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POLICY ANALYSIS

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Characterization of Economic Requirements for a "Carbon-Debt-Free Country"

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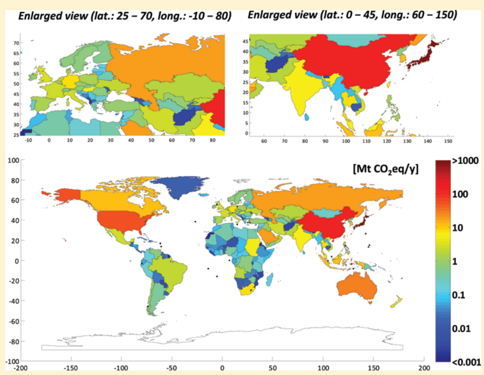
S Supporting Information



ABSTRACT: In recent years, greenhouse gas emission controls that incorporate the supply chains of products and services, thereby emphasizing the role of consumers rather than producers, have been drawing increasing attention. A country's consumption-based emissions, including those due to global supply chains, reflect the total emissions on which the national economy relies. To design effective emissions control strategies there is therefore an urgent need for countries to elucidate the structural relationship between their domestic economy and emissions occurring through global supply chains. Here we consider the structural characteristics of consumption-based emissions in Japan, which in 2005 totaled 1675 Mt CO_2eq. Outside the country the Japanese economy generated global emissions of 541 Mt CO_2eq, 35.7% of which were UNFCCC Annex I emissions and 64.3% were non-Annex I and other emissions. This figure of 64.3% reveals that Japan is actually relying to a considerable degree on emissions that are subject to no international obligations. We identify key economic contributors to consumption-based emissions at the commodity level and specify items of household expenditure that are effective options for both financial savings and emissions reduction. We then discuss the importance of emissions control for evolving toward a "carbon-debt-free country".

■ INTRODUCTION

The commitment period for the greenhouse gas (GHG) emission reductions specified in the Kyoto Protocol is drawing to an end, and countries that have ratified the protocol are engaged in final efforts to achieve their respective targets. In 1990 the global CO_2 emissions associated with fuel combustion and cement production stood at 22.55 Gt CO_2 (1 Gt = 10^9 tonne), for example, but by 2007 had risen to 30.67 Gt CO_2.[1] These emissions increases are largely attributable to the economic growth of emerging countries such as China,[2−4] India, and Russia. That growth has in turn been driven by a surge in demand for these countries' exports. Growth in emissions has, in other words, been induced by production activities to supply commodities to other countries, especially in the developed world. In the post-Kyoto period, therefore, such issues as where true responsibility lies for the growth in global emissions "behind the scenes" of the emission cuts based on the Kyoto Protocol and how this situation can best be managed will become extremely important.

Emission controls that incorporate the supply chains of products and services are currently drawing increasing attention as a new approach to controlling GHG emissions. The volume of emissions deriving from supply chains is equivalent to the emissions volume associated with the so-called product lifecycle,

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from raw materials mining through to product use and disposal. This novel approach seeks to control emissions from the consumer side rather than the commodity producer side. At the level of individual commodities, there is now growing use of carbon footprint labels.[5] At the corporate level, calculating and reporting standards have been developed for Scope 3 of the GHG Protocol Initiative,[6] and TR 14069 (organizational carbon footprint) has been prepared as a technical report to complement ISO14064-1.[7] In the United States, Walmart has announced its intention to reduce the GHG emissions from its entire global supply chain by 20 million tonnes by the end of 2015.[8] At the level of local government policy, too, there is a need to factor in the emissions occurring beyond municipal boundaries, yet ultimately attributable to the urban population.[9]

With regard to supply chain emissions at a national level, academic research on consumption-based emissions[10,11] has made important advances. The issue of responsibility[11−14] for these emissions in comparison to production-based emissions has also been discussed. Structural understanding and control of the emissions embodied in a country's global supply chains, i.e., the total amount of emissions on which the country's economy relies, are becoming an urgent issue that needs to be addressed by each country.

As demonstrated in earlier reviews,[15−17] an environmentally extended multiregional input−output (MRIO) model constitutes a powerful tool for calculating consumption-based emissions, and using such a model to describe the input−output structure of all the world's commodities would provide a means of doing the sums on actual global supply chains. To fully exploit the model's structural advantages means collecting a vast amount of robust economic and environmental data on all the world's countries, however. Large-scale research projects to this end[18,19] are already underway in Europe and positive results are expected. At present, though, there are only a limited number of MRIO-based studies[20−24] directed toward estimating consumption-based emissions based on the global system boundary. Another example of an MRIO study with a global system boundary is the GRAM model,[25] developed to assess the volume of direct and indirect resource extraction generated through international trade.

The first step in assessing a country's consumption-based emissions is to rigorously elucidate and understand the comprehensive interlinkage among the entire domestic economy, underlying global supply chains, and attendant GHG emissions. However, increasing the sectoral resolution of MRIO by adding to the number of countries considered and expanding the number of sectors in the commodity classification would dramatically increase the volume of data required, and the earlier studies cited[20−24] have therefore aggregated each country's commodities into 17−123 categories. In addition, data updates performed at regular intervals would not be simple,[24] either.

At the same time, an in-depth understanding is required of the structure of countries' consumption-based emissions. For this purpose two approaches are available. One is to develop a methodology and software that automates as far as possible the process of preparing the economic and environmental data in order to reduce the labor and time needed for such data development for MRIO with high commodity resolution based on the global system boundary.[26] An alternative approach is to develop a new modeling framework aimed at reducing the burden of data development while still adequately describing global supply chains, by designing a partially simplified form of MRIO tailored to the purpose of the analysis. For this latter approach, an analysis model called the Global Link Input−Output Model (GLIO)[27] has been proposed.

Against this background, the present study uses GLIO to elucidate in detail the relationship between the economic structure and GHG emissions, including those induced by global supply chains—i.e., consumption-based emissions—of Japan, the country with the world's fifth highest production-based GHG emissions in 2007. By addressing final demand, particularly, the study is designed to identify the kinds of demand contributing most to inducing consumption-based emissions at the commodity level. We present knowledge of fundamental importance for Japan's future strategy to control global GHG emissions and discuss options for such control.

