Study of Mid-Term Impact of Japanese Households on Formation of Low-Carbon Society from Consumption-Based Approach

(消費者基準アプローチによる低炭素社会実現に向けた日本の家計消費の中期的なインパクトに関する研究)

Yosuke Shigetomi

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1 Introduction

Since the Industrial Revolution, an unprecedented consumption-based society has been forming with both rapid development of industrial technologies and expansion of globalization. Reportedly, the amount of material resources consumption in the whole economy has increased eight-fold during the recent century. Human beings consume approximately 60 Giga ton (Gt: 10^9 t) of material resources (Krausmann et al., 2009). Underlying the benefits deriving from this consumption, however, are not only increasingly severe regional issues such as air and water pollution but also looming global concerns such as climate change associated with global warming (e.g., UN, 2015). To sustain population and economic activities at a certain level, harmonizing developments with natural environments is expected to be necessary because natural resources and their purification systems are limited.

This perspective can be summarized in "Sustainable Development," as introduced in the final report of the World Commission on Environment and Development (UN WCED), "*Our Common Future*" in 1987. This concept is defined as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). In this context, the "ecological footprint" (Rees, 1992; Wackernagel and Rees, 1996) was devised as one indicator to reflect "sustainability" from environmental points of view (Singh et al., 2009). The ecological footprint represents how much biologically productive land and sea area is necessary to maintain a given consumption pattern (Wiedmann et al., 2006). From use of this indicator, Wackernagel and his colleagues (2002) reported that the speed of development of the world economy in 1999 had exceeded the biosphere's regenerative capacity by 20%. In other words, they stated that a 20%

ecological “overshoot” had already occurred from human activities up to 1999. Today’s world economy shows a 60% overshoot beyond global capacity (Global Footprint Network, 2015), which means that the gap separating sustainable development and current economic activity is widening year by year.

Climate change is recognized as the most urgent environmental concern in the world for our devoting to sustainable development (e.g., UN, 2012). Global warming caused by anthropogenic greenhouse gases (GHG) such as carbon dioxide (CO_2) triggers increases in global temperature. Higher temperatures are expected to exacerbate damage on a global scale from food crises, rising average sea levels, extreme weather, ecosystem destruction, and other phenomena. The Fifth Assessment Report (AR5) on Intergovernmental Panel on Climate Change (IPCC) described that CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emissions increase that occurred during 1970–2010, with a similar percentage contribution for 2000–2010 (AR5 WG3, 2014, pp.6). This increase was mainly driven by population growth and economic activities. Therefore, without additional efforts to reduce GHG emissions beyond those in place today, emissions growth is expected to raise global mean surface temperatures in 2100 from 3.7 °C to 4.8 °C compared to pre-industrial levels (AR5 WG3, 2014, pp. 8).

Against such concerns of dangerous climate change as those above, the United Nations Framework Convention on Climate Change (UNFCCC) has been adopted in the United Nations Conference on Environment and Development (UNCED) at Rio de Janeiro in 1992, aimed to stabilize anthropogenic GHG concentrations in the atmosphere. The Kyoto Protocol (COP3) adopted in 1997 set binding national targets for GHG emissions reductions for the first time. In 2008, at the Toyako G8 summit held in Japan, the G8 countries agreed on a shared vision for all UNFCCC signatories to achieve at least a 50% worldwide reduction in GHG emissions by 2050. Furthermore, economically developed and developing countries have agreed to GHG mitigation targets in COP16 to accomplish a rise in global temperatures within 2°C since pre-industrial levels (CanCún Agreement). In the most recent year, the Paris Agreement (COP21) has set for a global action covering with all 195 parties to avoid dangerous climate change by limiting global warming to well below 2°C, or 1.5°C (EC, 2015).

Such environmental loads as GHG emissions associated with economic activities can be regarded as attributable to satisfaction with final human "consumption." From this perspective, Munksgaard et al. (2000) analyzed time-series CO_2 emissions during 1966–1992 directly and indirectly induced by Danish household consumption. They reported that "[…] Danish consumers are responsible for the global environmental consequences of their consumption." The following year, he and a colleague suggested two concepts of accounting responsibility for CO_2 emissions (Munksgaard and Pedersen, 2001): "producer responsibility" by which CO_2 generated by the production of energy, goods, and services is attributed to the producer, and "consumer responsibility" by which the consumer is responsible for CO_2 from the production of energy, goods, and services related to their final consumption. Based on these concepts, they argued for the necessity of expanding the accounting of CO_2 emissions to include CO_2 embodied in imported non-energy goods. Since then, discussions have often addressed environmental management mainly for GHG emissions mitigation with specific examination of "consumption-based accounting" (Peters; 2008; Peters and Hertwich, 2009; Wiedmann, 2009; Davis and Caldeira, 2010; Peters et al., 2011). Although some room remains for discussion of how the emissions responsibility should be attributed to the producer and the consumer (Rodrigues and Tiago, 2006, 2008;

Lenzen, 2007), it has been described that applying consumption-based accounting to GHG emissions, the so-called “carbon footprint” (Wiedmann and Minx, 2008), has many political advantages, as described below. Wiedmann (2009) summarized the benefits of consumption-based accounting for international policy-making related to climate change. As described in the opening, the accounting complements the territorial-based approach used in the UNFCCC by including all driving forces for GHG emissions associated with consumption. Peters (2008) and Peters and Hertwich (2008) demonstrated that it can be expected to increase the emissions mitigation options for developed countries and will inevitably promote the development of policies for clean production as well as international mitigation schemes such as clean development mechanisms (CDM). In addition, Kanemoto et al. (2014) estimated that the jurisdiction of the Kyoto protocol could grow from covering 28% of the fastest-growing flows to covering 80% of them if the same Kyoto signatories set targets based on consumption-based accounting in addition to production-based accounting.

From these points of view, particularly for developed nations, management on GHG emissions with consumption-based accounting is necessary for the accomplishment of Paris Agreements. In this context, it is also being broaden the perspective of quantifying not only consumption-based emissions of nations (e.g. Hertwich and Peters, 2009) but also those associated with product and organization through Scope 3 (WRI and WBCSD, 2009; Le and Ma, 2013) and ISO/TS14067 (ISO, 2013). Furthermore, this accounting approach is coming to be applied to other various environmental loads such as water and material resources consumption in pursuit of wider sustainability (EC, 2013). Environmental management using “environmental footprint” is expected to spread widely worldwide. The following section presents a brief review of environmental footprints.

1.1 Brief review of environmental footprint analyzed by the multi-regional input-output model approach

An environmental footprint is defined as an indicator representing whole life cycle environmental loads and resources consumption instigated by anthropogenic activities. During the last two decades, footprint analysis has been applied to biospheres (ecological footprint), GHG (carbon footprint), water resource (blue, green, and gray water footprints), land use (land footprint), biodiversity loss (biodiversity footprint), material use (material footprint) and other subjects (Kitzes et al., 2009; Čuček et al., 2012; Hoekstra and Wiedmann, 2014). More recently, several studies have applied the footprint concept to social issues such as labor conditions (Simas et al., 2014, 2015; Gómez-Paredes et al., 2015) and income inequality (Alsamawi et al., 2014).

Life Cycle Assessment (LCA) and Input–output Analysis (IOA) are widely used for footprint analyses (Fang et al., 2014; Fang and Heijungs, 2015). Actually, LCA is available to assess environmental impacts throughout a product's life cycle with differentiation of a product in the same category (Finnveden et al., 2009). The system boundary is, however, incomplete because not all inputs and outputs are covered by it ("cut-off flows") (Suh and Huppes, 2001; Finnveden et al., 2009). In contrast, IOA can analyze the environmental loads of the "average product," ensuring the system boundary under the input–output table (Leontief, 1970; Millar and Blair, 2009) that is used, whereas the resolution in terms of commodity classification is poor because of the high level of aggregation in industry and commodity classifications (Suh and Huppes, 2001; Suh et al., 2004). Although high costs of time and data compilation consuming are required, the model approach with benefits between LCA and IOA is called Hybrid-LCA (Suh et al., 2004; Suh and Huppes, 2005).

In recent years, along with performance improvement of personal computers, development of multi-regional input–output (MRIO) models has been remarkable (Leontief, 1985; Lenzen et al., 2004b, Wiedmann, 2009, 2011, 2013). Such models describe the input–output structure of global supply chains. Well-known models include OECD-MRIO (Yamano and Ahmad, 2006; Yamano, 2011), EORA (Lenzen et al., 2012a), WIOT (Dietzenbacher et al., 2013), EXIOBASE (Tukker et al., 2013), and GTAP-MRIO (Andrew and Peters, 2013). In addition, several MRIO models link specific regional input–output structures to the global economy such as GLIO (Nansai et al., 2009) and UK-MRIO (Wiedmann et al., 2010). In Japan, Nansai and his colleagues have developed a global-link input–output (GLIO) model that incorporates the global supply chains of 231 countries and regions with a domestic input–output structure based on the Japanese input–output table (Nansai et al., 2009, 2013a, b). The benefit of employing these MRIOs for footprint analysis is that they clearly identify and represent the production technologies of individual nations. National system boundaries can be extended to include global supply chains (Weinzettel et al., 2014). In this context, some recent studies have analyzed environmental footprints using the global MRIO approach. This subsection presents some of their studies as follows.

Although Lenzen et al. (2004b) have already demonstrated a method of applying the MRIO framework to calculate consumption-based CO_2 emission, Hertwich and Peters (2009) were the first to report quantification of the footprints of different countries related to the global economy. The authors emphasized that 72% of the human carbon footprint is related to household consumption, 10% to government consumption, and 18% to investments on a global level. Davis and Caldeira (2010) demonstrated that 23% of the global carbon footprint (CO_2 only) in 2004 was traded internationally, primarily as exports from China and other emerging markets to consumers in economically developed countries.

Peters et al. (2011) revealed the net emission transfers from UNFCCC non-Annex B (economically economically developed countries) to Annex B (mostly economically developing countries) countries had increased by 33% during 1997–2004. In specific regions, Wiedmann et al. (2010) linked sectoral and country-specific trade for the UK to the UK input–output table (UK-MRIO), and represented the time-series carbon footprint of UK for 1992–2004. Nansai et al. (2012) quantified Japan's carbon footprint in 2005 using the GLIO, which indicated that the Japanese economy had generated 63% of global indirect emissions in UNFCCC non-Annex I and other countries.

Beyond those carbon footprint analyses, non-numerical studies have analyzed other environmental footprints using global MRIO models. For ecological and water footprints, Ewing et al. (2012) presented the first paper propose the method within an MRIO modelling framework. Steen-Olsen et al. (2012) further applied this framework based on GTAP-MRIO to quantify the respective blue water footprints, which measure direct and indirect surface water and groundwater requirements (e.g., Hoekstra and Mekonnen, 2012) of the European Union (EU) 27 member states as well as their carbon and land footprints. Weinzettel et al. (2013) addressed the land footprint of nations which represents biomass input requirements and associated land and ocean use through global supply chains with the same framework. Weinzettel et al. (2014) presented characteristics of national ecological footprints calculated using process-based analysis and the two MRIO analyses. For a water footprint, Feng et al. (2011) also conducted a comparison of a top-down approach (MRIO analysis) and a bottom-up approach (process-based analysis). Both of these reports described the importance of the hybrid MRIO approach, based on the respective benefits and shortcomings of MRIO analysis and process-based analysis.

The biodiversity footprints of nations, which represents the number of species threatened as a result of international trade, was first presented by Lenzen et al. (2012b). The authors reported that 30% of globally threatened species (about 7500 species) are attributable to international trade, linking the IUCN Red List of Threatened Species plus a compatible list of threatened bird species from Bird Life International to EORA. Furthermore, Moran et al. (2016) examined the biodiversity footprints of specific products in several case studies (e.g., nickel mining in New Caledonia) using the EORA database compiled by Lenzen et al. (2012b), to elucidate how and when MRIO techniques can be useful for studying biodiversity associated with supply chains.

In terms of resource consumption, Bruckner et al. (2012) first analyzed the material footprints of nations within the global supply chains ensured by GRAM. The material footprint in this paper refers to raw material consumption (RMC) (Schoer et al., 2012), indicating direct and indirect raw material requirements such as those for agricultural biomass, fossil fuels, metals, and non-metallic minerals. The authors quantified each of the material footprints (RMCs) of the classification disaggregated from the target countries and regions with specific examination of economic differences. Wiedmann et al. (2015) analyzed the material footprints of nations during 1990–2008 based on EORA. The authors pointed out that, in cases of material footprints, no decoupling from GDP has occurred over the past two decades, in contrast to domestic material consumption (DMC), which denotes the total quantity of materials used within an economic system without indirect flows. The dependence of imports is considered in the material footprint. Giljum et al. (2015) compared national DMCs and material footprints in 1997 and those in 2007 using GTAP-MRIO. They demonstrated leakage effects in terms of material consumption: net material importers generally have RMC larger than DMC, although the reverse is observed for net exporters.

In recent years, the concept of “Footprint Family” (Galli et al., 2012, 2013; Fang et al., 2014), which is an integration of more than one footprint indicator, has received attention from the European Commission (EC) to develop sustainable and interdisciplinary policy measures. Fang et al. (2014) considered, for instance, that a shift to integration of footprint indicators is likely because no single indicator can be used to analyze all anthropogenic loads. It is important to comprehend tradeoffs among the multi-footprints measured simultaneously, and to implement policy measures to alleviate their footprints.

1.2 Main perspectives of this work

To achieve sustainable development in the future, it is necessary to form a low-carbon society for the mitigation of climate change, which is the most urgent environmental issue in the world. This section highlights three key factors to achieve low-carbon society based on the background described in previous sections.

1.2.1 Forecasting future carbon footprint

It is fundamentally important to forecast future GHG emissions scenarios for strategic reduction at the global emission level. For instance, the IPCC AR5 report collected about 900 GHG mitigation scenarios and proposed the Representative Concentration Pathway (RCP) based on them. The RCPs are identified by their approximate total radiative forcing in year 2100 relative to 1750: 2.6 watts per square meter (W/m^2) for RCP2.6, 4.5 W/m^2 for RCP4.5, 6.0 W/m^2 for RCP6.0, and 8.5 W/m^2 for RCP8.5 (IPCC, 2014). The International Energy Agency (IEA) also set a blue map scenario aimed at reducing global energy-related CO_2 emissions in 2050 to half of their current levels of 2010 (IEA, 2010).

These scenarios support a specific examination of the efficiency of introducing technological improvements on reduction in emissions from the perspective of conventional production-based approaches. In other words, the major contributor to future GHG emissions is not clear in their scenarios. Therefore, to design future low-carbon scenarios taking greater detail and broad areas into account, policy measures for alleviation of emissions should be discussed from the viewpoint not only of the supply side, but also of the demand side. In this context, it is important to predict GHG emissions quantitatively using consumption-based approaches that can cover wider emissions than production-based approaches described in the preceding section. Very few studies (Barrett and Scott, 2012; Chitnis et al., 2012; Girod et al., 2014) have applied future scenario analysis with consumption-based accounting.

Future estimation of consumption-based GHG emissions (carbon footprint) requires scenario analysis related to changes in the direct emissions associated with production (i.e., technological innovations such as fuel cell vehicles), those in economic structures (i.e., industry and trade structures), and those in consumption patterns (i.e., social factors such as lifestyle and demographic trend) presented in Figure 1.1.

1.2.2 Household consumption as a main driver of carbon footprint

Final demand of a nation is defined as household final demand, governmental final demand, fixed capital formation, and imports by the System of National Accounts (SNA). Numerous studies have analyzed environmental loads associated with household consumption, which is the single largest category of final demand, using the footprint concept (e.g., Munksgaard and Pedersen, 2000; Pachauri and Spreng, 2002; Lenzen et al., 2004a; Bin and Dowlatabadi, 2005; Nijdam et al., 2005; Takase et al., 2005; Collins et al., 2006; Peters and Hertwich, 2006; Wiedmann et al., 2006; Nansai et al., 2007; Park and Heo,

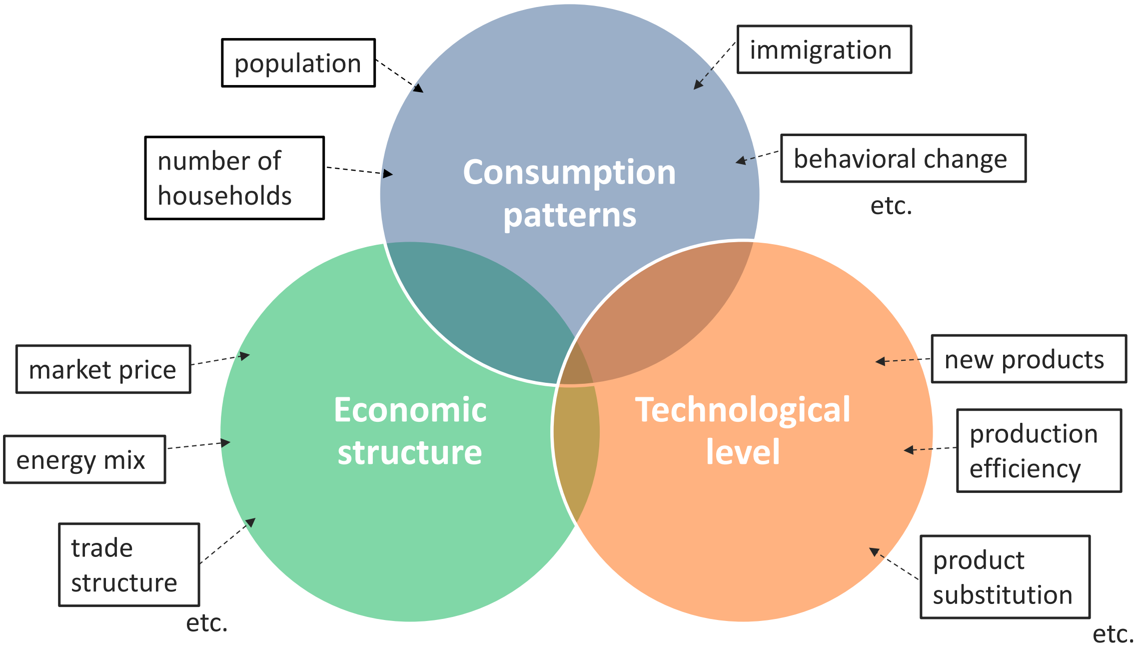


Figure 1.1 Key factors for future scenario estimation in consumption-based GHG emissions (carbon footprint).

2007; Druckman and Jackson, 2009; Liu et al., 2009; Baiocchi et al., 2010; Heinonen and Junnila et al., 2011a, 2011b; Druckman et al., 2011, 2012; Chitnis et al., 2012, 2013; Wiedenhofer et al., 2013). In addition, some studies have specifically examined socioeconomic factors such as household size (Wier et al., 2001; Webber and Matthews, 2008; Girod and de Haan, 2010; Jones and Kammen, 2011; Shirley et al., 2012; Kawajiri et al., 2015), household income level (Wier et al., 2001; Webber and Matthews, 2008; Kerkhof et al., 2009a, 2009b; Girod and de Haan, 2009; Jones and Kammen, 2011; Shirley et al., 2012; Saunders, 2013; Chitnis et al., 2014), and age of householder (Wier et al., 2001; Kronenberg, 2009), taking difference of lifestyles of households analyzed into account. Table 1.1 presents results of those earlier studies.

As these studies described above show, most analyses targeting household environmental loads are GHG emissions and energy consumption. In other words, except for studies that have specifically applied GHG emissions and energy consumption as multiple criteria, few studies to date have addressed multiple household loads. In the context of GHG emissions, household consumption reportedly makes the greatest contribution to the carbon footprint of a nation (Hertwich, 2005, 2011; Hertwich and Peters, 2009). In addition, Nansai et al. (2012) revealed that 61% of Japan's 2005 carbon footprint derived from domestic household consumption. Consequently, it is clear that strategies of changes in domestic consumption patterns (lifestyles) of household should reduce the carbon footprints of nations. Nevertheless, very few studies, such as Chitnis et al. (2012), predict future carbon footprints of household with consideration of global supply chains. No such study has been conducted in Japan. It is important to estimate the future structure of household carbon footprints to discuss how to encourage consumers to change their lifestyles to reduce domestic and international GHG emissions.

Table 1.1 List of studies analyzing the environmental loads associated with household consumption. SRIOA: analysis with single region input-output table, MRIOA: analysis with multi-regional input-output table, Hybrid LCA: process LCA + IOA.

Reference	*Location*	*Year*	*Approach*	*Target household type*	*Commodities*	*Environmental indicators*	*Future estimation*
Baiocchi et al. (2010)	UK	2000	SRIOA	17 lifestyle patterns	34	CO_2	
Bin and Dowlatabadi (2005)	US	1997	SRIOA	1 total household	62	Energy use, CO_2	
Chitnis et al. (2012)	UK	2010, 2020, 2030	MRIOA	1 total household	27	GHG	✓
Chitnis et al. (2013)	UK	2010	MRIOA	1 total household	27	GHG	
Chitnis et al. (2014)	UK	2010	MRIOA	5 income levels	27	GHG	
Collins et al. (2006)	Cardiff (in UK)	2001	Hybrid LCA	1 total household	43	Biocapacity	
Druckman and Jackson (2009)	UK	1992-2004	MRIOA	1 total household	27	GHG	
Druckman et al. (2011)	UK	2008	MRIOA	1 total household	27	GHG	
Druckman et al. (2012)	UK	2005	MRIOA	2 (men and women)	27	GHG	
Girod and de Haan (2009)	Switzerland	2000-2003	Process LCA	2 income levels	450	GHG	
Girod and de Haan (2010)	Switzerland	2002-2005	Process LCA	4 household sizes	450	GHG	
Heinonen and Junnila (2011a)	4 areas (in Finland) + Finland	2006	Hybrid LCA	1 total household	41	GHG	
Heinonen and Junnila (2011b)	Helsinki and Porvoo (in Finland)	2006	Hybrid LCA	1 total household	41	GHG	
Jones and Kanmen (2011)	50 states and 28 cities (in US)	2005	Hybrid LCA	6 household sizes + 12 income levels	289	GHG	
Kawajiri et al. (2015)	Japan	2005	MRIOA	4 expenditure levels + 5 household sizes	about 400	CO_2	
Kerkhof et al. (2009a)	Netherlands, UK, Sweden, Norway	around 2000	Hybrid LCA	5-10 invome levels	12	CO_2	
Kerkhof et al. (2009b)	Netherlands	2000	SRIOA	10 income levels	112	GHG, NOx, SPx, NH_3, VOCs, N, P	
Kronenberg (2009)	Germany	2006-2030	SRIOA	6 householder age types	about 60	GHG, Energy use	✓
Lenzen et al. (2004)	14 Sydney statistical divisions (in Australia)	2000	MRIOA	18 household types	135	Energy use	
Liu et al. (2009)	China	1992, 1997, 2002, 2005	SRIOA	2 income levels	52	Energy use	
Munksgaard et al. (2000)	Denmark	1966-1992	SRIOA	1 total household	66	CO_2	
Nansai et al. (2007)	Japan	1995	SRIOA	1 total household	94	Energy use, CO_2, Waste, NOx	
Nijdam et al. (2005)	Netherlands	1995	SRIOA	1 total household	360	GHG, NH3, PO_4^{3-}, and 11 others	
Pachauri and Spreng (2002)	India	1983-1984, 1989-1990, 1993-1994	SRIOA	1 total household	115	Energy use	
Park and Heo (2007)	Republic of Korea	1980, 1985, 1990, 1995, 2000	SRIOA	1 total household	168	Energy use	
Peters and Hertwich (2006)	Norway	2000	MRIOA	1 total household	49	CO_2, SO_2, NOx	
Saunders (2013)	US	1987, 2002	SRIOA	8 income levels	about 400	Energy use	
Shirley et al. (2012)	3 Virgin Islands (in US)	2005	Hybrid LCA	5 income levels + 5 household sizes	about 30	GHG	
Takase et al. (2005)	Japan	1995	Hybrid LCA	1 total household	80	CO_2, Waste	
Webber and Matthews (2008)	US	2004	MRIOA	5> expenditure levels + 8 household sizes	about 300	CO_2	
Wiedenhofer et al. (2013)	3 areas (in Australia)	1999	SRIOA	85 household types	135	Energy use	
Wiedmann et al. (2006)	UK	2000	SRIOA	55 household types	76	Biocapacity	
Wier et al. (2001)	Denmark	1995	SRIOA	3 income levels + 3 householder age types + 3 inhabitant types	72	CO_2	

1.2.3 Trade-off between GHG and critical resources necessary for introduction of low-carbon technologies

Improvement in energy efficiencies and introductions of both renewable energies and low-carbon technologies such as electric vehicles is necessary to achieve RCP and the blue map scenario described above. Therefore, metallic resources within rare metals and rare earth metals are necessary to implement these measures. Rare earth metals are 15 lanthanoid elements and 2 elements including scandium and yttrium. Neodymium, a rare earth metal, for instance, is used in permanent magnets for automobile motors and wind power turbines. Cobalt is used as a positive electrode material for lithium secondary batteries of electric and hybrid vehicles. Platinum is widely used as a catalyst for purifying automobile exhaust gases or as an electronic material. These rare metals are subject to supply constraints. Recycling of them is still extremely difficult (Reck and Graedel, 2012; Binnemans et al., 2013). In addition, one is extracted in conflict areas and is sold to armed groups as a *conflict mineral*. Therefore, among these metals are the so-called *critical metals* (National Research Council, 2008; EC, 2010). The importance of their stable supply has been increasing (Graedel et al., 2015; Nassar et al., 2015).

As the Footprint Family explained above, to obtain a more complete picture of sustainability, the use of critical metal resources must be quantified in conjunction with GHG emissions. The concept of material footprint can quantify direct and indirect metal requirements to meet final demand. Whereas previous studies have used material flow analysis (MFA) to present broad overviews of the flows of a range of mineral resources through the economy (Graedel et al., 2004; Müller et al., 2006; Hatayama et al., 2007; Reck et al., 2008; Du and Graedel, 2011; Chen and Graedel, 2012; Kablak and Graedel, 2013a, 2013b; Elshkaki and Graedel, 2013, 2014; Ohno et al., 2014; Guyonnet et al., 2015; Licht et al., 2015), the relation between the footprint of critical metals and final consumption has not been clarified. Improvements in resource efficiency have been proposed in some states, such as the dematerialization policy described in The Roadmap to a Resource Efficient Europe (EC, 2011), but few studies have precisely examined the material footprints for minerals in individual nations (Giljum et al., 2015; Wiedmann et al., 2015). Furthermore, no current study has examined the similarities and differences between the carbon and material footprints for critical metals. Understanding what consumption contributes greatly to creating dependence on critical metals, and elucidating the tradeoffs linking GHG reduction and critical metals usage through the global supply chains are important to achieve a low-carbon society while avoiding supply risks.

1.3 Objectives of the thesis

Against this background, the first objective of this dissertation is to present both the structures of the Japanese carbon footprint and material footprints for the critical metals necessary for low-carbon technologies associated with household consumption in 2005, considering the global supply chains. The target critical metals are neodymium, cobalt, and platinum, as described in Subsection 1.2.3. These are referred to be the critical metals with respect to supply risks, recycling restrictions, and demand growth by UNEP and UNU (2009). According to Graedel et al. (2015), additionally, the criticalities of neodymium and cobalt are relatively high in terms of supply risk and vulnerability to supply restriction, while that of platinum is markedly in terms of environmental implications and vulnerability to supply restriction.

Based on the analyses described herein, the dissertation also aims to provide scenario approaches to estimate future carbon and material footprints of Japanese households from the viewpoints of changes in demographic trends and international trade structures based on the concept as shown in Figure 1.1. Finally, the dissertation presents discussion of the policy implications and further perspectives for reduction of future carbon and material footprints of households.

1.4 Content of the thesis

The thesis contents are described below.

Chapter 2 presents the share of the Japanese carbon footprint and material footprints for the critical metals (neodymium, cobalt, platinum) attributable to domestic household consumption in 2005. The policy implications of the tradeoffs between GHG mitigation and critical metal consumption are considered within the context of differences in consumer income.

Chapter 3 elucidates the structure of the household carbon footprint of 2005 by the age of householders. Subsequently, this chapter provides the results of estimations of future household carbon footprints in Japan during 2010–2035 with specific examination of demographic changes (population and number of households).

Chapter 4 explains the respective impacts of shifts in demographic changes of the Japanese material footprints for neodymium, cobalt, and platinum, until 2035, in a similar manner to that presented for the carbon footprint in Chapter 3. This chapter also examines the extent to which products are dealt with under current Japanese recycling laws, with some coverage of the material footprints calculated for 2035.

Chapter 5 presents a model approach to estimate future material footprints for critical metals based on changes in the international trade structure. This chapter examines important economic drivers of global physical flows of the critical metals in the model.

Chapter 6 concludes this dissertation based on the previous chapters

2 Structures of Current Carbon Footprint and Material Footprints for Critical Metals Instigated by Japanese Household Consumption

Footprint analysis is used to identify entire product life cycles and the loads associated with consumption. Indeed, the application of a “Footprint Family” (see Galli et al., 2012, 2013; Fang et al., 2014) to develop sustainable and interdisciplinary policy measures that integrate more than one footprint indicator is increasing (Giljum et al., 2011; Ewing et al., 2012; Steen-Olsen et al., 2012). The application of multi-criteria decision making in industrial policy is also common practice. The European Commission (EC) started promoting the use of multiple footprints to analyze the footprints of products and organizations (EC, 2013). Similarly, the 17 Sustainable Development Goals (SDGs) put forward by the United Nations (UN) also need to consider multiple criteria and their synergies and trade-offs (Cucurachi and Suh, 2015). However, such multi-criteria assessments need to take into account consumer-side loads as well as producer-side loads.

