GLOBAL GHG EMISSIONS DRIVEN BY THE U.S. HOUSEHOLD CONSUMPTION FROM 1995 TO 2009

by

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Abstract

In the Paris Agreement, 195 countries are committed to making joint efforts to limit global temperature increase below 2℃ this century. Countries are motivated to take voluntary climate actions, but few studies have provided systematical analysis to inform households about their carbon footprints. This study analyzed global GHG emissions driven by U.S. household consumption between 1995 and 2009. Multi-Regional Input-Output (MRIO) method is applied to analyze global trade networks. Consumer Expenditure Survey is linked with the trade networks to provide details on the emission profile of U.S. households. The research finds that total GHG emissions driven by U.S. households ranged from 4.8 to 6.2 billion tCO_2eq/yr with an increasing trajectory over time. Housing and transportation contributed nearly 70% of the total domestic GHG emissions. Emissions overseas increased from 13% to over 20% of the total emissions in the studied period, mostly embodied in manufactured products including clothing, electronics and machinery supplies. Household carbon footprint amounted to 18.6-20.8 $tCO_2eq/cap{\cdot}yr^{-1}$, ranging from 11.5 to 29.6 $tCO_2eq/cap{\cdot}yr^{-1}$ among rich and poor households. This study implicates that trade policies could be applied to green the global supply chain, and people with higher income should take more climate responsibility to achieve the goal of sustainable production and consumption.

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1. Introduction

In the Paris Agreement, 195 countries are committed to making joint efforts to limit the global temperature increase by 2℃ and pursue further efforts for 1.5℃ by the end of this century, under the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 2017). This framework convention seeks to motivate the voluntary commitments from signatory countries. To implement the voluntary commitments, countries are obligated to submit their National Determined Contributions (NDCs). Meanwhile, a “bottom-up” approach from the community and city levels for climate actions has become indispensable for climate change mitigation and the collective action in pursuit of long-term well-being (Jacquet et al., 2016). Fulfilling the goal of the Paris Agreement requires accurate carbon accounting so that the responsibility of carbon reduction is clear and collaborative mitigation strategies are implementable.

One common challenge different countries face in mitigation implementation is the clarification of climate responsibility. The global trade networks have displaced the greenhouse gas (GHG) emissions from developed to developing nations (Kanemoto et al., 2016), making the environmental burden grow beyond countries consuming the relevant goods and services. Globally, international trade drove the CO_2 emissions from the production of exported products from 20% to 30% during 1990 to 2010, with a yearly growth rate of 4.3% (Peters et al., 2011). Another research focused on products consumed in the U.S. shows that about 30% of total household CO_2 emissions occurred overseas in 2004 (Weber et al., 2008). The overseas emissions from the second largest emitter, the U.S., have grown rapidly, surpassing China and India, nearly doubling since the 1970s (Kanemoto et al., 2016). The increasing overseas and territorial emissions were mainly driven by the increasing consumption volume (Feng et al., 2015). Given that the U.S. has withdrawn from the Paris Agreement, research on its emissions that facilitates the bottom-up mitigation will be of greater significance for non-state actors and individuals to develop strategies for climate actions.

Emissions associated with household consumption are estimated to be over 60% of the global GHG emissions, far more than the contributions from governments and nongovernment organizations (NGOs) (Ivanova et al., 2016). In the United States, household GHG emissions account for over 80% of the total and upward of 120% when emissions embodied in imports are adjusted for the carbon-intensity of production (Jones et al., 2011). Household actions provide a potentially useful behavior wedge to effectively reduce U.S. carbon emissions (Dietz et al., 2009). In addition to the unequal distribution of GHG emissions, carbon inequality associated with people's economic status also exists between countries. Studies showed that the global top 10% consuming households contributed 40-50% of global emissions, approximately 3-4 times larger than that of the majority poor (Wiedenhofer et al., 2017; Hubacek et al., 2017). A systematic analysis of household carbon footprint would help governments provide guidance for trade policies to be more environmentally friendly, and provide references about issue of carbon tax. It could also inform consumers about their carbon footprint as well as their shared responsibility for climate change.