■ METHODS AND DATA

Calculation of Japanese Consumption-Based GHG Emissions Using GLIO. To calculate consumption-based emissions, this study employed the GLIO model. This is an input−output model that primarily uses the input−output table of Japan to define Japan's production−consumption structure based on detailed sectoral classification while comprehensively and systematically describing the linkage with international supply chains. The input−output table for Japan covers as many as 400 commodity sectors. It is a detailed table of world prominence: commodity-by-commodity monetary transactions are compiled directly using various statistical data sets and special surveys of industrial activities. This compilation method yields a more realistic description of production technology, import structure, and export volume for each sector. GLIO enables our use of the original input−output table for Japan published by the Ministry of Internal Affairs and Communications,[28] Japan with no sector aggregation or change, although earlier studies cited[20,23,24] based on traditional MRIO use an input−output table for Japan with 57 sectors at most. That input−output table is not equivalent to the original input−output table because of various adjustments that must be made to it. Therefore, the use of GLIO for estimating Japanese emissions gives us the advantage of elaborate incorporation of characteristics of Japanese technologies, and import and export structures in an environmental input−output analysis that specifically examines the Japanese economy with global system boundaries.

Assuming that the amounts of GHGs emitted directly and indirectly within and outside Japan in order to meet domestic final demand for domestic products and imports is Q^{JP}_{global} and assuming that the amount of direct GHG emissions accompanying household and nonhousehold consumption expenditure is H^{JP}_{direct}, then the amount of Japan's consumption-based emission, U^{JP}_{coms}, can be derived from eq 1.

$$U^{JP}_{coms} = Q^{JP}_{global} + H^{JP}_{direct} \qquad (1)$$

This study estimates H^{JP}_{direct} based on data on the consumption of gasoline and diesel fuel for private automobiles and the consumption of kerosene, liquid petroleum gas, and mains gas for space heating and cooking. It then calculates Q^{JP}_{global} using the GLIO model.

According to the GLIO model centered on the Japanese economy, the domestic and overseas GHG emissions attributable to domestic final demand for domestic products $\mathbf{f}^{JD} = [f^{JD}_{i_1}]$ and to domestic final demand for imports $\mathbf{f}^{JI} = [f^{JI}_{i_2}]$, which are developed using the monetary flow based on the accounting framework in Table 1, are determined as follows. First,

Table 1. Matrices and Vectors for the Japanese Case Study Using the Global Link Input−Output (GLIO) Model[a]

		sc1	JP		OS		
		sc2	DC	IC	FC	FD	TO
sc1	sc2	sn	(j_1 = 1...406)	(j_2 = 1...406)	(q = 1...230)	[1]	[1]
JP	DC	(i_1 = 1...406)	$\mathbf{X}^{\mathbf{I}}$	$\mathbf{0}$	$\mathbf{X}^{\mathbf{III}}$	$\mathbf{f}^{\mathrm{JD}}$	$\mathbf{x}^{\mathrm{JD}}$
	IC	(i_2 = 1...406)	$\mathbf{0}$	$\mathbf{0}$	$\mathbf{0}$	$\mathbf{f}^{\mathrm{JI}}$	$\mathbf{x}^{\mathrm{JI}}$
OS	FC	(q = 1...230)	$\Sigma_{k=1}^{l}\mathbf{Y}^{\mathbf{I}(k)}$	$\Sigma_{k=1}^{l}\mathbf{Y}^{\mathbf{II}(k)}$	$\Sigma_{k=1}^{l}\mathbf{Y}^{\mathbf{III}(k)}$	$\mathbf{f}^{\mathrm{G}}$	$\mathbf{x}^{\mathrm{G}}$
VA		[1]	$\mathbf{v}^{\mathrm{JD}}$	$\mathbf{0}$	$\mathbf{v}^{\mathrm{G}}$		
TO		[1]	$\mathbf{x}^{\mathrm{JD}}$	$\mathbf{x}^{\mathrm{JI}}$	$\mathbf{x}^{\mathrm{G}}$		

[a] Abbreviations as follows: sc1, sector category (tier 1); sc2, sector category (tier 2); sn, sector number; **JP**, Japanese sector; **OS**, overseas sector; **FD**, final demand sector; **TO**, total output sector; **VA**, value added sector; DC, domestic commodity; IC, imported commodity directly input to Japanese final demands; FC, foreign country and region. Superscript k denotes the foreign commodity type.

exports in monetary units from overseas sectors to Japan and trade among overseas sectors ($\mathbf{Y}^{\mathbf{I}(k)}$, $\mathbf{Y}^{\mathbf{II}(k)}$, and $\mathbf{Y}^{\mathbf{III}(k)}$) are converted to the domestic GHG emissions embedded in each export commodity k ($\tilde{\mathbf{Y}}^{\mathbf{I}(k)}$, $\tilde{\mathbf{Y}}^{\mathbf{II}(k)}$, and $\tilde{\mathbf{Y}}^{\mathbf{III}(k)}$), or the direct and indirect GHG emissions generated within the exporting country in producing the commodities. Then, assuming that intermediate input and total output are directly proportional, regardless of whether one or both are converted to embodied GHG emissions, the input coefficient matrices are established as follows: $\mathbf{A}_{11} = \mathbf{X}^{\mathbf{I}}(\hat{x}^{\mathrm{JD}})^{-1}$, $\tilde{\mathbf{A}}_{13} = \mathbf{X}^{\mathbf{III}(k)}(\hat{\tilde{\mathbf{x}}}^{G})^{-1}$, $\tilde{\mathbf{A}}_{31}^{(k)} = \tilde{\mathbf{Y}}^{\mathbf{I}(k)}(\hat{\mathbf{x}}^{\mathrm{JD}})^{-1}$, $\tilde{\mathbf{A}}_{32}^{(k)} = \tilde{\mathbf{Y}}^{\mathbf{II}(k)}(\hat{\mathbf{x}}^{\mathrm{JI}})^{-1}$ and $\tilde{\mathbf{A}}_{33}^{(k)} = \tilde{\mathbf{Y}}^{\mathbf{III}(k)}(\hat{\tilde{\mathbf{x}}}^{G})^{-1}$. Here, $\tilde{\mathbf{x}}^{G}$ represents the total GHG emission arising in overseas region p. We then prepare the column vector $\mathbf{d}^{\mathrm{JD}}$, where each element $d_{i_1}^{\mathrm{JD}}$ indicates the direct GHG emission per unit production of Japanese commodity i_1. From eq 2 it is possible to obtain four block matrices $\mathbf{E}^{\mathrm{JD,JD}} = [e_{i_1j_1}^{\mathrm{JD,JD}}]$, $\mathbf{E}^{\mathrm{JD,JI}} = [e_{i_1j_2}^{\mathrm{JD,JI}}]$, $\mathbf{E}^{\mathrm{G,JD}} = [e_{pj_1}^{G,JD}]$, and $\mathbf{E}^{\mathrm{G,JI}} = [e_{pj_2}^{G,JI}]$. The element $e_{i_1j_1}^{\mathrm{JD,JD}}$ represents the GHG emissions in Japan from the production of commodity i_1 induced by $f_{i_1=j_1}^{JD}$, Japan's domestic final demand for commodity j_1. The element $e_{i_1j_2}^{\mathrm{JD,JI}}$ denotes the GHG emissions in Japan from the production of commodity i_1 induced by $f_{i_2=j_2}^{JI}$, Japan's domestic final demand for import commodity j_2. On the other hand, the elements $e_{pj_1}^{G,JD}$ and $e_{pj_2}^{G,JI}$ show the GHG emissions in foreign country p induced by $f_{i_1=j_1}^{JD}$ and $f_{i_2=j_2}^{JI}$, respectively.