In order to obtain a more complete picture of environmental loads instigated by household consumption, the use of “critical metal” resources needs to be quantified in conjunction with GHG emissions, as some metals play a key role in new energy technologies, such as in electric cars and fuel cells. This chapter simultaneously addresses the carbon and material footprints for the three critical metals (neodymium, cobalt, and platinum) in Japanese households with different income levels. In addition, the policy implications of the trade-offs between GHG mitigation and critical metal consumption are considered within the context of these differences in income.

2.1 Methods and Data

2.1.1 Carbon and material footprints per unit expenditure for commodities consumed by households

In recent years, the multiregional input-output (MRIO) models (Lenzen et al., 2004b; Wiedmann, 2009; Moran and Wood, 2014) that describe the input-output structure of international supply chains (Yamano and Ahmad, 2006; Lenzen et al., 2012a; Tukker et al., 2013; Dietzenbacher et al., 2013; Wood et al., 2014) have also been used for environmental footprint calculations (e.g., Hertwich and Peters, 2009; Feng et al., 2011; Lenzen et al., 2012b; Weinzettel et al., 2013; Wiedmann et al., 2015). In order to quantify carbon and material footprints for Japanese households, I clarified the expenditure on commodities by each household ((million Japanese Yen): M-JPY/y). The footprint per unit expenditure, or the footprint intensities, were calculated using a global link input–output model (GLIO) (Nansai et al., 2009, 2013a, b). The GLIO is a MRIO composed of a Japanese input–output structure with 409 sectors of domestic commodities and 409 sectors of imported commodities, and overseas sectors covering 230 countries and regions.

Derivation of the carbon footprint intensities is elaborated in Nansai et al. (2012), though, that of the material footprint intensities is not yet. Therefore, to introduce the structure of the GLIO, the method used to calculate material footprint intensities is described briefly below. Vector **q**, whose elements represent the material footprint intensities of commodities supplied to Japanese households, is calculated as shown in Equation (1):

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

Vector $\mathbf{q} = (\mathbf{q}^{JD} \quad \mathbf{q}^{JI} \quad \mathbf{q}^{G})'$ consists of sub-vectors $\mathbf{q}^{JD} = \left(q_i^{JD}\right)$, $\mathbf{q}^{JI} = \left(q_i^{JI}\right)$ and

$\mathbf{q}^G = \left(q_q^G\right)$, where elements q_i^{JD} and q_i^{JI} denote the material footprint intensities (t/M-JPY) of Japanese domestic commodity $i = (1 \ldots n^{JP}; n^{JP} = 409)$ and of directly to the final demand for imported commodity i, respectively. As an aside, q_q^G represents the material footprint intensities (t/M-JPY) of overseas commodities $q = (1 \ldots n^G; n^G = 230)$, but this is not used further in the present study. Row vector $\mathbf{d} = \begin{pmatrix}\mathbf{0} & \mathbf{0} & \mathbf{i}^G\end{pmatrix}$ has the same dimensions as vector **q** and includes the summation vector $\mathbf{i}^G$ in which all elements are unity. Matrix **I** is an identity matrix.

Matrix **A** is a mixed-unit input coefficient matrix 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 is shown in Equation (2):

$$\mathbf{A} = \begin{pmatrix} \mathbf{A}_{11} & \mathbf{0} & \tilde{\mathbf{A}}_{13} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \sum_{k=1}^{l} \tilde{\mathbf{A}}_{31}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{32}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{33}^{(k)} \end{pmatrix} \tag{2}$$

where $\mathbf{A}_{11}$ is the input coefficient matrix based on monetary units describing the input structure of domestic commodities i with regard to Japanese domestic commodities $j = \left(1 \ldots n^{JP}\right)$, 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 traded goods k in overseas sector $p = \left(1 \ldots n^G\right)$ for Japanese domestic commodities j, and $\tilde{\mathbf{A}}_{32}^{(k)}$ is a matrix showing the input structure of critical metals contained in traded goods k of overseas sector p for the input of commodities j imported directly to

Japanese final demand. $\tilde{\mathbf{A}}_{33}^{(k)}$ is a matrix showing the input structure for critical metals contained in traded goods k of overseas sector p for overseas sector q. The superscript ~ denotes a matrix whose coefficients are based on mass units. $k = (1 ... l)$ represents the type of traded goods that contain target metals, with l = 153 used for neodymium, l = 160 for cobalt and l = 151 for platinum. These traded goods were selected from the Base pour l’Analyze du Commerce International (BACI) database, which is an improvement of the UN Comtrade database and defines traded goods based on the Harmonized Commodity (HS) code. See Nansai et al. (2015) for a detailed explanation of the mixed-unit input coefficient matrix **A** and Nansai et al. (2014) for the selected traded goods.

2.1.2 Household expenditures by income level

To estimate the consumption trends of different household income levels, I defined household income quintiles calculated by dividing all of the households into five groups (quintiles) according to income (i.e., 20% of all households in each group). These income groups were then ordered from the lowest to the highest, i.e. Quintile1 to Quintile5, abbreviated as Q1, Q2, Q3, Q4, and Q5, respectively.

First, I obtained r_{ib}, which represents the expenditure ratio of commodity i per unit expenditure by each household income quintile (b = 1…5) for Q1 to Q5 using Equation (3).

$$r_{ib} = \frac{P_{ib}}{\sum_{i=1}^{N} P_{ib}} \tag{3}$$

Here P_{ib} is expenditure per month (M-JPY/m) on commodity i by each household income quintile taken from the National Survey of Family Income and Expenditure (NSFIE). N = 409 is the number of commodity sectors.

In Equation (4), s_{ib} denotes the market share of commodity i among households (b = 1…5). M = 5 denotes the number of household attributes.

$$s_{ib} = \frac{P_{ib}}{\sum_{b=1}^{M} P_{ib}} \tag{4}$$

It should be noted that since commodity sector classification in the NSFIE differs from that in the JIOT, I mapped the expenditure categories in the NSFIE onto the commodity sectors i in the JIOT. In doing so, I subdivided the *petroleum refinery products (incl. greases)* sector in the JIOT, whose GHG emissions were high due to burning. Hereafter, note that the names of the 409 commodities are written in *italics*. The NSFIE is the public statistical survey that presents consumption expenditures by Japanese households. The NSFIE contains the expenditures per household per month by household attribute, such as income level or size of household, for 100 categories of expenditures. It is possible to use the NSFIE to quantitatively understand differences in consumption composition based on differences in household attributes, but in the NSFIE, no distinction is made between domestic and imported commodities.

As Schreyer (2013) pointed out, there are major inconsistencies between the survey data on household consumption (e.g., NSFIE) for different countries and the Social Accounting Matrix (SAM) (e.g., JIOT household consumption expenditures) (Miller and Blair, 2009), and eliminating these inconsistencies is an important issue. Even if annual consumption is calculated by multiplying the NSFIE consumption amount by the number of households, and then multiplying that by 12, there is a large difference between that result and the previously mentioned JIOT household consumption expenditures that are in the SAM.

In this work, a quadratic programming (QP) algorithm was used to determine the optimal solution for variables $\tilde{r}_{ib}$ and $\tilde{s}_{ib}$ with the objective function defined in Equation (5) which minimizes the sum of the differences between r_{ib} and $\tilde{r}_{ib}$ and between s_{ib} and $\tilde{s}_{ib}$ under the constraints of Equations (6) through (9).

$$\underset{\tilde{r}_{ib},\tilde{s}_{ib}}{\text{Min.}} \sum_{b=1}^{M}\sum_{i=1}^{N}\left(\frac{\tilde{r}_{ib}-r_{ib}}{r_{ib}}\right)^2+\sum_{b=1}^{M}\sum_{i=1}^{N}\left(\frac{\tilde{s}_{ib}-s_{ib}}{s_{ib}}\right)^2 \tag{5}$$

subject to

$$g_i=\sum_{b=1}^{M}\tilde{r}_{ib}g_b \tag{6}$$

$$\sum_{i=1}^{N}\tilde{r}_{ib}=1 \tag{7}$$

$$\tilde{r}_{ib}\geq 0 \tag{8}$$

$$\tilde{s}_{ib}=\tilde{r}_{ib}g_b/g_i \tag{9}$$

Here g_i and g_b represent the total consumption expenditure of commodity *i* based on the JIOT and the total consumption expenditure by household income quintile, respectively. Equation (6) shows that g_i should be equal to the sum of consumption expenditure of commodity *i* for each of the households. Since $\tilde{r}_{ib}$ is a ratio, and the total of each household is 1 (nonnegative), Equations (7) and (8) are satisfied. Equation (9) expresses the relationship between $\tilde{r}_{ib}$ and $\tilde{s}_{ib}$.

I determined g_{ib} (M-JPY/y), which is the consumption expenditure of commodity *i* by household income quintile, by multiplying the optimal solutions of the above QP problem, $\hat{\tilde{r}}_{ib}$, and g_b. However, for the JIOT sectors with no corresponding the NSFIE expenditure category (such as waste processing, wholesale, retail, etc.), I calculated g_{ib} by proportionally distributing the total expenditures according to the JIOT's g_i by the size of g_b. Since g_{ib} is based on consumers' prices and the carbon footprint intensity (t-CO_2eq/M-JPY) and material footprint intensity (t/M-JPY) are calculated on a producers' price basis, g_{ib} was converted to a producers' price basis, f_{ib} as following subsection.

2.1.3 Conversion of the household expenditures in terms of consumer prices into those in terms of producer prices

In estimating carbon footprint derived from household consumption, it is necessary to convert the obtained household expenditures in terms of consumer prices into expenditures in terms of producer prices in order to obtain values that correspond to the carbon footprint intensity. Consumer prices are producer prices plus margins related to retail and transport costs. Here I describe the calculations for conversion of the obtained expenditures in terms of consumer prices into those in terms of producer prices.

I first obtained $m_{ib,u}$, which is the cost of margin *u* (such as *retail trade, railway transport (freight),* or *road freight transport*) of household *b* for a commodity sector *i* as

$$m_{ib,u} = w_{ib,u} g_{ib} \tag{10}$$

For sector *i*, and $w_{i,u}$ represents the ratio of margin *u* to g_i, which is the household expenditure in terms of consumer prices for sector *i* from the JIOT. $w_{i,u}$ is calculated by dividing $m_{i,u}$, the cost of margin *u* of household *b* for commodity sector *i*, by g_i. Note that $m_{i,u}$ and $m_{ib,u}$ must satisfy Equation (11).

$$m_{i,u} = \sum_{b=1}^{M} m_{ib,u} \tag{11}$$

Using $m_{ib,u}$ and g_{ib}, f_{ib} which represents the household expenditure in terms of producer prices of household *b* for sector *i* can be defined as

$$f_{ib} = g_{ib} - \sum_{u=1}^{U} m_{ib,u} (i \neq u) \tag{12}$$

where *U*=9 and is the number of margins.

Due to the expenditure in terms of consumer prices on *harbor transport service*, which is a margin sector, being zero, non-zero $m_{ib,u}$ and f_{ib} cannot be obtained by Equations (11) and (12). In the JIOT, the cost of providing margin *u* is negative as a total input into all sectors except margin *u*. Therefore, when sector *i* is margin *u*, f_{ib} can be calculated as in the following:

$$f_{ib} = g_{ib} - \sum_{u=1}^{U} m_{ib,u} (i = u) \tag{13}$$

$$m_{lb,u} = 0 \tag{14}$$

The sum of f_{ib} over all households, f_i, represents total household expenditure in terms of producer prices for sector *i* from the JIOT:

$$f_i = \sum_{b=1}^{M} f_{ib} \tag{15}$$

By multiplying the ratio of imported commodities $im_i \left(0 \le im_i \le 1\right)$, obtained from the JIOT, by f_{ib}, the consumption expenditure for domestic commodities f_{ib}^{JD} (M-JPY/y) and the consumption expenditure for imported commodities f_{ib}^{JI} (M-JPY/y) were determined as follows:

$$f_{ib}^{JD} = \left(1 - im_i\right) f_{ib} \tag{16}$$

$$f_{ib}^{JI} = im_i \, f_{ib} \tag{17}$$

Accordingly, the sum of consumption expenditure for each household income quintile estimated here is consistent with the total household expenditure in the JIOT.

2.1.4 Adjustment of educational and medical expenditures used in the footprint calculations

Expenditures related to education and health care are subsidized by the Japanese government. I incorporated the amount of these subsidies into the consumption expenditures obtained in the previous subsection and used these adjusted expenditures in subsequent calculations of the carbon and material footprints.

2.1.5 Calculation of equivalized consumption expenditure by household income

quintile

Although it is anticipated that household expenditure increases with household size, this increase is not linear. Furthermore, even when household size is the same, the number of adults and children in a household can vary, making simple comparisons of household footprint characteristics per inhabitant difficult. In this chapter, the consumption expenditure per household was therefore equivalized using the “square root scale” (OECD, 2008). This scaling method allows us to consider differences in the size of individual households and their associated carbon and material footprints. This is similar to the method employed in previous studies in which households were compared using a conventional “OECD-modified equivalence scale” (Girod and de Haan, 2010; Chitnis et al., 2014). However, this method was not used because, according to an OECD working paper (OECD, 2008), the reported differences between the results obtained using these two scaling methods are small.

I calculated the equivalized consumption expenditure of commodity *i* for each household income quintile, y_{ib}^{JD} and y_{ib}^{JI}, using Equations (18) and (19) with f_{ib}^{JD} and f_{ib}^{JI}, respectively. These variables were used to calculate the carbon and material footprints for comparisons between households.

$$y_{ib}^{JD} = \frac{f_{ib}^{JD}}{H_b\sqrt{n_b}} \tag{18}$$

$$y_{ib}^{JI} = \frac{f_{ib}^{JI}}{H_b\sqrt{n_b}} \tag{19}$$

where H_b denotes the number of households in each household income quintile. In the case of this chapter, the number of households in each quintile is identical for all households

(H_b=9.81×10^7), since the analysis distinguishes households by income quintile. n_b denotes the size of the household income quintile, with n_1=1.49, n_2=2.11, n_3=2.64, n_4=3.11, and n_5=3.53.

2.1.6 Calculation of carbon and material footprints induced by equivalized household consumption

Carbon footprints induced by equivalised household consumption, CF_b (t-CO_2eq/y), is defined as shown in Equation (20) as the sum of direct emissions derived from burning fuel through the use of private cars and home heaters, D_b (t-CO_2eq/y), and indirect emissions generated by the supply chains of products and services consumed, S_b (t-CO_2eq/y). The GHG considered are CO_2, CH_4, N_2O, HFCs (hydro fluorocarbons), PFCs (per fluorocarbons), and SF_6 (sulfur hexafluoride).

$$CF_b = D_b + S_b \tag{20}$$

D_b was calculated as shown in Equation (21) by multiplying expenditures f_{ib}^{JD} and f_{ib}^{JI} by emissions coefficient q_i^{direct} (t-CO_2eq/M-JPY), which expresses the GHG directly produced by burning fuel associated with the unit consumption of sector *i*.

$$D_b = \sum_{i=1}^{N} q_i^{direct} y_{ib}^{JD} + \sum_{i=1}^{N} q_i^{direct} y_{ib}^{JI} \tag{21}$$

q_i^{direct} was calculated based on the direct emissions from the household consumption expenditures sector (2005 figures) reported in the Embodied Energy and Emission Intensity

Data for Japan Using Input-Output Tables (3EID) (Nansai and Moriguchi, 2005). CO_2 is classified as an emission from the *gasoline, light oil, kerosene, LPG, coal products*, and *gas supply* sectors, so I found q_i^{direct} by dividing the direct emissions by the consumption for each sector. Likewise, CH_4 and N_2O were classified into auto emissions, using *gasoline* and *light oil*, and household emissions, using *kerosene, LPG, coal products*, and *gas supply*. For the HFCs, I allocated emissions from the use of fixed air conditioners to *household air conditioners* and emissions from the use of household refrigerators as *household electric appliances* I categorized emissions from the use of air conditioners in transport equipment as *passenger motor cars* and *trucks, buses and other cars*, and classified emissions associated with the disposing of these devices as *waste management services (private)*.

Likewise, the indirect emissions, S_b, resulting from the domestic and international supply chains associated with household consumption were calculated based on Equation (22) using the embodied emission intensities, called the carbon footprint intensities, $q_{\mathrm{CF},i}^{JD}$ (t-CO_2eq/M-JPY) and $q_{\mathrm{CF},i}^{JI}$ (t-CO_2eq/M-JPY). The element $q_{\mathrm{CF},i}^{JD}$ is the embodied emission intensity expressing the GHG volume caused by the global supply chain associated with the unit production of the Japanese domestic (JD) commodity sector *i*, while $q_{\mathrm{CF},i}^{JI}$ is the embodied emission intensity for the Japanese imported (JI) commodity sector *i*.

$$S_b = \sum_{i=1}^{N} q_{\mathrm{CF},i}^{JD} y_{ib}^{JD} + \sum_{i=1}^{N} q_{\mathrm{CF},i}^{JI} y_{ib}^{JI} \tag{22}$$

On the other hand, MF_b, which denotes the equivalized material footprint for each household income quintile, was calculated using Equation (23).

$$MF_b = \sum_{i=1}^{N} q_{\mathrm{MF},i}^{JD} y_{ib}^{JD} + \sum_{i=1}^{N} q_{\mathrm{MF},i}^{JI} y_{ib}^{JI} \qquad (23)$$

where $q_{\mathrm{MF},i}^{JD}$ and $q_{\mathrm{MF},i}^{JI}$ denote the material footprint intensities (t/M-JPY) for domestic commodity *i* and for imported commodity *i*, respectively. y_{ib}^{JD} and y_{ib}^{JI} express the equivalized consumption expenditure of commodity *i* for each household income quintile as calculated in Subsection 2.1.2. This study used the material footprint intensities obtained for neodymium, cobalt, and platinum, elaborated in Subsection 2.1.1.

2.1.7 Aggregation of commodities based on category of individual consumption by purpose (COICOP)

In order to express the calculated equivalized consumption expenditure, carbon footprints, and material footprints for the three target metals examined in this chapter, I aggregated 409 commodity sectors into 17 categories based on the Category of Individual Consumption by Purpose (COICOP) data published by the United Nations Statistics Division (Table 2.1). COICOP is a classification method for all areas of individual consumption expenditures and that has been used in numerous previous studies (Collins et al., 2006; Tukker and Jansen, 2006; Wiedmann et al., 2006). The categories 1–16 are in line with the previous studies (Druckman et al., 2011; Chitnis et al., 2012, 2014) in order to elaborate carbon footprints associated with direct household energy consumption. The 17th category contained the household consumption expenditure sectors listed in the JIOT (e.g., *retail trade, wholesale trade, public administration*) that did not belong to the other 16 categories.

2.1.8 Limitations of the methodology used to quantify carbon and material

footprints

The GLIO model used in this chapter describes domestic commodity sectors with very high sectoral resolution. On the other hand, each of the overseas sectors was abbreviated into a single sector. Hence, the model represents the input-output structure for the target metal among foreign countries, but it does not describe the supply chain structure for the foreign commodities that contain each metal. The accuracy with respect to the indirect effect of both GHG emissions and metal 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 relative metal content of the same Japanese export commodity was used instead. As a result, the metal flows associated with export commodities from developing countries may have been overestimated in some cases. This is because Japanese exports of high-tech commodities might be of higher quality (e.g. low energy consumption, low noise, high durability, multi-functional) and might require more critical metals than the same ones produced in developing countries. Since these data were then linked to the GLIO model, the material footprints via exports from developing countries are also likely to have been overestimated.

Table 2.1 Correspondence between 17 commodity categories employed in this study and those of the Category of Individual Consumption by Purpose (COICOP) employed by the United Nations Statistics Division.

Number	COICOP category	Description
1	1	Food and non-alcoholic beverages
2	2	Alcoholic beverages, tobacco and narcotics
3	3	Clothing and footwear
4	5	Furnishings, household equipment and household maintenance
5	6	Health
6	8	Communication
7	9	Recreation and culture
8	10	Education
9	11	Restaurants and hotels
10	12	Miscellaneous goods and services
11	4.5.1	Electricity
12	4.5.2	Gas
13	4.5.3	Other fuels
14	4.1 to 4.4	Other housing*
15	7.2.2.2	Vehicle fuels and lubricants
16	Rest of 7	Other transport**
17		Other services***

* House rent, house repair, water fees, waste disposal costs, etc.

** Transportation utilization fees for transport modes such as airplanes, buses, and taxis.

*** Some commodities, such as Wholesale and Public Administration not belonging to a Category of Individual Consumption by Purpose (COICOP) category shown above.

2.2 Results

2.2.1 Equivalized consumption expenditure by household income quintile

Figure 2.1 presents the equivalized consumption expenditure (M-JPY/y) for 17 COICOP categories by household income quintile. The mean denotes the simple arithmetic average of each household; the same applies to Figures 2.2-2.5. The total consumption expenditure increases uniformly as the household income increases and the difference between the minimum Q1 (2.53 M-JPY) and the maximum Q5 (4.65 M-JPY) is approximately 1.8 times. When the breakdown is examined, for “other housing,” which represents housing expenditures such as house rent and water bills but excludes “electricity” and “gas” usages, then the difference between Q1 (0.54 M-JPY) and Q5 (1.13 M-JPY) is 0.59 M-JPY, which is the highest. The classifications that show the second and third largest difference between Q1 and Q5 are 0.34 M-JPY (Q1: 0.48 M-JPY, Q5: 0.82 M-JPY) for “other services” and 0.27 M-JPY (Q1: 0.16 M-JPY, Q5: 0.43 M-JPY) for “other transport”, which consists of transport cost excluding vehicle fuel (e.g., private vehicle expenses and public transportation), respectively. However, of the COICOP categories, expenses on categories such as “health” do not necessarily rise as household income increases. For “gas,” the value for Q1 (0.030 M-JPY) is greater than that for Q5 (0.017 M-JPY). Although this may seem somewhat surprising, one might infer that households with higher household incomes are larger in size, so when this is converted to a per-capita amount in the equivalized household, Q5 uses “gas” more efficiently.

For the share of consumption expenditure, the percentage of the total expenditure in categories related to food supply (“food and non-alcoholic beverages” and “alcoholic beverages, tobacco and narcotics”) decreases from 13% to 9.0% as household income increases. The share for expenditure in categories related to household energy (“electricity”, “gas”, and “other fuels”) decreases from 4.2% to 2.0% as income increases. The share for “restaurants and hotels”, which reflects an increase in dining out, increases from 5.0% to 8.0% alongside a reduction in the share of “food and non-alcoholic beverages” and “alcoholic beverages, tobacco and narcotics”. The share of expenditure for “education” and “other transport”, both of which show a significant difference between quintiles, increases

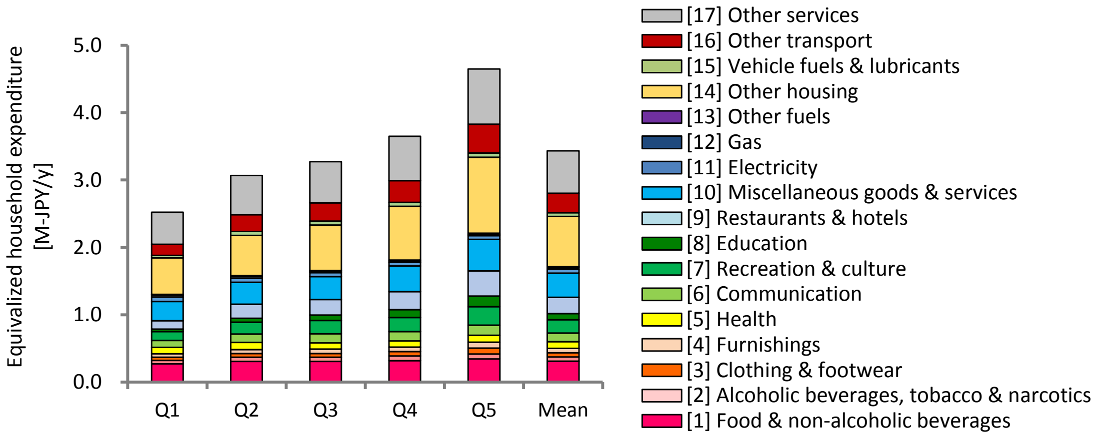


Figure 2.1 Equivalized household consumption expenditure (M-JPY/y) for each household income quintile in 2005. Means are simple arithmetic averages of five expenditures per household.

from 1.5% to 3.4% and from 6.5% to 9.2% with increase in income, respectively.

As well, these tendencies of consumption expenditure by income quintile described above are consistent with those from the NSFIE. This indicates, therefore, that the QP method to obtain the consumption expenditures by household attribute is confirmed stable.

2.2.2 Equivalized carbon footprint by household income quintile

The equivalized carbon footprints (t-CO_2eq/y) of the 17 categories and the carbon footprints per unit expenditure by income quintile are shown in Figure 2.2. The carbon footprint increases as household income increases. The difference between the minimum Quintile1 (12 t-CO_2eq/y) and the maximum Quintile5 (17 t-CO_2eq/y) is about 1.4 times, and the average carbon footprint is 14 t-CO_2eq/y. Interestingly, despite the difference in expenditure between Q2 and Q3 being 0.20 M-JPY, the carbon footprints for these quintiles

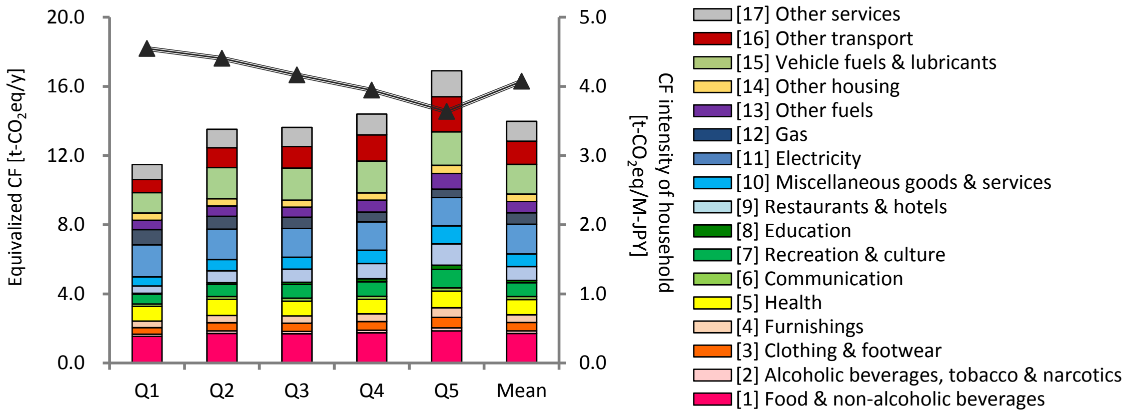


Figure 2.2 Equivalized carbon footprint (CF) (t-CO$_2$eq/y) for each household income quintile in 2005. Triangles denote the carbon footprint per unit expenditure (t-CO$_2$eq/M-JPY) for each household income quintile (corresponding to the right vertical axis).

are nearly identical, and the carbon footprint only increases again from Q4 upwards. This trend differs from the relationship between household income and consumption expenditure where a steady increase is observed: the reason for this difference can be explained by analyzing the carbon footprints in each category. Detailed analysis reveals that the carbon footprints induced by “electricity”, “vehicle fuels and lubricants”, and “food and non-alcoholic beverages” are marked, and that the mean value for each category was 1.7 t-CO$_2$eq. Similarly, marked differences in carbon footprints between Q1 and Q5 are observed in “other transport”, “restaurant and hotels”, and “vehicle fuels and lubricants”, which represent 1.2 t-CO$_2$eq/y, 0.83 t-CO$_2$eq/y, 0.76 t-CO$_2$eq/y, respectively. Although larger carbon footprints in these categories are induced in Q3 than in Q2, more “electricity” and “gas”, which are highly carbon intensive categories, are consumed by Q2 than by Q3. This higher consumption of “electricity” and “gas” is the reason why the carbon footprints of these quintiles are very similar despite the total expenditure of Q3 being larger than that of Q2.

For the equivalized carbon footprint of each household, the share of both “food and non-alcoholic beverages” and “vehicle fuels and lubricants” is greater than 10%. The proportion of the carbon footprint occupied by “restaurants and hotels” and “other transport” increases with annual household income. In Q5, the combined total of these two categories is as much as 19%.

The carbon footprints per unit household expenditure (carbon footprint intensity of household) for Q1 to Q5 reveal that Q1, which was 4.6 t/M-JPY, is the most GHG-intensive quintile, while that of Q5 decreased to 3.6 t/M-JPY. This is because the share of “electricity” and “gas” for the lower-income households is larger than that for the higher-income households, for the reasons described in the comparisons of Q2 and Q3 above.

2.2.3 Equivalized material footprints by household income quintile

(a) Neodymium

Figure 2.3 shows the equivalized material footprint for neodymium (g/y) in the 17 categories and the material footprint per unit expenditure for each household income quintile. As in the case of carbon footprints, the equivalized neodymium footprint increases as the household income rises. For example, the material footprints for Q1 and Q5 are 2.2 g/y and 7.1 g/y, respectively, and the difference between the two quintiles is approximately 3.3 times; the average material footprint for neodymium is 4.4 g/y. When the material footprint is broken down by category, the contribution of “other transport” is considerable. This category includes usage of private cars, public buses and taxis that have neodymium in their motors and audio systems. The material footprint for this category in Q5 is 3.7 g/y, which alone exceeds the combined material footprint for Q1 and Q2 and suggests that attention should be focused on expenditure on “other transport” in the high-income class.