To assist climate change mitigation, a detailed profile of people's emission driven by consumption is highly important. This research investigates how much emissions were driven by U.S. household and how they distributed on the globe. It also examines the roles of different types of household consumption (such as food, housing, clothing, transportation, service, and etc.) played in the total emissions during the year 1995 to 2009. As carbon inequality exists between developing and developed countries, this research explores how much responsibility, in the U.S., that people with lower income and higher income should take. This study would help people better understand their responsibility for climate change and how much responsibility they should take in support of climate advocacy. It potentially provides references for international or national trade policies and helps the non-state actors to develop strategies to mitigate climate change.

2. Literature reviews

2.1 Accounting methods of GHG emissions

Production-based accounting and consumption-based accounting are the two main approaches to quantify emissions and evaluate global warming potentials (Wiedmann, 2009). Compared with traditionally territory emission accounting that traces emissions from the sources terrestrially, both of the two approaches account for the entire global supply chain and avoid potentially carbon leakage (Peters, 2008; Weber et al., 2008). The differences between these two methods lie in the climate responsibility from the production side versus consumption side. Production-based accounting follows the traditional norm that producers take responsibility and it analyzes emissions driven by consumption along the supply chain beyond the territory. It takes into account emissions embodied in imported goods and services, but excludes emissions associated with the exports. Emissions are measured by carbon footprint which reflects the life-cycle global warming potentials from human activities (Wiedmann & Minx, 2008; Lenzen et al., 2012; Hertwich et al., 2009; Minx et al., 2013).

The Multi-Regional Input-Output (MRIO) method has been developed to trace emissions driven by consumers by linking the upstream production and downstream consumption (Kitzes, 2013). It allows us to quantify emissions embodied in the complex trade networks among countries with captures of both direct and indirect emissions. Compared to Life-Cycle Assessment (LCA), MRIO has the advantage of examining how emissions are embodied in the global trade networks for the entire supply chain systematically and avoiding truncation errors caused by system boundary defined in traditional LCA method (Steen-Olsen et al., 2016). It has been increasingly used in recent studies on globally effected climate issues (Wiedmann, 2009; Hubacek et al., 2017; Feng et al., 2015; Mi et al., 2017).

2.2 Emissions from household consumption

Household consumption is increasingly paid attention in recent studies as it drives over 60% global GHG emissions and plays an essential role in voluntary climate actions (Ivanova et al., 2016; Dietz et al., 2009). In previous years, people studied emissions from household consumption only use the national Input-Output Tables (IOTs) linked with expenditure statistical data (Munksgaard et al., 2000; Weber & Matthews, 2008). Bin et al. (2005) built a framework of Consumer Lifecycle Approach (CLA) that quantifies the direct and indirect emissions from household consumption in the U.S. in 1997 using the EIO-LCA developed from Carnegie Mellon University (CMU). Only in recent years did more research focus on improving the accuracy of methodology on linking IO data with Consumer Expenditure Survey (CES) data.

Consumer Expenditure Survey (CES) data from national statistics include detailed information on household consumption structure and consumer groups (Fernández-Villaverde et al., 2007). It has been linked with input-output assessment for analyzing the life-cycle emissions driven by different types of consumption. Despite uncertainties existing in environmental effects of detailed CES products, linking CES and IOTs still allows to assess the complete household footprint without complex bottom-up analyses of every single household expenditure category (Steen-Olsen et al., 2016). It has been adopted to analyze emissions from major categories in many nations, including the U.S. (Weber et al., 2008; 2009; Bin et al., 2005; Jones et al, 2011; Jones et al., 2014), Norway (Hertwich et al., 2011; Steen-Olsen et al., 2016), the UK (Druckman et al., 2009), China (Liu et al., 2011; Wiedenhofer et al., 2016), and EU regions (Ivanova et al., 2017). Emissions from the U.S. household consumption are getting attention. Weber et al. (2008) analyzed the household carbon footprint by household size and income level in the U.S in 2004. Jones et al. (2011) further quantified GHG emissions and financial savings from 13 potential mitigation actions across 6 household sizes and 12 income brackets. A high-resolution spatial analysis on household GHG emissions was studied in which the U.S. was divided into 31,531 areas based on zip codes (Jones et al., 2014). Although these studies provided insights on household emissions, few analyzed distributions of these emissions with the whole global supply chain taken into consideration.

