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Analysis

Trends in Japanese households' critical-metals material footprints

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ABSTRACT

This study adopts the concept of material footprint (MF), an indicator for consumption-based material extraction via international trade, and identifies the relationship between the MFs of critical metals for low-carbon technologies – neodymium, cobalt, and platinum – and Japanese household consumption through a multiregional input–output approach using the global link input–output model. We focus solely on the impact of changes in consumption patterns caused by demographic change on the structures of the MFs from 2005 to 2035. As a result, the total MFs of neodymium, cobalt, and platinum in 2035 are estimated to be 11%, 6.6% and 4.7% lower than in 2005, respectively. In terms of commodity sectors, the MFs of the three metals induced by "passenger motor cars" are estimated to decrease most between 2005 and 2035. Finally, we carried out an assessment of the extent to which the products dealt with under current Japanese recycling laws cover the MFs calculated for 2035. This indicates that continued enforcement of the recycling laws can play an important role in alerting consumers to the MFs of critical metals, particularly neodymium. For improving the accuracy of the above estimates, further studies need to incorporate other future trends like technologies and trade.

1. Introduction

As product supply chains become ever more fragmented and globalized, discussions on environmental management in the world's nations are focusing increasingly on consumption-based inventories, with final consumers assumed to bear part-responsibility for the upstream environmental burdens of the products they use (Davis and Caldeira, 2010; Kagawa et al., forthcoming; Munksgaard and Pedersen, 2001; Peters, 2008; Peters and Hertwich, 2008). A variety of "footprint" indicators have been proposed to quantify such consumption-based burdens (Čuček et al., 2012; Galli et al., 2012; Hoekstra and Wiedmann, 2014). Starting with the ecological footprint (Wackernagel et al., 2002), we have for example seen development of a carbon footprint for greenhouse gases (Peters, 2008; Peters et al., 2011), a water footprint for water use (Feng et al., 2011; Hoekstra and Mekonnen, 2012), a land footprint for land use change (Steen-Olsen et al., 2012; Weinzettel et al., 2013), a biodiversity footprint for threatened species (Lenzen et al., 2012a) and a health impact footprint for $PM_{2.5}$ intake (Takahashi et al., 2014). Against the background of rising concerns about growing resource consumption, the direct and indirect resource use of individual nations are now measured using the indicators known as raw material consumption and material footprint (MF), which are conceptually similar to the aforementioned footprints (Bruckner et al., 2012; Schoer et al., 2013; Wiedmann et al., 2013). MF is defined as amount of material extraction in the mining country induced by final demand in the consumer country.

Using the footprint concept, numerous studies have analyzed the environmental burdens induced by household consumption, the single largest category of final demand (Druckman and Jackson, 2009; Druckman et al., 2012; Duarte et al., 2014; Hertwich and Peters, 2009; Hubacek et al., 2009; Kerkhof et al., 2009; Lenzen et al., 2004a; Lenzen et al., 2004b; Munksgaard and Pedersen, 2000; Pachauri and Spreng, 2002; Park and Heo, 2007; Webber and Matthews, 2008; Wiedenhofer et al., 2013). Particularly in developed nations, it is reported that household consumption contributes most to greenhouse gas (GHG) emissions (Hertwich, 2005). For example, Nansai et al. (2012) have revealed that about 61% of Japan's 2005 carbon footprint derived from the consumption of Japanese households.

The Japanese economy is highly dependent on material-processing and machine industries and imports large quantities of mineral resources. In order to reduce the country's GHG emissions, widespread adoption of low-carbon technologies is now accepted as being essential. However, moving towards a low-carbon society implies growing use of a number of scarce metals and other so-called "critical metals" that are indispensable for new technologies like electric vehicles and wind power plants. These metals are also used in the permanent magnets

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that are key components of personal computer disk drives, cell phones and other electronic devices in widespread use today. Since Japan, too, is a major consumer of such critical metals, it is important to quantify the MFs of these metals associated with Japanese household consumption. While previous studies have used material flow analysis to present broad overviews of the flows of a range of mineral resources through the economy (Chen and Graedel, 2012; Du and Graedel, 2011; Graedel et al., 2004; Kablak and Graedel, 2013a; Kablak and Graedel, 2013b; Müller et al., 2006; Reck et al., 2008), though, the relationship between the footprint of critical metals and household consumption has not yet been clearly charted.

Against this background, we here aim to analyze the MFs of neodymium, cobalt and platinum, demand for which is projected to grow as new low-carbon consumer technologies become more widely adopted, and to identify the relationship between household final demand and the respective MFs. Neodymium is a rare earth metal whose main application is in permanent magnets in electric motors, which find widespread use in clean technologies. Cobalt is often utilized as the positive-electrode material in lithium-ion rechargeable batteries, and in the superalloys used in aerospace and other engineering industries. Platinum, for its part, is used in the catalytic converters used for treating vehicle exhausts and in applications in the electronics industry. Crucially, demand for these metals is expected to increase significantly the world over (Elshkaki, 2013; Elshkaki and Graedel, 2013; Harper et al., 2012), despite a continued decline in populations due to aging and lower birth rates in developed nations, particularly in Japan. The potential impact of this trend on environmental burdens is a concern from the perspective of sustainability (Kronenberg, 2009; O'Neill et al., 2010). This study therefore analyzes the impact of changes in consumption patterns in an aging society with fewer children on the MFs of neodymium, cobalt and platinum.