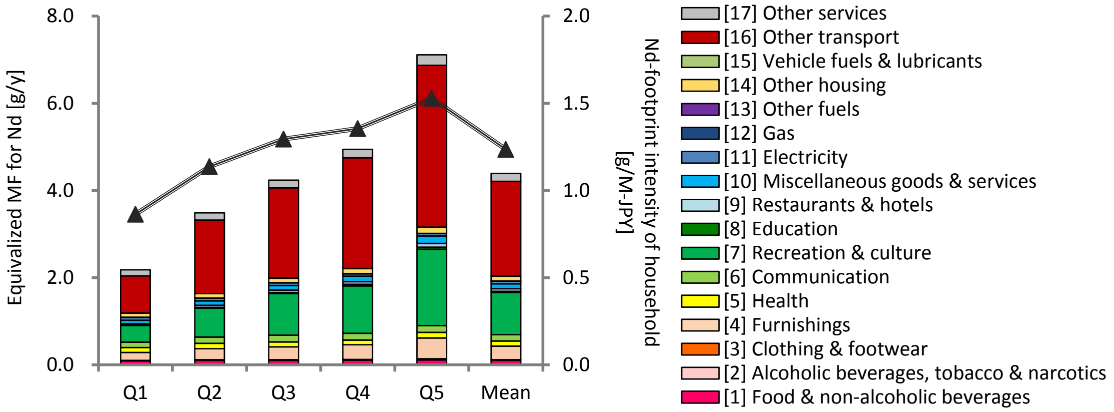


Figure 2.3 Equivalized material footprint (MF) for neodymium (g/y) for each household income quintile in 2005. Triangles denote the material footprint per unit expenditure (g/M-JPY) for each household income quintile (corresponding to the right vertical axis).

In terms of the proportion of each category in the material footprint for neodymium, the sum of "other transport" and "recreation and culture" exceeded 50% in all households, while the average share of each category is 48% and 21%, respectively. In the latter category, a large contributor is high-tech electronic equipments, such as the hard drives in personal computers. This trend toward an increase in the size of the material footprint becomes more apparent as the household income increases; for example, the sum of the shares of "other transport" and "recreation and culture" in Q5 accounts for 77% of the whole.

In contrast to the carbon footprint intensity for households, a trend toward an increase in the material footprint for neodymium per unit household expenditure (Nd-footprint intensity of household) is observed as household income increases. This is because, compared to lower income households, higher income households can afford to purchase non-essential items, such as personal computers. The material footprint for neodymium per unit expenditure in Q5 reaches 1.5 g/M-JPY, which is 1.8 times the expenditure of 0.86 g/M-JPY in Q1.

(b) Cobalt

The total equivalized material footprint for cobalt increases by about 2.1times from 32 g/y (Q1) to 67 g/y (Q5) as household income increases (Figure 2.4). The average material footprint for cobalt is 47 g/y. When the material footprint is broken down by category, the contribution of “other transport” from Q2 to Q5 to the whole is the greatest. For Q1 only, “health” exceeds “other transport” by 0.33 g/y, and has the greatest contribution of 5.5 g/y. These categories appear to be related to heat resisting materials. “Food and non-alcoholic beverages”, which could be associated with use of industrial inorganic chemicals, is the third largest category in Q1 (3.8 g/y) and Q2 (4.3 g/y). The difference in the cobalt material footprint between Q1 and Q5 is most marked in “other transport”, and accounts for 5.1 g/y and 24 g/y in both quintiles, respectively.

Regarding the proportion of each category in the material footprint for cobalt, a marked increase is observed in the share of “other transport”, with the difference in the share of this category between Q1 (16%) and Q5 (35%) being nearly 20%. The share in the three categories of “other transport”, “furnishings,” and “recreation and culture,” exceeds 10% in all households.

The Co-footprint intensity of household in Q5 reaches 14 g/M-JPY (maximum), which is similar to the 13 g/M-JPY (minimum) in Q1.

(c) Platinum

As household income increases, the total equivalized material footprint for platinum increases by approximately 2.1 times, from 0.073 g/y (Q1) to 0.16 g/y (Q5) (Figure 2.5). The average material footprint for platinum is 0.11 g/y. The material footprint induced by "health" reaches maxima of 0.024 g/y (Q1) and 0.027 g/y (Q2). After Q3, the maximum material footprints induced by "other transport" in Q3, Q4, Q5 are 0.027 g/y, 0.035 g/y and 0.052 g/y, respectively, implying that platinum is essential for the synthesis in medicines and automobile catalysts, respectively. The maximum disparity between households is observed in "other transport", which varies more than 5 times between Q1 (0.010 g/y) and Q5 (0.052 g/y).

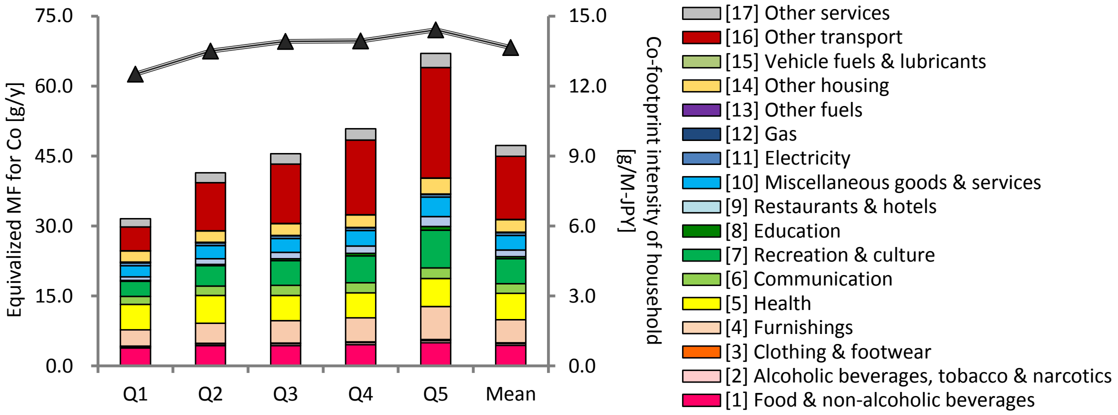


Figure 2.4 Equivalized material footprint (MF) for cobalt (g/y) for each household income quintile in 2005. The triangles denote the material footprint per unit expenditure (g/M-JPY) for each household income quintile (corresponding to the right vertical axis).

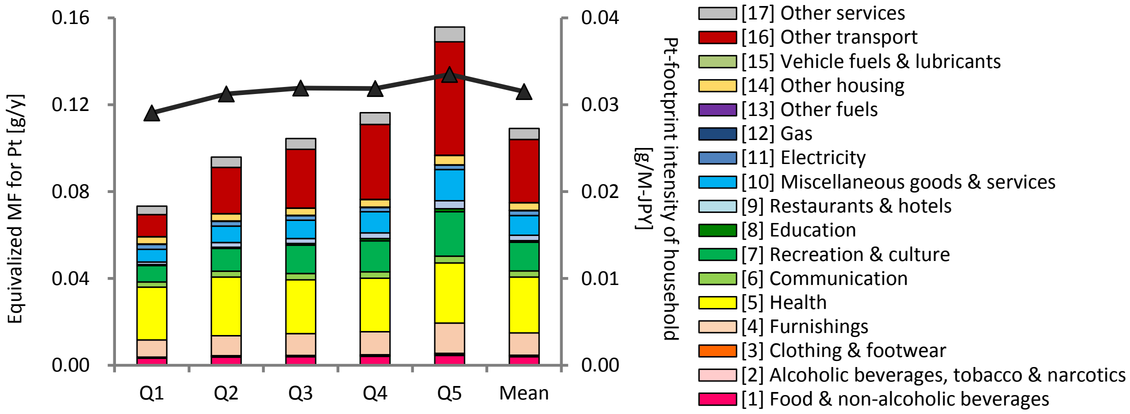


Figure 2.5 Equivalized material footprint (MF) for platinum (g/y) for each household income quintiles in 2005. Triangles denote the material footprint per unit expenditure (g/M-JPY) for each household income quintile (corresponding to the right vertical axis).

Regarding the proportion of each category in the material footprint of platinum, the share of “other transport” rises with household income, increasing from 14% (Q1) to 34% (Q5). Conversely, the share of “health” decreases markedly from Q1 (33%) to Q5 (18%).

The Pt-footprint intensity of household changes only slightly, from 0.029 g/M-JPY (Q1) to 0.033 g/M-JPY (Q5), showing that this is similar among households, especially in the middle range (Q2-Q4).

2.3 Discussions

2.3.1 Common features of commodities contributing to each footprint

In order to elucidate the common characteristics of commodities consumed by households in terms of footprint generation, I compared footprints at the 409 commodity level.

The material footprints for three metals induced by passenger motor cars and repair of motor vehicles attributed to “other transport” were considerable, but *air transport* and *railway transport (passenger)* in the same category accounted for the majority of the carbon footprint. As described in the Results section, it is considered that the size of material footprints for neodymium and platinum are related to their utilization in car motors and audio systems, and the automotive catalysts, respectively. In the case of cobalt, the size of material footprint would be related to the use of heat resistant materials for engine parts. The rechargeable batteries for hybrid vehicles and the metallic soap-based grease for wheels are also associated with cobalt usage.

Of the material footprints for cobalt that were induced by commodities related to “food and non-alcoholic beverages”, the contributions of confectionery and soft drinks were the highest, as both products are manufactured using equipment in which heat-resistant materials are used extensively. In the case of carbon footprints, slaughtering and meat processing and frozen fish and shellfish were large, presumably due to the energy that is required for farming processes and transportation. The material footprints for cobalt and platinum, as well as the carbon footprint induced by medical services in “health” were all noteworthy. Cobalt is used as the radioactive isotope in X-ray irradiation devices and as the alloy for implants, and platinum is used in pacemakers and syringes, and also as a catalyst in drug syntheses. Compared to the utilization of these metals in automobiles and household electric appliances, these applications are currently not considered to be very important in terms of resource recovery by recycling. Since the demand for medical care will likely increase as the domestic population ages and the number of children diminish (Shigetomi et al., 2014), any technical improvements and increases in “green” consumer behavior are considered to be important in reducing these footprints.

To analyze the degree of similarity among footprint patterns, I used Spearman’s rank correlation coefficients (Black et al., 2009) to compare footprints in terms of the rank of commodities arranged in descending order of each footprint value. The obtained correlations between carbon and material footprints were 0.34 (neodymium), 0.63 (cobalt), and 0.10 (platinum), indicating that the degree of similarity between the carbon and the cobalt footprints was highest. The rank correlation coefficient between material footprints was calculated to be 0.52 for neodymium and cobalt, 0.10 for neodymium and platinum, and 0.13 for cobalt and platinum. Since the degree of similarity among the material footprints of metals was not marked, relative differences in the demand for these target metals is considered important. Importantly, a reduction in the size of a material footprint depends on the species of the footprint, which in turn differs depending on the commodity being utilized. Thus, saving money through decreasing the consumption of gasoline, which has a high carbon footprint intensity, and then using those savings to buy a personal computer, which has a lower carbon intensity, the total carbon footprint is reduced. However, in such a situation, the size of the material footprint for neodymium would increase in response the higher Nd-footprint intensity for personal computers (the so-called rebound effect: e.g., Hertwich, 2005).

2.3.2 Comparison with the UK case on carbon footprint

This section highlights the features of equivalized expenditures and carbon footprints and compares them to a study conducted in the UK (Chitnis et al., 2014). The UK study was conducted to clarify the relationship between household carbon footprint and income level with a global system boundary, and employed the same categorization for commodities as this chapter. Briefly, the common features and differences between the two studies are as follows. The equivalized expenditure of each quintile increases with household income. In the Japanese case (this chapter), the difference in expenditure between Q1 and Q5 was 1.8 times (2.53 M-JPY and 4.65 M-JPY), while in the UK it was 5.2 times (€4.7×10^3 and €24.6×10^3), indicating the existence of a marked disparity between high- and low-income households in that country. However, in both Japan and the UK, consumption expenditures on "other housing" and "education" both increase markedly with increasing in household income. In Japan, the share of expenditure on "health" decreases as household income increases, while the share of "clothing and footwear" remains almost unchanged among households; this differs from the UK case in which the shares for both categories increase with household income. Generally, however, the share of expenditures in both countries is very similar.

For the relationship between the equivalized carbon footprints by quintile and household income, marked differences were observed between Japan and the UK. In Japan, the difference in the carbon footprint between Q1 and Q5 was 1.5 times (12 t-CO_2eq and 17 t-CO_2eq; average for all quintiles: 14 t-CO_2eq), while the difference between Q1 and Q5 in the UK was about 4.5-fold (about 6 t-CO_2eq and about 27 t-CO_2eq). Interestingly, the average equivalized carbon footprint per quintile in the UK was also about 14 t-CO_2eq, which is similar to that estimated in this chapter. Indeed, even the contribution of categories to the carbon footprint for each household income group is similar between Japan and the UK. For example, in both countries, the contribution of "other transport" increases as the household income increases. Furthermore, the share of the carbon footprints associated with goods that are essential for life, such as energy, city water, and food increases as the annual household income decreases. As in Chitnis et al. (2014), this work considered “food and non-alcoholic beverages,” “alcoholic beverages, tobacco and narcotics,” “communication,” “electricity,” “gas,” “other fuels,” and “other housing” to be goods that are essential for life. The share of these categories in Q1 and Q5 was 48% and 34% in Japan, and 57% and 27% in the UK, respectively. In both countries, the carbon footprint per unit of household expenditure increases as household income decreases. The difference in the carbon footprint intensity for Q1 and Q5 is 25% in Japan and 16% in the UK.

Unlike carbon footprints, no previous studies have been conducted on the material footprints of the target metals caused by household consumption. Consequently, direct comparison with overseas data are not possible. However, based on similarities in the trend of equivalized expenditures and carbon footprints in the UK and Japan, it seems likely that the material footprints for neodymium, cobalt, and platinum instigated by household consumption are similar among developed countries. It is hoped that a similar analysis will be conducted to verify this possibility in foreign countries.

2.3.3 Policy implications of simultaneous carbon and material footprint analyses

The results reported herein show that carbon and material footprints both increase as household income increases. However, analysis of the relationship between household income and the size of a household’s footprint per unit of household expenditure revealed that carbon and material footprints have contrasting characteristics. Thus, as household income increases, lifestyles likely shift to less GHG-intensive consumption, but more intensive on the use of metal resources. As described in Section 2.3.2, the former trend is seen in both Japanese and the UK households, even though the difference in the carbon footprint intensity of household between Q1 and Q5 in this work was larger than that in the

UK. This difference in the trend suggests that if a carbon tax policy is implemented in Japan, then the tax burden on low-income groups will be higher than that on higher-income groups, and the extent of this burden will be higher than it is in the UK.

The fact that an increase in income leads to a decrease in carbon footprint intensity of household and an increase in their material footprint intensity is primarily attributable to gas and electricity having a relatively large carbon footprint intensity. Gas consumption does not increase with household income, but increased income is associated with an increase in the consumption of commodities related to amusement and transportation (e.g., dining out and traveling). In particular, payments for cars, especially for a second, or subsequent cars - the average number of cars owned by households is 0.51 in Q1 and 1.8 in Q5 (NSFIE, 2004) -, and for durable products for amusement, such as personal computers, can strongly affect the material footprints for the critical metals examined in this work. A salient benefit of comparing footprints at the household-level and how these footprints are affected by household income is that it is possible to consider how increases in consumption expenditures affect the footprints.

Within this context, factors affecting both material footprints and carbon footprints should be carefully considered when developing policies for mitigating global warming. For example, in Japan, preferential treatment was given to the replacement of old vehicles with fuel-efficient vehicles in an attempt to reduce carbon footprints (Kagawa et al., 2013). If subsidies or tax incentives are implemented for vehicles powered by fuel cells, then an increase in material footprints might be accelerated since it seems that an increase in income spurs purchases of cars and other commodities (rebound effect). In addition, national economic policies may also adversely affect households. For example, although the government of Japan announced that an increase in the average national income level is an economic goal, such an increase could result in material footprints increasing faster than carbon footprints. An increase in income would allow Q1 to adopt the lifestyle of Q5, resulting in the carbon footprint per-capita increasing 1.4 times, while the material footprints for neodymium, cobalt and platinum would increase as much as 3.3 times, 2.1 times, and 2.1 times, respectively. This relationship between the carbon and material footprints is likely to apply to developing countries as well, where income levels are expected to increase markedly in the future.

It is considered that the methods described in this work for understanding the effects of reduction in GHG emissions and increased economic activity on both carbon and material footprints can also be applied to predicting the tradeoffs between global warming, resource consumption, and economic growth.

3 Future Projection of Household Carbon Footprint in Japan in an Aging Society

Controlling emissions of airborne greenhouse gases (GHG), which promote global warming, is the most pressing global environmental problem facing us today, and measures are being taken to address this challenge by countries all over the world. In recent years, there has been discussion of the use of consumption-based accounting, in which the country or region that consumes a produced item is responsible for emissions (Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008; Peters, 2008).

Considering the several benefits of this accounting elaborated in the previous articles (e.g., Wiedmann, 2009), it is essential to look to the future with an eye on promoting the management and reduction of emissions on a consumption basis, particularly in developed countries. Additionally, it will be particularly meaningful to perform estimates and structural analysis of emissions focusing on household consumption. From the perspective of consumption-based accounting, domestic household consumption in Japan, one of the world's most prominent trading countries according to the UN statistics (UN, 2012), is expected to contribute significantly to increased GHG emissions abroad. It is therefore growing increasingly important to quantitatively evaluate the future impacts of these changes on domestic and international GHG emissions.

This chapter is designed to highlight the impact of changes in Japanese household composition on GHG emission structure using current consumption-based accounting (carbon footprint structure). As the aging and lower birthrate trends continue in Japan, and its working population and consumption patterns change, new factors are expected to have an impact on carbon footprint. The results also show that there are commodity sectors in which technological improvements will be necessary if selective emission reductions are to be achieved.

3.1 Methods and Data

3.1.1 Estimates of consumption expenditures by household attributes

To focus on the effects of the aging and low birthrate trends on carbon footprints in this work, I defined household attributes ($b = 1\ldots6$) following Kronenberg (2009) by the age of the head of household (1=20s: -29, 2=30s: 30-39, 4=40s: 40-49, 4=50s: 50-49, 5=60s: 60-69, 6=70s: 70-). In fact, the method employed here to obtain consumption expenditures by the age of the head of household is analogous to Subsection 2.1.2.

I first calculated the expenditure ratio r_{ib} of commodity sector *i* per unit expenditure of household attributes as:

$$r_{ib} = \frac{P_{ib}}{\sum_{i=1}^{N} P_{ib}} \tag{24}$$

where P_{ib} is the expenditure (M-JPY/m) from the JIOT for commodity sector *i* taken from the National Survey of Family Income and Expenditure (NSFIE) and *N* (=409) is the number of JIOT sectors. I used Equation (25) to calculate s_{ib}, the share of household *b* accounted for by commodity sector *i*.

$$s_{ib} = \frac{P_{ib}}{\sum_{b=1}^{M} P_{ib}} \tag{25}$$

Here, *M* (=6) is the number of household attributes. Equation (25) captures that, for example, households in their 60s have relatively higher medical expenses than households in their 20s.

In this chapter, I formulated a QP algorithm such that the distance function in terms of r_{ib} and s_{ib} is minimized under the following constraints (26)-(30).

$$\underset{\tilde{r}_i^{att},\,\tilde{s}_i^{att}}{\text{Min}}.\sum_{att=1}^{M}\sum_{i=1}^{N}\left(\frac{\tilde{r}_i^{att}-r_i^{att}}{r_i^{att}}\right)^2+\sum_{att=1}^{M}\sum_{i=1}^{N}\left(\frac{\tilde{s}_i^{att}-s_i^{att}}{s_i^{att}}\right)^2 \tag{26}$$

subject to

$$g_i=\sum_{b=1}^{M}\tilde{r}_{ib}g_b \tag{27}$$

$$\sum_{i=1}^{N}\tilde{r}_{ib}=1 \tag{28}$$

$$\tilde{r}_{ib}\geq 0 \tag{29}$$

$$\tilde{s}_{ib}=\tilde{r}_{ib}g_b/g_i \tag{30}$$

where g_i and g_b represent the total expenditure for commodity sector *i* in the JIOT and the total expenditure of household *b*, respectively. Equation (27) indicates that JIOT household consumption expenditures of commodity sector *i* should coincide with the sum of the annual consumption of household attributes. Equations (28) and (29) indicate that the total of the household expenditure ratios is equal to 1 and each ratio is non-negative, respectively. Equation (30) expresses the relationship between r_{ib} and s_{ib}.

As same manner demonstrated in Chapter 2, specifically in Subsection 2.1.2, f_{ib} that denotes consumption expenditures by household attribute *b* for producer price was obtained with the optimal solution $\hat{\hat{r}}_{ib}$. Also, the consumption of domestic commodities f_{ib}^{JD} (M-JPY/y) and the consumption of imported commodities f_{ib}^{JI} (M-JPY/y) were determined using the ratio of imports im_i obtained from the JIOT.

3.1.2 Calculating household carbon footprint for each age group of household

The carbon footprint for each age group of household was defined as the sum of direct emissions and indirect emissions associated with household consumption of commodities (See Subsection 2.1.6). This was calculated as following Equations (31) and (32), respectively:

$$D_b = \sum_{i=1}^{N} q_i^{direct} f_{ib}^{JD} + \sum_{i=1}^{N} q_i^{direct} f_{ib}^{JI} \tag{31}$$

$$S_b = \sum_{i=1}^{N} q_{\mathrm{CF},i}^{JD} f_{ib}^{JD} + \sum_{i=1}^{N} q_{\mathrm{CF},i}^{JI} f_{ib}^{JI} \tag{32}$$

where q_i^{direct} (t-CO$_2$eq/M-JPY) is emissions coefficient, which expresses the GHG directly produced by burning fuel associated with the unit consumption of sector *i*. $q_{\mathrm{CF},i}^{JD}$ is the carbon footprint intensity for the Japanese domestic (JD) commodity sector *i*, while $q_{\mathrm{CF},i}^{JI}$ is the carbon footprint intensity for the Japanese imported (JI) commodity sector *i*.

3.1.3 Estimating future household consumption expenditures by household attribute in an aging society with fewer children

Since the average household size per householder age group 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, I 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 work). First, I take $h_{\alpha}^{(\beta)}$ to express household expenditure on item α = (1…44) by households comprising β persons as represented in the FIES. When $\bar{\beta}_b$, denoting average household size by householder age group *b*, is between β and β +1, assuming there is $h_{\alpha b}$, representing household expenditure on item α by householder age group *b*, on the straight line going through points $\left(\beta, h_{\alpha}^{(\beta)}\right)$ and $\left(\beta+1, h_{\alpha}^{(\beta+1)}\right)$ (here, β = 1, 2, 3), I hypothesize $h_{\alpha b}$ as follows:

$$h_{\alpha b} = \left(h_{\alpha}^{(\beta+1)} - h_{\alpha}^{(\beta)}\right)\left(\bar{\beta}_b - \beta\right) + h_{\alpha}^{(\beta)} \tag{33}$$

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

When average household size by householder age group *b* shifts from $\beta_b^{(t)}$ to $\beta_b^{(t+1)}$, the change in consumption expenditure on items α, $\theta_{\alpha b}^{(t+1)}$, in association with the change in household constitution can be expressed by Equation (34), in which superscript figures in parentheses reflect the target year of this work (1: 2005, 2:2010, 3: 2015, 4: 2020, 5: 2025, 6: 2030, 7: 2035).

$$\theta_{\alpha b}^{(t+1)} = \frac{h_{\alpha b}^{(t+1)}}{h_{\alpha b}^{(t)}} \tag{34}$$

As items α in the FIES that correspond to the commodity sectors in the JIOT, I could obtain $\theta_{ib}^{(t+1)}$, which is the 'adjustment coefficient' for household size for each commodity *i* by householder age group *b*.

However, because future $\beta_b^{(t)}$ is not available in any official Japanese statistics, I 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, $\tilde{\beta}_b^{(t)}$, 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 $\tilde{\beta}_b^{(t)}$ by the corresponding number of households, $N_b^{(t)}$, should be consistent with the future total population, $Pop^{(t)}$, provided by the Japanese public statistics office (IPSS, 2012). As an inconsistency among these values was identified, however, I adjusted $\tilde{\beta}_b^{(t)}$ and computed $\beta_b^{(t)}$ consistent with $Pop^{(t)}$ by using the optimization with quadratic programing as formulated in Equations (35) and (36).

$$\underset{\beta_b^{(t)}}{\text{Min.}} \sum_{b=1}^{6} \sum_{t=1}^{T} \left(\frac{\beta_b^{(t)} - \tilde{\beta}_b^{(t)}}{\tilde{\beta}_b^{(t)}} \right)^2 \quad , \tag{35}$$

subject to

$$Pop^{(t)} = \sum_{b=1}^{6} N_b^{(t)} \beta_b^{(t)} \tag{36}$$

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 group in each year, $f_{ib}^{JD(t)}$ and $f_{ib}^{JI(t)}$, were then calculated from Equations (37) and (38). Substituting the expenditures obtained in Equations (31) and (32), the respective carbon footprint were then determined from 2005 through to 2035.

$$f_{ib}^{JD(t+1)} = f_{ib}^{JD(t)} \times \frac{N_b^{(t+1)}}{N_b^{(t)}} \times \theta_{ib}^{(t+1)} \tag{37}$$

$$f_{ib}^{JI(t+1)} = f_{ib}^{JI(t)} \times \frac{N_b^{(t+1)}}{N_b^{(t)}} \times \theta_{ib}^{(t+1)} \tag{38}$$

Since this chapter focuses on emissions that are impacted by changes in household composition, and since it is not easy to estimate future technological changes, including changes in global supply chains, the carbon footprint intensities were fixed, regardless of the target year, and the estimated value for 2005 was used. I based the rigid factors for estimating the carbon footprints in this chapter on the following considerations.

- The shares of both domestic and import products for household expenditures are assumed to be constant as of 2005.
- Assuming that there are no improvements in technologies and global supply chains since 2005, the carbon footprint intensities and the coefficient matrix of GLIO2005 are rigid.
- Future consumption patterns for 2010 to 2035 for each household keep being based on those of 2005.

3.2 Results

3.2.1 Estimates of the number of households and population by household attributions from 2005 to 2035

Figure 3.1 depicts the breakdown of households and population by six household attributes from 2005 to 2035. The number of households (on the left) refers to national statistics (IPSS, 2013) and the population (on the right) is estimated by the method of this work. Total households are expected to increase from 4.91 million households in 2005 to 5.31 million households in 2020. After that, the number decreases to 4.96 million households by 2035. This number is almost the same as in 2005. On the other hand, the total population is estimated to be 126 million in 2010, and then fall, finally dropping to 109 million in 2035. This is 13% less than in 2005. The difference between the change in number of households and population will occur mainly due to a rapid increase in the number of older households and a decrease in the younger and middle (under 50s) population as Japan's society ages and there are with fewer children. The number of households headed by those in their 70s in 2035 is estimated to be about 1.7 times larger than in 2005. In other words, the share of 70s households will climb steeply from 19% to a dominant 32% in those 30 years. Adding households in their 60s to the 70s makes up more than half of total households (52%) in 2035, reflecting the rapidly aging society. At the same time, the larger effect of fewer children is expected to cause the population of those in both their 40s and 50s to have smaller households. Those in their 40s, in particular, are estimated to drop by 9.19 million (-34%) persons from 2005 to 2035.

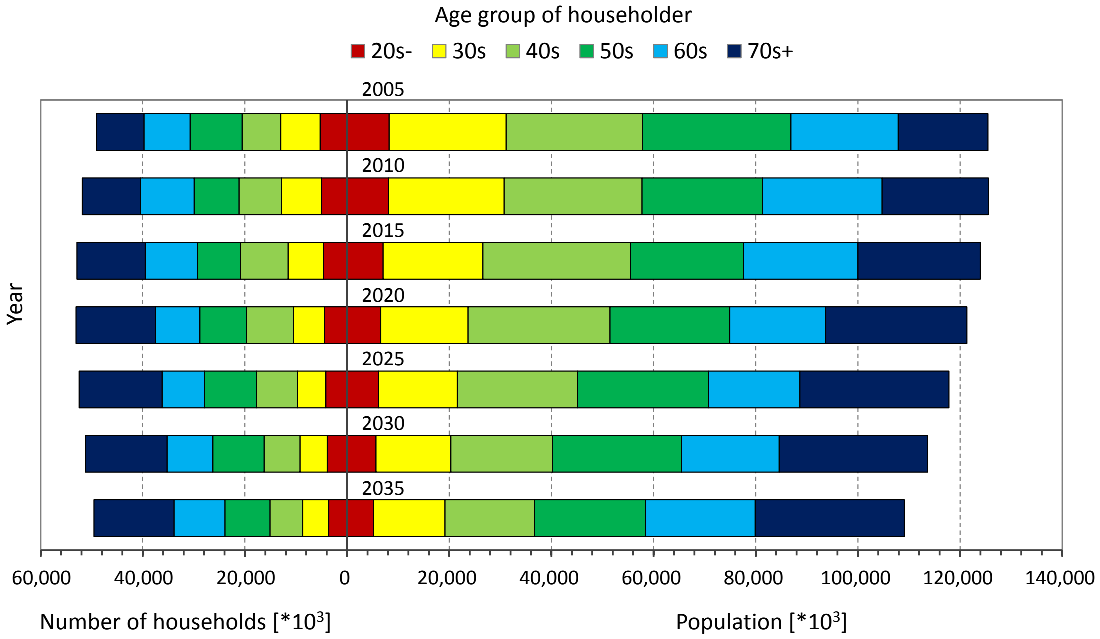


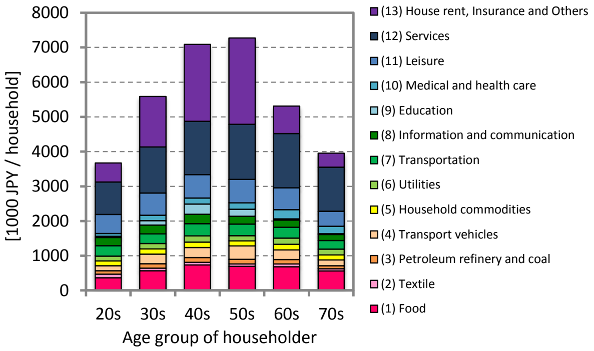
Figure 3.1 Composition of number of households (left) and population (right) by household attribute from 2005-2035.