$$\begin{pmatrix} \mathbf{E}^{\mathrm{JD,JD}} & \mathbf{E}^{\mathrm{JD,JI}} & 0 \\ 0 & 0 & 0 \\ \mathbf{E}^{\mathrm{G,JD}} & \mathbf{E}^{\mathrm{G,JI}} & 0 \end{pmatrix} = \mathrm{diag}\begin{pmatrix} \mathbf{d}^{\mathrm{JD}} \\ 0 \\ \mathbf{i}^{\mathrm{G}} \end{pmatrix}\left\{\mathbf{I} - \begin{pmatrix} \mathbf{A}_{11} & 0 & \tilde{\mathbf{A}}_{13} \\ 0 & 0 & 0 \\ \sum_{k=1}^{l}\tilde{\mathbf{A}}_{31}^{(k)} & \sum_{k=1}^{l}\tilde{\mathbf{A}}_{32}^{(k)} & \sum_{k=1}^{l}\tilde{\mathbf{A}}_{33}^{(k)} \end{pmatrix}\right\}^{-1}\mathrm{diag}\begin{pmatrix} \mathbf{f}^{\mathrm{JD}} \\ \mathbf{f}^{\mathrm{JI}} \\ 0 \end{pmatrix} \tag{2}$$

Here, matrix $\mathbf{I}$ represents the identity matrix of size $((n^{\mathrm{JD}} + n^{\mathrm{JI}} + n^{\mathrm{G}}) \times (n^{\mathrm{JD}} + n^{\mathrm{JI}} + n^{\mathrm{G}}))$, vector $\mathbf{i}^{\mathrm{G}}$ ($n^{\mathrm{G}} \times 1$) is the aggregation vector of which all elements are unity, and diag means diagonalization of the vector.

Therefore, $Q_{\mathrm{global}}^{\mathrm{JP}}$ is obtainable from eq 3, determining $C_{\mathrm{coms}}^{\mathrm{JP}}$ in eq 1.

$$Q_{\mathrm{global}}^{\mathrm{JP}} = \sum_{i_1=1}^{n^{\mathrm{JD}}}\sum_{j_1=1}^{n^{\mathrm{JD}}} e_{i_1j_1}^{\mathrm{JD,JD}} + \sum_{i_1=1}^{n^{\mathrm{JI}}}\sum_{j_2=1}^{n^{\mathrm{JI}}} e_{i_1j_2}^{\mathrm{JD,JI}} + \sum_{p=1}^{n^{\mathrm{G}}}\sum_{j_1=1}^{n^{\mathrm{JD}}} e_{pj_1}^{G,JD} + \sum_{p=1}^{n^{\mathrm{G}}}\sum_{j_2=1}^{n^{\mathrm{JI}}} e_{pj_2}^{G,JI} \tag{3}$$

The definition of "consumption-based emissions" employed in this study and the detailed expansion into eq 2 are described in the Supporting Information (SI). For the advantages and limitations of the GLIO model we refer the reader to a previous paper.[27]

Economic and GHG Data Compilation for the Empirical Study: The 2005 Japanese Economy. For the empirical study, we compiled economic data for the matrices and vectors shown in Table 1. The total number of Japanese sectors, n^{JD} and n^{JI}, were in both cases 406, while the total number of overseas sectors, n^{G}, was 230. Trade in 111 types (l = 111) of foreign commodities was accounted for.

$\mathbf{X}^{\mathbf{I}}$ was taken from the currently latest, 2005 Japanese IO table (JIOT).[28] $\mathbf{X}^{\mathbf{III}}$ was compiled from JIOT and export data from the Trade Statistics of Japan (TSJ).[29] $\mathbf{Y}^{\mathbf{I}(k)}$ and $\mathbf{Y}^{\mathbf{II}(k)}$ are from JIOT and TSJ import data. $\mathbf{Y}^{\mathbf{III}(k)}$ was determined using BACI,[30] which improves on UN Comtrade[31] for goods and UN service trade data for services.[32] Here, $\mathbf{f}^{\mathrm{JD}}$ and $\mathbf{f}^{\mathrm{JI}}$ were broken down into five categories, $\mathbf{f}^{\mathrm{JD}[s]}$ and $\mathbf{f}^{\mathrm{JI}[s]}$ (s = 1 households, 2 government, 3 public fixed capital, 4 private fixed capital, and 5 others), with the respective values being inferred from JIOT. $\mathbf{f}^{\mathrm{G}}$ was estimated from the Common Database (UNCDB)[33] of the United Nations Statistics Division (UNSD) and UN Comtrade. The total outputs $\mathbf{x}^{\mathrm{JD}}$ and $\mathbf{x}^{\mathrm{JI}}$ were set from JIOT and $\mathbf{x}^{\mathrm{G}}$ was estimated from UNSD National Accounts Official Country Data.[34] UN Comtrade and UNCDB data are in US dollars and were converted to Japanese yen at the rate of 110.21 JPY/USD.

In terms of GHG data, we included the six gases (CO_2, CH_4, N_2O, PFCs, HFCs, and SF_6) targeted in the Kyoto Protocol and evaluated them as CO_2-equivalent emissions (CO_2eq). For the Japanese emission data $\mathbf{d}^{\mathrm{JD}}$ and $H_{\mathrm{direct}}^{\mathrm{JP}}$ we used the Embodied Energy and Emission Intensity Data for Japan Using Input−Output Tables (3EID)[35−37] from the Japanese environmental input−output database, which reports the annual direct GHG emissions of about 400 sectors and their embodied GHG emission intensities based on a domestic system boundary.