2. Methods and Data

2.1. Estimating Material Footprints According to Householder Age Group

The methodology employed in this study is based on Shigetomi et al. (2014), who estimated the CF associated with Japanese household consumption from 2005 to 2035, with a focus on projected demographic trends, i.e., changes in the number of households and total population. This study employs the global link input–output model (GLIO: Nansai et al., 2009), a multiregional input–output model (MRIO) (Lenzen et al., 2004a; Lenzen et al., 2004b; Moran and Wood, 2014; Wiedmann, 2009) that specifies the global supply chains of Japanese commodities (goods and services), to calculate the respective MFs of neodymium, cobalt and platinum. Several institutions have developed MRIOs covering global supply chains, such as the Organization for Economic Co-operation and Development (OECD)-MRIO (Yamano, 2012), UK-MRIO (Wiedmann et al., 2010), EORA (Lenzen et al., 2012b), EXIOBASE (Tukker et al., 2013; Wood et al., 2014) and WIOT (Arto et al., 2014; Dietzenbacher et al., 2013), each of which is available for environmental analyses. One key advantage of using an MRIO is that it enables calculation of the environmental burdens generated by final consumption of commodities all the way back up global supply chains. The input–output structure of GLIO allows detailed description of Japan's input–output structure (with 406 sectors of domestic commodities and 406 sectors of imported commodities) and inclusion of 230 countries and regions as international sectors. Using the GLIO also allows for more ready comparison of the results of the present study with those of the previous studies of Nansai and colleagues (Nansai et al., 2013a; Nansai et al., 2013b).

To link the trend of an aging society with fewer children with household consumption expenditures, we followed Kronenberg (2009) and defined household attributes $b = (1 \ldots 6)$ according to the age group of the head of the household ($1 = 20\text{s}$: ≤ 29, $2 = 30\text{s}$: 30–39, $3 = 40\text{s}$: 40–49, $4 = 50\text{s}$: 50–59, $5 = 60\text{s}$: 60–69, $6 = 70\text{s}$: ≥ 70), and then calculated annual household consumption expenditures by householder age bracket (million yen (M-JPY)/y). While these figures for consumption expenditures can in principle be obtained from official Japanese household statistics (e.g., Family Income and Expenditure Survey: FIES; National Survey of Family Income and Expenditure: NSFIE), some of these figures are inconsistent with the amount of final demand reported in the Social Accounting Matrix (SAM) (Miller and Blair, 2009). At the same time, because the 2005 Japanese input–output table (JIOT, 2005) includes a single sector of household final demand, consumption expenditures by householder age bracket are unavailable, although the data in the JIOT are based on the values cited in the SAM. This is therefore an inconsistency that needs to be addressed (Schreyer, 2013). Here, we attempted to decompose the household consumption sector in the JIOT into the consumption expenditures by householder age bracket by means of mathematical programming.

After calculating household expenditures by age bracket, we estimated Q_{ib} (t/y), which represents the MF of commodity $i = (1 \ldots n^{JP}$; $n^{JP} = 409)$ by householder age bracket b, as shown in Eq. (1).

$$Q_{ib} = q_i^{JD} f_{ib}^{JD} + q_i^{JI} f_{ib}^{JI} \tag{1}$$

where q_i^{JD} and q_i^{JI} are the material footprint intensities of a specific critical metal (in this study, neodymium, cobalt and platinum) for domestic commodity i per unit expenditure (t/M-JPY) and for imported commodity i per unit expenditure (t/M-JPY), respectively. f_{ib}^{JD} refers to household consumption expenditures for domestic commodity i by householder age bracket b, while f_{ib}^{JI} refers to household consumption expenditures for imported commodity i by householder age bracket b.

In this study, we applied the material footprint intensities of neodymium, cobalt and platinum estimated by Nansai et al. (2015) to q_i^{JD} and q_i^{JI}; the methodology used to estimate these intensities is briefly described below. The GLIO model formulates the material footprint of a commodity per unit expenditure as an element of vector $\mathbf{q}$ in Eq. (2).

$$\mathbf{q} = \mathbf{d}(\mathbf{I} - \mathbf{A})^{-1} \tag{2}$$

Vector $\mathbf{q} = (\,\mathbf{q}^{JD} \quad \mathbf{q}^{JI} \quad \mathbf{q}^{G}\,)'$ consists of sub-vectors $\mathbf{q}^{JD} = (q_i^{JD})$, $\mathbf{q}^{JI} = (q_i^{JI})$ and $\mathbf{q}^{G} = (q_q^{G})$, in which elements q_i^{JD} and q_i^{JI} denote the MF per unit expenditure (t/M-JPY) of Japanese domestic commodities and the MF per unit expenditure (t/M-JPY) of directly imported-commodities to final demand sectors, respectively. In fact, q_q^G shows the MF per unit expenditure of overseas sector $q = (1 \ldots n^G$; $n^G = 230)$, although this was not used in the present study. Row vector $\mathbf{d} = (\,\mathbf{0} \quad \mathbf{0} \quad \mathbf{i}^G\,)$ is of the same dimension as vector $\mathbf{q}$ and has summation vector $\mathbf{i}^G$ in which all elements are unity. Matrix $\mathbf{I}$ is an identify matrix.

Matrix $\mathbf{A}$ is a mix-unit-type input coefficient matrix having a monetary unit and a mass unit consisting of block matrices $\mathbf{A}_{11}$, $\tilde{\mathbf{A}}_{13}$, $\tilde{\mathbf{A}}_{31}^{(k)}$, $\tilde{\mathbf{A}}_{32}^{(k)}$ and $\tilde{\mathbf{A}}_{33}^{(k)}$, as expressed by Eq. (3).

$$\mathbf{A} = \begin{pmatrix} \mathbf{A}_{11} & \mathbf{0} & \tilde{\mathbf{A}}_{13} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \sum_{k=1}^{l} \tilde{\mathbf{A}}_{31}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{32}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{33}^{(k)} \end{pmatrix} \tag{3}$$

where, $\mathbf{A}_{11}$ is the input coefficient matrix describing the input structure of domestic commodities i with regard to Japanese domestic commodities $j = (1 \ldots n^{JP})$ and $\tilde{\mathbf{A}}_{13}$ is a matrix showing the import structure of domestic commodities i in overseas sector q. $\tilde{\mathbf{A}}_{31}^{(k)}$ is a matrix showing the input structure of critical metals contained in trade goods k of overseas sector $p = (1 \ldots n^G)$ with regard to Japanese domestic commodities j, and $\tilde{\mathbf{A}}_{32}^{(k)}$ is a matrix showing the input structure of critical metals contained in goods k of overseas sector p with regard to input of imported commodities j directly to Japanese final demand. $\tilde{\mathbf{A}}_{33}^{(k)}$ is a matrix showing the input structure of critical metals contained in goods k of overseas sector p with regard to overseas sector q. Superscript ~ denotes a matrix having mass unit coefficients as its elements. $k = (1 \ldots l)$ represents the type of traded goods that contains target metals, with $l = 153$ used for neodymium, $l = 160$ for cobalt and $l = 151$ for platinum. See Nansai et al. (2015) for a detailed explanation of input coefficient matrix **A**.