3.2.2 Characteristics of carbon footprint by age group of householder in 2005

This section describes the characteristics of carbon footprint by household attribute in 2005 from the following three perspectives. Figure 3.2 integrates the 409 sector types defined in this work into 13 aggregated sectors without distinguishing between domestic and imported commodities, and provides (a) a breakdown of household consumption expenditures per household by aggregated sector, (b) a breakdown of GHG emissions by consumption expenditure sector, and (c) a breakdown of GHG emissions by supply chain. Here note that "transportation" mainly includes the commodity sectors associated with public transportation and cargo services. *Gasoline* and *light oil* associated with driving cars are in "petroleum refinery and coal", while commodity sectors related to purchasing cars such as *passenger motor car* are in “transport vehicles”. Again, the names of the 409 sectors are written in *Italics*. The corresponding relationships between the 409 sectors and the 13 aggregated sectors are shown in Table S1 in Appendix. The supply chain categories reflecting the source of emissions are, as in previous studies (Nansai et al., 2012), direct emissions from households (in Japan, direct), indirect emissions from the domestic supply chain (in-Japan supply chain), and indirect emissions from the overseas supply chain (overseas).

Figure 3.2 (a) shows that the largest household consumption expenditures per household occur among those in their 50s, followed closely by those in their 40s. Households whose heads are in their 40s to 50s are in periods of life when their household incomes are larger and, generally, when their children are growing older. Also, in households of this age, many people have purchased their own home, or have purchased or are trading up to better cars, and for this reason, they tend to have higher expenditures than other households. This trend is also evident in the fact that household consumption expenditures are larger among those in their 40s and 50s in such categories as "education," "transportation," and "house rent, insurance, and others." However, as shown in Figure 3.2 (b), the carbon footprint per household follow a different trend from the household consumption expenditures. The age group with the highest emissions per household is the 40s, at 25.3 t-CO_2eq/household, followed by the 60s and the 50s, at 24.7 t-CO_2eq/household and 24.6 t-CO_2eq/household, respectively. One key reason that emissions are lower among households in their 50s, which have the highest consumption expenditures per household, is the particular characteristics of the household consumption expenditures pointed out above. Compared to the second place group (those in their 40s), for *house rent (imputed house rent)*, which is a category within "house rent, insurance, and others" and that has an extremely low global emissions intensity,

(a) Expenditures of aggregated sectors



(b) GHG emissions of aggregated sectors

(c) GHG emissions of locational sectors

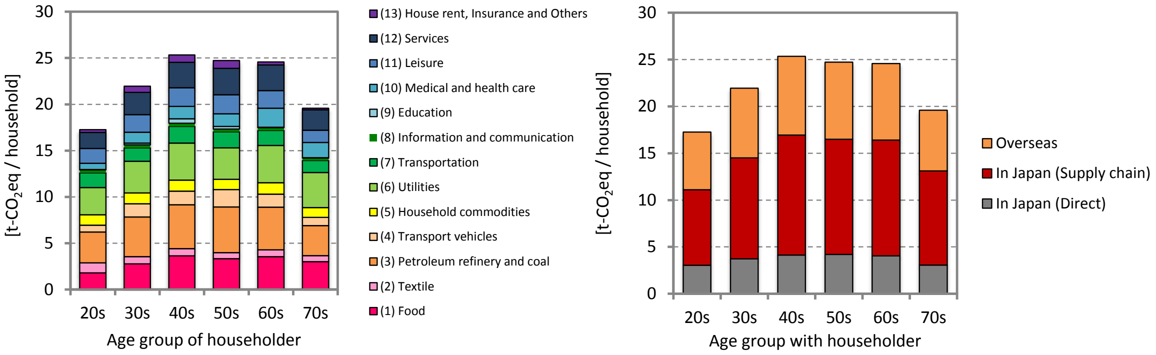


Figure 3.2 (a) Household expenditures of 13 aggregated sectors by householder age group in 2005. (b) GHG emissions of 13 aggregated sectors by householder age group in 2005. (c) GHG emissions of three locational sectors by householder age group in 2005. “In Japan (Direct)”, direct emissions; “In Japan (Supply chain)”, indirect emissions from Japanese supply chains; “Overseas”, indirect emissions from foreign countries’ supply chains.

the impact of allocating over 400,000 JPY more per year of household consumption expenditures is particularly significant. These consumption trends for those in their 50s seem to be strongly related to their highest income. On the other hand, the emission contributions from “medical and health care” and “utilities" are larger once people reach their 60s. That is, in many households in this age group and older, people spend more time at home due to retirement, which causes them to consume more household energy (costs for electricity and heating, for example). Also, their childrearing and rent burdens are greatly reduced, creating extra room for returning those consumption expenditures to other commodity sectors. This is one reason that the overall emissions per household are greater among this group than among those in their 50s.

Next, Figure 3.2 (c) shows emission sources by supply chain, and reveals that differences in emissions in the "in-Japan supply chain" category significantly impact the overall differences. There is little difference between households in the "in-Japan direct" category, which reflects direct emissions, but a breakdown shows that the characteristic differ between the 20-to-40s, and the 50-to-70s. While the former reflects a larger consumption of *gasoline* and *light oil* than the latter due to the use of private cars, the trend for *kerosene*, which is consumed in household heaters, is the opposite. This seems to be related to the fact that the amount of time spent at home, as mentioned above, differs among households. A similar trend has been seen in Germany (Kronenberg, 2009).

Finally, a comparison of households using the carbon footprint intensity of household (kg-CO_2eq/1,000 JPY) indicates that emissions are 1.5 times larger among those in their 70s, the age when emissions are highest, at 4.95 kg-CO_2eq/1,000 JPY, than among those in their 50s, when emissions are lowest, at 3.40 kg-CO_2eq/1,000 JPY. While the emissions per unit expenditure by those in their 30s, 40s and 50s are fewer than 4 kg-CO_2eq/1,000 JPY, those in their 70s and older and 60s whose emissions are 4.63 kg-CO_2eq/1,000 JPY are an important segment given that the number of senior households is expected to increase.

3.2.3 Estimating carbon footprint from 2005 to 2035

Figure 3.3 shows a breakdown of carbon footprints derived from household consumption by consumption expenditure sector from 2005 to 2035. Figure 3.3 (a) shows the trends in total emissions, while the graphs in Figures 3.3 (b) to (g) show the trends in emissions by the six age groups of the head of household, from those in their 20s to those in their 70s and older. In all of the years in this period "food," "petroleum refinery and coal," "utility," and "service" accounted for 70% or more of GHG emissions. This trend is generally consistent with the future estimates for the US in 2004 (Webber and Matthews, 2008) and the UK in 2030 (Chitnis et al., 2012). Additionally, the trends do not change much each year. It is therefore important to reduce emissions effectively to try to make way for technological improvements related to those sectors toward 2035.

From 2005 to 2035, the total number of households is expected to be highest in 2020, but the carbon footprint derived from Japanese household consumption looks to be highest in 2015, at 1,150 Mt-CO_2eq. This is 3.8% more than in 2005. After that, both figures decline, but ultimately, carbon footprint in 2035 are estimated to be 1,061 Mt-CO_2eq (4.2% lower than in 2005). In other words, due to changes in family composition, the household carbon footprint is expected to increase by 42.6 Mt-CO_2eq from 2005 to 2015, and then fall, decreasing to just 46.5 Mt-CO_2eq below the 2005 level in 2035. Thus, some decreases in carbon footprint can be expected to occur simply as a result of changes in household composition due to aging and the low birthrate trend. But it is going to be necessary to make further efforts to reduce emissions through technological means or trade structure strategies. The same has been said regarding GHG emissions derived from household consumption in Germany, where aging and the low birthrate trend are expected to progress much as they have in Japan (Kronenberg, 2009).

According to the trends in carbon footprint by head of household age group, the emissions of those in their 20s is expected to decline to 2035. Emissions of those in their 30s' and 40s' seem to be increasing to 2010 and 2015, respectively, then both decrease. Similar to those in their 20s, emissions for those in their 50s peaks in 2005, but after decreasing from then to 2015, increases to 2025, finally decreasing again to 2035. In contrast, the emissions for those in their 60s peaks in 2010, then decreases to 2025, finally increasing again to 2035. Meanwhile, for those in their 70s, emissions are expected to increase steeply from 2005 to 2025, finally being 67% larger than their initial emissions. This increase is 122 Mt-CO_2eq. Remarkable reductions for those in their 20s and 30s of 75.1 Mt-CO_2eq will occur, but the reductions achieved by the younger generations will not offset the increased emissions being produced by the older generations. The proportion of total emissions accounted for by households in their 60s and 70s will gradually rise from about 37% in 2005 to about 51% by 2035. For this reason, achieving technological improvements focused on commodity sectors strongly correlated with the consumption habits and lifestyles of middle-aged and older-aged households is likely to be effective in achieving emissions reductions.

Figure 3.4 shows the trends in carbon footprint derived from household consumption by emission source for the same time period. "In-Japan supply chain" accounts for the most emissions at about 50%, but "overseas" also accounts for 34%. This “overseas” share is generally close to the “overseas” shares in the UK's household consumption in 2004, which is estimated at about 40% (Druckman et al., 2012). These indicate the importance of the overseas spillover effect of GHG emissions resulting from household consumption by developed countries like Japan and the UK. Also note that the emission sources of each

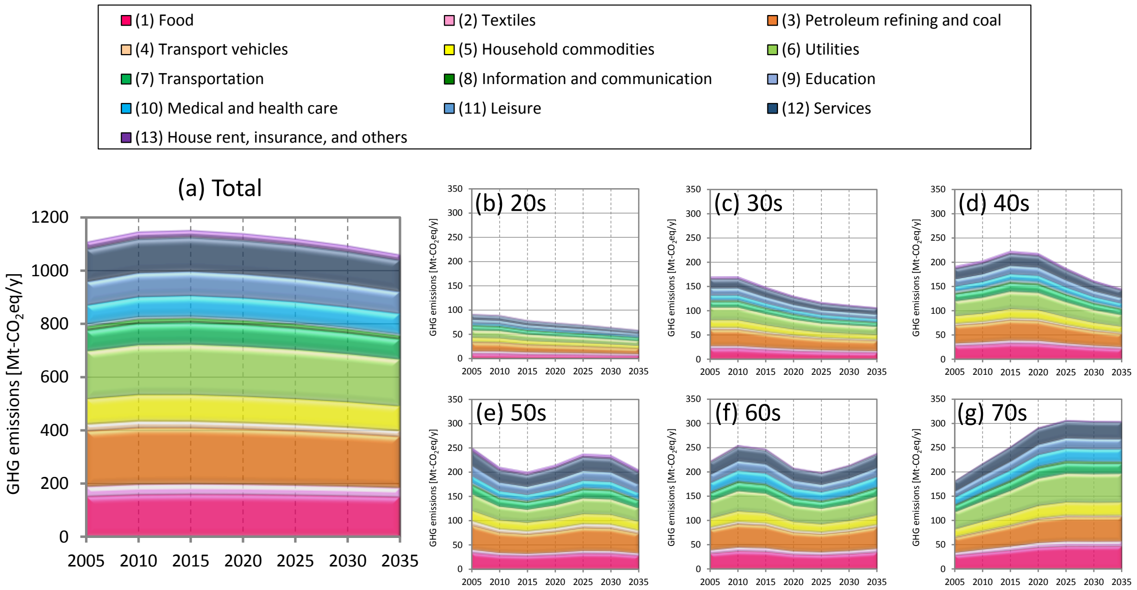


Figure 3.3 Variations in the GHG emissions of the 13 aggregated sectors from 2005 to 2035. (a) Total emissions. (b)–(g) Emissions for each age group (20s to 70s and older).

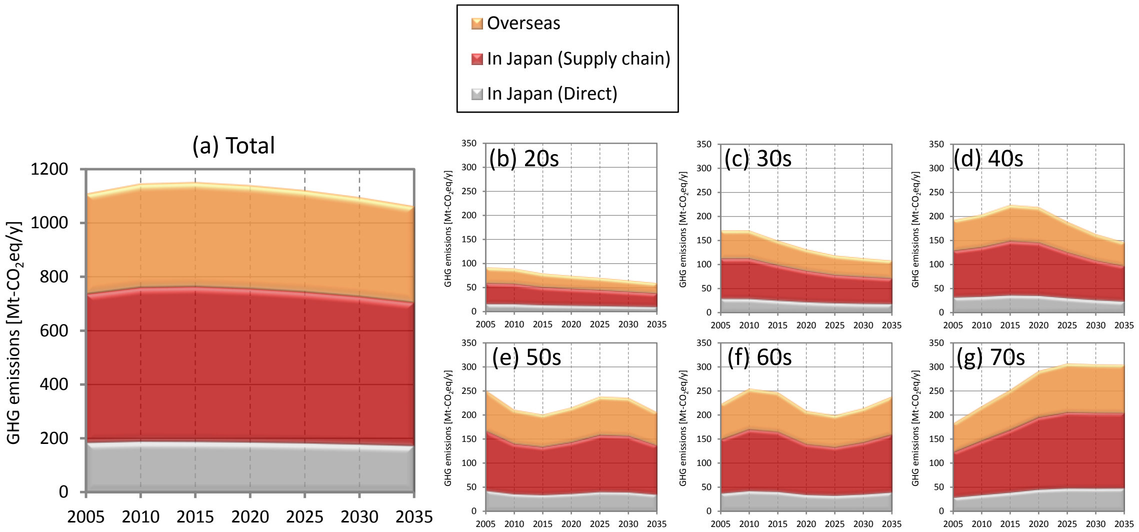


Figure 3.4 Variations in the GHG emissions of the 13 aggregated sectors from 2005 to 2035. (a) Total emissions. (b)–(g) Emissions for each age group (20s to 70s and older).

household are almost the same.

3.3 Discussions

3.3.1 Characteristics of carbon footprint derived from household consumption in 2035

The major expenditures that will shape carbon footprint in 2035 are shown in Table 3.1. Table 3.1 shows the expenditure sectors that have the top five largest GHG emissions in 13 categories, differentiating between domestic products (JD) and imported ones (JI), and indicating the ratio of those expenditures attributed to the imported commodities. The expenditure category that yields the highest emissions is *JD296: electricity*, at 132 Mt-CO_2eq. The next highest are *JD137: gasoline* at 106 Mt-CO_2eq and *JD306: retail trade* at 61.3 Mt-CO_2eq. By aggregated sector, the largest expenditure category is "petroleum refinery and coal." Since emissions associated with the direct consumption of petrochemical products accounts for the vast majority of this, a first step will be to reduce the consumption of such products, in addition to electricity. This is also seen in Germany and the UK in 2030 by Kronenberg (2009) and Chitnis et al. (2012), respectively.

On the other hand, the amounts of emissions in the commodity sectors related to diet, such as *JD394: general eating and drinking places* in category "leisure" and *JD36: slaughtering and meat processing* in category "food", were remarkable. Emissions in the eating and drinking places category were higher than those produced by *JI140: LPG*, the third largest in "petroleum refinery and coal," and emissions in *slaughtering and meat processing* were very close to that level. Furthermore, since the vast majority of emissions

Table 3.1 Top 5 household domestic (JD) and imported (JI) commodity sectors of each aggregated sector, their highest household carbon footprints for 2035, and the ratios of expenditures attributed to the imported commodities. The total emissions for Japan and overseas are also shown.

Aggregated sector (Sectoral emission)	Commodity No.	Top 5 household commodity sectors in the aggregated sector	Amont of GHG emission (Mt-CO$_2$eq)	Import ratio (%)	Japan (%)	Overseas (%)
	JD36	*slaughtering and meat processing*	10.1	14.1	53.2	46.8
(1) food	JD60	*dishes, sushi and lunch boxes*	9.4	0.2	56.7	43.3
149.6 Mt-CO$_2$eq	JD45	*grain milling*	9.2	0.0	86.0	14.0
	JD39	*dairy farm products*	8.5	4.6	66.0	34.0
	JD69	*soft drinks*	8.4	1.7	65.2	34.8
	JI84	*woven fabric apparel*	12.3	97.9	1.1	98.9
(2) textiles	JI85	*knitted apparel*	11.9	91.9	3.3	96.7
35.1 Mt-CO$_2$eq	JI86	*other wearing apparel and clothing accessories*	4.3	71.5	8.4	91.6
	JI87	*bedding*	1.7	75.5	5.1	94.9
	JI88	*other ready-made textile products*	1.1	28.6	29.1	70.9
	JD137	*gasoline*	105.7	3.3	80.7	19.3
(3) petroleum refinery and coal	JD138	*kerosene*	53.1	3.2	89.7	10.3
192.8 Mt-CO$_2$eq	JI140	*LPG (liquified petroleum gas)*	12.6	67.0	81.8	18.2
	JD139	*light oil*	7.4	4.7	83.8	16.2
	JD140	*LPG (liquified petroleum gas)*	6.0	67.0	81.8	18.2
	JD252	*passenger motor cars*	15.8	12.7	61.4	38.6
(4) transport vehicles	JD253	*trucks, buses and other cars*	3.1	0.0	68.3	31.7
60.1 Mt-CO$_2$eq	JI252	*passenger motor cars*	2.0	12.7	61.4	38.6
	JI266	*bicycles*	1.0	76.4	6.5	93.5
	JI254	*two-wheel motor vehicles*	0.4	58.9	16.1	83.9
	JI279	*jewelry and adornments*	5.9	82.8	3.7	96.3
(5) household commodities	JD130	*cosmetics, toilet preparations and dentifrices*	5.6	14.1	56.1	43.9
54.9 Mt-CO$_2$eq	JD235	*household electric appliances*	5.1	16.9	41.1	58.9
	JI151	*miscellaneous leather products*	4.3	90.1	3.1	96.9
	JI243	*personal computers*	3.4	55.5	9.9	90.1
	JD296	*electricity*	131.8	0.0	91.5	8.5
(6) utilities	JD298	*gas supply*	30.5	0.0	83.3	16.7
176.3 Mt-CO$_2$eq	JD302	*sewage disposal*	9.7	0.0	88.8	11.2
	JD304	*waste management services (private)*	2.1	0.0	96.3	3.7
	JD300	*water supply*	1.6	0.1	77.4	22.6
	JD324	*air transport*	14.0	43.7	50.9	49.1
(7) transportation	JD318	*road freight transport(except Self-transport by private cars)*	13.0	0.0	84.1	15.9
74.7 Mt-CO$_2$eq	JD314	*railway transport (passengers)*	11.6	4.0	57.6	42.4
	JI324	*air transport*	9.5	43.7	50.9	49.1
	JI314	*railway transport (passengers)*	5.4	4.0	57.6	42.4
	JD337	*mobile telecommunication*	3.2	0.1	74.9	25.1
(8) information and communication	JD346	*newspaper*	2.4	0.0	73.5	26.5
13.9 Mt-CO$_2$eq	JD336	*fixed telecommunication*	1.9	0.2	75.8	24.2
	JD347	*publication*	1.4	3.5	76.6	23.4
	JD343	*information services*	1.2	3.4	68.3	31.7
	JD352	*school education (private)*	3.2	0.0	77.4	22.6
(9) education	JD356	*other educational and training institutions (profit-making)*	0.7	0.0	84.4	15.6
4.8 Mt-CO$_2$eq	JD351	*school education (public)*	0.7	0.0	84.8	15.2
	JD354	*social education (private, non-profit)*	0.1	0.0	76.8	23.2
	JD353	*social education (public)*	0.1	0.0	80.4	19.6
	JD366	*medical service (medical corporations, etc.)*	43.8	0.0	66.7	33.3
(10) medical and health care	JD365	*medical service (non-profit foundations, etc.)*	15.2	0.0	69.3	30.7
76.7 Mt-CO$_2$eq	JD364	*medical service (public)*	14.2	0.0	69.1	30.9
	JD372	*social welfare (private, non-profit)*	1.1	0.0	72.5	27.5
	JD371	*social welfare (public)*	0.7	0.0	74.1	25.9
	JD394	*general eating and drinking places*	30.6	6.2	55.1	44.9
(11) leisure	JD397	*hotels*	13.4	25.6	48.6	51.4
83.4 Mt-CO$_2$eq	JD390	*amusement and recreation facilities*	12.5	1.0	81.6	18.4
	JI397	*hotels*	6.3	25.6	48.6	51.4
	JD396	*eating and drinking places for pleasures*	4.6	4.4	59.0	41.0
	JD306	*retail trade*	61.3	0.0	84.3	15.7
(12) services	JD305	*wholesale trade*	22.2	0.0	71.2	28.8
118.5 Mt-CO$_2$eq	JD381	*repair of motor vehicles*	6.5	0.0	67.5	32.5
	JD404	*ceremonial occasions*	6.3	0.2	80.0	20.0
	JD406	*supplementary tutorial schools, instruction services*	4.1	0.0	81.3	18.7
	JD313	*house rent (imputed house rent)*	7.9	0.0	70.9	29.1
(13) house rent, insurance and others	JD312	*house rent*	5.8	0.0	74.2	25.8
20.6 Mt-CO$_2$eq	JD308	*life insurance*	5.8	0.0	72.3	27.7
	JD309	*non-life insurance*	1.1	0.1	75.8	24.2
	JI409	*activities not elsewhere classified*	0.1	22.3	35.5	64.5

resulting from *LPG* are accounted for by domestic emissions associated with direct consumption, *general eating and drinking place* emissions are 1.7 times higher than overseas emissions. This example demonstrates the size of our hidden emissions influenced by the use of everyday services and foods. Particularly remarkable in overseas emissions are the *JI84: woven fabric apparel* and *JI85: knitted apparel* categories in sector "textiles," whose production bases are expanding quickly in Southeast Asia due to its low costs. Therefore, commodity sectors like these are highlighted not in production-based accounting but in consumption-based accounting.

Dietary habits reflect differences in living standards and household patterns, as well as differing preferences depending on the age of the head of household. For example, among younger households, the percentage of favorite foods accounted for by eating out, boil-in-the-bag foods, and juices is higher than in other households. Their staple tends to be bread rather than rice, and meat tends to account for a larger percentage of consumption than fish and seafood. On the other hand, among older households, fresh vegetables, fish and seafood, fruit, and rice account for the highest ratios of foods consumed, reflecting what would be considered a more traditional Japanese diet (National Health and Nutrition Survey, 2005). Also, Japan has a low rate of food self-sufficiency and thus has to rely on imports for a large majority of its food, including its livestock feed. These necessarily make a sizable emissions contribution to the overseas supply chain, and constitute an important commodity cluster when considering the relationship between the trade structure and carbon footprint.

A review of transportation of such items is also important. For example, carbon footprint derived from the use of private cars is 117 Mt-CO_2eq, which is the sum of emissions from both *gasoline* and *light oil*. This is 5.3 times the emissions derived from *railway* *transport (passenger)* and *bus transport service,* which are public means of transportation used on a daily basis. Of this, the emissions derived from the use of private cars were largest, at 7.5 times the domestic emissions and 2.4 times the overseas emissions of public transport. This suggests that expanding campaigns conducted by local governments aimed at promoting the use of public transportation, such as "no car days," would be an effective way to reduce both domestic and overseas GHG emissions. In addition, the total emissions related to health care, for *JD364: medical service (public), JD365: medical service (non-profit foundation, etc.),* and *JD366: medical service (medical corporation, etc.),* is 73.2 Mt-CO_2eq, making them the second highest overall. For a country that is experiencing rapid aging like Japan, controlling GHG emissions indirectly generated by the expansion of the health care system is going to become increasingly important.

Table 3.2 shows the 10 sectors with the largest differences in carbon footprint between 2035 and 2005 by total emissions. This gives a view of the situation from a different perspective than total emissions, and suggests the need to make controlling such increases a policy priority. The increases in emissions from *JD138: kerosene* are most remarkable. Since *kerosene* and *electricity*, which produce the largest emissions from 2005 to 2035 are due to direct use by households, consumers need to introduce energy-saving products and make greater efforts to adopt energy-saving strategies in their everyday lives. On the other hand, four of items in this table are accounted for by commodity sectors related to diet, such as *JI40 (and JD40): frozen fish and shellfish*, *JI6: fruits*, and *JD5: vegetables*. Since these are in categories where emissions themselves are high, and where, in contrast to *kerosene* and *electricity*, it is difficult for consumers to restrict their consumption, the government and corporate sectors need to prioritize developing technological improvements to reduce emissions. Specifically, neither the technologies nor the supply chain associated with *frozen*

Table 3.2 The top 10 sectors with the largest differences and change ratios in household carbon footprint between 2035 and 2005

Rank	Sector No.	Commodity sector	Difference [Mt-CO_2eq]	Difference [%]
1	JD140	*kerosene*	3.95	8.0
2	JD368	*medical service (medical corporations, etc.)*	3.49	8.7
3	JD367	*medical service (non-profit foundations, etc.)*	1.28	9.1
4	JD366	*medical service (public)*	1.20	9.2
5	JD399	*hotels*	0.66	5.2
6	JI41	*frozen fish and shellfish*	0.51	8.1
7	JD41	*frozen fish and shellfish*	0.44	8.1
8	JI336	*travel agency and other services relating to transport*	0.39	15.4
9	JI6	*fruits*	0.37	14.5
10	JD5	*vegetables*	0.33	5.4

fish and shellfish have seemed to do particularly well in reducing emissions. For Japan, which is also a great fisheries country, it will be important to pay attention to them. The three medical demand sectors are strongly influenced by the increase in middle- and older-aged households, which have higher ratios of medical expenditures, and are commodity sectors that must be paid close attention to as Japan's society continues to age. The *hotels* sector is also expected to be impacted by trends among middle-aged and older households, which tend to enjoy more post-retirement sightseeing and travel.

Hertwich (2011) showed a graph that illustrates the carbon footprint of per capita household consumption (t/capita/y) referred to in several articles. In it, the emission shares of "Health" in some countries like the UK, the US, the Netherlands and Denmark were estimated to rise remarkably from the 1990's to the 2000's. Although it is quite difficult to simply compare their results with ours due to the different methods used, consumption categories and the system boundaries, the results related to medical demands in this work seem generally consistent with such past trends in developed countries.

3.3.2 Further perspectives of estimating future household carbon footprint

This chapter identified current carbon footprint precisely by the age of the head of household in 2005 using the GLIO model and domestic household consumption data. Next, the chapter estimated future carbon footprint derived from Japanese household consumption due to changes in household composition. I also highlighted the commodity sectors expected to require priority efforts in order to reduce emissions in 2035. Kronenberg (2009) also estimated GHG emissions derived from household consumption, focusing on changes in household composition, but because that study looked at the domestic supply chain using German SIO tables, it differs from the analysis of this chapter, which uses consumption-based accounting. Barrett and Scott (2012) and Chitnis et al. (2012), who made future estimates using consumption-based accounting, both presented results achieved through macro sector resolution based on a scenario analysis, while this chapter analyzed the impact on consumption-based emissions for each commodity sector in as much detail as possible. For example, the mere identification of large "food" emissions does little to show specifically what kind of "food" supply chain improvements or policies for consumers would be effective. The results presented here can not only be used to reveal more information, such as the future importance of foods such as *frozen fish and shellfish* and *fruits*, but also as a resource for developing policies to make more meticulous and efficient emissions reductions based on emission and import rates for each domestic and overseas commodity supply chain. With regard to the effectiveness of consumption-based accounting, Wiedmann (2009) argued that it is possible to make consumers aware of indirect GHG emissions derived from their lifestyles and consumption habits, and that future estimates of carbon footprint based on this kind of detailed sector resolution will play an important role in taking advantage of this approach.

Because this work focused on how changes in household composition will affect carbon footprint, as noted in Subsection 3.3.2, the production technologies (emission intensities), global supply chain structures (GLIO coefficients), prices and household consumption patterns in this work are fixed on 2005 data, except for the numbers of households and populations. For example, when today's 20-year olds enter their 50s in 30 years, they will not be able to have the same consumption patterns as they do now. Their incomes and expenditures will increase as they get married and have children. Also, what patterns to expect of future 20-year-olds being born now is difficult. Thus, I assumed that today's young households will adopt the consumption patterns of today's older households as they grow older.

Since the Fukushima Daiichi Nuclear plant disaster of 2011, the need to review Japan's energy mix has come to the forefront. After the disaster, the territorial GHG emissions for 2011 were reported to be 1.31 Gt-CO_2eq, about 4% larger than the 1.26 Gt-CO_2eq of 2010, Moreover emissions continued to increase in 2012 to 1.34 Gt-CO_2eq (Green Gas Inventory Office of Japan). Now the trend is not toward increasing generation by nuclear plants and resuming the operation of those that have been stopped, so the amount of LNG imported is expected to continue to rise, at least for a while. Therefore, the prices and emission intensities of energy sectors in 2005 are potentially much higher since 2011.

On the other hand, the results of this work indicate that Japanese carbon footprint derived from household consumption are estimated to drop naturally because of an aging society with low birthrate without interventions of any new technologies and new policies. In other words, the data presented here might be considered a base scenario for 2035. In the future, incorporating future trends in technology levels or changes in the international trade that incorporate the international supply chain into the scenario will improve the accuracy of the estimates so they can be better used in the management of carbon footprint.

4 Future Projection of Household Material Footprints for Critical Metals in Japan in an Aging Society

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. Since Japan, too, is a major consumer of such critical metals, it is important to quantify the material footprints 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 (Graedel et al., 2004; Müller et al., 2006; Reck et al., 2008; Du and Graedel, 2011; Chen and Graedel, 2012; Kablak and Graedel, 2013a; Kablak and Graedel, 2013b), though, the relationship between the footprint of critical metals and household consumption has not yet been clearly charted.

Against this background, this chapter aims to analyze the material footprints 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 material footprints. Crucially, demand for these metals is expected to increase significantly the world over (Harper et al., 2011; Elshkaki, 2013; Elshkaki and Graedel, 2013), 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 material footprints of neodymium, cobalt and platinum.