To convert the monetary value of trade ($\mathbf{Y}^{\mathbf{I}(k)}$, $\mathbf{Y}^{\mathbf{II}(k)}$, and $\mathbf{Y}^{\mathbf{III}(k)}$) to the embodied GHG amounts, we estimated emission coefficients representing the direct and indirect GHG emissions generated domestically in overseas country p per unit of export commodity k. In cases where country p had a unique input−output table in the GTAP[38] v. 7 database,[39] the coefficients were calculated using conventional environmental input−output analysis.[35] In the analysis, each country's sectoral GHG emissions were determined using the UNFCCC inventory,[40] IEA data,[41] Enerdata,[42] EDGAR[43] v. 4.1, and CDIAC[1] for 2005. GTAP v. 7 is for 2004, so we adjusted its base price for 2005 using the

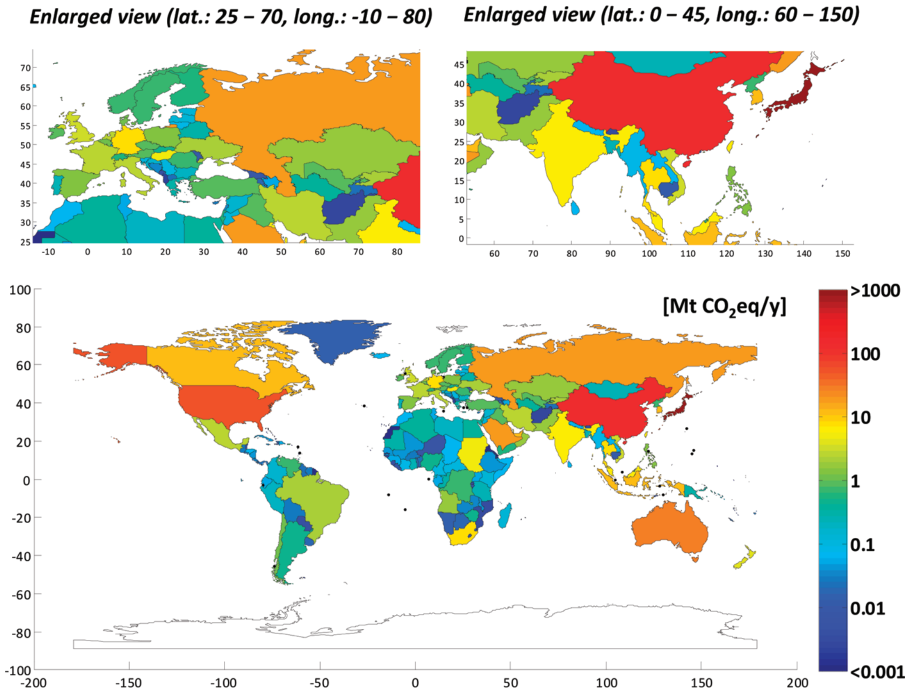

Figure 1. Global distribution of Japanese consumption-based GHG emissions in 2005. The diagram in the upper left is an expanded view of the emissions distribution largely of Europe, between −10° N and 80° N latitude and 25° W and 70° W longitude. The diagram on the upper right is an expanded view of the emission distribution mostly of East Asia, between 0° N and 45° N latitude and 60° E and 150° E longitude.

2004−2005 percentage change in GDP for each country. Meanwhile, for cases where country p did not have a unique input−output table (being defined as a composite region in GTAP), we differentiated the coefficients of GHG emissions by country but not by commodity type. The common coefficient for all the commodities produced in such a country is obtainable by dividing the total domestic GHG emissions of the country in question, excluding the final demand sector's direct GHG emissions, by the total final demand ($\mathbf{f}^G$ plus exports) of that country. The total domestic GHG emissions and the direct GHG emissions from final demand were estimated from the aforementioned data sources. The emissions associated with international transportation were not included. Although the method to be used for national allocation of emissions from bunker fuels for international transportation is not specified in the UNFCCC inventory reporting guidelines,[40] if such emissions were to be factored in, imports of manufactured products to Japan would be accompanied by a further increase in the country's consumption-based emissions,[44] although this would not hold for imports of services. A detailed description of data building is also included in the SI.

RESULTS AND DISCUSSION

Consumption-Based GHG Emissions of Japan in 2005. The GHG emissions Q^{JP}_{global} (for nomenclature, see Methods section, below) induced within and outside Japan by the country's domestic final demand have been estimated as 1489 Mt CO_2eq. Because H^{JP}_{direct}, the direct emissions associated with final demand, due primarily to household consumption, are 186 Mt CO_2eq, the consumption-based emissions U^{JP}_{coms} total 1675 Mt CO_2eq. In this study a figure of 1419 Mt CO_2eq has been taken for Japan's production-based emissions U^{JP}_{prod}, thus indicating a difference of 256 Mt CO_2eq from the country's consumption-based emissions. The consumption-based emissions comprise 541 Mt CO_2eq of overseas emissions, which is similar to the values of 560 Mt CO_2eq (2001[20]) and 468 Mt CO_2 (2004;[23] combustion sources for CO_2 only) used in previous studies with MRIO.

The following provides a detailed analysis of the geographical structure of the country's consumption-based emissions. Figure 1 gives a schematic representation of the global distribution of Japan's consumption-based emissions U^{JP}_{coms}, showing how 541 Mt CO_2eq of these emissions is distributed around the world. Whereas China and the U.S. are the only countries colored red, indicating a high level of Japanese-driven emissions, the countries and regions colored orange and yellow, indicating lower levels of induced emissions, include South Africa, in addition to Russia, Australia, and parts of East Asia, Europe, and the Middle East.

The specific amounts of Japanese-induced GHG emissions are as follows. The largest contributor is China, with 165 Mt CO_2eq, or 30% of these global emissions. Next come the U.S. (12%), Australia (6.5%), Saudi Arabia (4.8%), Russia (4.2%), and Indonesia (3.1%), with the top ten being completed by the UAE (2.7%), Canada (2.6%), South Korea (2.5%), Thailand (1.8%), and Germany (1.7%). Dividing the amount of emissions of these countries between Annex I and Non-Annex I of the UNFCCC results in 193 Mt CO_2eq for the former, comprising 35.7% of total overseas emissions, 343Mt CO_2eq for the latter, comprising 63.3%, and 5 Mt CO_2eq for the remainder, comprising 1.00%. In other words, the emissions from countries and regions other than those included in Annex I add up to 348 Mt CO_2eq of the 1675 Mt CO_2eq constituting Japan's consumption-based emissions. Approximately 21% of the emissions are thus subject to no international obligations.