2.2. Metals Contained in Medical Instruments

Medical instruments such as Magnetic Resonance Imaging (MRI) scanners contain a considerable amount of neodymium in their permanent magnets. Given the likely change in demand for medical services in an aging society, it is therefore important to consider the amount of metal in these medical instruments. In the JIOT, however, household demand for use of these scanners is added not to the sector of household consumption expenditure but to that of fixed-capital investments, which means the total demand for medical instruments induced by household demand cannot be derived directly from the JIOT. We therefore used the Leontief inverse matrix and the fixed capital matrix supplied by the JIOT to estimate the additional demand for medical instruments (mi), $f^{add}_{i=mi}$, from the capital investment triggered by household consumption expenditure on medical services (ms), $f^{JD}_{i=ms}$, as expressed in Eq. (4):

$$f^{add}_{i=mi} = B_{mi,ms} \times L_{ms,ms} \times f^{JD}_{i=ms} \tag{4}$$

where $L_{ms,ms}$ is the diagonal element of the medical services sector in the Leontief inverse, which indicates the direct and indirect demand for the medical services sector generated by unit demand for the sector. $B_{mi,ms}$ represents the direct demand for the medical instruments sector induced by a unit of the medical services sector. We here considered three medical service sectors: “medical services (public)”, “medical services (non-profit foundations, etc.)” and “medical services (medical corporations, etc.)”, and calculated $f^{add}_{i=mi}$ for each. Adding $f^{add}_{i=mi}$ to the corresponding f^{JD}_{ib} in Eq. (1) gives the associated MF.

2.3. Estimating Future Household Consumption Expenditures by Household Attribute in an Aging Society with Fewer Children

Since the average household size per householder age bracket is shrinking with development of an aging society with fewer children, household expenditure patterns will be influenced. Consumption expenditures do not necessarily decrease with declining household size, but are influenced by the specific lifestyle of individual households. For example, while expenditures on food will generally be lower in smaller households, certain expenditures such as eating out are higher for single-person households than for larger ones (FIES, 2005). Here, we define coefficients for such influences by using the values provided in the FIES for 2005.

FIES reports the allocated annual consumption expenditures on commodities by several household types (e.g., household size, in this study). First, we take $h^{(\beta)}_{\alpha}$ to express household expenditure on item $\alpha = (1 \ldots 44)$ by households comprising β persons as represented in the FIES. When $\overline{\beta}_b$, denoting average household size by householder age bracket b, is between β and $\beta + 1$, assuming there is $h_{\alpha b}$, representing household expenditure on item α by householder age bracket b, on the straight line going through points $(\beta, h^{(\beta)}_{\alpha})$ and $(\beta + 1, h^{(\beta+1)}_{\alpha})$ (here, $\beta = 1, 2, 3$), we hypothesize $h_{\alpha b}$ as follows:

$$h_{\alpha b} = \left(h^{(\beta+1)}_{\alpha} - h^{(\beta)}_{\alpha}\right)\left(\overline{\beta}_b - \beta\right) + h^{(\beta)}_{\alpha} \tag{5}$$

which specifies that expenditures between $h^{(\beta)}_{\alpha}$ and $h^{(\beta+1)}_{\alpha}$ change linearly.

When average household size by householder age bracket b shifts from $\beta^{(t)}_b$ to $\beta^{(t+1)}_b$, the change in consumption expenditure on items α, $\theta^{(t+1)}_{\alpha b}$, in association with the change in household constitution can be expressed by Eq. (6), in which superscript figures in parentheses reflect the target year of this study (1: 2005, 2:2010, 3: 2015, 4: 2020, 5: 2025, 6: 2030, 7: 2035).

$$\theta^{(t+1)}_{\alpha b} = \frac{h^{(t+1)}_{\alpha b}}{h^{(t)}_{\alpha b}} \tag{6}$$

As items α in the FIES that correspond to the commodity sectors in the JIOT, we could obtain $\theta^{(t+1)}_{ib}$, which is the ‘adjustment coefficient’ for household size for each commodity i by householder age bracket b.

However, because future $\beta^{(t)}_b$ is not available in any official Japanese statistics, we estimated it using linear regression and optimization as follows. Since average household sizes in the FIES from 2000 to 2010 show a decreasing trend that is almost linear, $\tilde{\beta}^{(t)}_b$, representing future average household size, was set at the value yielded by linear approximation of the 2000 to 2010 trend. In principal, summing each of the household populations calculated by multiplying $\tilde{\beta}^{(t)}_b$ by the corresponding number of households, $N^{(t)}_b$, should be consistent with the future total population, $Pop^{(t)}$, provided by the Japanese public statistics office (National Institute of Population and Social Security Research, IPSS). As an inconsistency among these values was identified, however, we adjusted $\tilde{\beta}^{(t)}_b$ and computed $\beta^{(t)}_b$ consistent with $Pop^{(t)}$ by using the optimization with quadratic programing as formulated in Eqs. (7) and (8).

$$\underset{\beta^{(t)}_b}{\text{Min.}} \sum_{b=1}^{6} \sum_{t=1}^{T} \left(\frac{\beta^{(t)}_b - \tilde{\beta}^{(t)}_b}{\tilde{\beta}^{(t)}_b} \right)^2 , \tag{7}$$

subject to

$$Pop^{(t)} = \sum_{b=1}^{6} N^{(t)}_b \beta^{(t)}_b \tag{8}$$

where $T = 1 \ldots 7$ is the number of target years (from 2005 to 2035).