2.3 Contribution of income disparity to unequal carbon footprints

The carbon footprints are unequal across nations. A recent study showed that the global top 10% income earners were responsible for 36% of global GHG emissions, while the bottom half of income earners contributed approximately 13% of the total emissions using the country average data (Hubacek et al, 2017). The carbon inequality issue was also investigated among rural and urban people in China. The very rich Chinese urban dwellers induced carbon emissions approximately four times as much as the average in China. The urban poor and rural people account for nearly 60% of the population but have only 31% of the total household footprint (Wiedenhofer et al., 2017). The carbon inequality issue is getting increasing attention; however, the carbon footprint of American people with different income levels is unknown.

2.4 General challenges and limitations

There are several challenges in analyzing emissions from household consumption in previous research. First, different classification schemes exist in reconciling IOTs and CES. The industries in IOTs for most databases are based on the differentiation between raw materials, while CES data are collected by the purpose of use. For example, the IOT would have sectors like road transportation, while consumers might report as public transportation and private transportation. There is no universal classification standard applied to every country. Second, the valuation scheme does not share between CES and IOTs. Most IOTs are in basic price or producer's price, while CES uses consumer's price. This challenge needs to be addressed when applying the CES data to new final demand vectors. The conversion from purchaser price to producer price requires the detailed information for each sector and each money flow from one sector to another. Third, the MRIO framework traced emissions along the supply chain; however, the direct use of MRIO method may cause neglect of direct emissions from households, such as burning natural gas onsite and burning gasoline while driving. The emissions in the use stage need to be added to the corresponding consumption categories manually.

There are also general limitations for data and methods. First, the time lag of data may prevent people from investigating the emissions in latest years. Second, it is based on the assumption that the consumption structure in the domestic and overseas are the same due to data limitations. Third, there is no differentiation within sectors. The method of MRIO only provides information on the sector level but no differences within sectors. When using MRIO to analyze the carbon footprints from the rich and poor people, the results are highly dependent on the expenses even it is caused by quality not quantity.

Research on household footprint is still limited in accuracy, availability and update of data. Uncertainties also remain in linking the classification between CES and IOTs. Only recently has research explored the systematical methodology of CES-MRIO in analyzing household footprints along the supply chain (Steen-Olsen et al., 2016; Ivanova et al., 2017). Steen-Olsen et al. (2016) constructed CES-MRIO methodology by a concordance matrix linking Norwegian CES to EXIOBASE based on COICOP with different accounting challenges taken into consideration. However, this methodology has only been applied to the EU countries due to the shorted classification scheme of both CES and IOT database. To encourage a coherent methodological approach by the research communities and to allow comparison across studies, this study outlined a practical approach for combining a standard CES data in the U.S. with World Input-Output Database (WIOD). Applying this method, this study enables us to have a better understanding of the composition of household final demand in terms of specific purchases and activities. Besides, it fills in the gap between research in recent years and past years, and allows a time series analyses on emission changes. Additionally, it could inform consumers about their carbon footprint and how their carbon footprint changed over time. It could also inform people about the disparity of the carbon footprints driven by different consumption patterns. This could help people gain references to carbon tax implementation and substantial guide on bottom-up climate actions.

3. Methods

3.1 Multi-Regional Input-Output (MRIO) method

The Multi-Regional Input-Output (MRIO) model serves to calculate GHG emissions embodied in international trade (Miller & Blair, 2009). In the MRIO framework, different sectors are connected by trade between countries and by trade within countries, T^{rs}(*r*≠*s*) and T^{rs}(*r* = *s*) respectively (Kanemoto et al., 2016). To calculate the trade flow matrix T_{ij}^{rs}, the technical coefficient matrix (A^{rs}) is introduced, in which each element is given by $a_{ij}^{rs} = t_{ij}^{rs}/x_j^s$. *i* and *j* are sectors of origin and destination, and *r* and *s* are exporting and importing countries. t_{ij}^{rs} means the money flow from sector *r* in region *i* to sector *s* in region *j*.

