland	21163	23412	3800	736	4608
	Poland	27782	31384	2693	1350	5745
	Denmark	22189	26137	3582	794	5403
	Norway	18571	20914	2913	557	3736
	Austria	17556	20612	2296	888	5025
	Portugal	23385	29001	2687	728	3176
	America	1232970	1429036	169525	20026	323513
	Canada	295683	339319	47216	3536	55877
	Mexico	60548	64255	8024	1124	9152
	Brazil	33166	35101	4110	2731	9436
	Australia	503597	571227	135240	4953	101921
Domestic tourist		88973000	90677000	60749000	55038000	73831000

Table A2. CO_2 emissions coefficients by energy type ($ktCO_2$/MEUR).

Energy type	Average low calorific value (KJ/kg; KJ/m^3)	Carbon content (kg-C/GJ)	Oxidation rate
Gasoline	43070	18.90	0.98
Diesel Oil	42652	20.20	0.98
Gas	3763	70.80	0.99
Kerosene	43070	18.90	0.98
LPG	50179	17.20	0.98

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