Household consumption expenditures on domestic and import commodities by householder age bracket in each year, $f^{JD(t)}_{ib}$ and $f^{JI(t)}_{ib}$, were then calculated from Eqs. (9) and (10). Substituting the expenditures obtained in Eq. (1), the respective MFs of neodymium, cobalt and platinum were then determined from 2005 through to 2035.

$$f^{JD(t+1)}_{ib} = f^{JD(t)}_{ib} \times \frac{N^{(t+1)}_b}{N^{(t)}_b} \times \theta^{(t+1)}_{ib} \tag{9}$$

$$f^{JI(t+1)}_{ib} = f^{JI(t)}_{ib} \times \frac{N^{(t+1)}_b}{N^{(t)}_b} \times \theta^{(t+1)}_{ib} \tag{10}$$

2.4. Limitations of the Methodology Used in This Study

2.4.1. Use of the GLIO Model to Calculate the Material Footprints

The most salient feature of the GLIO is its description of the targeted domestic commodity sectors with very high sectoral definition. On the other hand, each of the foreign sectors is condensed into a single sector. Hence, the model represents the input–output structure of the target metal among foreign countries, but it does not describe the supply chain structure among foreign commodities that contain the metals. The accuracy with respect to the indirect effect of metals consumption in countries other than Japan may therefore be lower.

The material data embodied in the GLIO are obtained by multiplying the trade volumes of each commodity by its percentage metal content as described in Nansai et al. (2014). Given the large number (231) of targeted countries, however, the metal content of some of the commodities exported from certain foreign countries was unavailable. In these cases, the percentage metal content of the Japanese export commodity was used instead. As a result, the metal flows associated with export commodities from developing countries may in some cases have been overestimated. Since these data were then linked to the GLIO model, the MFs via exports from developing countries are also likely to have been overestimated.

2.4.2. The Future Scenario Used in This Study

In this study, all the factors to be taken into account in estimating future household expenditures were fixed at the 2005 level, with the exception of number of households and household size. In other words, we assumed that factors having a potential influence on the respective MFs, such as technological innovation and structure of global supply chains, remain unchanged post-2005. The reasoning is as follows. According to the International Energy Agency's Blue Map scenario (Technology Roadmap: Electric and Plug-in Hybrid Electric Vehicles (EV/PHEV), 2011), for example, Japan aims to increase the domestic market share of electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) to 20% by 2020. If demand for these vehicles indeed expands to this extent, the future MFs of neodymium, cobalt and platinum per expenditure will rise accordingly, given the increased use of rechargeable batteries. On the other hand, the MF of platinum for automobile catalytic converters will decline with rising use of these vehicles. Given the potential development of substitute materials, however, these projections may prove to work out differently, making it difficult to forecast these factors with any certainty. In estimating the MFs over the period, we therefore assumed that q_i^{JD} and q_i^{JI} remain unchanged from 2005 through to 2035.

In addition, consumption patterns will change over the next 30 years. For example, today's 30-year-olds consume more cell phones and other electronics than 60-year-olds, but in 30 years' time 60-year-olds may well consume as much as today's 30-year-olds. In addition, consumption patterns will vary with changes in factors such as marriage, having children and urban/suburban migration. Given data constraints, however, we here assumed that, as they age, today's young households will basically adopt the same consumption patterns as current older households.

In conclusion, the results presented in this study can be considered a base scenario for 2035 in the absence of any technological or policy interventions post-2005, with the sole focus on changes in household size and total population. Thus, although it is by no means straightforward to resolve and then incorporate such future trends, this challenge needs to be met in order to improve the accuracy of the estimates in the future.

3. Results

3.1. Characteristics of Household Consumption Expenditures and Material Footprints According to Householder Age Bracket in 2005

Although the characteristics of household consumption expenditures by householder age bracket in 2005 have already been explained in a previous study (Shigetomi et al., 2014), we here describe them again in order to identify the relationship between household expenditures and the respective MFs of neodymium, cobalt and platinum.

Fig. 1 shows the distribution of average consumption expenditures per household on 13 aggregated sectors by householder age bracket in 2005. These aggregated sectors integrate the 409 sectors used in this study without distinguishing between domestic and imported commodities. Consumption expenditures are highest for households with householders in their 50s, followed closely by those with householders in their 40s. In both cases, annual expenditures amount to over 7 M-JPY, which is far more than the figure for households with householders in their 30s (5.58 M-JPY), which rank third largest. This difference is due mainly to the high expenditures of the first two household categories on "household rent (imputed household rent)", aggregated into [13] house rent, insurance, and others, reflecting the fact that many householders in these age categories have purchased their own home thanks to their high income. For those in their 50s, expenditures on [4] transport vehicles and [12] services rank highest. On the other hand, those in their 40s spend more on [1] food and [9] education than others, since the average size of these households is highest. Compared with those in their 20s and 70s, i.e., the youngest and oldest households, the differences in expenditures on [1] food, [2] textiles, [10] medical and health care and [12] services are remarkable. These results indicate differences in lifestyle, because the average household sizes are very close.

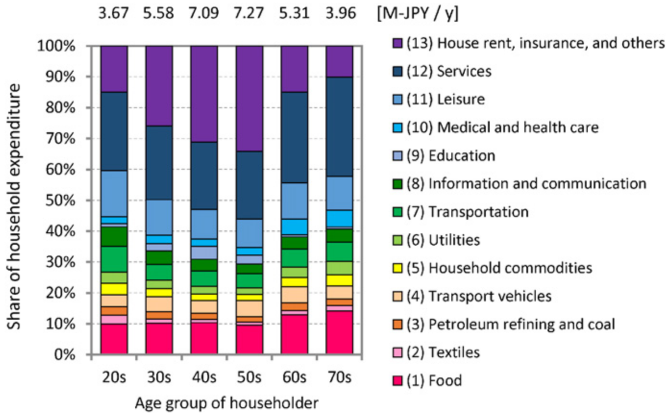

Fig. 1. Distribution of average consumption expenditures per household on 13 aggregated sectors by householder age bracket and total level (number above the bar) in 2005.