The technical coefficient matrix is $\mathbf{A} = \begin{bmatrix} A^{11} & A^{12} & \dots & A^{1R} \\ A^{21} & A^{22} & \dots & A^{2R} \\ \vdots & \vdots & \ddots & \vdots \\ A^{R1} & A^{R2} & \dots & A^{RR} \end{bmatrix}$;

The final demand matrix is $\mathbf{Y} = \begin{bmatrix} y^{11} & y^{12} & \dots & y^{1F} \\ y^{21} & y^{22} & \dots & y^{2F} \\ \vdots & \vdots & \ddots & \vdots \\ y^{R1} & y^{R2} & \dots & y^{RF} \end{bmatrix}$;

The total output matrix is $\mathbf{X} = \begin{bmatrix} x^{1} \\ x^{2} \\ \vdots \\ x^{R} \end{bmatrix}$.

In the equations above, *R* denotes the total number of countries and *F* denotes the total number of final demand categories.

The mathematical structure is $\boldsymbol{AX} + \boldsymbol{Y} = \boldsymbol{X}$, rewritten as $\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}}\boldsymbol{Y}$.

where $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief inverse matrix (Leontief, 1986), which captures both direct and indirect effects that one unit of the final demand has on the output (Miller & Blair, 2009). This inverse matrix multiplies a household's consumption vector $\boldsymbol{y}$, so we get a total output vector accounting for all the direct and indirect inputs triggered throughout global supply chains by household's consumption. $\boldsymbol{I}$ is an identity matrix with ones on the main diagonal and zeros everywhere else.

3.2 Environmental Extended MRIO (EE-MRIO)

For the environmental extended MRIO, the total GHG emissions embodied along the supply chain can be calculated by:

$$\boldsymbol{Q_{mrio}} = \boldsymbol{E} \times (\boldsymbol{I} - \boldsymbol{A})^{-1} \times \boldsymbol{W}$$

where $\boldsymbol{E}$ is emission intensity, which is the amount of emissions generated per unit of output in each sector, and $\boldsymbol{W}$ is the household consumption.

The IO tables in 1995-2009 are derived from the World Input-Output Database (WIOD) (Timmer et al., 2015). WIOD covers 35 economic sectors for 40 countries, including all the EU (EU-27) member states and 13 of the world's largest economies. The 40 countries together represent over 85% of the world's economy (Dietzenbacher et al., 2013). Other countries are grouped in the Rest of the World (RoW). This table links many single-region input-output tables into one consistent account of intra-regional and inter-regional trade.

To calculate the emissions intensity, total emissions are derived from the satellite account in the WIOD database. Three main GHGs including CO_2, CH_4, and N_2O are quantified in CO_2-equivalent (CO_2eq) per year using Global Warming Potential cumulative forcing over 100 years (GWP100); the GWPs for CO_2, CH_4, and N_2O are 1, 28, 265, respectively (Pachauri et al, 2014).

The double-deflation method was used for many studies in estimation of the value added or GDP in constant prices (Lan et al., 2016; Malik et al., 2016). Referring to this method, this study applies the price index of gross output (GO_P) and the price index of intermediate input (II_P) to the current price in IOT in the base year 1995 for deflation purposes. The deflation removes the change of emission intensity (CO_2eq tons per unit dollar) due to economic inflation. GO_P and II_P for the 40 countries for each sector were derived from WIOD Socio Economic Accounts. For the RoW, a global average GDP deflator is applied by adjusting into the base year 1995, deriving from the World Bank statistics (World Bank, 2018).

3.3 Direct use of energy

The MRIO method captures the direct and indirect emissions along the supply chain; however, it does not include the direct emissions from the use phase in household consumption, such as gasoline burning during car driving and on-site natural gas burning during cooking. The total GHG emissions are calculated by the sum of embodied emissions and direct emissions, as follows:

$$\boldsymbol{Q_{total}} = \boldsymbol{Q_{mrio}} + \boldsymbol{Q_{direct}}$$

The direct emission is calculated by the energy price and CO_2eq coefficients. The gasoline price in the U.S. for each year is derived from the U.S. Department of Energy (US DOE, 2016). The natural gas price for each year is from the U.S. Energy Information Administration (EIA) (EIA, 2018). The CO_2 coefficients for natural gas and gasoline combustion are from the Environmental Protection Agency (USEPA, 2018). Direct emissions from household are calculated as follows:

$$\boldsymbol{Q_{direct}} = \boldsymbol{Gas} \times a + \boldsymbol{Petro} \times b$$

where a and b are CO_2 coefficient in kgCO_2eq/\$(1995).