Main Economic Contributors to Consumption-Based Emissions. This section presents an analysis of the structure of the consumption-based emissions of Japan, with particular

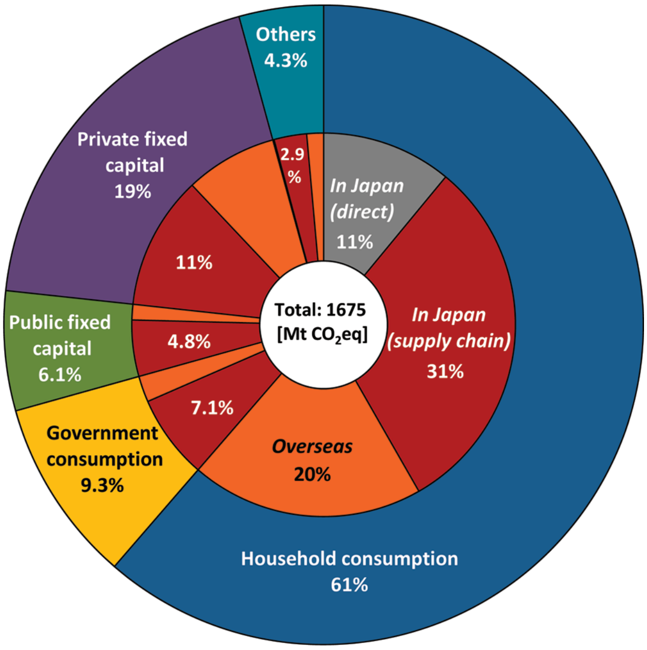

Figure 2. Contributions of five final demand categories to Japanese consumption-based GHG emissions in 2005 and composition of each category's emission locations: in Japan (direct), in Japan (supply chain), or overseas.

reference to economic demand. In Figure 2 the outer ring of the pie chart shows the contribution of domestic final demand to consumption-based GHG emissions, broken down into five categories. The inner ring of the chart provides a breakdown of the emissions of each category of final demand into (a) direct domestic emissions, (b) induced domestic emissions from the supply chains of commodities demanded, and (c) induced overseas emissions from the global supply chains of commodities demanded. Table S1 in the SI presents, for each category of final demand, the top 10 commodities inducing the greatest overseas emissions, i.e., type (c) above. Commodity names beginning with "JD" (plus a sector number) denote a domestic commodity demanded from $\mathbf{f}^{JD}$, while those beginning with "JI" are import commodities demanded from $\mathbf{f}^{JI}$. The percentage share reported for each commodity represents its contribution to the total consumption-based emissions of Japan (1675 Mt CO_2eq).

The data reported in Table S1 thus support a quantitative understanding of (c), i.e., consumption of which commodities cause the induced overseas emissions from each of the final demand categories.

As can be seen in Figure 2, the household consumption segment of final demand induces the largest share of emissions: 1028 Mt CO_2eq (61%). The domestic emissions are a combination of 184 Mt CO_2eq (11%) from the direct combustion of fuels such as gasoline and kerosene and 515 Mt CO_2eq (31%) emitted in the domestic supply chain underlying production of consumed commodities. The overseas emissions, 329 Mt CO_2eq, represent 20% of total emissions.

As Table S1 shows, in the case of household consumption expenditure on "JD138: Petroleum refinery products" accounts for 1.9%, followed by "JD391: General eating and drinking places" (0.8%) and "JD293: Electricity" (0.68%). Although the top 3 are domestic commodities, numbers 4, 6, 7, and 10 on the list are imports: "JI85: Woven fabric apparel" (0.67%), "JI321: Air transport" (0.57%), "JI86: Knitted apparel" (0.54%), and "JI394: Hotels" (0.33%). The total share of the top 10 commodities is just 6.9%. The share of households in overseas emissions is 20%, as described above. The remaining 13.1% therefore derives from commodities other than these ten, all of which contribute less than the 0.33% of "JI394: Hotels". This can be interpreted as signifying that the, in themselves, relatively minor overseas emissions associated with household consumption of each of a multitude of individual commodities accumulate to form the greatest contributor to overseas emissions associated with final demand.

The above characteristics of other final demand categories (government expenditure, fixed capital formation (public), fixed capital formation (private), and "others") are described in the SI.

Relationship between Annual Expenditures and Consumption-Based Emissions in Households. As mentioned above, household consumption expenditure makes the single largest contribution to Japan's consumption-based emissions. Contrary to other types of final demand, in this segment the top 10 commodities contribute very little to overseas emissions, however, implying that even minor contributions can together generate substantial overseas emissions, driven by demand for a very wide range of commodities. Given this finding, this study continued by analyzing in greater detail the emissions associated with the full range of household expenditure items in order to elucidate comprehensively the structure of consumption-based emissions attributable to household consumption. The remainder of this paper therefore presents the results of translating Japan's aggregate household consumption expenditure into per-household expenditure in an attempt to connect the emissions with tangible aspects of everyday life and help understand their structure in more familiar terms.

As a figure for gross expenditure, the per-household average for 2005, 5.638 million Japanese yen (M-JPY),[45] was used and 17 items (see the legend of Figure 3) were set up as expenditure items by referring to general household accounts:[46] The horizontal axis in Figure 3 shows the accumulated amounts of per-household expenditure, in M-JPY, on these 17 items into which expenditure ($\mathbf{f}^{JD}$ + $\mathbf{f}^{JI}$) on commodities in household consumption expenditure has been categorized. Into each of these expenditure items the commercial margins and the cost of domestic freight services have already been incorporated, so that the horizontal axis shows the purchaser's price-based expenditure. Based on these purchase prices, the vertical axis represents the consumption-based emission in t CO_2eq/M-JPY per unit expenditure on each item. The emissions deriving from implicit expenditure on commercial margins and domestic freight services are thus included in the emissions per unit expenditure on each commodity. The area of the bar for each item is the consumption-based emission (t CO_2eq) from expenditure on that item, with the lower part representing domestic emissions and the upper part representing overseas emissions. The items are listed from left to right in the order of emission per unit expenditure. The pie chart in the upper right of the figure shows the contribution of each expenditure item to total consumption-based emissions from household consumption.

The three items with the highest consumption-based emissions can be categorized as utilities: [04] electricity, [05] mains gas, and [07] fuel. Because the latter two include direct emissions from fuel combustion by households, the proportion of overseas emissions (upper part of the bar) is small. However, because Japan is entirely dependent on imports for its oil resources,

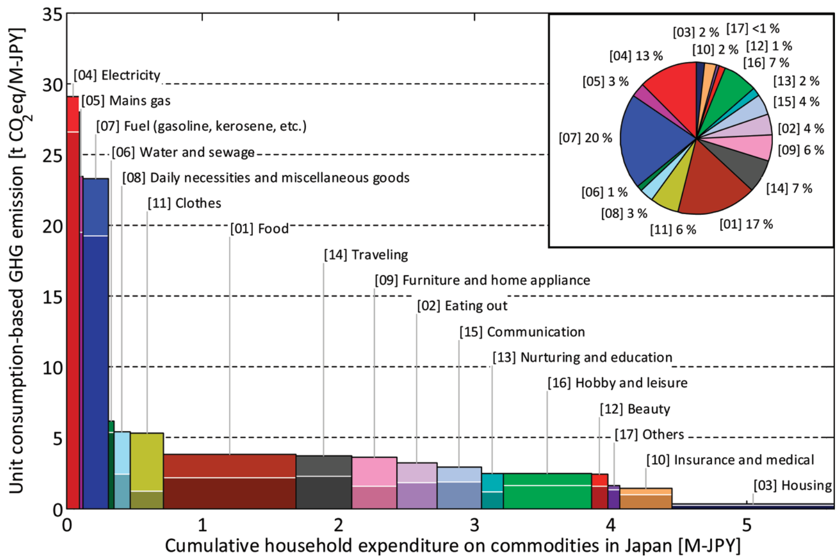

Figure 3. Skyline figure representing the relationship between a household's annual expenditure and consumption-based GHG emissions in 2005.