Fig. 2 depicts the respective MFs of neodymium, cobalt and platinum per household for 13 aggregated sectors by household age bracket in 2005. For neodymium, in Fig. 2(a), the 50s age bracket – which scores highest on overall household consumption expenditure – has the highest MF per household: 10 g. The key reason for this is the MF induced by "passenger motor cars" within [4] transport vehicles, which is much greater for the 50s age bracket than for others. This is due largely to the fact that households in their 50s have purchased or traded up to better cars, including ecologically-friendly cars, because they also have the highest household incomes. Additionally, the MF induced by "household electric appliances" within [5] household commodities is also striking in this age bracket. The second highest MF for neodymium is by households with householders in their 40s; in this case, however, the MF associated with [4] transport vehicles is considerably less than that of households with householders in their 50s. Next, the MF of those in their 20s is about 2% larger than that of those in their 70s, in contrast to their respective household expenditures. This fact is associated mainly with the difference in the MFs induced by "household electric appliances" and "cell phones" within [5] household commodities, which highlights the effect of distinguishing between younger and older lifestyles on their respective MFs. In particular, the difference in the MFs induced by "cell phones" is consistent with the 2005 consumer survey (Consumer Confidence Survey, 2005).

Besides neodymium, households in their 50s also rank highest with respect to the MFs of both cobalt and platinum, which are 97 g and 0.22 g per household, respectively. In the case of cobalt, though, the MFs of households in their 40s and 60s, ranking second and third, respectively, are only slightly smaller. For platinum, the MF of households in their 60s is larger than that of households in their 40s, which is again a different pattern from that holding for neodymium. Additionally, for both cobalt and platinum the relative magnitude of the MF of households in their 20s and 70s is inverse to the situation for neodymium, and the same holds for households in their 30s and 60s. This is probably because the footprint for neodymium (but not for cobalt or platinum) reflects a relatively young lifestyle, with those in their 30s (and not

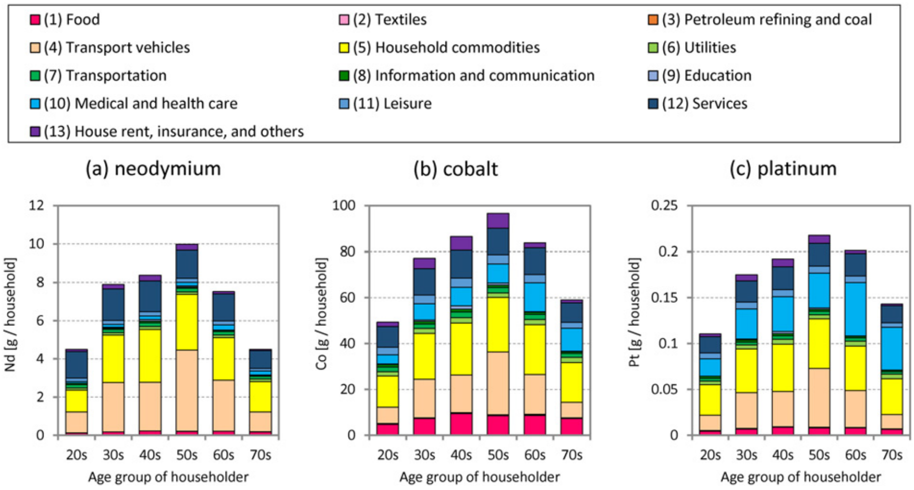

Fig. 2. MFs of (a) neodymium, (b) cobalt and (c) platinum per household by householder age bracket in 2005.

those in their 60s) following those in their 40s (the second largest users of neodymium).

3.2. Impact of Aging and Declining Birth Rates on the Material Footprints of Neodymium, Cobalt and Platinum From 2005 to 2035

Fig. 3 provides a breakdown of trends in the MFs of neodymium, cobalt and platinum from 2005 through to 2035 derived from household consumption per consumption expenditure sector. During this period the total MFs of neodymium, cobalt and platinum are estimated to decrease from 3.6×10^2 t to 3.2×10^2 t, from 3.8×10^3 t to 3.6×10^3 t and from 8.8 t to 8.3 t, respectively. They would thus be 11%, 6.6% and 4.7% lower than in 2005. In the case of neodymium and cobalt, the total MF is projected to peak in 2010, while for platinum it appears to peak in 2015. The increase in MF between 2005 and the peak year is 0.56%, 2.1% and 3.1% for neodymium, cobalt and platinum, respectively. After peaking, all three MFs are expected to decline naturally in Japan as a result of an aging society with fewer children. For neodymium, for example, if the average household size in each household age bracket remains stable during this period (i.e., $\theta_{ib}^{(t+1)} = 1$ in Eq. (6)), the MF of this metal is estimated to be 4.3% lower in 2035 than in 2005. Thus, this value indicates the effect on the MF of neodymium of a change in the total number of households, while the remaining 6.5% (11%–4.5%) reflects a declining population due to fewer children. Although the same factors are projected to cause the MFs of cobalt and platinum to decline from 2005 to 2035, in both cases it is projected to be only 1.6% and 0.69%, respectively. Over this period, the total number of households is expected to increase slightly, by 1.0%, despite the fact that the total population is projected by IPSS to decrease by 13% (IPSS, 2012a; IPSS, 2013). Whatever the case, the noteworthy fact is that the total MFs of neodymium, cobalt and platinum are estimated to fall between 2005 and 2035, in contrast to the rising number of households over the same period. This trend is particularly marked in the case of neodymium, where it is due mainly to the decline in the number of the under middle-aged, who tend to purchase more high-tech products than older people.