4.1 Methods and Data

4.1.1 Estimating household material footprints during 2005-2035

The methodology employed in this work is based on Chapter 3, which estimated the carbon footprints 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. Thus, this work also utilized household expenditures of six household attributes *b*, expressed as f_{ib}^{JD} and f_{ib}^{JI} which are already explained in Subsection 3.1.1. Note that f_{ib}^{JD} refers to household consumption expenditures for domestic commodity *i* by householder age group *b*, while f_{ib}^{JI} refers to household consumption expenditures for imported commodity *i* by householder age group *b*. $b = (1\ldots6)$ is corresponded to the age group of the head of the household (1=20s: ≤29, 2=30s: 30-39, 3=40s: 40-49, 4=50s: 50-59, 5=60s: 60-69, 6=70s: ≥70), and $i = (1\ldots409)$ refers the number of commodity sector based on the JIOT.

In addition, I here considered metals contained in medical instruments as following: 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. I therefore used the Leontief inverse matrix and the fixed capital matrix supplied by the JIOT to estimate the additional demand for medical instruments (*mi*), $f_{i=mi}^{add}$, from the capital investment triggered by household consumption expenditure on medical services (*ms*), $f_{i=ms}^{JD}$, as expressed in Equation (39):

$$f_{i=mi}^{add} = B_{mi,ms} \times L_{ms,ms} \times f_{i=ms}^{JD} \tag{39}$$

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. I here considered three medical service sectors (note that the sector names based on the JIOT is written in italics): *medical services (public)*, *medical services (non-profit foundations, etc.)*, and *medical services (medical corporations, etc.)*, and calculated $f_{i=mi}^{add}$ for each. Adding $f_{i=mi}^{add}$ to the corresponding f_{ib}^{JD} gives the associated material footprint.

After the above treatment, I estimated future household consumption expenditures on domestic and import commodities by householder age group in each year, $f_{ib}^{JD(t)}$ and $f_{ib}^{JI(t)}$, from Equations (40) and (41). *t* denotes the target year of this work (1: 2005, 2:2010, 3: 2015, 4: 2020, 5: 2025, 6: 2030, 7: 2035)

$$f_{ib}^{JD(t+1)} = f_{ib}^{JD(t)} \times \frac{N_b^{(t+1)}}{N_b^{(t)}} \times \theta_{ib}^{(t+1)} \tag{40}$$

$$f_{ib}^{JI(t+1)} = f_{ib}^{JI(t)} \times \frac{N_b^{(t+1)}}{N_b^{(t)}} \times \theta_{ib}^{(t+1)} \tag{41}$$

$N_b^{(t)}$ referes to the number of householder age group *b* from IPSS (2013), while $\theta_{ib}^{(t)}$ is the adjustment coefficient expressing the influence on future household expenditures in sector *i* due to changes in household size. I here omit to explain the methodology of introducing $\theta_{ib}^{(t)}$ since it is already elaborated in Subsection 3.1.4.

Finally, I estimated $MF_{ib}^{(t)}$ (t/y), which represents the material footprint of commodity *i* by householder age group *b* from 2005 to 2035, as shown in Equation (42).

$$MF_{ib}^{(t)} = q_{\mathrm{MF},i}^{JD} f_{ib}^{JD(t)} + q_{\mathrm{MF},i}^{JI} f_{ib}^{JI(t)} \tag{42}$$

where $q_{\mathrm{MF},i}^{JD}$ and $q_{\mathrm{MF},i}^{JI}$ are the material footprint intensities of a specific critical metal (in this work, 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.

4.1.2 Limitations of the future scenario used in this chapter

In this work, 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, I assumed that factors having a potential influence on the respective material footprints, 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, 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 material footprints of neodymium, cobalt and platinum per expenditure will rise accordingly, given the increased use of rechargeable batteries. On the other hand, the material footprint 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 material footprints over the period, I therefore assumed that $q_{\mathrm{MF},i}^{JD}$ and $q_{\mathrm{MF},i}^{JI}$ 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, I 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 work 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.

4.2 Results

4.2.1 Characteristics of household consumption expenditures and material footprints according to householder age group in 2005

Although the characteristics of household consumption expenditures by householder age group in 2005 have already been explained in Chapter 3, I here describe them again in order to identify the relationship between household expenditures and the respective material footprints of neodymium, cobalt and platinum.

Figure 4.1 shows the distribution of average consumption expenditures per household on 13 aggregated sectors by householder age group in 2005. These aggregated sectors integrate the 409 sectors used in this work 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 “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 “transport vehicles” and “services” rank highest. On the other hand, those in their 40s spend more on “food” and “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 “food,” “textiles,” “medical and health care” and “services” are remarkable. These results indicate differences in lifestyle, because the average household sizes are very

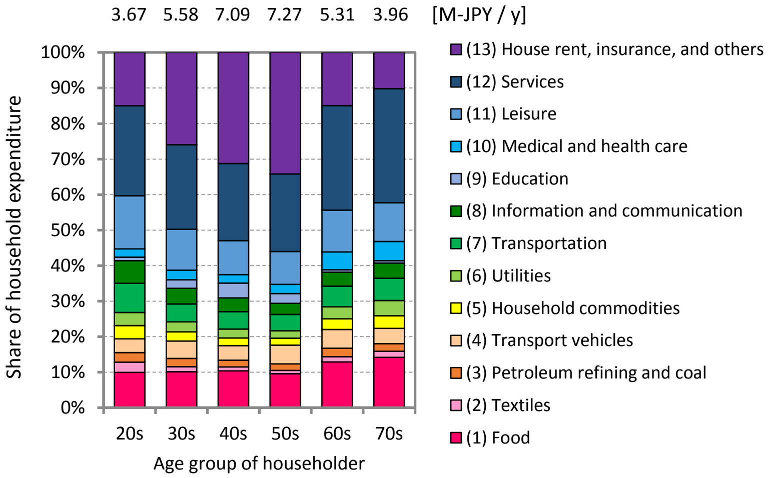


Figure 4.1 Distribution of average consumption expenditures per household on 13 aggregated sectors by householder age group and total level (number above the bar) in 2005.

close.

Figure 4.2 depicts the respective material footprints of neodymium, cobalt and platinum per household for 13 aggregated sectors by household age group in 2005. For neodymium, in Figure 4.2 (a), the 50s age group – which scores highest on overall household consumption expenditure – has the highest material footprint per household: 10 g. The key reason for this is the material footprint induced by *passenger motor cars* within “transport vehicles”, which is much greater for the 50s age group 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 material footprint induced by *household electric appliances* within “household commodities” is also striking in this age group. The second highest material footprint for neodymium is by households with householders in their 40s; in this case, however, the material footprint associated with “transport vehicles” is considerably less than that of households with householders in their 50s. Next, the material footprint 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 material footprints induced by *household electric appliances* and *cell phones* within “household commodities,” which highlights the effect of distinguishing between younger and older lifestyles on their respective material footprints. In particular, the difference in the material footprints 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 material footprints of both cobalt and platinum, which are 97 g and 0.22 g per household, respectively. In the case of cobalt, though, the material footprints of households in their 40s and 60s, ranking second and third, respectively, are only slightly smaller. For platinum, the material footprint 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 material footprint 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 those in their 60s) following those in their 40s (the second largest users of neodymium).

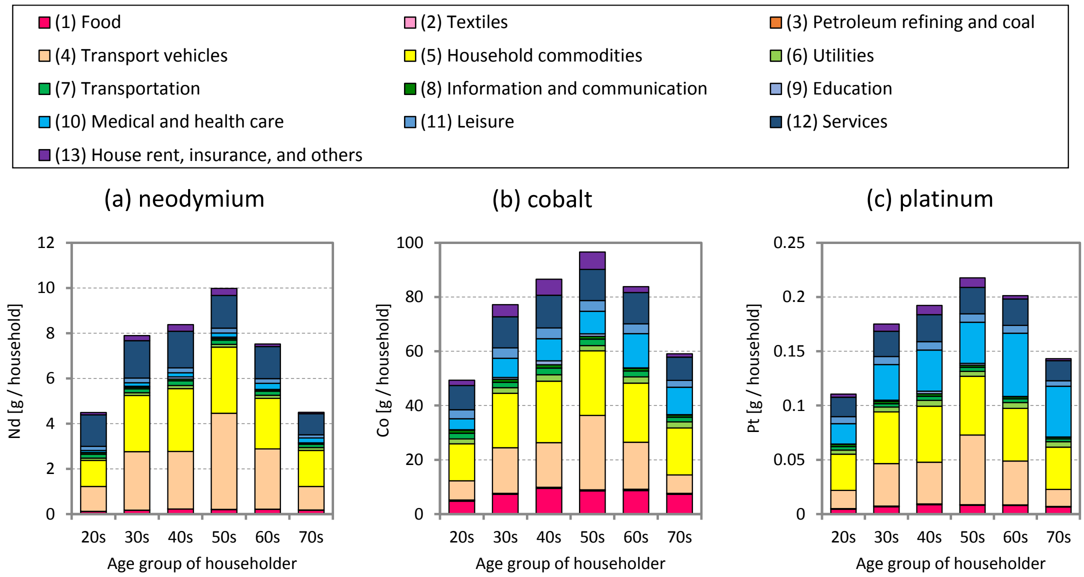


Figure 4.2 Material footprints of (a) neodymium, (b) cobalt and (c) platinum per household by householder age group in 2005.

4.2.2 Impact of aging and declining birth rates on the material footprints of neodymium, cobalt and platinum from 2005 to 2035

Figure 4.3 provides a breakdown of trends in the material footprints of neodymium, cobalt and platinum from 2005 through to 2035 derived from household consumption per consumption expenditure sector. During this period the total material footprints 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 material footprint is projected to peak in 2010, while for platinum it appears to peak in 2015. The increase in material footprint between 2005 and the peak year is 0.56%, 2.1% and 3.1% for neodymium, cobalt and platinum, respectively. After peaking, all three material footprints 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 group remains stable during this period (i.e., $\theta_{ib}^{(t+1)} = 1$ in Equations (40) and (41)), the material footprint of this metal is estimated to be 4.3% lower in 2035 than in 2005. Thus, this value indicates the effect on the material footprint 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 material footprints of cobalt and platinum to decline from 2005 to 2035, in both cases it is projected to be only1.6% 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, 2013). Whatever the case, the noteworthy fact is that the total material footprints 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 material footprints of the three metals induced by *passenger motor cars* are estimated to decrease most between 2005 and 2035. The total material footprints 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 material footprints due to *trucks, buses and other vehicles* within "transport vehicles" and by *repair of motor vehicles* within "services" are also expected to decline significantly; shrinkage of transport-related demand will therefore be a key contributor to a decline in total material footprints. Additionally, the projected decline in total population will mean a substantially smaller

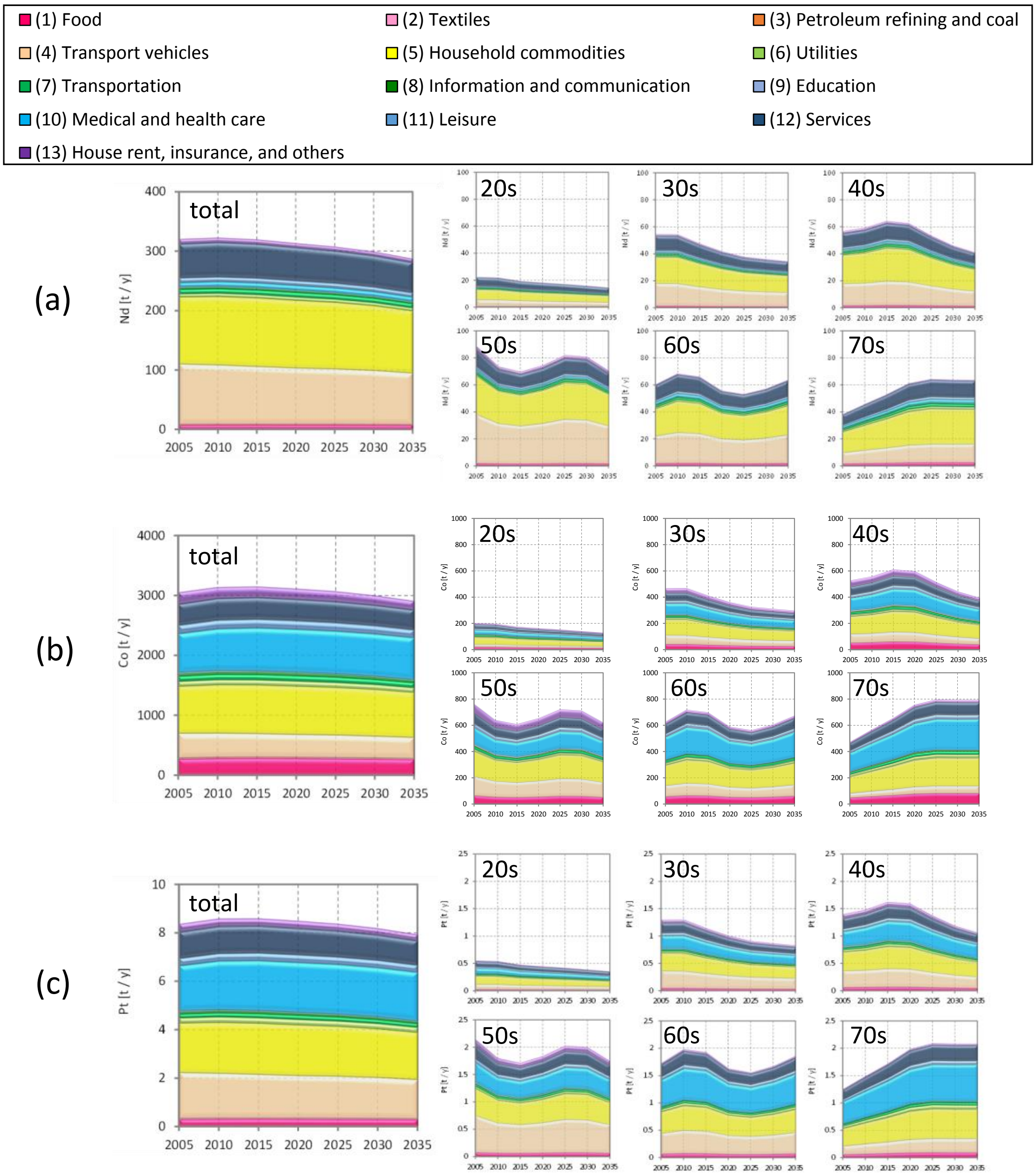


Figure 4.3 Variation in the material footprints of (a) neodymium, (b) cobalt and (c) platinum from 2005 to 2035, including total material footprint and material footprint per household age group.

contribution of *house rent (imputed house rent)* to the respective material footprints.

Particularly in the case of cobalt and platinum, the material footprints 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 material footprints is “medical and health care,” including *medical service (medical corporations, etc.)*, reflecting the trend towards an aging society. Note that while many of the material footprints induced by household electrical products like *personal computers* and *cell phones* will drop, those induced by *household air conditioners* are expected to rise.

When I consider trends in material footprints according to the age of the head of household, I see that the 50s age group had the highest material footprints in 2005. For the 70+ age group, in contrast, material footprints rise rapidly from this date onwards, with the material footprints of both cobalt and platinum estimated to ultimately peak in 2035. The material footprints of those in their 70s generally account for no less than a quarter of each total material footprint in 2035, while the neodymium material footprint of those in their 50s will continue to contribute most to the total material footprint 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 material footprints 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 material footprints 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 material footprints of all households are expected to decline from their respective peak years through to 2035. The material footprints of those in their 50s decrease between 2005 and 2015, increase up to 2025, and finally decrease again through to 2035. In contrast, the material footprints 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 4.1.3.

4.2.3 Comparison of material footprints with the carbon footprint induced by household consumption of 2035

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) and resource consumption (material footprint) in relation to, respectively, a low-carbon society and a sustainable material cycle society. Against this background, I now compare the respective material footprints of neodymium, cobalt and platinum with the carbon footprint induced by Japanese household consumption from 2005 to 2035.

As described in Chapter 3, the carbon footprint of the Japanese household in 2035 is estimated to be 1,061 Mt-CO_2eq, which is 4.2% less than in 2005. This decrease is relatively small in comparison with that estimated for the material footprints considered in this work. The carbon footprint is projected to gradually increase from 2005 by 3.8% and peak in 2015, a trend similar to that for the material footprint of cobalt. The 40s household age group has the highest carbon footprint per household in 2005: 25 t-CO_2eq/household, which contrasts with the observation that the material footprints 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 carbon footprint than those in their 40s is that the former have purchased 400,000 JPY more *house rent (imputed house rent).*

Let me next consider which commodity sectors contribute most to the various footprints. Figure 4.4 shows the contributions of each of the 13 aggregated sectors to the three material footprints and the carbon footprint in 2035. Compared with the material footprints these sectors induce, “transport vehicles” and “household commodities” contribute only marginally to the carbon footprint; the contributions of “petroleum refining and coal” and “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 material footprints considered in this work. Additionally, the contribution of “food” to total carbon footprint 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 “medical and health care” to the overall footprint is greater for the material footprints than for the carbon footprint, particularly for the material footprints of both cobalt and platinum.

In conclusion, while trends in the total material footprints and carbon footprints 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 group 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.

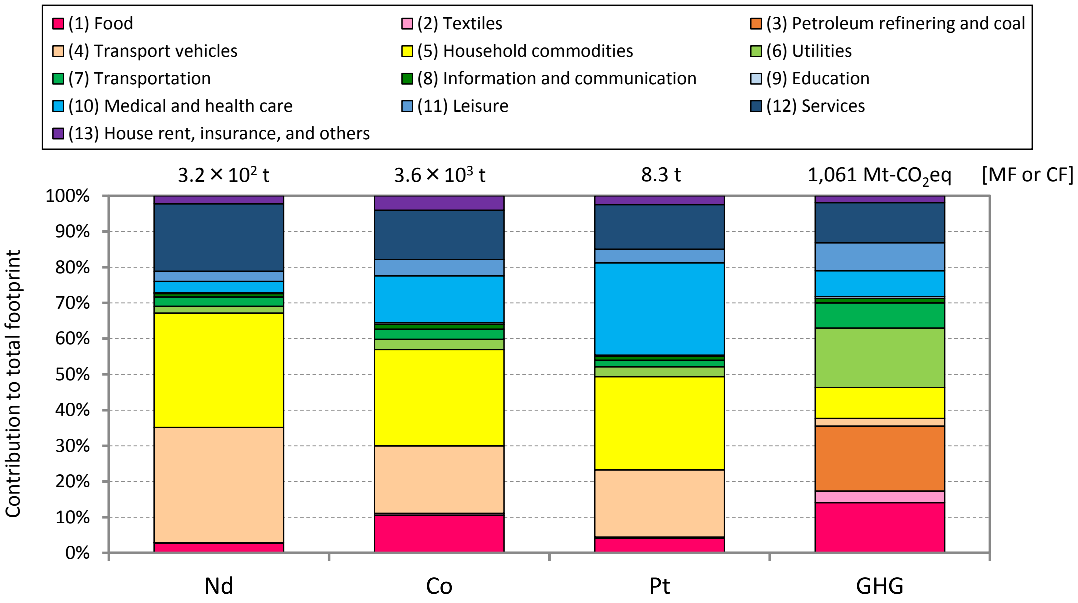


Figure 4.4 Distribution of the material footprints (MFs) of neodymium, cobalt and platinum and the carbon footprint (CF) associated with Japanese household consumption in 2035. The values above the bars denote each total amount.

4.2.4 Sensitivity analysis of the material footprints based on Japanese population scenarios

The material footprint values reported in Subsections 4.2.2 and 4.2.3 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 material footprint in this chapter estimates are based on the "medium" scenario for both fertility and mortality, which I shall refer to as the "reference scenario."

The material footprint 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 group, as in 2010), I obtained the respective numbers of households in each of the scenarios by multiplying these shares by the total number of households cited above. Finally, I determined the household expenditures and the material footprints for each of the scenarios by using these numbers of households.

Using this procedure, the highest total material footprints (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 material footprints (low fertility and high mortality) were estimated to be 4.1% smaller than in that scenario. The figures calculated in this work for the material footprints 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 $+1.7\times10^2$ t/y and -0.34 to +0.39 t/y, respectively.

4.3 Discussions

4.3.1 Opportunities for consumers to recognize their household material footprints

To reduce the household material footprints analyzed in this work 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 material footprints. 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 material footprint. 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 material footprints calculated for 2035.

In the case of neodymium, the material footprints induced by the products in the 30 commodity sectors collected under the cited legislation is an estimated 76% of the total value, with the material footprints 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 material footprint. For neodymium, then, the Automobile Recycling Act already provides quite significant coverage. The material footprints 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 material footprint, 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 material footprints induced by products in these 30 commodity sectors will be an estimated 43% of the total material footprint, the lowest coverage of all the three metals. The commodity sector contributing most to the total material footprint 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 material footprint of cobalt induced by the five commodity sectors relating more broadly to passenger cars is only 24% of the total material footprint, far less than in the case of neodymium.

Finally, the material footprint of platinum induced by these 30 commodity sectors is expected to be 41% of the total material footprint, 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 material footprint 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 material footprints 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.

4.3.2 Projected role of household material footprints in future resource management

Effective reduction of the material footprints 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 work 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 material footprints 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 Subsection 4.3.1, it is not only through technological innovation but also by "greening" consumer behavior (by maximizing recycling and separate waste recovery, for example) that material footprints can be significantly reduced, even if only gradually. The estimates derived in this work indicate that the material footprints 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 material footprint 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 material footprints of these metals, and citizens should be informed accordingly.

While the material footprints 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, I can expect the alleviation of the carbon footprint of *electricity* to be accompanied by an increase in the material footprint 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 Subsection 4.2.4, since the focus of the present study was on how changes in household composition will affect the material footprints 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 work 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 work indicate solely the effect of an aging society with fewer children on the respective material footprints of these metals; for this reason, future technological innovations have the potential to achieve further reductions in material footprints. 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.

5 Examination of the Significant Economic Drivers for Changes in Trade Structures of Critical Metals

Chapters 3 and 4 illustrated an approach to estimate future carbon and material footprints for the three critical metals induced by Japanese households with a focus on the domestic demographic changes. From the other point of view, it is possible to estimate the future material footprints with respect to change in international trade structures of the metals if the structure of trade flows on the GLIO model can be quantitatively predicted. This chapter therefore, as the first step, provides an approach to predict future global flows of neodymium, cobalt, and platinum which can be comprised of the trade structure on the GLIO model.

The utilization structure of critical metals have been recently visualized quantitatively through MFA (e.g., Du and Graedel, 2011) as well as iron (e.g., Müller et al., 2008), aluminium (e.g., Hatayama et al., 2007), and other base metals and alloy elements (Ohno et al., 2014). Although these preceding studies have analyzed the current flow structures of critical metals in their supply chains, the estimation of future flow structures will be more useful in reducing future supply risks associated with resources. No preceding studies, however, have yet to forecast the future flow of critical metals.

Such estimation of structure in critical metal flow requires to identify socio-economic drivers related to the flow and elucidate the quantitative relationship between the flow and the drivers. There have been preceding studies examining the drivers important to the physical flow related to environmental load such as virtual water flow (Fracasso, 2014; Tamea et al., 2014) and waste flow (Kellenberg, 2012). Tamea et al. (2014) identified economic factors that are significant to the virtual water flow of one country and that of the entire world in view of food demand and farmland related to the water resources consumption based on the panel data during 1986–2010. Fracasso (2014) discussed relations among various explanatory variables related to international trade and virtual water flow based on cross-sectional data of 2006 at the regional and global levels. Kellenberg (2012) examined whether “international waste haven effects,” which would result from the export of waste by-products rather than the production of products depending on different levels of environmental regulations, would occur in a country with lax environmental regulations. These studies have applied the gravity model of trade (Tinbergen, 1962). However, the factors that exert a significant effect on critical metal flows have yet to be identified.

From this background, this chapter aims to identify factors having a significant effect on the international flow of critical metals using an approach of the gravity model. The target critical metals here are neodymium, cobalt, and platinum described above. Forecasting the future structure of their paths is required since demand for these critical metals is expected to increase in the future (Elshkaki, 2013; Elshkaki and Graedel, 2013; Harper et al., 2012).

5.1 Method and Data

5.1.1 Synopsis of the gravity model of trade

The gravity model of trade is often used as a method of explaining the flow of trade value from the perspective of trade structure. Because this model is among the most successful empirical models in economics (Anderson, 2011), it has been applied to various flows (Tayyab et al., 2012) such as those of emigration (Simini et al., 2012), air travelers (Grosche et al., 2007), and trade value flows. In addition to the studies described in the *Introduction*, examples of application to environmental issues include that of Managi et al. (2009), who analyzed the effects of trade openness (bilateral trade flow / GDP of exporter) in trade policies on air pollutant concentrations and water-quality indicators. Costantini and Crespi (2008) analyzed the effects of tighter environmental controls on energy technology transfer.

The gravity model of trade expresses international trade between two regions analogously to Newton's gravity equation, as shown in Equation (43) below.

$$Y_{ij} = G\frac{M_i M_j}{D_{ij}^2} \tag{43}$$

where Y_{ij} is the bilateral flow from initial point i to destination j, and M_i and M_j are the economic scale in respective regions. If Y is a monetary value flow, i.e., the value of export between Region i and Region j, then M generally uses the GDP or GNI of each region. D_{ij} is the distance between the two regions. G is a constant. In general, the parameters of interest are estimated by ordinary least squares (OLS) after log-linearized Equation (43) (Santos and Tenreyro, 2006).

This study has estimated the factors that determine the international flows of neodymium, cobalt, and platinum from four perspectives including the economic scales, trade barriers, and demand and supply related to the use of metals in the countries or regions to be analyzed. A set of GDP or both GDP per capita and population is often used to express an economic scale. Trade barriers are represented by dummy variables of language and currency commonalities and membership in the World Trade Organization and regional trade agreements, as well as the distance separating the two countries. In addition, variables that are presumably related to the analyzed flows such as food consumption per capita in terms of virtual water (Tamea et al., 2009) are used in some cases. This study therefore has also selected variables that are likely to be related to a future increase in the consumption of critical metals from the demand and supply sides for the analysis.

Here in, I set the following Equation (44) to estimate the international flow of critical metals based on the above four perspectives.

$$
\begin{aligned}
\ln F_{ij} = \beta_0 + &\underbrace{\beta_1 \ln(gdp_i) + \beta_2 \ln(gdp_j) + \beta_3 \ln(pop_i) + \beta_4 \ln(pop_j)}_{\textit{Economic scale variables}} + \underbrace{\beta_5 \ln(dist_{ij}) + \beta_6 (rta_{ij})}_{\textit{Trade-related variables}} \ldots \\
&\underbrace{+\beta_7 \ln(m_i) + \beta_8 \ln(m_j) + \beta_9 \ln(c_i) + \beta_{10} \ln(c_j) + \beta_{11} \ln(w_i) + \beta_{12} \ln(w_j)}_{\textit{Demand-related variables}} \ldots \\
&\underbrace{+\beta_{13} \ln(ind_i) + \beta_{14} \ln(ind_j) + \beta_{15} \ln(re_i) + \beta_{16} \ln(re_j) + \beta_{17} (mc_i) + \beta_{18} (mc_j)}_{\textit{Supply-related variables}}
\end{aligned}
\tag{44}
$$

The explained variable *F* is the physical flow of critical metals from Region *i* to Region *j*. Variable *gdp* represents GDP per capita *(GDPpc*), *pop* denotes population (*Population*), and *dist* shows the distance between the two regions (*Distance*). Variable *rta* is a dummy variable that takes a value of 1 when the two regions have a regional trade agreement signed between them; it is 0 otherwise (*RTA).* Variable *m* stands for the percentage of motor vehicle ownership except for motor bikes (*Motor Vehicles*), c signifies the percentage of cellular phone contracts signed (*Cellular Phones*), and w denotes the percentage of internet access (*Internet Access*). Variable ind represents the value added of secondary industry as a percentage of GDP (*Industry Value Added*). Variable re represents the percentage of renewable energy in all energy production (*Renewable Energy*). Variable mc is a dummy variable that takes a value of 1 when the country mines the metal to be analyzed; it is 0 otherwise (*Mining Country*). $\beta = \beta_0, \beta_1, \ldots$ is a model parameter.

The terms in the first line of Equation (44) comprise variables related to the economic scales and trade barriers of the two countries. Based on a general gravity model of trade, the coefficients of *GDPpc* and *Population* are expected to be positive, and the coefficient of *distance* is expected to be negative. *RTA* expresses the effect of a bilateral regional trade agreement on the metal flows. The terms in the second line assess the effect on the demand side that is likely to have a strong relation with the critical metals analyzed in this work. *Motor Vehicles* is a variable that is expected to indicate relevance with the flows of neodymium, which is used commonly in motors, audio devices, and various other auto-parts, and platinum, which is useful as a catalyst for the purification of automobile exhaust gases. *Cellular Phones* and *Internet Access* are likely to reflect, indirectly, the diffusion of cellular phones, personal computers, and their accessories containing lithium secondary batteries made primarily of cobalt. Furthermore, the fact that household final demand for these variables induces significantly higher output of neodymium, cobalt, and platinum than other products has been confirmed in Chapters 2 and 4. Finally, the terms in the third line include variables to confirm the effect of changes in the supply side on the critical metal flows. *Industry Value Added* is an indicator included to assess the relation between the progress of industrialization in the regions analyzed and metal flows. *Renewable Energy* is used to observe how the diffusion of renewable energy such as wind power and solar power affects these critical metals. *Mining country* is used to assess the role of the countries mining the critical metals.

5.1.2 Dataset used for the gravity model

Table 5.1 presents the explanatory and explained variables in for the analysis. This study has used the flows of neodymium, cobalt, and platinum, between two countries in the 231 countries and regions identified by Nansai et al. (2014) as the explained variables. These flows were quantified by means of MFA, using trade data (BACI) and the metal contents of trade commodities, resolving the optimization problem to ensure the material balance of the metals within each country and regions (Nansai et al., 2014). The composition of these flows includes all the primary products, intermediate goods, final products, and scrap. The dummies in *Mining Countries* were also determined using the results of Nansai et al. (2014). These results are values from year 2005. For the corresponding cross-section data, the values for year 2005 or the nearest years in the World Development Indicators database (World Bank) were used for *GDP per capita, Population, Motor Vehicles, Cellular Phones, Internet Access, Industry Value Added*, and *Renewable Energy*. For *Distance* and *RTA*, dummy variables indicating the distances between the capitals of two regions in the study and presence of bilateral regional trade agreements were quoted from the CEPII distance database (Head et al., 2010).