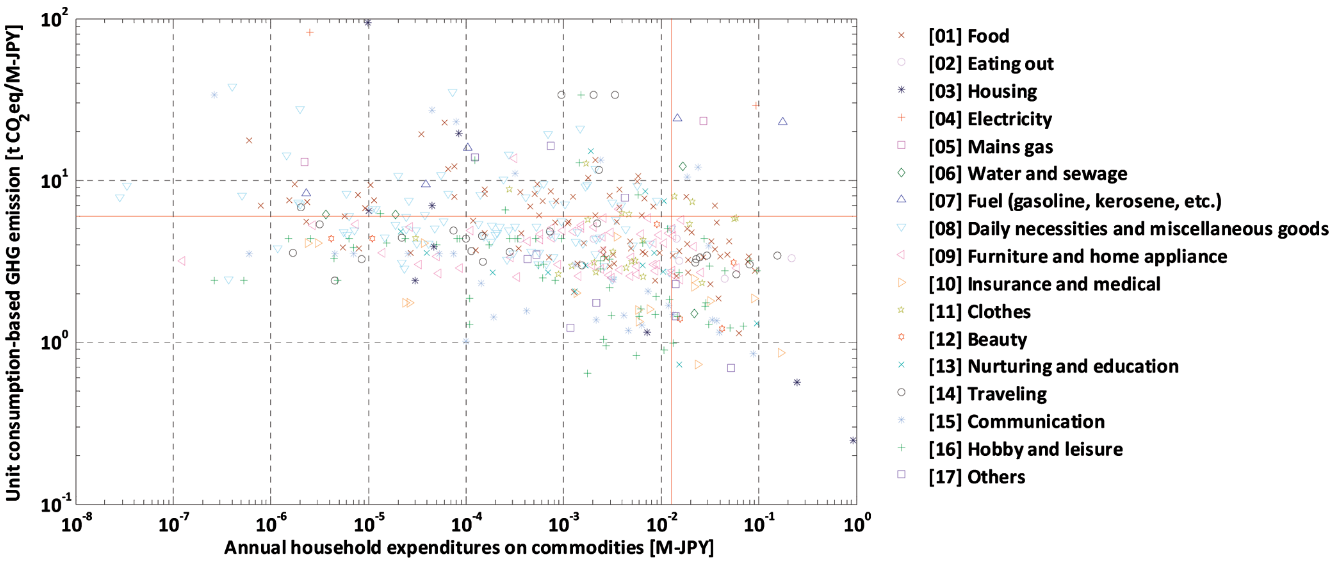

Figure 4. Relationship between a household's annual expenditure on each commodity and its unit consumption-based GHG emissions: the eleven commodities in the top right quadrant bounded by the red lines are JD37: Slaughtering and meat processing, JD138 and JI138: Petroleum refinery products (incl. greases), JD293: Electricity, JD295: Gas supply, JD299: Sewage disposal, JD321 and JI321: Air transport, JI41: Frozen fish and shellfish, JI87: Other wearing apparel and clothing accessories, and JI276: Jewelry and adornments. The prefixes JD and JI denote demand for domestic products and import products, respectively.

the amount of emissions (the area of the upper part) is not itself small relative to that of other expenditure items. Although the per-unit emissions of the following items are very low compared with the first three, there is only a relatively moderate decrease from [06] water and sewage to [03] housing at the end. Items [08] daily necessities and miscellaneous goods and [11] clothes account for a large proportion of overseas emissions. The reasons include the large volume of imported materials used in production of these domestic goods and the frequent direct purchases of imported products made by households.

In terms of absolute household expenditure, meanwhile, the top three items are [03] housing, [01] food, and [16] hobby and leisure, for each of which the bar forms a wide rectangle, despite the small per-unit emissions involved, implying that the emission volumes involved cannot be ignored. As the pie chart at the upper right of Figure 3 shows, the contributions of [04] electricity, [05] mains gas, and [07] fuel, i.e., the "utilities" segment of the consumption-based emissions from household consumption, are 13%, 3%, and 20%, respectively, thus together accounting for no more than 36%. Of the remaining 64%, [01] food is the largest contributor, at 17%, substantially more than [04] electricity. Considering that [02] eating out contributes 4%, the emissions associated with meals (domestically consumed plus eating out) are in fact comparable to those of the top contributor, [07] fuel. The demand for services from [02] eating out, [03] housing, [10] insurance and medical, and [14] traveling through to [17] others, ultimately accounts for 30% of the total, implying that the GHGs originating in services are not necessarily negligible[47−49] even from the perspective of consumption-based emissions.

Although a decrease in expenditure on each item would naturally reduce the consumption-based emissions from household consumption, if the amount of expenditure on an item is small to begin with, then no significant expenditure savings are to be expected even if the commodity could greatly contribute to the reduction of emissions per unit. Meanwhile, items with a large amount of expenditure would presumably provide considerable scope for savings because of the potentially large deductible amount, even if the per-unit emissions are small. In this study the potential for savings (expenditure cuts) and the effect of reducing consumption-based emissions at the commodity level have therefore been analyzed.

Figure 4 is the result of plotting each of the domestic commodities and imports subsumed under the 17 expenditure items used in Figure 3 on a graph having as its horizontal axis the purchaser's price-based annual expenditure on each commodity and on its vertical axis the consumption-based emissions per unit expenditure (carbon intensity). The further to the right of the graph a commodity lies, the greater the expenditure on it. For such items the savings potential would appear to be high. The further toward the top a commodity lies, the greater its carbon intensity and the greater the impact in reducing consumption-based emissions. The simple average of annual expenditure on the commodities shown is 0.0126 M-JPY, while the average carbon intensity is 6.02 t CO_2eq/M-JPY. These average values, shown as red lines, divide the graph into four quadrants. The scatter of points generally tends to slope downward to the right, which means that the greater the savings potential of the commodity, the smaller the impact of reducing the emissions. This situation suggests that even if households reduce expenditure on items that can be readily be saved on, no marked emission cuts will ensue, as the amount saved would in all likelihood be spent on commodities with higher per-unit emissions. This so-called "rebound effect"[50] would ultimately engender an increase in consumption-based emissions.