In terms of commodity sectors, the MFs of the three metals induced by “passenger motor cars” are estimated to decrease most between 2005 and 2035. The total MFs of neodymium, cobalt and platinum are projected to decline by 15 t, 98 t and 0.23 t, respectively. With respect to “passenger motor cars”, the MFs due to “trucks, buses and other vehicles” within [4] transport vehicles and by “repair of motor vehicles” within [12] services are also expected to decline significantly; shrinkage of transport-related demand will therefore be a key contributor to a decline in total MFs. Additionally, the projected decline in total population will mean a substantially smaller contribution of “house rent (imputed house rent)” to the respective MFs. Particularly in the case of cobalt and platinum, the MFs induced by “school education (private)” look likely to decline considerably. In contrast, the only one of the 13 aggregated sectors projected to induce an increase in MFs is [10] medical and health care, including “medical service (medical corporations, etc.)”, reflecting the trend towards an aging society. Note that while many of the MFs induced by household electrical products like “personal computers” and “cell phones” will drop, those induced by “household air conditioners” are expected to rise.

When we consider trends in MFs according to the age of the head of household, we see that the 50s age bracket had the highest MFs in 2005. For the 70+ age bracket, in contrast, MFs rise rapidly from this date onwards, with the MFs of both cobalt and platinum estimated to ultimately peak in 2035. The MFs of those in their 70s generally account for no less than a quarter of each total MF in 2035, while the neodymium MF of those in their 50s will continue to contribute most to the total MF from 2005 right through to 2035. The household demand of those in their 50s therefore needs to be considered as a key determinant of neodymium consumption. The MFs of those in their 20s and 50s appear to have peaked in 2005, while those in their 30s and 60s were largest in 2010. The MFs of those in their 40s and 70s will peak in 2015 and 2025, respectively. Except in the case of those in their 50s and 60s, the MFs of all households are expected to decline from their respective peak years through to 2035. The MFs of those in their 50s decrease between 2005 and 2015, increase up to 2025, and finally decrease again through to 2035. In contrast, the MFs of those in their 60s decrease from 2010 to 2025 and increase again through to 2035. It is noted that the above results should be interpreted on the basis of limitations described in subsection 2.4.2.

3.3. Comparison of Material Footprints with the Carbon Footprint Induced by Household Consumption

In the overall context of environmental policy it is important to consider trade-offs between different types of environmental burden, as measured using footprint analyses. Hoekstra and Wiedmann (2014), among others, report that developing a better understanding of such trade-offs as a key challenge that needs to be met in setting footprint reduction targets. In particular, there is significant interplay between GHG emissions (carbon footprint, CF) and resource consumption (material footprint, MF) in relation to, respectively, a low-carbon society and a sustainable material cycle society. Against this background, we now compare the respective MFs of neodymium, cobalt and platinum with the CF induced by Japanese household consumption from 2005 to 2035.

A previous study (Shigetomi et al., 2014) reported that the CF of the Japanese household in 2035 is estimated to be 1061 Mt-CO_2eq, which is