Table 5.1 Statistics of cross sectional data for 2005.

Variables	Obs.	Mean	Std. Dev.	Min	Max
Dependent					
Nd flow [t]	53361	0.32	19.6	0	4047
Co flow [t]	53361	2.88	76.6	0	7750
Pt flow [t]	53361	0.0075	0.31	0	35.5
Independent					
GDP per capita [US$]	45507	9444	16970	0	126599
Population [million person]	47124	31.4	127.7	0	1303.7
Motor vehicles [%]	35343	15.0	20.4	0	81.6
Cellular phone [%]	39732	38.8	37.7	0	166.5
Internet access [%]	45507	17.3	22.0	0	87.0
Industry, value added [% of GDP]	42273	23.2	17.3	0	87.1
Renewable electricity output [% of T.E]	33726	25.1	32.3	0	100.0
Mining country of Nd dummy	924			0	1
Mining country of Co dummy	11550			0	1
Mining country of Pt dummy	4389			0	1
RTA dummy	2704			0	1

5.1.3 Treatment of zero flow in explained variables

The critical metal flows used in the analysis include a considerable number of zero data due to not only non-existent bilateral flows, but also incomplete data. As noted in Subsection 5.2.1, the conventional gravity model (OLS) uses the logarithms of flows between two countries and therefore excludes the zero flows. However, using such data may cause significant errors in the parameter estimates, as indicated in the several literature (Fracasso, 2014; Kellenberg, 2012; WTO, 2012). This study therefore used the Poisson pseudo-maximum likelihood (PPML) estimator, which is known as one solution to such a problem (Santos and Tenreyro, 2006). This method allows estimation using values before taking the logarithms of the flows. It is therefore regarded as a strong approach to the scattering or unevenness that is often found in data related to international trade (Santos

Silva and Tenreyro, 2006). This method is used also by Fracasso (2014) and Kellenberg (2012) introduced in Subsection 5.2.1. Using Equation (45) based on PPML, this work examined the significance of parameters and their usefulness in the estimation of value of the flows.

$$F_{ij} = \exp\left[\begin{array}{l} \beta_0 + \beta_1 \ln(gdp_i) + \beta_2 \ln(gdp_j) + \beta_3 \ln(pop_i) + \beta_4 \ln(pop_j) + \beta_5 \ln(dist_{ij}) + \beta_6 (rta_{ij})... \\ \\ +\beta_7 \ln(m_i) + \beta_8 \ln(m_j) + \beta_9 \ln(c_i) + \beta_{10} \ln(c_j) + \beta_{11} \ln(w_i) + \beta_{12} \ln(w_j)... \\ \\ +\beta_{13} \ln(ind_i) + \beta_{14} \ln(ind_j) + \beta_{15} \ln(re_i) + \beta_{16} \ln(re_j) + \beta_{17} (mc_i) + \beta_{18} (mc_j) \end{array}\right] \tag{45}$$

5.2 Results

5.2.1 Results of OLS-based estimation

Table 5.2 presents the results of estimating the international flows of neodymium, cobalt, and platinum using OLS. Signs *i* and *j* in the tail respectively indicate the coefficients of the export side and import side. The following sections describe the characteristics of the estimation results for each of the critical metals.

(a) Neodymium

The neodymium flow indicated high significance in the coefficients of economic scale (*GDPpc* and *Population)*, distance (*Distance*), and regional trade agreements (*RTA).* The signs of the coefficients of economic scale and *RTA* are positive, suggesting these are factors that increase the flow. The coefficient of *Distance* is negative, indicating this is a factor that decreases the flow.

Subsequently among the variables related to demand, the export-side coefficient of *Motor Vehicles* is negative at a significance level of 1% or below, which suggests that the progress of motorization in regions on the export side has the function of reducing the outflow of neodymium to other countries. The coefficient of *Cellular Phones* is not significant, thus there seems less relation between the diffusion of cellular phones and the neodymium flow. In contrast, the coefficients of both the export and import sides of *Internet Access* are positive with highly significant. This indicates these factors contribute strongly to an increase in the flow. A probable reason for this is related to the use of neodymium for motors in hard disk drives.

Unlike the variables related to demand, the results of all variables related to supply, including *Industry Value Added*, *Renewable Energy*, and *Mining Country*, are not significant. In other words, these factors are likely to have little effect on the neodymium flow. Part of the reason for the little effect of the distinction of whether the country engages in mining is presumably the fact that there are only four neodymium mining countries.

Table 5.2 Gravity regressions of the critical metal flows for neodymium, cobalt, and platinum in OLS estimates.

	Dependent variables		
Variables	Nd flow	Co flow	Pt flow
GDP per capita i	1.944***	1.773***	1.934***
	(0.113)	(0.113)	(0.101)
GDP per capita j	0.750***	0.994***	0.673***
	(0.108)	(0.110)	(0.097)
Population i	2.179***	1.654***	1.997***
	(0.046)	(0.047)	(0.039)
Population j	1.045***	1.355***	0.961***
	(0.045)	(0.046)	(0.039)
Distance	-2.189***	-2.279***	-1.891***
	(0.085)	(0.087)	(0.077)
RTA (dummy)	1.491***	1.196***	1.069***
	(0.203)	(0.208)	(0.182)
Motor vehicles i	-1.447***	-1.174***	-1.519***
	(0.141)	(0.145)	(0.126)
Motor vehicles j	-0.096	-0.337***	-0.102
	(0.125)	(0.128)	(0.112)
Cellular phone i	0.114	-0.649***	-0.475***
	(0.140)	(0.143)	(0.129)
Cellular phone j	0.153	0.205*	0.137
	(0.119)	(0.122)	(0.108)
Internet access i	1.565***	1.027***	1.718***
	(0.123)	(0.122)	(0.109)
Internet access j	0.301***	0.317***	0.346***
	(0.111)	(0.110)	(0.099)
Industry, value added i	-0.251	-0.328	-1.070***
	(0.238)	(0.240)	(0.214)
Industry, value added j	-0.214	-0.474**	-0.423**
	(0.210)	(0.218)	(0.189)
Renewable energy i	0.032	-0.108***	-0.081***
	(0.034)	(0.035)	(0.031)
Renewable energy j	-0.025	0.002	-0.002
	(0.033)	(0.034)	(0.030)
Mining country i (dummy)	0.343	-0.237	0.634***
	(0.313)	(0.150)	(0.153)
Mining country j (dummy)	0.261	-0.363**	0.495***
	(0.367)	(0.151)	(0.168)
Constant	-69.46***	-59.86***	-65.61***
	(1.699)	(1.776)	(1.537)
R-squared	0.396	0.302	0.403
Adjusted R-squared	0.395	0.301	0.402
S.E. of regression	6.08	6.25	5.45
Observations	9317	9464	9233

Standard errors in parenthesis.
*10% significant level.
**5% significant level.
***1% significant level.

(b) Cobalt

The observation confirmed that the coefficients of *GDPpc* and *Population, Distance,* and *RTA* of the cobalt flow are all significant at 1% or below. The coefficients of economic scale and *RTA* of the cobalt flow are positive, which are factors that induce an increase in the flow. The coefficient of *Distance* is negative, which contributes to a decrease in the flow. These tendencies of coefficient are same as those of the neodymium flow. Among the variables related to demand, the coefficients of *Motor Vehicles, Cellular Phones,* and *Internet Access* are significant both on the export and import sides. Both of the coefficients of *Motor Vehicles* on the export and import sides are negative, which are factors that are important to a decrease in the cobalt flow. The effect of diffusion of cellular phones in the export countries on the cobalt flow differs from the tendency where does not influence on the neodymium flow. Among the variables related to supply, the coefficient of export-side *Renewable Energy* and that of import-side *Industry Value Added* and *Mining Country* indicate negative significance. Form the tendency of *Mining Country*, it seems that mining countries of cobalt do not receive a large inflow of cobalt, suggesting the flow is likely to be unidirectional.

(c) Platinum

Like the two flows described earlier, the platinum flow demonstrates a tendency by which it is proportional to an economic scale and inversely proportional to an interregional distance. Among the variables related to demand, only the export-side coefficients of *Motor Vehicles* and *Cellular Phones* were found to be negative and significant, which implies that all factors work to reduce the outflow of platinum. In the same manner of the neodymium and cobalt flows, the result of *Internet Access* demonstrates the contribution of personal computer diffusion rate to the growth of the flow on both the export and import sides. As shown the variables related to supply, a tendency of *Industry Value Added* is, in contrast to *Internet Access,* negative and significant on both sides. *Renewable Energy* indicates negative significance only on the export side, as in the case of the cobalt flow. The coefficient of *Mining Country* of the platinum flow, however, exhibits high positive significance on both sides in contrast to the results of the neodymium and cobalt flows. These points suggest that, unlike cobalt, platinum inflow occurs also in the mining countries.

5.2.2 Assessment of strength of coefficients with PPML estimation

Table 5.3 exhibits the results of estimating the neodymium, cobalt, and platinum flows using PPML. The coefficients of determination in this table were calculated from the linear approximation using flow values utilized for the explained variables and flow values obtained from the results of PPML estimation equation.

Table 5.3 reveals that most variables are significant at the 1% level. Particularly all coefficients other than the export-side *Cellular Phones* in the neodymium flow and all coefficients in the cobalt flow are highly significant. Therefore, the PPML of the neodymium and cobalt flows supports all variables indicated to be highly significant in the OLS. Some variables, however, have coefficients with signs opposite of those in the OLS. The sign of *RTA* became negative in the PPML from positive in the OLS in the neodymium flow, which is a factor contributing to a decrease in the flow. In the cobalt flow, the coefficients of *RTA* and the export-side of *Internet Access* changed to negative, and the coefficients of the export-side of *Cellular Phone* and *Renewable Energy* and the import-side of *Motor Vehicles, Cellular Phones, Industry Value Added,* and *Mining Country* changed to positive. Regarding the platinum flow, the coefficient of the import-side *Cellular Phones* became positive and the coefficients of *Internet Access* and *Mining Country* turned to be negative. *RTA* and the import-side of *Internet Access* were found to be significant in the OLS, but no significance was found in the PPML. The signs and significance of the coefficients of *GDPpc*, *Population*, and *Distance* became the same as the OLS results in all the neodymium, cobalt, and platinum flows, demonstrating more strength than the demand and supply-related variables.

Table 5.3 Gravity regressions of critical metal flows for neodymium, cobalt, and platinum in PPML estimates.

	Dependent variables		
Variables	Nd flow	Co flow	Pt flow
GDP per capita i	0.731***	1.001***	1.508***
	(0.035)	(0.005)	(0.226)
GDP per capita j	0.446***	0.246***	2.696***
	(0.029)	(0.007)	(0.318)
Population i	1.134***	0.389***	0.871***
	(0.011)	(0.002)	(0.066)
Population j	0.957***	0.762***	1.201***
	(0.008)	(0.002)	(0.062)
Distance	-1.001***	-0.803***	-0.204***
	(0.012)	(0.003)	(0.076)
RTA (dummy)	-0.261***	-0.527***	-0.024
	(0.038)	(0.010)	(0.172)
Motor vehicles i	-1.071***	-0.561***	-0.702***
	(0.033)	(0.005)	(0.197)
Motor vehicles j	0.374***	0.127***	-1.597***
	(0.031)	(0.007)	(0.239)
Cellular phone i	1.018***	0.354***	3.585***
	(0.046)	(0.005)	(0.264)
Cellular phone j	-0.046	-0.872***	0.382
	(0.032)	(0.006)	(0.313)
Internet access i	0.996***	-0.567***	-2.031***
	(0.038)	(0.005)	(0.217)
Internet access j	0.420***	1.106***	0.349
	(0.030)	(0.007)	(0.251)
Industry, value added i	1.954***	0.670***	-1.742***
	(0.067)	(0.010)	(0.339)
Industry, value added j	0.328***	1.060***	0.511
	(0.054)	(0.013)	(0.404)
Renewable energy i	0.044***	0.174***	-0.076*
	(0.009)	(0.002)	(0.040)
Renewable energy j	0.176***	0.080***	0.130**
	(0.009)	(0.002)	(0.065)
Mining country i (dummy)	1.135***	1.490***	1.893***
	(0.050)	(0.007)	(0.164)
Mining country j (dummy)	0.463***	0.037***	-0.354**
	(0.044)	(0.006)	(0.153)
Constant	-54.34***	-27.84***	-78.60***
	(0.587)	(0.106)	(4.838)
R-squared	0.905	0.066	0.540
Log likelihood	52724	398565	-247
Observations	20592	20592	20592

Standard errors in parenthesis.

*10% significant level.

**5% significant level.

***1% significant level.

5.2.3 Estimation of critical metal flows using the gravity model

This subsection specifically examines the real values of flows obtained from the estimation equations based on the OLS and PPML in the previous subsections. The sum totals of neodymium, cobalt, and platinum flows explained by the OLS estimation equation were 42%, 1.3%, and 9.1%, respectively, of the total of the flows used for the explained variables. On the other hand, in the PPML estimation, each of the sum total of the critical metal flows exceeded 85% of the relative total flow in the explained variables. It might be occurred an error, however, that places where the explained variable is 0 can be greater than 0 in the PPML estimation. Errors caused by such zero-flow estimation were calculated as 1.6% for neodymium, 12% for cobalt, and 0.8% for platinum of the total flow. Particularly in cross-section data, however, identifying true 0 flows in incomplete data is extremely difficult (WTO, 2012).

Next, I observed the difference between the composition of the estimated flows and the composition of the original explained variables. Figure 5.1 is a scatter diagram with the values of explained variables normalized to the total amount on the horizontal axis and the flows calculated from the OLS estimation equation normalized to the total amount on the vertical axis. The coefficient of determination for any of the critical metal flows is extremely small, which implies the calculated structure of flows is not similar to that of original flows as the explained variables at all. Figure 5.2 is a scatter diagram that compares the composition of PPML estimates and the original explained variables using the same method as Figure 5.1. A comparison with the OLS reveals a good general correlation in neodymium and platinum. Among the critical metals, the coefficients of determination of neodymium, platinum, and cobalt, from the highest to the lowest, are, respectively, 0.905, 0.540, and

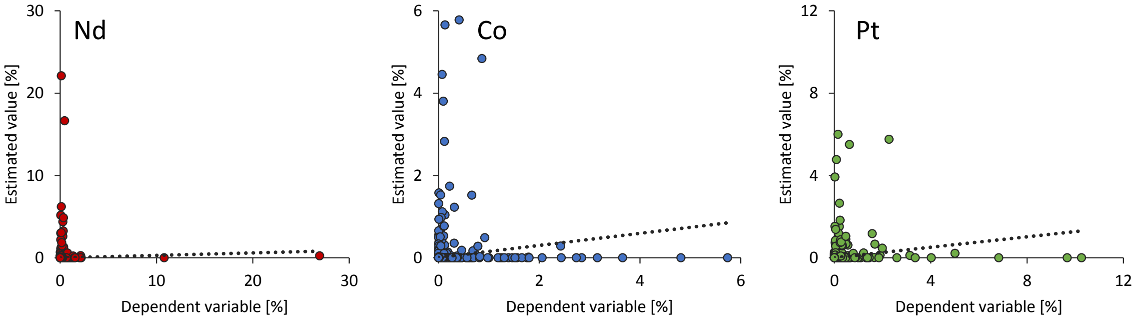


Figure 5.1 Flows estimated by the OLS and flows used for the explained variables. Values on the horizontal axis are values of explained variables normalized to the total amount. Values on the vertical axis are those of the critical metal flows calculated from the OLS estimation normalized to the total amount.

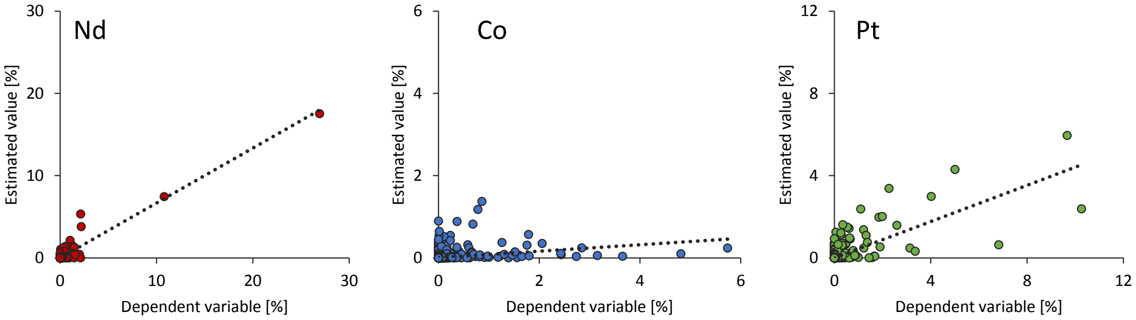


Figure 5.2 Flows estimated using PPML and flows used for the explained variables. Values on the horizontal axis are the values of explained variables normalized to the total amount. Values on the vertical axis are those of the critical metal flows calculated from the PPML estimation normalized to the total amount.

0.066.

Based on the similarity to the composition of the original flows as explained variables and the total amount of them, therefore, a PPML estimation equation is more appropriate than OLS for the prediction of real values of flows. The reason why the result of OLS estimation occurred the large deviation from the original flow can be the significant error that might result from returning the expected value taken for log linearization in the estimation to the real number.

5.3 Discussions

5.3.1 Estimation of critical metal flows by economic group

Preceding sections presented discussion of the use of a gravity model for the neodymium, cobalt, and platinum flows of the entire world. As noted in Subsection 5.2.2, the economic scale (*GDPpc* and *Population*) of two countries engaging in bilateral trade was indicated as an important and strong factor in all the flows. Considering the recent rapid economic growth particularly of emerging countries, I here examines the applicability of a gravity model to critical metal flows at the regional level with focus on differences in economic standards of nation as follows.

First, countries of interest were classified into three groups (Table S2 in Appendix) – *H* ("high income (OECD)" and "high income"), *M* ("upper middle income" and "lower middle income"), and *L* ("low income") – based on the country income classes published by the World Bank. Hereafter, each of bilateral flows will be expressed as for instance, *H*to*M* (from a country belonging to *H* to a country belonging to *M*).

Tables 5.4–5.6 display results of PPML estimation of the nine flow patterns from *H*to*H*

Table 5.4 Gravity regressions of neodymium flows between economic groups in PPML estimates.

	Nd flow								
Variables	*H* to *H*	*H* to *M*	*H* to *L*	*M* to *H*	*M* to *M*	*M* to *L*	*L* to *H*	*L* to *M*	*L* to *L*
GDP per capita i	0.337***	2.648***	3.726	-0.314**	-0.203	-0.525	2.206	2.392	0.848
	(0.063)	(0.179)	(3.593)	(0.150)	(0.175)	(0.496)	(1.716)	(4.651)	(4.206)
GDP per capita j	-0.139**	-1.230***	-0.640	2.061***	0.278***	5.930***	1.477**	-2.705	1.492
	(0.066)	(0.104)	(2.435)	(0.081)	(0.105)	(1.307)	(0.606)	(2.231)	(2.461)
Population i	0.828***	1.682***	1.180*	1.264***	0.784***	1.184***	-0.059	2.933*	1.280
	(0.018)	(0.054)	(0.656)	(0.053)	(0.059)	(0.261)	(0.676)	(1.671)	(1.326)
Population j	0.674***	1.187***	1.421*	1.066***	1.137***	0.598	0.258**	-0.359	-0.150
	(0.016)	(0.041)	(0.848)	(0.020)	(0.040)	(0.388)	(0.115)	(0.567)	(0.735)
Distance	-0.780***	-1.234***	-1.886	-1.212***	-1.206***	-1.466***	-3.788***	-0.913	-1.606**
	(0.026)	(0.039)	(2.349)	(0.019)	(0.058)	(0.265)	(0.971)	(0.617)	(0.740)
RTA (dummy)	-0.244***	-0.413***	3.763	0.072	1.509***	-0.156	-14.41	2.242	1.220
	(0.070)	(0.099)	(5.782)	(0.107)	(0.121)	(0.654)	(471.1)	(1.613)	(1.423)
Motor vehicles i	-0.620***	-2.341***	-0.845	-0.828***	-1.488***	0.698	0.076	0.494	-0.802
	(0.096)	(0.224)	(4.363)	(0.111)	(0.145)	(0.456)	(0.638)	(1.140)	(0.823)
Motor vehicles j	1.115***	0.660***	-0.664	-0.676***	0.958***	-1.972***	0.988	-1.122	0.223
	(0.114)	(0.079)	(0.693)	(0.104)	(0.094)	(0.433)	(1.104)	(1.349)	(0.679)
Cellular phone i	1.028***	-1.672***	3.983	2.228***	3.093***	-0.587*	-0.762	0.721	1.760
	(0.106)	(0.182)	(2.964)	(0.128)	(0.171)	(0.350)	(0.637)	(1.943)	(2.425)
Cellular phone j	0.551***	1.554***	0.303	-1.007***	0.061	-0.588	1.402	4.526*	-0.599
	(0.106)	(0.094)	(1.137)	(0.083)	(0.079)	(0.449)	(1.499)	(2.436)	(1.124)
Internet access i	1.076***	0.752***	-1.509	0.970***	0.544***	0.070	-0.034	1.408	0.521
	(0.069)	(0.129)	(2.314)	(0.088)	(0.113)	(0.321)	(0.579)	(1.404)	(1.003)
Internet access j	1.009***	0.834***	1.450*	-0.346***	0.157**	1.276***	1.014	-0.902	-1.162
	(0.076)	(0.068)	(0.836)	(0.069)	(0.072)	(0.392)	(0.788)	(1.051)	(1.027)
Industry, value added i	0.661***	2.365***	-1.085	3.553***	1.865***	-0.610	6.014***	-6.601	-1.282
	(0.113)	(0.251)	(3.219)	(0.202)	(0.275)	(0.772)	(1.631)	(7.674)	(4.123)
Industry, value added j	0.207*	1.528***	-0.110	-0.052	-0.180	10.61***	0.259	1.776	1.096
	(0.110)	(0.178)	(2.835)	(0.117)	(0.168)	(1.775)	(0.929)	(1.874)	(1.774)
Renewable energy i	0.013	0.219***	0.013	0.064	-0.080	-0.604***	0.428	0.973	-0.190
	(0.015)	(0.026)	(0.634)	(0.045)	(0.052)	(0.169)	(0.372)	(1.444)	(0.220)
Renewable energy j	0.010	0.215***	-0.136	0.243***	0.119***	-0.526**	-0.305**	0.077	0.255
	(0.017)	(0.032)	(0.234)	(0.016)	(0.036)	(0.228)	(0.145)	(0.578)	(0.323)
Mining country i (dummy)	0.000	0.000	0.000	0.707***	1.508***	0.149	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.132)	(0.151)	(0.775)	(0.000)	(0.000)	(0.000)
Mining country j (dummy)	0.000	-1.416***	0.000	0.000	0.692***	0.000	0.000	1.723	0.000
	(0.000)	(0.115)	(0.000)	(0.000)	(0.086)	(0.000)	(0.000)	(4.446)	(0.000)
Constant	-40.70***	-67.48***	-72.31*	-63.55***	-45.13***	-80.62***	-36.60	-39.15	-27.86
	(1.343)	(2.802)	(43.48)	(1.638)	(1.842)	(13.11)	(23.99)	(32.94)	(37.36)
R-squared	0.265	0.393	0.265	0.977	0.796	0.622	0.039	0.354	0.375
Observations	1980	3375	1035	3375	5550	1725	1035	1725	506

Standard errors in parenthesis.

*10% significance level.

**5% significance level.

***1% significance level.

Table 5.5 Gravity regressions of cobalt flows between economic groups in PPML estimates.

	Co flow								
Variables	*H* to*H*	*H* to*M*	*H* to*L*	*M* to*H*	*M* to*M*	*M* to*L*	*L* to*H*	*L* to*M*	*L* to*L*
GDP per capita i	0.594***	0.634***	0.149	-0.588***	0.678***	-2.024***	-5.506***	-4.024***	0.592*
	(0.015)	(0.035)	(0.274)	(0.022)	(0.029)	(0.115)	(0.307)	(0.235)	(0.306)
GDP per capita j	1.683***	1.146***	2.874**	1.438***	0.328***	-1.432***	-1.300***	0.884***	0.325
	(0.023)	(0.051)	(1.341)	(0.031)	(0.033)	(0.220)	(0.066)	(0.050)	(0.342)
Population i	0.470***	0.506***	-0.094	-0.084***	-0.089***	-0.123***	1.596***	0.649***	1.251***
	(0.004)	(0.009)	(0.075)	(0.007)	(0.008)	(0.023)	(0.106)	(0.081)	(0.104)
Population j	0.725***	1.362***	2.844***	0.657***	0.700***	1.092***	-0.794***	0.056***	1.833***
	(0.005)	(0.019)	(0.444)	(0.006)	(0.013)	(0.089)	(0.033)	(0.012)	(0.111)
Distance	-0.864***	-0.997***	-0.236	-0.475***	-0.269***	-1.354***	-0.249***	-0.231***	-3.649***
	(0.007)	(0.014)	(0.428)	(0.010)	(0.017)	(0.027)	(0.089)	(0.010)	(0.096)
RTA (dummy)	-1.992***	0.162***	3.767*	0.140***	1.102***	2.068***	-5.491	4.528***	-5.381***
	(0.019)	(0.034)	(2.275)	(0.026)	(0.039)	(0.083)	(391.2)	(0.082)	(0.150)
Motor vehicles i	-0.851***	0.409***	1.114**	-1.345***	-1.465***	-0.008	-0.879***	-1.201***	2.048***
	(0.022)	(0.047)	(0.475)	(0.019)	(0.023)	(0.070)	(0.137)	(0.075)	(0.124)
Motor vehicles j	-0.606***	0.150***	-0.410	0.463***	-0.676***	-0.105*	1.019***	-2.877***	2.039***
	(0.028)	(0.040)	(0.304)	(0.039)	(0.028)	(0.055)	(0.159)	(0.038)	(0.099)
Cellular phone i	0.314***	-0.662***	0.311	1.339***	0.902***	0.083	0.205	-0.374***	-0.113
	(0.022)	(0.059)	(0.637)	(0.016)	(0.021)	(0.090)	(0.143)	(0.084)	(0.173)
Cellular phone j	-0.959***	0.253***	1.415**	-1.128***	1.507***	-0.191**	3.141***	1.430***	1.216***
	(0.030)	(0.038)	(0.583)	(0.041)	(0.033)	(0.089)	(0.209)	(0.032)	(0.201)
Internet access i	0.958***	1.750***	-0.684*	-0.038***	-0.270***	0.846***	1.261***	1.494***	-1.458***
	(0.017)	(0.044)	(0.392)	(0.013)	(0.014)	(0.061)	(0.168)	(0.088)	(0.114)
Internet access j	1.245***	0.001	0.419	1.250***	-0.338***	1.841***	5.712***	-0.030	0.827***
	(0.021)	(0.029)	(0.446)	(0.031)	(0.022)	(0.078)	(0.136)	(0.026)	(0.128)
Industry, value added i	0.335***	1.471***	0.471	3.639***	2.607***	1.279***	4.847***	6.573***	-0.157
	(0.026)	(0.055)	(0.392)	(0.037)	(0.044)	(0.145)	(0.341)	(0.231)	(0.408)
Industry, value added j	0.598***	2.169***	-8.107***	0.568***	1.657***	-1.218***	0.447***	4.220***	-4.101***
	(0.027)	(0.064)	(1.182)	(0.038)	(0.048)	(0.281)	(0.115)	(0.061)	(0.445)
Renewable energy i	0.117***	-0.024***	0.203***	-0.410***	-0.390***	-0.240***	-0.274***	2.677***	0.088
	(0.003)	(0.008)	(0.069)	(0.008)	(0.009)	(0.037)	(0.037)	(0.168)	(0.060)
Renewable energy j	-0.036***	-0.078***	0.064	-0.132***	0.005	-0.114***	-0.635***	-0.182***	1.315***
	(0.004)	(0.012)	(0.127)	(0.006)	(0.011)	(0.026)	(0.027)	(0.015)	(0.103)
Mining country i (dummy)	1.097***	0.146***	0.106	3.982***	2.517***	2.565***	2.028***	2.660***	3.633***
	(0.011)	(0.024)	(0.255)	(0.034)	(0.035)	(0.068)	(0.155)	(0.096)	(0.223)
Mining country j (dummy)	-0.567***	-1.253***	1.003	-0.460***	0.366***	0.378***	6.064***	4.384***	-0.144
	(0.012)	(0.049)	(0.767)	(0.016)	(0.037)	(0.114)	(0.113)	(0.079)	(0.146)
Constant	-36.34***	-57.27***	-48.52***	-33.86***	-34.58***	14.29***	-28.69***	-45.27***	-24.50***
	(0.381)	(0.690)	(13.832)	(0.472)	(0.425)	(2.001)	(2.848)	(1.685)	(3.656)
R-squared	0.178	0.462	0.178	0.332	0.240	0.995	0.465	0.935	0.999
Observations	1980	3375	1035	3375	5550	1725	1035	1725	506

Standard errors in parenthesis.
*10% significance level.
**5% significance level.
***1% significance level.

Table 5.6 Gravity regressions of platinum flows between economic groups in PPML estimates.