As the graph shows, even commodities in the same expenditure category occupy different positions on the graph and involve different amounts of expenditure and carbon intensity levels. This diffuse spread of expenditure items across the graph prevents identification of expenditures that are easy to save on and commodities that are likely to cause a rebound effect if the saved money were spent on them. This fact suggests the importance of analyzing carbon intensity at the commodity level, as performed in this study.

Although there are not many commodities (see the caption of Figure 4) in the top right quadrant of Figure 4, there are a few, permitting identification of a handful of expenditure items that would be effective in terms of savings and emissions reduction. Whereas this paper presents the average spending structure of Japan as a whole, the spending structure of each household is likely to vary substantially. Identifying such commodities in each household would contribute to the efficient reduction of consumption-based emissions.

Importance of Emissions Control for Becoming a "Carbon-Debt-Free Country". As calculated above, Japan's consumption-based emissions exceed its production-based emissions by 256 Mt-CO_2eq, with the overseas emissions associated with the country's imports exceeding the domestic emissions from its exports to meet foreign demand. This trade deficit in terms of GHG emissions implies the country can be said to have a "carbon debt" in the global economy. Under the Kyoto Protocol, Japan is obliged to reduce its production-based emissions by 6% relative to the amount recorded in 1990. The overseas emissions (the gap between consumption-based and production-based emissions) induced by the Japanese economy in addition to its production-based emissions are not subject to any control, however, and to all intents and purposes the situation can be interpreted as a "free ride" in disguise. Given that approximately 64.3% of Japan's overseas emissions occur in countries and regions other than those included in UNFCCC's Annex I, Japan is actually relying to a considerable degree on emissions that are subject to no international obligations.

Placing Japan under a formal obligation to reduce the emissions on this "free ride" would necessitate the design of an international framework for emissions control based on consumption-based emissions. In reality, however, the road toward such a framework, including development of calculation methods and achievement of international consensus, would require numerous obstacles to be overcome. In particular, the methods to be employed for handling the basic data used in calculations and for treatment of analysis errors, as well as other issues, would have to be approved by all the countries concerned. If the consumption-based emissions of each country were to be defined using conventional MRIO, a universally approved MRIO table would need to be developed. At present, the MRIOs issued by international organizations include the OECD table,[21] which, however, is the result of research projects and not a table officially approved by signatory countries. The road to establishing international rules for establishing consumption-based emissions would be long and tortuous if it were to begin with development of an MRIO initiated by an international organization. Nevertheless, development of tools to support creation of an extensive MRIO encompassing the entire globe is already in progress.[26] The use of such tools is expected to reduce the time that might eventually be necessary for MRIO development.

For the time being, then, we have no choice but to continue to control and reduce production-based emissions, in line with the framework of the Kyoto Protocol. Estimating national emissions within such a framework is more straightforward and accurate than in the case of consumption-based emissions,[11] making the former path more amenable to approval by signatory countries. However, the existence of a considerable gap between production-based and consumption-based emissions (with the former lower than the latter), particularly in developed countries,[24] may prove to be a severe obstacle for incorporating developing countries that have not in the past joined the Kyoto Protocol into a framework of emissions reduction. Developing countries exporting numerous commodities to developed countries might refuse to participate in emissions reduction, arguing that much of their emissions serve developed countries. With a view to including more countries and regions in the emissions reduction framework, it would therefore be prudent for developed countries to voluntarily control their consumption-based emissions. At the very least, controls designed to balance production-based and consumption-based emissions would appear to be necessary.

Balancing the two types of emissions in Japan will certainly contribute to establishing the country's leadership in international consensus-building on emissions reduction. In addition, further improvement of the low-carbon technologies that will necessarily be involved in achieving the goals is expected to enhance Japan's scientific and technical infrastructure as well as its international competitiveness. In view of diplomatic and economic benefits, too, balancing production-based and consumption-based emissions, or in other words evolving into a "carbon-debt-free country", should be identified as a policy issue that Japan should pursue strategically. Indeed, this should adopted as a common cause, particularly by developed countries.[24]

■ ASSOCIATED CONTENT

S Supporting Information. Additional descriptions of methodologies, data, and results. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ REFERENCES

(1) CDIAC. Carbon Dioxide Information Analysis Center. http://cdiac.ornl.gov/ (04/15).

(2) Weber, C. L.; Peters, G. P.; Guan, D.; Hubacek, K. The contribution of Chinese exports to climate change. *Energy Policy* **2008**, *36* (9), 3572–3577.

(3) Guan, D.; Peters, G. P.; Weber, C. L.; Hubacek, K., Journey to world top emitter: An analysis of the driving forces of China's recent CO(2) emissions surge. *Geophys. Res. Lett.* **2009**, *36*.

(4) Minx, J. C.; Baiocchi, G.; Peters, G. P.; Weber, C. L.; Guan, D.; Hubacek, K. A Carbonizing Dragon: China's fast growing CO_2 emissions revisited. *Environ. Sci. Technol.* **2011**, *45* (21), 9144–9153.

(5) Trust, C. *Carbon footprinting.* http://www.carbontrust.co.uk/cut-carbon-reduce-costs/calculate/carbon-footprinting/pages/carbon-footprinting.aspx.

(6) Greenhouse Gas Protocol. Product and Supply Chain. http://www.ghgprotocol.org/ (04/15).

(7) International Organization for Standardization. GHG -- Quantification and reporting of GHG emissions for organizations (Carbonfootprint of organization) -- Guidance for the application of ISO 14064-1. http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=43280.

(8) Walmart. Greenhouse Gas Commitment. http://walmartstores.com/Sustainability/9660.aspx (04/15).

(9) Larsen, H. N.; Hertwich, E. G. Identifying important characteristics of municipal carbon footprints. *Ecol. Econ.* **2010**, *70* (1), 60–66.

(10) Munksgaard, J.; Pedersen, K. A. CO_2 accounts for open economies: Producer or consumer responsibility? *Energy Policy* **2001**, *29* (4), 327–334.

(11) Peters, G. P. From production-based to consumption-based national emission inventories. *Ecol. Econ.* **2008**, *65* (1), 13–23.

(12) Andrew, R.; Forgie, V. A three-perspective view of greenhouse gas emission responsibilities in New Zealand. *Ecol. Econ.* **2008**, *68* (1−2), 194–204.