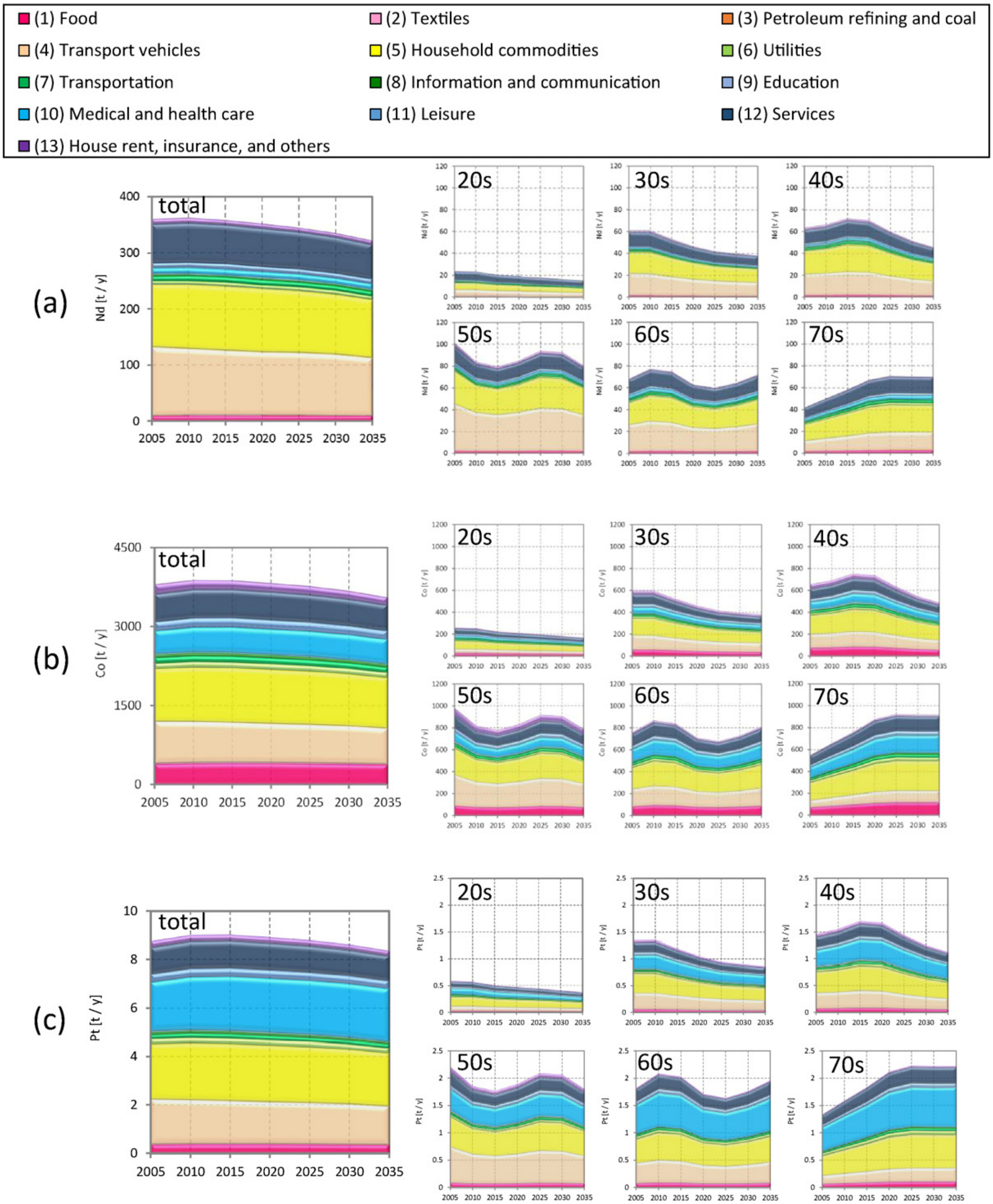

Fig. 3. Variation in the MFs of (a) neodymium, (b) cobalt and (c) platinum from 2005 to 2035, including total MF and MF per household age group.

4.2% less than in 2005. This decrease is relatively small in comparison with that estimated for the MFs considered in this study. The CF is projected to gradually increase from 2005 by 3.8% and peak in 2015, a trend similar to that for the MF of cobalt. The 40s household age bracket has the highest CF per household in 2005: 25 t-CO_2eq/household, which contrasts with the observation that the MFs of those in their 50s in 2005 are larger than those of other households. One key reason that those in their 50s have a lower CF than those in their 40s is that the former have purchased 400,000 JPY more "house rent (imputed house rent)".

Let us next consider which commodity sectors contribute most to the various footprints. Fig. 4 shows the contributions of each of the 13 aggregated sectors to the three MFs and the CF in 2035. Compared with the MFs these sectors induce, [4] transport vehicles and [5] household commodities contribute only marginally to the CF; the contributions of [3] petroleum refining and coal and [6] utilities, in contrast, are striking. The latter are due predominantly to direct emissions of GHG through consumption of "gasoline" and "kerosene" in passenger car transport and domestic heating, and indirect emissions induced by "electricity", respectively. These are commodity sectors that have no influence on the MFs considered in this study. Additionally, the contribution of [1] food to total CF is 14%, pointing to the significant impact of food-related sectors like "slaughtering and meat processing" and "dishes, sushi and lunch boxes" within this category. On the other hand, the contribution of [10] medical and health care to the overall

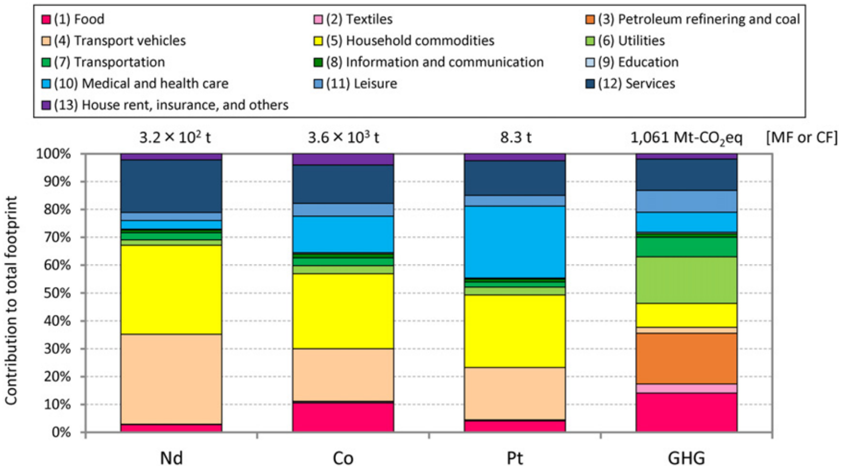

Fig. 4. Distribution of the MFs of neodymium, cobalt and platinum and the CF associated with Japanese household consumption in 2035. The values above the bars denote each total amount.

footprint is greater for the MFs than for the CF, particularly for the MFs of both cobalt and platinum.

In conclusion, while trends in the total MFs and CFs induced by an aging society with fewer children are similar from 2005 to 2035, the characteristics of each of these footprints in terms of household age bracket and commodity sectors are entirely different in 2035. It is therefore important to accurately monitor these respective footprints with a view to reducing carbon emissions while at the same maintaining secure supplies of critical metals.

3.4. Sensitivity Analysis of the Material Footprints Based on Japanese Population Scenarios

The MF values reported in sections 3.2 and 3.3 were estimated using future population and household numbers based on one particular population scenario developed by IPSS. This institute publishes 8 other population scenarios, however, with varying projections of both fertility and mortality (a high, medium and low variant for each; for details, see (IPSS, 2012b). The population and household data used for our MF estimates are based on the "medium" scenario for both fertility and mortality, which we shall refer to as the "reference scenario."

The MF estimates were subjected to a sensitivity analysis using all 9 population scenarios. Because no data were available on the numbers of households associated with each of these scenarios, these were estimated as follows. Proceeding on the assumption that average household sizes by household attribute (age group) all remain the same as in the reference scenario, the total number of households in each of the population scenarios can be obtained by dividing each of the total populations in the scenario by the average overall household size in the reference scenario. Next, assuming that the relative share of households per household attribute is also the same as in the reference scenario (e.g., 22% of total households continue to be accounted for by those in the 70s age bracket, as in 2010), we obtained the respective numbers of households in each of the scenarios by multiplying these shares by the total number of households cited above. Finally, we determined the household expenditures and the MFs for each of the scenarios by using these numbers of households.

Using this procedure, the highest total MFs (for the scenario with high fertility and low mortality) were estimated to be 4.7% larger than in the reference scenario, while the lowest total MFs (low fertility and high mortality) were estimated to be 4.1% smaller than in that scenario. The figures calculated in this study for the MFs of neodymium, cobalt and platinum in 2035 as a result of future demographic shifts thus have uncertainty margins of -13 to $+15$ t/y, -1.4×10^2 to $+1.7 \times 10^2$ t/y and -0.34 to $+0.39$ t/y, respectively.