	Pt flow								
Variables	*H* to*H*	*H* to*M*	*H* to*L*	*M* to*H*	*M* to*M*	*M* to*L*	*L* to*H*	*L* to*M*	*L* to*L*
GDP per capita i	1.365***	4.162**	2.619	3.457**	1.188	0.326	-1.169	-1.241	-2.526
	(0.416)	(1.893)	(46.40)	(1.558)	(1.877)	(20.99)	(59.64)	(25.24)	(88.13)
GDP per capita j	2.677***	1.554	-1.225	2.971***	0.299	1.766	5.890	-0.606	4.221
	(0.572)	(0.957)	(40.63)	(1.047)	(2.030)	(30.93)	(77.78)	(16.73)	(110.8)
Population i	1.194***	2.117***	1.680	1.705***	0.913	1.126	1.260	-0.298	3.216
	(0.111)	(0.553)	(11.18)	(0.442)	(0.659)	(5.815)	(22.11)	(9.179)	(45.34)
Population j	1.186***	1.211***	1.356	2.228***	1.341***	0.908	1.578	0.684	0.504
	(0.124)	(0.268)	(14.36)	(0.309)	(0.503)	(11.37)	(16.54)	(5.003)	(27.12)
Distance	-0.697***	-0.790**	-1.470	-1.061*	-0.276	-1.293	-1.879	-0.126	-2.903
	(0.128)	(0.327)	(27.44)	(0.557)	(1.119)	(6.830)	(40.05)	(9.425)	(28.54)
RTA (dummy)	-0.490	-0.986	-0.061	-2.789***	2.947	1.897	2.693	2.792	1.404
	(0.328)	(0.807)	(164.1)	(0.468)	(2.509)	(19.51)	(75.50)	(20.51)	(36.75)
Motor vehicles i	-1.950***	-5.390**	-2.182	-0.837	-0.410	-0.130	0.360	-0.045	-0.909
	(0.481)	(2.230)	(54.90)	(1.064)	(1.858)	(17.82)	(16.90)	(7.906)	(28.17)
Motor vehicles j	-0.504	-0.696	-0.531	-4.269***	-0.671	0.377	-7.419	0.819	1.325
	(0.797)	(0.710)	(14.23)	(1.105)	(1.488)	(11.70)	(75.81)	(15.67)	(28.70)
Cellular phone i	1.942***	2.022	-0.562	2.357*	1.427	-1.401	2.344	0.625	4.415
	(0.464)	(1.603)	(50.41)	(1.291)	(2.056)	(12.30)	(43.22)	(14.65)	(82.27)
Cellular phone j	0.853*	0.635	1.263	5.948***	1.057	0.628	-5.083	1.436	0.661
	(0.513)	(0.690)	(27.01)	(1.588)	(1.750)	(14.46)	(116.8)	(17.02)	(51.08)
Internet access i	0.142	0.504	1.446	-0.862	-0.359	1.907	-0.140	-0.170	-0.421
	(0.390)	(1.288)	(30.64)	(1.141)	(1.457)	(11.43)	(18.45)	(10.58)	(31.07)
Internet access j	0.568	0.458	-0.354	2.215**	0.818	-0.129	0.528	-0.793	-3.202
	(0.402)	(0.634)	(13.71)	(0.982)	(1.228)	(11.81)	(39.29)	(10.55)	(44.52)
Industry, value added i	-0.338	-0.919	3.245	-2.606	-2.971	-0.056	-5.718	-0.352	-6.821
	(0.627)	(2.043)	(48.17)	(3.021)	(3.903)	(26.33)	(85.30)	(27.66)	(165.3)
Industry, value added j	1.166**	-0.230	0.348	-1.848*	-0.537	-2.688	0.922	-1.399	-2.765
	(0.556)	(1.470)	(56.07)	(1.062)	(3.190)	(45.20)	(55.04)	(26.47)	(94.08)
Renewable energy i	0.211**	0.991**	0.098	-0.942***	-0.652	0.288	0.598	0.342	0.223
	(0.093)	(0.466)	(5.841)	(0.284)	(0.518)	(7.191)	(15.94)	(8.027)	(8.148)
Renewable energy j	-0.051	-0.357	0.060	0.867***	0.001	0.790	0.255	0.176	1.505
	(0.112)	(0.245)	(5.012)	(0.251)	(0.689)	(11.66)	(6.679)	(5.575)	(28.07)
Mining country i (dummy)	0.768***	-0.912*	-1.202	2.889***	1.445	1.075	2.143	-0.716	8.094
	(0.185)	(0.535)	(18.97)	(0.855)	(1.402)	(14.99)	(84.05)	(50.31)	(144.6)
Mining country j (dummy)	-0.454**	-0.021	2.950	-1.250***	-0.006	-0.693	-3.625	1.047	-5.135
	(0.208)	(0.737)	(62.23)	(0.327)	(1.602)	(48.07)	(52.48)	(18.14)	(2681)
Constant	-88.26***	-100.7***	-78.46	-132.2***	-51.5**	-43.93	-38.91	-7.190	-49.42
	(8.968)	(23.10)	(750.3)	(21.98)	(24.03)	(319.8)	(859.6)	(249.1)	(941.8)
R-squared	0.457	0.435	0.457	0.818	0.979	0.639	0.747	0.348	0.871
Observations	1980	3375	1035	3375	5550	1725	1035	1725	506

Standard errors in parenthesis.
*10% significance level.
**5% significance level.
***1% significance level.

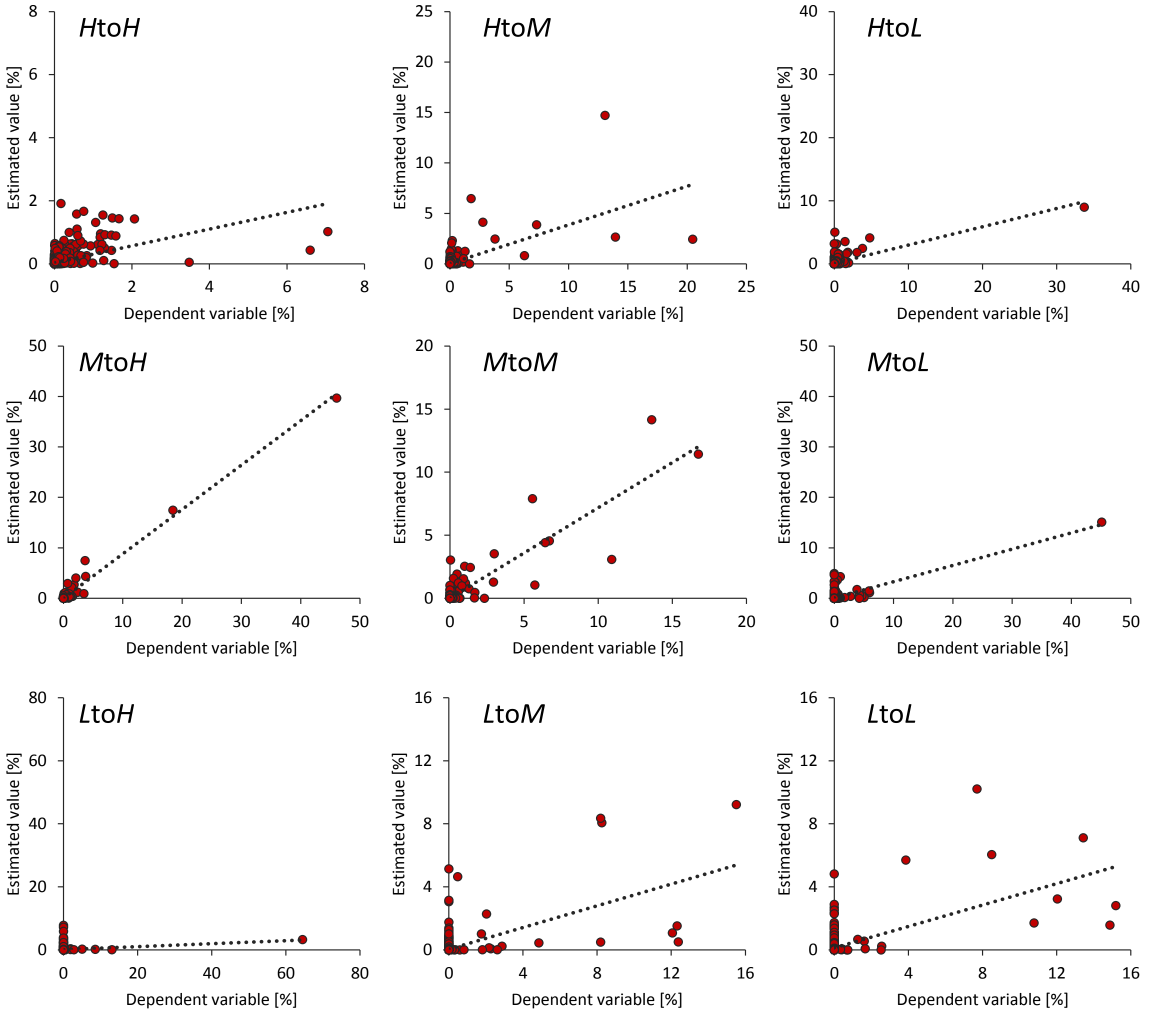


Figure 5.3 Flows of neodymium between economic groups estimated using PPML and flows used for the explained variables.

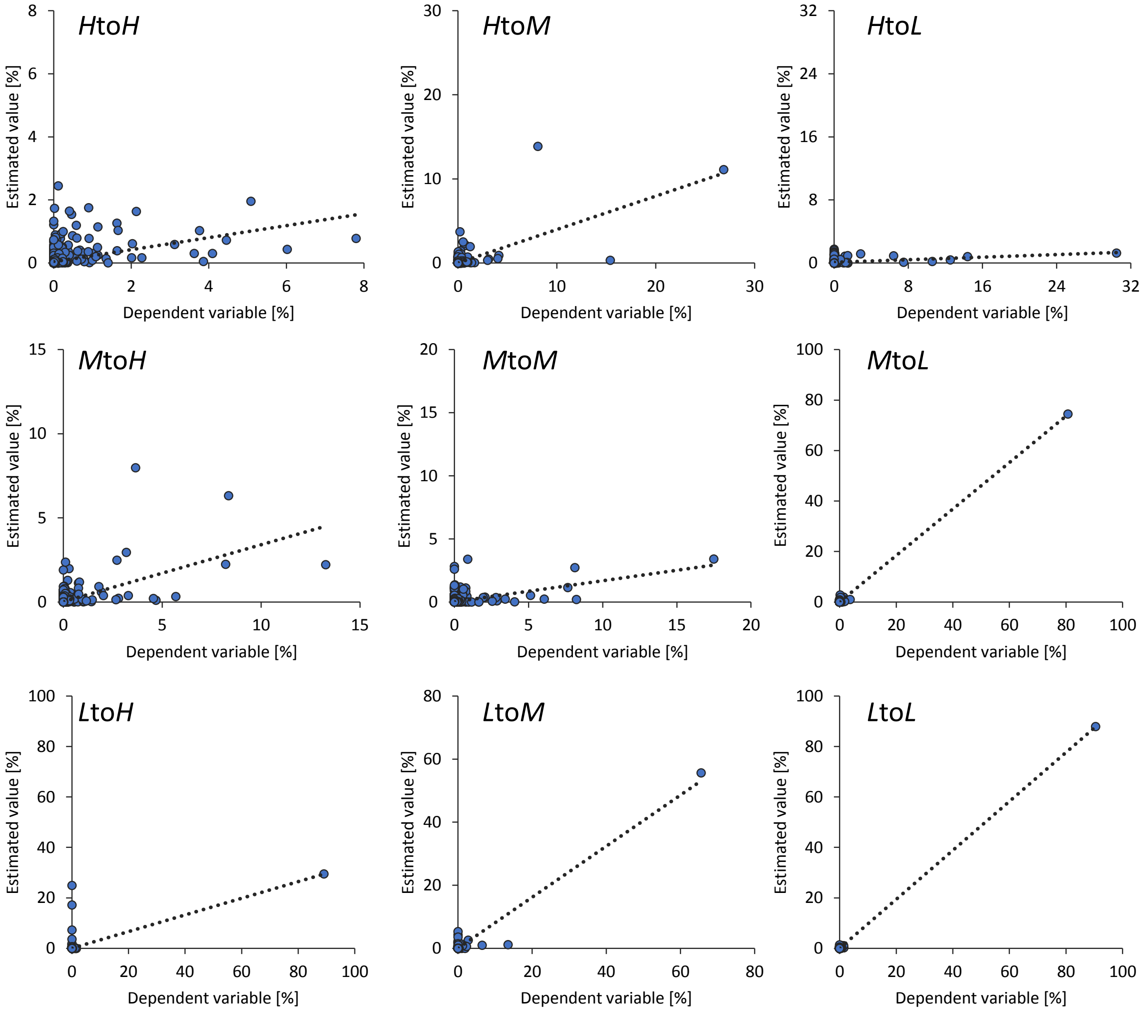


Figure 5.4 Flows of cobalt between economic groups estimated using PPML and flows used for the explained variables.

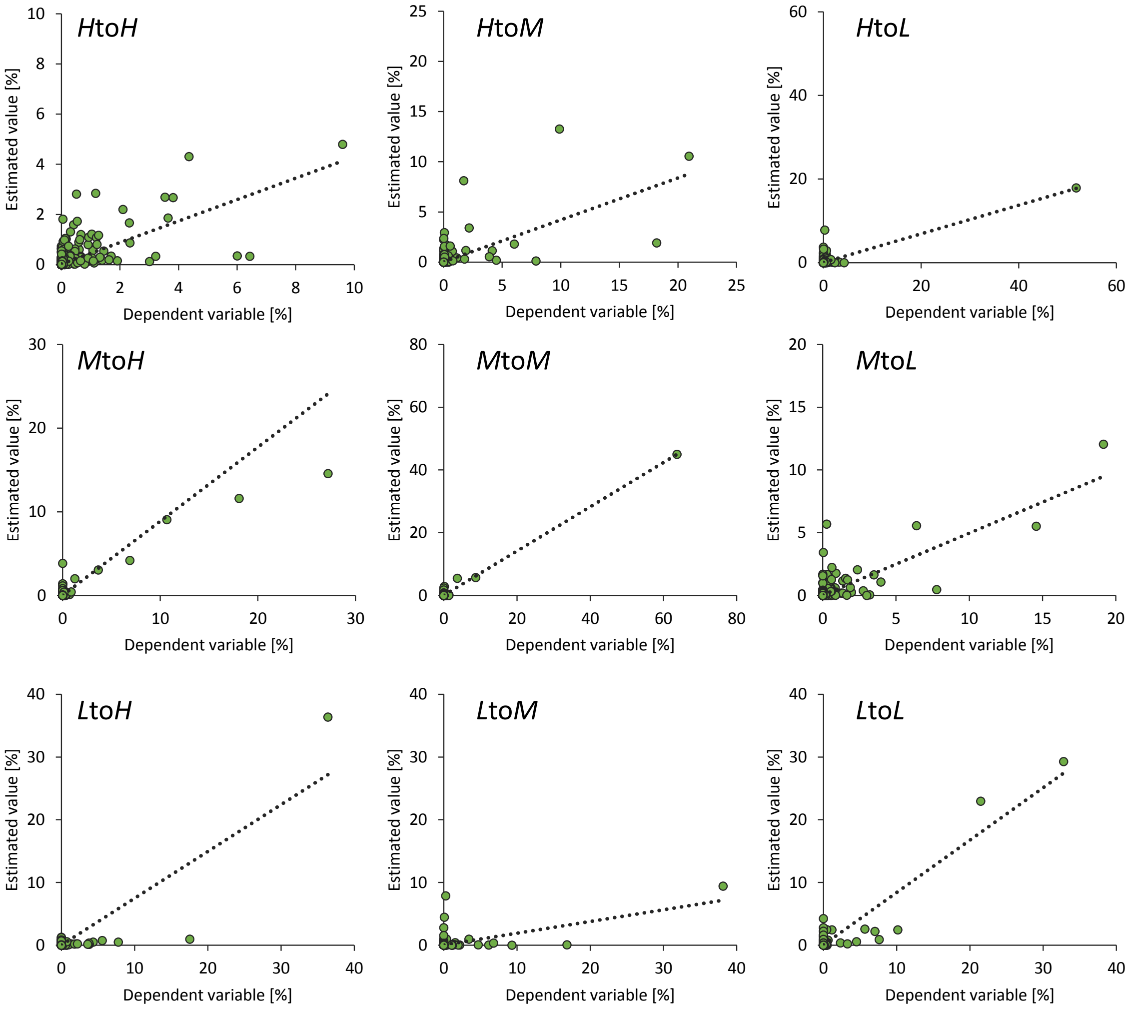


Figure 5.5 Flows of platinum between economic groups estimated using PPML and flows used for the explained variables.

to *L*to*L* for each of the critical metals. In addition, Figures 5.3–5.5 present scatter diagrams comparing the values calculated from the estimation equation and the values of the explained variables as Figure 5.2. The results of OLS estimation are here omitted because of the low reproducibility of real numbers of flows described in Subsection 5.3.3.

(a) Neodymium

Table 5.5 confirms that the coefficients of both sides of *GDPpc* and *Population* in the *H*to*H*, *H*to*M*, and *M*to*H* flows are significant. Thus, these flows are readily affected by the economic scale differences between two regions as the global flows. The sign of the coefficient of *GDPpc*, however, was negative in some flow patterns. *GDPpc* of a country belonging to *M*, for example, contributes to a decrease in the export flow to a country belonging to *H*. An increase in the import-side *GDPpc* contributes to an increase in the flow moving from *M* to *M*. Therefore, the economic growth of *M* which would be the most in the near future is expected to affects the remarkable promotion of flows between emerging countries. According to the demand-related variables, the tendency of high significance of *H*to*H* and *H*to*M* was found, as in the case of economic scale variables. Many of the coefficients are positive, suggesting that they are factors that increase the flows. Regarding the supply-related variables, significance was not found in *H*to*H* except *Industry Value Added*. All supply-related variables on the export and import sides in *H*to*M* are significant (the coefficient of the export-side *Mining Country* is zero because no country belonging to *H* is a mining country). All but the negative coefficient of the import-side *Mining Country* are positive coefficients. In contrast, the significance of the variables of the flows going through *L* is generally low.

As presented in Figure 5.3, the correlations of *M*to*H* and *M*to*M* are high when excluding those with a seemingly high coefficient of determination because of a certain point or multiple points (e.g. *M*to*L*). The flow calculated from the *M*to*H* estimation equation particularly covers approximately 60% of the overall flow. The gravity model is regarded as capable of estimating the key part of the neodymium flow.

(b) Cobalt

The coefficients of both sides of *GDPpc* and *Population* became in seven flows other than *H*to*L* and *L*to*L* (Table 5.5). Among these, only *H*to*H* and *H*to*M* had positive coefficients, which follows the basic form of the gravity model. All variables in *H*to*H* were found to be significant at the 1% level; *H*to*M* also had all variables except the export-side *Internet Access* as highly significant. Differences in the coefficients of variables of these two flows were found in *RTA, Motor Vehicles, Cellular Phones,* and *Renewable Energy*. Although *RTA*, the import-side and export-side *Motor Vehicles*, and the import-side *Cellular Phone* are factors that increase the *H*to*M* flow, all of these variables in *H*to*H* contribute to a decrease in the flow. An overall comparison with the neodymium flows reveals that the significance of coefficients is relatively high and that coefficients of many variables are significant in the flows made from *L*. As Figure 5.4 shows, however, the correlations between the estimates and original flows tend to be lower than those of neodymium. Although both the coefficients of determination for *M*to*L* and *L*to*L* exceed 0.9, the correlations are 0.1 or below if excluded one of the maximum values from the flows.

(c) Platinum

Table 5.6 reveals that the coefficients of both sides of *GDPpc* and *Population* in the *H*to*H* and *M*to*H* flows are positively significant. In these two flows, *Motor cars*, *Cellular phones* and *Renewable energy* in the countries belonging to *H* tend to contribute to an increase in the flows. The results of estimating these flows are likely to reflect the values of the original explanatory variable to a certain extent (Figure 5.5). No remaining flow aside from *H*to*M* showed significance in their coefficients. The correlation of *M*to*M* is the highest and the coefficient of determination still exceeds 0.6 after removing the maximum points.

However, its reliability of the estimation seems low since significance was found for only a few coefficients in the estimation equation.

5.3.2 Further perspective aiming to predict future critical metal flows

This chapter specifically addressed the factors that are expected to make a significant contribution to the formation of the traded physical flows of three critical metals: neodymium, cobalt, and platinum. The analyses presented herein were conducted using a gravity model of trade, which has been applied for estimation of various flows including those related to environmental loads such as virtual water and waste. To estimate flows of these critical metals, the study used two methods: OLS and PPML. Results revealed that economic scales such as GDP per capita, population, and distance between two regions were statistically significant in global flows. The global flows of these critical metals are likely to be explained by the gravity model. Therefore, economic growth in emerging countries, particularly in the near future, can be expected to increase flows. Demand-related and supply-related variables selected in this study also showed characteristic significance in each critical metal flow. In comparison to the OLS results, the PPML results revealed more coefficients indicating significance. Almost all of the variables of the neodymium and cobalt flows were significant at the 1% level. Real values of the flows calculated from PPML estimation were also much closer to those of the original flows as the explained variables than those from the OLS. These results imply that PPML, which is capable of assessing incomplete flows without log-linearization, is more appropriate than OLS for estimating critical metal flows. For estimations of the flows between particular countries with the focus on country income classes, however, only the flows between developed countries, flows from developed countries to emerging countries, and flows from emerging countries to developed countries were explained by the gravity model. Consequently, room for argument still exists for an approach that applies the gravity model to more detailed flow analysis.

As noted in the *Introduction* of this chapter, a stable supply of critical metals is necessary for sustainable development. Forecasting the future structure of demand and supply for such metals is expected to support policy making for securing resource supplies. Some preceding studies have forecasted future amounts of demand for critical metals by taking a dynamic approach that specifically examines demand for end products and stock scenarios (Elshkaki and Graedel, 2013, 2014; Seo and Morimoto, 2014). In contrast, the present study has specifically examined economic drivers that are important for estimating the bilateral flows of critical metals. The proposed analysis, which specifically examines changes in such economic factors, is expected to contribute to future projections of critical metal flows. This analytical method can support the discussion of policy implementation for stable supplies of critical metals from the viewpoint of dynamics of the identified drivers. To comprehend such factors more accurately, it is urgently necessary to examine the significant variables of the estimation equation based on comparison with time-series data created by identification of global flows of critical metals around year 2005

6 Conclusions

The importance of “consumption-based accounting,” which measures environmental loads in supply chains driven by final consumption, has been increasing in recent years for environmental management within a framework of sustainable development. The environmental load induced directly and indirectly by consumption can be visualized as an “environmental footprint;” Particularly the carbon footprint analysis, which addresses the pressing issue of climate change, has been advancing. However, nothing has been done to predict Japan’s mid-to-long-term footprint using consumption-based accounting. The footprint structure of household consumption, a strong contributor to Japan’s environmental footprint, also remains unclear. Furthermore, when examining sustainability in a broader context, the tradeoff with the critical metal resources necessitated by low-carbon technologies must be considered. Therefore, this dissertation presents the current situation and a future scenario analysis of carbon footprints and material footprints for neodymium, cobalt, and platinum as dictated by Japanese households, with recommendations of policy solutions for the reduction of footprints of both types. Hereinafter, the consequential policy implications and further perspectives of this dissertation are discussed.

The quantification of household carbon and material footprints as presented in this dissertation is a visualization of the net amount of GHG emissions on the globe. It is a picture of human dependence on critical metals to sustain our daily lives. Such visualization provides two benefits for the formation of a low-carbon society.

First, the footprint can inform consumers of their contribution to alleviation of climate change in addition to saving electricity and car usage. For instance, because they recognize the difference of impacts between dining out and self-catering on the carbon footprint, it would be expected that they reconsider the frequency of restaurant dining as well as that of car usage. The Japanese government has been leading consumers to undertake decarbonization through a national project: “team minus 6%” (MOE, 2008). However, the policy measure was implemented uniformly for consumers. By using footprints to address characteristics of consumers by household attributes, it would be possible to expand searches for opportunities for GHG emissions mitigation. Chapter 2 highlighted, for instance, differences of consumption patterns by income levels: the share of income spent for food and electricity consumption for lower-income households is greater than that for higher-income households. For this reason, the carbon footprint intensity of household expenditures (t-CO_2eq/M-JPY) decreases as household income increases because of differences of consumption patterns. This fact implies that implementing a carbon tax policy uniformly might create a situation in which the tax burden on low-income groups will be higher than that on higher-income groups. In addition, Chapter 3 explained that trends in carbon footprints of demand areas strongly correlate with the consumption habits and lifestyles of older-aged households. Therefore, policy measures designed to reduce their footprints is necessary.

In contrast to GHG, however, consumers’ recognition and their education related to metallic resource management do not proceed. As presented in Chapter 2, if economic policies specifically address increasing the level of household income and introducing low-carbon technologies, then reducing material footprints by encouraging consumers to reuse products and extend product lifetimes must be considered. For instance, Chapter 4 emphasized that continued enforcement of recycling laws such as the Automobile Recycling Act, the Home Appliance Recycling Law, and the Small Home Appliance Recycling Law can play an important role in alerting consumers to consciousness about the material footprints of neodymium, cobalt, and platinum. Because less half of the cobalt and platinum footprints are covered under these recycling laws (i.e., medical services), some means must be developed to reduce these footprints using policy measures for consumers. In addition, material footprints for critical metals can be reworded the amount of the metals mined which satisfies final household demands. Emphasizing that reduction in the material footprint contributes to mitigating critical material problems such as export restraints (i.e., neodymium exported by China) and conflict minerals. This viewpoint is particularly important for economically developed countries such as Japan, which is highly dependent on materials processing and machining industries and which imports large quantities of mineral resources. Furthermore, quantification of the criticality involved in the mining of metals, as the political risk (Nansai et al., 2015) and loss of biodiversity (Moran et al., 2013), is expected to support sustainable development.

Such efforts to visualize environmental loads and resource consumption from the demand-side viewpoint can also be beneficial for supply-side policy implementation. Identifying household footprints indicates to producers those demand areas which should be prioritized for improvement of supply chains and which should have environmental regulation to reduce their respective footprints. Particularly for medical services, which have large cobalt and platinum footprints, as shown in Chapter 4, achieving reduction in utilization is nearly impossible given the high demand for these services. For this reason, emphases on technological improvements and seeking alternative materials are important, as is the extraction of these metals from obsolete medical equipment. In addition, the quantification of both carbon and material footprints could assess a national energy policy for the purpose of expansion in new energy technologies aimed at GHG emissions mitigation. This indicates, for instance, that the assessment with the both footprints is applicable to a case of solutions to energy poverty which denotes the lack of access to electricity and the reliance on the traditional use of biomass for cooking (IEA, 2010) in terms of critical metals consumption.

To implement policy measures described above, it is extremely important to improve the accuracy of scenario analysis for estimating the footprints as described in this dissertation. As explained in Chapters 3–4, the carbon and material footprints were estimated with specific examination of the demographic changes during 2005–2035, whereas technologies, international trade structures, and consumption patterns are assumed to be constant from 2005. Chapter 5 presented examination of important economic drivers of the global flows of the critical metals necessary to calculate the material footprint using the GLIO model, which is a possible approach to incorporate changes in trade structures into account to estimate the footprint.

Additionally, it is necessary to break down the results presented in this dissertation to elucidate more details about the structures of the footprints. The carbon footprint and material footprints explained herein are based on macroscale analyses targeting all Japanese households. Consequently, a possible approach for greater comprehension of these footprints is to conduct mesoscale analyses of the footprint induced by households in the regions or cities of interest, and to identify key geographical factors that can contribute to footprint reduction.

For a makeover in consumption patterns toward achievement of a low-carbon society, bottom-up approaches such as conventional environmental education must be used to build up consumers' environmental consciousness. Carbon and material footprints associated with household consumption can make consumers aware of how much their consumption contributes to climate issues indirectly, even though they might occur far away (i.e., mining resources). Educating consumers to be able to understand these meanings and encouraging them to undertake “green consumption” is important. Additionally, it has been pointed out that pursuing environmental literacy goals not only for the consumers but for the producers can strongly influence green consumption (Leire and Thidell, 2005; Rex and Baumann, 2007). Therefore, the use and provision of data of visualized footprints is also an important issue.

Finally, the UN has agreed upon 17 Sustainable Development Goals (SDGs) that include “Ensuring sustainable consumption and production patterns” as the 12th goal (UN, 2015). It is hoped that the present thesis can become a valuable contribution, with results supporting policy implementations to achieve this goal from the perspective of Japanese households. Furthermore, it is desirable that the thesis be expanded into a case study using Japan as a model case of an economically developed nation, which can provide emerging countries the vision to pursue sustainable consumption and production patterns.