(13) Rodrigues, J.; Domingos, T. Consumer and producer environmental responsibility: Comparing two approaches. *Ecol. Econ.* **2008**, *66* (2−3), 533–546.

(14) Lenzen, M. Aggregation (in-)variance of shared responsibility: A case study of Australia. *Ecol. Econ.* **2007**, *64* (1), 19–24.

(15) Wiedmann, T.; Lenzen, M.; Turner, K.; Barrett, J. Examining the global environmental impact of regional consumption activities - Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade. *Ecol. Econ.* **2007**, *61* (1), 15–26.

(16) Wiedmann, T. A review of recent multi-region input-output models used for consumption-based emission and resource accounting. *Ecol. Econ.* **2009**, *69* (2), 211–222.

(17) Hertwich, E. G. The Life Cycle Environmental Impacts of Consumption. *Econ. Syst. Res.* **2011**, *23* (1), 27–47.

(18) Tukker, A.; Poliakov, E.; Heijungs, R.; Hawkins, T.; Neuwahl, F.; Rueda-Cantuche, J. M.; Giljum, S.; Moll, S.; Oosterhaven, J.; Bouwmeester, M. Towards a global multi-regional environmentally extended input-output database. *Ecol. Econ.* **2009**, *68* (7), 1928–1937.

(19) WIOD. World Input-Output Database: Construction and Applications. http://www.wiod.org/ (04/15).

(20) Hertwich, E. G.; Peters, G. P. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environ. Sci. Technol.* **2009**, *43* (16), 6414–6420.

(21) Nakano, S.; Okamura, A.; Sakurai, N.; Suzuki, M.; Tojo, Y.; Yamano, N. *The Measurement of CO_2 Embodiments in International Trade: Evidence from the Harmonised Input-Output and Bilateral Trade Database*; OECD: Paris, 2009.

(22) Wiedmann, T.; Wood, R.; Minx, J. C.; Lenzen, M.; Guan, D. B.; Harris, R.; Carbon, A Footprint Time Series of the UK - Results from a Multi-Region Input-Output Model. *Econ. Syst. Res.* **2010**, *22* (1), 19–42.

(23) Davis, S. J.; Caldeira, K. Consumption-based accounting of CO_2 emissions. *Proc. Natl. Acad. Sci. U.S.A.* **2010**, *107* (12), 5687–5692.

(24) Peters, G. P.; Minx, J. C.; Weber, C. L.; Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. U.S.A.* **2011**, *108* (21), 8903–8908.

(25) Giljum, S.; Lutz, C.; Jungnitz, A. *The Global Resource Accounting Model (GRAM): A Methodological Concept Paper*; Sustainable Europe Research Institute, 2008.

(26) Lenzen, M.; Kanemoto, K.; Geschke, A.; Moran, D.; Ugon, P. M. J.; Wood, R.; Yu, T. A global multi-region input-output time series at high country and sector detail. In *18th International Conference on Input-Output Analysis*, Sydney, 2010; p 30.

(27) Nansai, K.; Kagawa, S.; Kondo, Y.; Suh, S.; Inaba, R.; Nakajima, K. Improving the Completeness of Product Carbon Footprints Using a Global Link Input-Output Model: The Case of Japan. *Econ. Syst. Res.* **2009**, *21* (3), 267–290.

(28) JIOT. *2005 Input-Output Tables*; National Federation of Statistical Associations, Ministry of Internal Affairs and Communications Japan: Tokyo, 2009.

(29) MOF. *2005 Trade Statistics of Japan*; Ministry of Finance Japan, 2011.

(30) CEPII. BACI (Base pour l'Analyse du Commerce International). *A CEPII World Database of International Trade at the Product Level*; 2011.

(31) *UNCOMTRADE. United Nations Commodity Trade Statistics Database*; UN Statistics Division, 2011.

(32) *UNServiceTrade. United Nations Service Trade Statistics Database*; UN Statistics Division, 2011.

(33) *UNCD. United Nations Common Database*; UN Statistics Division, 2011.

(34) *NAOCD. National Accounts Official Country Data*; UN Statistics Division, 2011.

(35) *Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables (3EID)*; Center for Global Environmental Research, National Institute for Environmental Studies: Ibaraki, 2002.

(36) Nansai, K.; Moriguchi, Y.; Tohno, S. Compilation and application of Japanese inventories for energy consumption and air pollutant emissions using input-output tables. *Environ. Sci. Technol.* **2003**, *37* (9), 2005–2015.

(37) Nansai, K. Environmental Input-Output Database Building in Japan. In *Handbook on Input-Output Economics in Industrial Ecology*; Suh, S., Ed.; Springer: Dordrecht, 2009; pp 653−688.

(38) Hertel, T. W. *Global Trade Analysis: Modeling and Applications*; Cambridge University Press, 1999.

(39) GTAP. *The Global Trade Analysis Project*; 2009.

(40) UNFCCC. GHG Data. http://unfccc.int/2860.php.

(41) IEA. *CO_2 Emissions from Fuel Combustion 1971-2005*; International Energy Agency: Paris, 2007.

(42) Enerdata. http://www.enerdata.net/.

(43) *EDGAR. The Emissions Database for Global Atmospheric Research (EDGAR)*; European Commission - JRC Joint Research Centre, 2011.

(44) Peters, G. P.; Andrew, R.; Lennox, J. Constructing an Environmentally-Extended Multi-Regional Input-Output Table Using the GTAP Database. *Econ. Syst. Res.* **2011**, *23* (2), 131–152.

(45) Ministry of Health, Japan. 2006 National Livelihood Survey Japan; http://www.mhlw.go.jp/toukei/saikin/hw/k-tyosa/k-tyosa06/2-4.html.

(46) Eco-Hana (Online environmental housekeeping book); Special universal-access business zone project of Japanese Ministry of Internal Affairs and Communications; https://www.ecohana.jp/ecosaas/ecohana.html.

(47) Padilla, E.; Alcantara, V. Input-output subsystems and pollution: An application to the service sector and CO_2 emissions in Spain. *Ecol. Econ.* **2009**, *68* (3), 905–914.

(48) Suh, S. Are services better for climate change? *Environ. Sci. Technol.* **2006**, *40* (21), 6555–6560.

(49) Nansai, K.; Kagawa, S.; Suh, S.; Fujii, M.; Inaba, R.; Hashimoto, S. Material and Energy Dependence of Services and Its Implications for Climate Change. *Environ. Sci. Technol.* **2009**, *43* (12), 4241–4246.

(50) Hertwich, E. G. Consumption and the rebound effect - An industrial ecology perspective. *J. Ind. Ecol.* **2005**, *9* (1−2), 85–98.