4. Discussion

4.1. Opportunities for Consumers to Recognize Their Household Material Footprints

To reduce the household MFs analyzed in this study requires not just technological improvements (including longer product lifetimes, more recycling and development of alternative materials) but also some form of control on consumer demand. From this perspective, it is also important for consumers to be aware of the relationship between their lifestyles and their MFs. Recycling is an ecological activity that consumers can engage in on their own initiative, and has a key role to play in connecting lifestyles and resource consumption. Since implementation of the Home Appliance Recycling Law in Japan in 2001, dealers have been under obligation to collect all used/broken air conditioners, televisions, refrigerators and washing machines marketed in Japan. Additionally, the Small Home Appliance Recycling Law in Japan, which targets cell phones and personal computers, has been in force in certain municipalities since 2013. Finally, all end-of-life motor vehicles except for motorcycles have been collected under the terms of the Automobile Recycling Act in Japan since 2005. If consumers are aware that the many of the products collected under these various laws contain "critical metals", these laws can provide leverage for getting consumers to recognize the implied amount of mined metals, that is to say their MF. With this in mind, an exploratory analysis was carried out to assess the extent to which the products dealt with under these laws cover the MFs calculated for 2035.

In the case of neodymium, the MF induced by the products in the 30 commodity sectors collected under the cited legislation is an estimated 76% of the total value, with the MFs associated with just five commodity sectors related to passenger cars (including "passenger motor cars" and "repair of motor vehicles") dominating the picture: 45% of the total MF. For neodymium, then, the Automobile Recycling Act already provides quite significant coverage. The MFs associated with "personal computers" and "electrical audio equipment," covered by the Small Home Appliances Recycling Law, are 8.8% and 4.8% of the total MF, respectively. These figures are higher than those for "household electric appliances" and "household air conditioners", which are collected under the Home Appliances Recycling Law.

For cobalt, the MFs induced by products in these 30 commodity sectors will be an estimated 43% of the total MF, the lowest coverage of all the three metals. The commodity sector contributing most to the total MF is "passenger motor cars", at 16%, followed by "household electric appliances", at 4.7%. In terms of other domestic electric products, "video recording and playback equipment," "cell phones" and “personal computers” contribute 2.0%, 1.8% and 1.6%, respectively. The MF of cobalt induced by the five commodity sectors relating more broadly to passenger cars is only 24% of the total MF, far less than in the case of neodymium.

Finally, the MF of platinum induced by these 30 commodity sectors is expected to be 41% of the total MF, with the five commodity sectors related to passenger cars contributing 23%. Among domestic electric products, the sector contributing most is “household electric appliances”, followed by “personal computers” and “video recording and playback equipment.” Extending the lifetimes of these products therefore provides an effective means of reducing the MF not only of platinum but also of neodymium and cobalt.

At the same time, the three medical commodity sectors “medical services (medical corporations, etc.)”, “medical services (non-profit foundations, etc.)” and “medical services (public)”, which are not covered by these three recycling laws, also make a sizeable contribution to the MFs of both cobalt and platinum: 12% and 26%, respectively. It will therefore be important to address demand from these sectors, too, particularly against the backdrop of an aging society.

4.2. Projected Role of Household Material Footprints in Future Resource Management

Effective reduction of the MFs of critical metals associated with household consumption will contribute to security of global procurement and stable supply to consumers. The three metals analyzed in this study are an intrinsic element of many of the commodities vital to contemporary everyday life, such as passenger cars and cell phones. Visualizing the relationships between the MFs of mineral resources and consumption patterns along the lines developed in the present study can provide a useful communications tool for improving technologies and steering lifestyles from the consumption perspective. As described in section 4.1, it is not only through technological innovation but also by “greening” consumer behavior (by maximizing recycling and separate waste recovery, for example) that MFs can be significantly reduced, even if only gradually. The estimates derived in this study indicate that the MFs induced by the commodity sectors covering automobiles and domestic electric appliances, which are targeted by current Japanese recycling laws, will continue to prevail, particular in the case of neodymium. Continued enforcement of the Automobiles Recycling Act, the Home Appliance Recycling Law and the Small Home Recycling Law can thus play an important role in alerting consumers to the MF of neodymium in terms of the changes in household demand associated with an aging society with fewer children. In the case of cobalt and platinum, too, it is also important that consumers recognize the significance of aspects of their lifestyles that are not covered by these recycling laws. For example, keeping in good health will help reduce not only their medical expenditures but also the MFs of these metals, and citizens should be informed accordingly.

While the MFs induced by “passenger motor cars” are expected to decrease most between 2005 and 2035 this trend is highly uncertain in light of the future penetration of electric and hybrid motor vehicles envisaged as a means of reducing carbon footprints. Additionally, as the share of wind power in electricity generation increases, we can expect the alleviation of the CF of “electricity” to be accompanied by an increase in the MF of neodymium. It can be concluded that household demand relating to these commodity sectors, plus health care demands that will likely increase in association with an aging society, should be preferentially monitored to design an effective resource strategy in the low carbon society of the future.

As explained in section 2.4, since the focus of the present study was on how changes in household composition will affect the MFs of neodymium, cobalt and platinum, as noted in the Methods and data section, the production technologies, global supply chain structures, prices and household consumption patterns used in this study were fixed at the 2005 level, with only the number of households and total population subject to variation. In other words, the results of this study indicate solely the effect of an aging society with fewer children on the respective MFs of these metals; for this reason, future technological innovations have the potential to achieve further reductions in MFs. Additionally, against the background of how Japan's future energy strategy is to be adjusted following the Fukushima Daiichi nuclear plant disaster of 2011 (McLellan et al., 2013), changes in consumer awareness and purchasing behavior will also have an important bearing not only on the country's energy strategy but also policies with respect to resource use.

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