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Appendix

Table S1 Correspondences between the 13 aggregated sectors and the 409 commodity sectors. (Referred in Chapter 3) (1/7)

Aggregated sector	Sector no.		Commodity sector
	Domestic	Import	
(1) Food	JD1	JI1	Rice
(1) Food	JD2	JI2	Wheat, barley and the like
(1) Food	JD3	JI3	Potatoes and sweet potatoes
(1) Food	JD4	JI4	Pulses
(1) Food	JD5	JI5	Vegetables
(1) Food	JD6	JI6	Fruits
(1) Food	JD7	JI7	Sugar crops
(1) Food	JD8	JI8	Crops for beverages
(1) Food	JD9	JI9	Other edible crops
(1) Food	JD10	JI10	Crops for feed and forage
(1) Food	JD11	JI11	Seeds and seedlings
(1) Food	JD12	JI12	Flowers and plants
(1) Food	JD13	JI13	Other inedible crops
(1) Food	JD14	JI14	Dairy cattle farming
(1) Food	JD15	JI15	Hen eggs
(1) Food	JD16	JI16	Fowls and broilers
(1) Food	JD17	JI17	Hogs
(1) Food	JD18	JI18	Beef cattle
(1) Food	JD19	JI19	Other livestock
(1) Food	JD22	JI22	Silviculture
(1) Food	JD23	JI23	Logs
(1) Food	JD24	JI24	Special forest products (inc. hunting)
(1) Food	JD25	JI25	Marine fisheries
(1) Food	JD26	JI26	Marine culture
(1) Food	JD27	JI27	Inland water fisheries and culture
(1) Food	JD36	JI36	Slaughtering and meat processing
(1) Food	JD37	JI37	Processed meat products
(1) Food	JD38	JI38	Bottled or canned meat products
(1) Food	JD39	JI39	Dairy farm products
(1) Food	JD40	JI40	Frozen fish and shellfish
(1) Food	JD41	JI41	Salted, dried or smoked seafood
(1) Food	JD42	JI42	Bottled or canned seafood
(1) Food	JD43	JI43	Fish paste
(1) Food	JD44	JI44	Other processed seafood
(1) Food	JD45	JI45	Grain milling
(1) Food	JD46	JI46	Flour and other grain mill products
(1) Food	JD47	JI47	Noodles
(1) Food	JD48	JI48	Bread
(1) Food	JD49	JI49	Confectionery
(1) Food	JD50	JI50	Bottled or canned vegetables and fruits
(1) Food	JD51	JI51	Preserved agricultural foodstuffs (other than bottled or canned)
(1) Food	JD52	JI52	Sugar
(1) Food	JD53	JI53	Starch
(1) Food	JD54	JI54	Dextrose, syrup and isomerized sugar
(1) Food	JD55	JI55	Vegetable oils and meal
(1) Food	JD56	JI56	Animal oils and fats
(1) Food	JD57	JI57	Condiments and seasonings
(1) Food	JD58	JI58	Prepared frozen foods
(1) Food	JD59	JI59	Retort foods
(1) Food	JD60	JI60	Dishes, sushi and lunch boxes
(1) Food	JD61	JI61	School lunch (public)
(1) Food	JD62	JI62	School lunch (private)
(1) Food	JD63	JI63	Other foods
(1) Food	JD64	JI64	Refined sake
(1) Food	JD65	JI65	Beer
(1) Food	JD66	JI66	Whiskey and brandy
(1) Food	JD67	JI67	Other liquors
(1) Food	JD68	JI68	Tea and roasted coffee
(1) Food	JD69	JI69	Soft drinks
(1) Food	JD70	JI70	Manufactured ice
(1) Food	JD71	JI71	Feeds
(1) Food	JD72	JI72	Organic fertilizers, n.e.c.
(1) Food	JD73	JI73	Tobacco
(2) Textiles	JD74	JI74	Fiber yarns
(2) Textiles	JD75	JI75	Cotton and staple fiber fabrics (inc. fabrics of synthetic spun fibers)
(2) Textiles	JD76	JI76	Silk and artificial silk fabrics (inc. fabrics of synthetic filament fibers)

Table S1 (2/7)

Aggregated sector	Sector no. Domestic	Import	Commodity sector
(2) Textiles	JD77	JI77	Woolen fabrics, hemp fabrics and other fabrics
(2) Textiles	JD78	JI78	Knitting fabrics
(2) Textiles	JD79	JI79	Yarn and fabric dyeing and finishing (processing on commission only)
(2) Textiles	JD80	JI80	Ropes and nets
(2) Textiles	JD81	JI81	Carpets and floor mats
(2) Textiles	JD82	JI82	Fabricated textiles for medical use
(2) Textiles	JD83	JI83	Other fabricated textile products
(2) Textiles	JD84	JI84	Woven fabric apparel
(2) Textiles	JD85	JI85	Knitted apparel
(2) Textiles	JD86	JI86	Other wearing apparel and clothing accessories
(2) Textiles	JD87	JI87	Bedding
(2) Textiles	JD88	JI88	Other ready-made textile products
(3) Petroleum refinery and coal	JD137	JI137	Gaoline
(3) Petroleum refinery and coal	JD138	JI138	Kerosene
(3) Petroleum refinery and coal	JD139	JI139	Light oil
(3) Petroleum refinery and coal	JD140	JI140	LPG
(3) Petroleum refinery and coal	JD141	JI141	Other petroleum products
(3) Petroleum refinery and coal	JD142	JI142	Coal products
(3) Petroleum refinery and coal	JD143	JI143	Paving materials
(4) Transport vehicles	JD252	JI252	Passenger motor cars
(4) Transport vehicles	JD253	JI253	Trucks, buses and other cars
(4) Transport vehicles	JD254	JI254	Two-wheel motor vehicles
(4) Transport vehicles	JD255	JI255	Motor vehicle bodies
(4) Transport vehicles	JD256	JI256	Internal combustion engines for motor vehicles and parts
(4) Transport vehicles	JD257	JI257	Motor vehicle parts and accessories
(4) Transport vehicles	JD258	JI258	Steel ships
(4) Transport vehicles	JD259	JI259	Ships (except steel ships)
(4) Transport vehicles	JD260	JI260	Internal combustion engines for vessels
(4) Transport vehicles	JD261	JI261	Repair of ships
(4) Transport vehicles	JD262	JI262	Rolling stock
(4) Transport vehicles	JD263	JI263	Repair of rolling stock
(4) Transport vehicles	JD264	JI264	Aircrafts
(4) Transport vehicles	JD265	JI265	Aircraft repair
(4) Transport vehicles	JD266	JI266	Bicycles
(4) Transport machinery	JD267	JI267	Other transport equipment
(5) Household commodities	JD89	JI89	Timber
(5) Household commodities	JD90	JI90	Plywood
(5) Household commodities	JD91	JI91	Wooden chips
(5) Household commodities	JD92	JI92	Other wooden products
(5) Household commodities	JD93	JI93	Wooden furniture and fixtures
(5) Household commodities	JD94	JI94	Wooden fixtures
(5) Household commodities	JD95	JI95	Metallic furniture and fixture
(5) Household commodities	JD96	JI96	Pulp
(5) Household commodities	JD97	JI97	Paper
(5) Household commodities	JD98	JI98	Paperboard
(5) Household commodities	JD99	JI99	Corrugated cardboard
(5) Household commodities	JD100	JI100	Coated paper and building (construction) paper
(5) Household commodities	JD101	JI101	Corrugated card board boxes
(5) Household commodities	JD102	JI102	Other paper containers
(5) Household commodities	JD103	JI103	Paper textile for medical use
(5) Household commodities	JD104	JI104	Other pulp, paper and processed paper products
(5) Household commodities	JD105	JI105	Printing, plate making and book binding
(5) Household commodities	JD106	JI106	Chemical fertilizer
(5) Household commodities	JD107	JI107	Industrial soda chemicals
(5) Household commodities	JD108	JI108	Inorganic pigment
(5) Household commodities	JD109	JI109	Compressed gas and liquefied gas
(5) Household commodities	JD110	JI110	Salt
(5) Household commodities	JD111	JI111	Other industrial inorganic chemicals
(5) Household commodities	JD112	JI112	Petrochemical basic products
(5) Household commodities	JD113	JI113	Petrochemical aromatic products (except synthetic resin)
(5) Household commodities	JD114	JI114	Aliphatic intermediates
(5) Household commodities	JD115	JI115	Cyclic intermediates
(5) Household commodities	JD116	JI116	Synthetic rubber
(5) Household commodities	JD117	JI117	Methane derivatives
(5) Household commodities	JD118	JI118	Oil and fat industrial chemicals

Table S1 (3/7)

Aggregated sector	Sector no.		Commodity sector
	Domestic	Import	
(5) Household commodities	JD119	JI119	Plasticizers
(5) Household commodities	JD120	JI120	Synthetic dyes
(5) Household commodities	JD121	JI121	Other industrial organic chemicals
(5) Household commodities	JD122	JI122	Thermo-setting resins
(5) Household commodities	JD123	JI123	Thermoplastics resins
(5) Household commodities	JD124	JI124	High function resins
(5) Household commodities	JD125	JI125	Other resins
(5) Household commodities	JD126	JI126	Rayon and acetate
(5) Household commodities	JD127	JI127	Synthetic fibers
(5) Household commodities	JD128	JI128	Medicaments
(5) Household commodities	JD129	JI129	Soap, synthetic detergents and surface active agents
(5) Household commodities	JD130	JI130	Cosmetics, toilet preparations and dentifrices
(5) Household commodities	JD131	JI131	Paint and varnishes
(5) Household commodities	JD132	JI132	Printing ink
(5) Household commodities	JD133	JI133	Photographic sensitive materials
(5) Household commodities	JD134	JI134	Agricultural chemicals
(5) Household commodities	JD135	JI135	Gelatin and adhesives
(5) Household commodities	JD136	JI136	Other final chemical products
(5) Household commodities	JD144	JI144	Plastic products
(5) Household commodities	JD145	JI145	Tires and inner tubes
(5) Household commodities	JD146	JI146	Rubber footwear
(5) Household commodities	JD147	JI147	Plastic footwear
(5) Household commodities	JD148	JI148	Other rubber products
(5) Household commodities	JD149	JI149	Leather footwear
(5) Household commodities	JD150	JI150	Leather and fur skins
(5) Household commodities	JD151	JI151	Miscellaneous leather products
(5) Household commodities	JD152	JI152	Sheet glass and safety glass
(5) Household commodities	JD153	JI153	Glass fiber and glass fiber products, n.e.c.
(5) Household commodities	JD154	JI154	Other glass products
(5) Household commodities	JD155	JI155	Cement
(5) Household commodities	JD156	JI156	Ready-mixed concrete
(5) Household commodities	JD157	JI157	Cement products
(5) Household commodities	JD158	JI158	Pottery, china and earthenware
(5) Household commodities	JD159	JI159	Clay refractories
(5) Household commodities	JD160	JI160	Other structural clay products
(5) Household commodities	JD161	JI161	Carbon and graphite products
(5) Household commodities	JD162	JI162	Abrasive
(5) Household commodities	JD163	JI163	Miscellaneous ceramic, stone and clay products
(5) Household commodities	JD164	JI164	Pig iron
(5) Household commodities	JD165	JI165	Ferro alloys
(5) Household commodities	JD166	JI166	Crude steel (converters)
(5) Household commodities	JD167	JI167	Crude steel (electric furnaces)
(5) Household commodities	JD168	JI168	Scrap iron
(5) Household commodities	JD169	JI169	Hot rolled steel
(5) Household commodities	JD170	JI170	Steel pipes and tubes
(5) Household commodities	JD171	JI171	Cold-finished steel
(5) Household commodities	JD172	JI172	Coated steel
(5) Household commodities	JD173	JI173	Cast and forged steel
(5) Household commodities	JD174	JI174	Cast iron pipes and tubes
(5) Household commodities	JD175	JI175	Cast and forged materials (iron)
(5) Household commodities	JD176	JI176	Iron and steel shearing and slitting
(5) Household commodities	JD177	JI177	Other iron or steel products
(5) Household commodities	JD178	JI178	Copper
(5) Household commodities	JD179	JI179	Lead and zinc (inc. regenerated lead)
(5) Household commodities	JD180	JI180	Aluminum (inc. regenerated aluminum)
(5) Household commodities	JD181	JI181	Other non-ferrous metals
(5) Household commodities	JD182	JI182	Non-ferrous metal scrap
(5) Household commodities	JD183	JI183	Electric wires and cables
(5) Household commodities	JD184	JI184	Optical fiber cables
(5) Household commodities	JD185	JI185	Rolled and drawn copper and copper alloys
(5) Household commodities	JD186	JI186	Rolled and drawn aluminum
(5) Household commodities	JD187	JI187	Non-ferrous metal castings and forgings
(5) Household commodities	JD188	JI188	Nuclear fuels
(5) Household commodities	JD189	JI189	Other non-ferrous metal products
(5) Household commodities	JD190	JI190	Metal products for construction
(5) Household commodities	JD191	JI191	Metal products for architecture

Table S1 (4/7)

Aggregated sector	Sector no.		Commodity sector
	Domestic	Import	
(5) Household commodities	JD192	JI192	Gas and oil appliances and heating and cooking apparatus
(5) Household commodities	JD193	JI193	Bolts, nuts, rivets and springs
(5) Household commodities	JD194	JI194	Metal containers, fabricated plate and sheet metal
(5) Household commodities	JD195	JI195	Plumber's supplies, powder metallurgy products and tools
(5) Household commodities	JD196	JI196	Other metal products
(5) Household commodities	JD197	JI197	Boilers
(5) Household commodities	JD198	JI198	Turbines
(5) Household commodities	JD199	JI199	Engines
(5) Household commodities	JD200	JI200	Conveyors
(5) Household commodities	JD201	JI201	Refrigerators and air conditioning apparatus
(5) Household commodities	JD202	JI202	Pumps and compressors
(5) Household commodities	JD203	JI203	Machinists' precision tools
(5) Household commodities	JD204	JI204	Other general industrial machinery and equipment
(5) Household commodities	JD205	JI205	Machinery and equipment for construction and mining
(5) Household commodities	JD206	JI206	Chemical machinery
(5) Household commodities	JD207	JI207	Industrial robots
(5) Household commodities	JD208	JI208	Metal machine tools
(5) Household commodities	JD209	JI209	Metal processing machinery
(5) Household commodities	JD210	JI210	Machinery for agricultural use
(5) Household commodities	JD211	JI211	Textile machinery
(5) Household commodities	JD212	JI212	Food processing machinery and equipment
(5) Household commodities	JD213	JI213	Semiconductor making equipment
(5) Household commodities	JD214	JI214	Vacuum equipment and vacuum component
(5) Household commodities	JD215	JI215	Other special machinery for industrial use
(5) Household commodities	JD216	JI216	Metal molds
(5) Household commodities	JD217	JI217	Bearings
(5) Household commodities	JD218	JI218	Other general machines and parts
(5) Household commodities	JD219	JI219	Copy machine
(5) Household commodities	JD220	JI220	Other office machines
(5) Household commodities	JD221	JI221	Machinery for service industry
(5) Household commodities	JD222	JI222	Rotating electrical equipment
(5) Household commodities	JD223	JI223	Transformers and reactors
(5) Household commodities	JD224	JI224	Relay switches and switchboards
(5) Household commodities	JD225	JI225	Wiring devices and supplies
(5) Household commodities	JD226	JI226	Electrical equipment for internal combustion engines
(5) Household commodities	JD227	JI227	Other electrical devices and parts
(5) Household commodities	JD228	JI228	Applied electronic equipment
(5) Household commodities	JD229	JI229	Electric measuring instruments
(5) Household commodities	JD230	JI230	Electric bulbs
(5) Household commodities	JD231	JI231	Electric lighting fixtures and apparatus
(5) Household commodities	JD232	JI232	Batteries
(5) Household commodities	JD233	JI233	Other electrical devices and parts
(5) Household commodities	JD234	JI234	Household air-conditioners
(5) Household commodities	JD235	JI235	Household electric appliances (except air-conditioners)
(5) Household commodities	JD236	JI236	Video recording and playback equipment
(5) Household commodities	JD237	JI237	Electric audio equipment
(5) Household commodities	JD238	JI238	Radio and television sets
(5) Household commodities	JD239	JI239	Wired communication equipment
(5) Household commodities	JD240	JI240	Cellular phones
(5) Household commodities	JD241	JI241	Radio communication equipment (except cellular phones)
(5) Household commodities	JD242	JI242	Other communication equipment
(5) Household commodities	JD243	JI243	Personal Computers
(5) Household commodities	JD244	JI244	Electronic computing equipment (except personal computers)
(5) Household commodities	JD245	JI245	Electronic computing equipment (accessory equipment)
(5) Household commodities	JD246	JI246	Semiconductor devices
(5) Household commodities	JD247	JI247	Integrated circuits
(5) Household commodities	JD248	JI248	Electron tubes
(5) Household commodities	JD249	JI249	Liquid crystal element
(5) Household commodities	JD250	JI250	Magnetic tapes and discs
(5) Household commodities	JD251	JI251	Other electronic components
(5) Household commodities	JD268	JI268	Camera
(5) Household commodities	JD269	JI269	Other photographic and optical instruments
(5) Household commodities	JD270	JI270	Watches and clocks
(5) Household commodities	JD271	JI271	Professional and scientific instruments
(5) Household commodities	JD272	JI272	Analytical instruments, testing machine, measuring instruments
(5) Household commodities	JD274	JI274	Toys and games

Table S1 (5/7)

Aggregated sector	Sector no.		Commodity sector
	Domestic	Import	
(5) Household commodities	JD275	JI275	Sporting and athletic goods
(5) Household commodities	JD276	JI276	Musical instruments
(5) Household commodities	JD277	JI277	Audio and video records, other information recording media
(5) Household commodities	JD278	JI278	Stationery
(5) Household commodities	JD279	JI279	Jewelry and adornments
(5) Household commodities	JD280	JI280	"Tatami" (straw matting) and straw products
(5) Household commodities	JD281	JI281	Ordnance
(5) Household commodities	JD282	JI282	Miscellaneous manufacturing products
(6) Utilities	JD283	JI283	Reuse and recycling
(6) Utilities	JD284	JI284	Residential construction (wooden)
(6) Utilities	JD285	JI285	Residential construction (non-wooden)
(6) Utilities	JD286	JI286	Non-residential construction (wooden)
(6) Utilities	JD287	JI287	Non-residential construction (non-wooden)
(6) Utilities	JD288	JI288	Repair of construction
(6) Utilities	JD289	JI289	Public construction of roads
(6) Utilities	JD290	JI290	Public construction of rivers, drainages and others
(6) Utilities	JD291	JI291	Agricultural public construction
(6) Utilities	JD292	JI292	Railway construction
(6) Utilities	JD293	JI293	Electric power facilities construction
(6) Utilities	JD294	JI294	Telecommunication facilities construction
(6) Utilities	JD295	JI295	Other civil engineering and construction
(6) Utilities	JD296	JI296	Electricity
(6) Utilities	JD297	JI297	On-site power generation
(6) Utilities	JD298	JI298	Gas supply
(6) Utilities	JD299	JI299	Steam and hot water supply
(6) Utilities	JD300	JI300	Water supply
(6) Utilities	JD301	JI301	Industrial water supply
(6) Utilities	JD302	JI302	Sewage disposal
(6) Utilities	JD303	JI303	Waste management services (public)
(6) Utilities	JD304	JI304	Waste management services (private)
(7) Transportation	JD314	JI314	Railway transport (passengers)
(7) Transportation	JD315	JI315	Railway transport (freight)
(7) Transportation	JD316	JI316	Bus transport service
(7) Transportation	JD317	JI317	Hired car and taxi transport
(7) Transportation	JD318	JI318	Road freight transport(except Self-transport by private cars)
(7) Transportation	JD319	JI319	Self-transport by private cars (passengers)
(7) Transportation	JD320	JI320	Self-transport by private cars (freight)
(7) Transportation	JD321	JI321	Ocean transport
(7) Transportation	JD322	JI322	Coastal and inland water transport
(7) Transportation	JD323	JI323	Harbor transport service
(7) Transportation	JD324	JI324	Air transport
(7) Transportation	JD325	JI325	Consigned freight forwarding
(7) Transportation	JD326	JI326	Storage facility service
(7) Transportation	JD327	JI327	Packing service
(7) Transportation	JD328	JI328	Facility service for road transport
(7) Transportation	JD329	JI329	Port and water traffic control
(7) Transportation	JD330	JI330	Services relating to water transport
(7) Transportation	JD331	JI331	Airport and air traffic control (public)
(7) Transportation	JD332	JI332	Airport and air traffic control (industrial)
(7) Transportation	JD333	JI333	Services relating to air transport
(7) Transportation	JD334	JI334	Travel agency and other services relating to transport
(8) Infromation and communication	JD335	JI335	Postal service
(8) Infromation and communication	JD336	JI336	Fixed telecommunication
(8) Infromation and communication	JD337	JI337	Mobile telecommunication
(8) Infromation and communication	JD338	JI338	Other telecommunication
(8) Infromation and communication	JD339	JI339	Other services relating to communication
(8) Infromation and communication	JD340	JI340	Public broadcasting
(8) Infromation and communication	JD341	JI341	Private broadcasting
(8) Infromation and communication	JD342	JI342	Cable broadcasting
(8) Infromation and communication	JD343	JI343	Information services
(8) Infromation and communication	JD344	JI344	Internet based services
(8) Infromation and communication	JD345	JI345	Image information production and distribution
(8) Infromation and communication	JD346	JI346	Newspaper
(8) Infromation and communication	JD347	JI347	Publication
(8) Infromation and communication	JD348	JI348	News syndicates and private detective agencies

Table S1 (6/7)

Aggregated sector	Sector no.		Commodity sector
	Domestic	Import	
(9) Education	JD351	JI351	School education (public)
(9) Education	JD352	JI352	School education (private)
(9) Education	JD353	JI353	Social education (public)
(9) Education	JD354	JI354	Social education (private, non-profit)
(9) Education	JD355	JI355	Other educational and training institutions (public)
(9) Education	JD356	JI356	Other educational and training institutions (profit-making)
(9) Education	JD357	JI357	Research institutes for natural science (pubic)
(9) Education	JD358	JI358	Research institutes for cultural and social science (public)
(9) Education	JD359	JI359	Research institutes for natural sciences (private, non-profit)
(9) Education	JD360	JI360	Research institutes for cultural and social science (private,non-profit)
(9) Education	JD361	JI361	Research institutes for natural sciences (profit-making)
(9) Education	JD362	JI362	Research institutes for cultural and social science (profit-making)
(9) Education	JD363	JI363	Research and development (intra-enterprise)
(10) Medical and health care	JD273	JI273	Medical instruments
(10) Medical and health care	JD364	JI364	Medical service (public)
(10) Medical and health care	JD365	JI365	Medical service (non-profit foundations, etc.)
(10) Medical and health care	JD366	JI366	Medical service (medical corporations, etc.)
(10) Medical and health care	JD367	JI367	Health and hygiene (public)
(10) Medical and health care	JD368	JI368	Health and hygiene (profit-making)
(10) Medical and health care	JD369	JI369	Social insurance (public)
(10) Medical and health care	JD370	JI370	Social insurance (private, non-profit)
(10) Medical and health care	JD371	JI371	Social welfare (public)
(10) Medical and health care	JD372	JI372	Social welfare (private, non-profit)
(10) Medical and health care	JD373	JI373	Social welfare (profit-making)
(10) Medical and health care	JD374	JI374	Nursing care (In-home)
(10) Medical and health care	JD375	JI375	Nursing care (In-facility)
(11) Leisure	JD379	JI379	Goods rental and leasing (except car rental)
(11) Leisure	JD380	JI380	Car rental and leasing
(11) Leisure	JD388	JI388	Movie theaters
(11) Leisure	JD389	JI389	Performances (except otherwise claasified), theatrical comranies
(11) Leisure	JD390	JI390	Amusement and recreation facilities
(11) Leisure	JD391	JI391	Stadiums and companies of bicycle, horse, motorcar and motorboat races
(11) Leisure	JD392	JI392	Sport facility service, public gardens and amusement parks
(11) Leisure	JD393	JI393	Other amusement and recreation services
(11) Leisure	JD394	JI394	General eating and drinking places (except coffee shops)
(11) Leisure	JD395	JI395	Coffee shops
(11) Leisure	JD396	JI396	Eating and drinking places for pleasures
(11) Leisure	JD397	JI397	Hotels
(11) Leisure	JD401	JI401	Public baths
(11) Leisure	JD403	JI403	Photographic studios
(11) Leisure	JD20	JI20	Veterinary service
(12) Services	JD21	JI21	Agricultural services (except veterinary service)
(12) Services	JD305	JI305	Wholesale trade
(12) Services	JD306	JI306	Retail trade
(12) Services	JD307	JI307	Financial service
(12) Services	JD310	JI310	Real estate agencies and managers
(12) Services	JD311	JI311	Real estate rental service
(12) Services	JD349	JI349	Public administration (central)
(12) Services	JD350	JI350	Public administration (local)
(12) Services	JD376	JI376	Private non-profit institutions serving enterprises
(12) Services	JD377	JI377	Private non-profit institutions serving households, n.e.c.
(12) Services	JD378	JI378	Advertising services
(12) Services	JD381	JI381	Repair of motor vehicles
(12) Services	JD382	JI382	Repair of machine
(12) Services	JD383	JI383	Building maintenance services
(12) Services	JD384	JI384	Judicial, financial and accounting services
(12) Services	JD385	JI385	Civil engineering and construction services
(12) Services	JD386	JI386	Worker dispatching services
(12) Services	JD387	JI387	Other business services
(12) Services	JD398	JI398	Cleaning
(12) Services	JD399	JI399	Barber shops
(12) Services	JD400	JI400	Beauty shops
(12) Services	JD402	JI402	Other cleaning, barber shops, beauty shops and public baths
(12) Services	JD404	JI404	Ceremonial occasions
(12) Services	JD405	JI405	Miscellaneous repairs, n.e.c.

Table S1 (7/7)

Aggregated sector	Sector no. Domestic	 Import	Commodity sector
(12) Services	JD406	JI406	Supplementary tutorial schools, instruction services for arts, culture and technical skills
(12) Services	JD407	JI407	Other personal services
(12) Services	JD28	JI28	Metallic ores
(13) House rent, Insurance and others	JD29	JI29	Materials for ceramics
(13) House rent, Insurance and others	JD30	JI30	Gravel and quarrying
(13) House rent, Insurance and others	JD31	JI31	Crushed stones
(13) House rent, Insurance and others	JD32	JI32	Other non-metallic ores
(13) House rent, Insurance and others	JD33	JI33	Coal mining
(13) House rent, Insurance and others	JD34	JI34	Crude petroleum
(13) House rent, Insurance and others	JD35	JI35	Natural gas
(13) House rent, Insurance and others	JD308	JI308	Life insurance
(13) House rent, Insurance and others	JD309	JI309	Non-life insurance
(13) House rent, Insurance and others	JD312	JI312	House rent
(13) House rent, Insurance and others	JD313	JI313	House rent (imputed house rent)
(13) House rent, Insurance and others	JD408	JI408	Office supplies
(13) House rent, Insurance and others	JD409	JI409	Activities not elsewhere classified

Table S2 Country list. high income countries: “high income (OECD)” and “high income”, middle income countries: “upper middle income” and “lower middle income”, low income countries: “low income”, based on the country income classes published by the World Bank.

High income countries

Argentine
Australia
Austria
Belgium
Brunei Darussalam
Canada
Chile
Croatia
Cyprus
Czech
Denmark
Estonia
Finland
France
Germany
Hellenic
Hungary
Iceland
Ireland
Italy
Japan
Latvia
Lithuania
Luxembourg
Malta
Netherlands
New Zealand
Norway
Poland
Portuguese
Puerto Rico
Republic of Korea
Russia
Saudi Arabia
Singapore
Slovak
Slovenia
Spain
Sweden
Swiss Confederation
Trinidad and Tobago
United Kingdom
United States of America
Uruguay
Venezuela

Middle income countries

Albania
Algeria
Angola
Armenia
Azerbaijan
Bangladesh
Belarus
Belize
Bhutan
Bolivia
Bosnia and Herzegovina
Brazil
Bulgaria
Cameroon
Cape Verde
China
Colombia
Commonwealth of Dominica
Costa Rica
Cote d'Ivoire
Cuba
Dominican Republic
Ecuador
Egypt
El Salvador
Fiji Islands
Georgia
Ghana
Guatemala
Honduras
India
Indonesia
Iran
Jamaica
Jordan
Kazakhstan
Kenya
Kingdom of Thailand
Kyrgyz
Lao People
Macedonia
Malaysia
Mauritius
Moldova
Montenegro
Morocco
Myanmar
Namibia
Nicaragua
Nigeria
Pakistan
Papua New Guinea
Paraguay
Peru
Philippines
Republic of Panama
Republic of the Congo
Romania
Saint Vincent and the Grenadines
Sao Tome and Principe
Senegal
Serbia
South Africa
Sri Lanka
Sudan
Suriname
Swaziland
Syrian Arab
Tajikistan
Tunisia
Turkey
Ukraine
United Mexican States
Vietnam
Zambia

Low income countries

Afghanistan
Benin
Burkina Faso
Burundi
Cambodia
Central African Republic
Comoros
Congo
Eritrea
Ethiopia
Guinea
Madagascar
Malawi
Mali
Mozambique
Nepal
Niger
Rwanda
Sierra Leone
Tanzania
Togo
Uganda
Zimbabwe

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Index of the publications

This PhD thesis consists of synopsis of the research work presented in three published and one submitted papers as below.

Chapter 1

Introduction

Chapter 2

Structures of Current Carbon Footprint and Material Footprints for Critical Metals Instigated by Japanese Household Consumption

- Shigetomi, Y., Nansai, K., Kagawa, S., Tohno, S., Influence of income difference on carbon and material footprints for critical metals: the case of Japanese households. *Journal of Economic Structures*. 2016, 5 (1), 1-19.

Chapter 3

Future Projection of Household Carbon Footprint in Japan in an Aging Society

- Shigetomi, Y., Nansai, K., Kagawa, S., Tohno, S., 2014. Changes in the carbon footprint of Japanese households in an aging society. *Environmental Science and Technology.* 48 (11), 6069–6080.

Chapter 4

Future Projection of Household Material Footprints for Critical Metals in Japan in an Aging Society

- Shigetomi, Y., Nansai, K., Kagawa, S., Tohno, S., 2015. Trends in Japanese households' critical-metals material footprints. *Ecological Economics*. 119, 118-126.

Chapter 5

Examination of the Significant Economic Drivers for Estimation of Changes in Trade Structures of Critical Metals

- Shigetomi Y., Nansai K., Kagawa S., Kondo, Y., Tohno S. Determinants of international physical flows of critical metals. In preparation.

Chapter 6

Conclusions

In addition, the following publications have been made during this PhD work (not included in the thesis):

[Reference paper]

- Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Suh, S., Shigetomi, Y., Oshita, Y., 2014. Global flows of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt and platinum, *Environmental Science and Technology*. 48 (3), 1391-1400.

- Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Shigetomi, Y., Suh, S., 2015. Global mining risk footprint of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum in Japan. *Environmental Science and Technology*. 49 (4), 2022-2031.