3.4 Household consumption

To analyze the GHG emissions from households in more detail, recent studies use CES/IO method to bridge the MRIO and Consumer Expenditure Survey (CES) (Steen-Olsen et al., 2016). My study refers to this method to analyze not only the domestic emissions but also emissions exerted on other countries driven by U.S. household consumptions. The CES of the U.S. includes 13 parent categories and 74 sub-categories (According to *Glossary of Terms*, each sub-category has a detailed description containing several to dozens of items, and over 600 items in total). The classification of CES is based on product level but in alignment with North American Industry Classification System (NAICS). The CES data is linked with sectors of the U.S. in the WIOD database which are based on the Statistical

Classification of Economic Activities in the European Community (NACE) revision 1 that corresponds to the International Standard Industrial Classification of All Economic Activities (ISIC) revision 3 (Dietzenbacher et al., 2013).

3.4.1 Types of consumption

The first step of this linkage is to aggregate the 74 sub-categories in CES into 16 categories that represent the main types of household consumption (Table 1). Bridging these two refers to the classification concordance between NAICS and ISIC (Ambler, 1998). The 16 categories are different from the 13 parent categories which exist in the original CES table by aggregating the service sectors and grouping large emission of expenditures in housing with more details. For those types of consumption in CES which correspond to more than one sectors in IOT, they are allocated according to the proportion in the final demand vector in IOT. It is based on the assumption that although each household varies from another, the households' consumptions are similar to the national household final demand on the national level.

Table 1. Categories of household consumption

Food	Food at home
	Food away from home
Housing	Shelter
	Utility
	Electronics
	Furnishing and supplies
	Miscellaneous goods
Clothing	Clothing
Transportation	Vehicle purchase
	Fuels
	Public transportation
	Transport service
Services	Entertainment
	Education
	Health
	Other services

The second step is to adjust the price in the CES. Consumer Price Index (CPI) (α) is assigned for CES by product to deflate to the price in the base year 1995. CPI for the 74 products is derived from the U.S. Bureau of Labor Statistics. The closest substitution is applied for those categories that have no available data in the corresponding year. The 16 categories of consumption with 35 industries in WIOTs. In the build-up of the concordance matrix, data for wholesale and retail is derived from the Annual Wholesale Trade Survey (AWTS) and Annual Retail Trade Survey (ARTS) (U.S. Census Bureau, 2018a & 2018b). Tax and transportation margins are also subtracted to adjust the purchaser's price to basic price in correspondence with data in WIOD.

Previous studies (Brizga et al., 2017) used one concordance matrix for multiple years; however, this does not take into account the nuanced structure change of economies. This study builds a concordance matrix for each year with price index adjustment. A country-level final demand matrix by each type of consumption (***Wcons***) is expressed as follows:

$$\boldsymbol{W_{cons}} = \boldsymbol{H} \times \boldsymbol{C_{cons}}$$

Where ***H*** is a vector of final demand on households of the U.S., ***Ccons*** is the concordance matrix (see Appendix A) bridging the categories in IOT and those in CES by types of consumption. The overseas final demand structure is assumed to be the same as the domestic due to data limitation.

3.4.2 Income groups

Following a similar process of building up a concordance matrix and bridging the sectors in IOT and consumption structure, another concordance matrix (see Appendix B) is built up to bridge the categories in IOT and different income groups (***Winc***).

$$\boldsymbol{W_{inc}} = \boldsymbol{H} \times \boldsymbol{C_{inc}}$$

Households are divided into 13 groups of different incomes: < $5,000, $5,000-$9,999, $10,000-$14,999, $15,000-19,999, $20,000-$29,999, $30,000-$39,999, $40,000-$49,999, $50,000-$69,999, $70,000-$79,999, $80,000-$99,999, $100,000-$119,999, $120,000-$149,999, >$150,000. Data of incomes below $6,9999 are derived from table *Income* *before tax*, and data of income above $70,000 are derived from table *Higher income before taxes*. Only the mean values in the census statistics are considered in this study. Data of household size and average persons in a typical household are also from the Consumer Expenditure Survey from 1995 to 2009.

4. Results

4.1 Total domestic and overseas GHG emissions

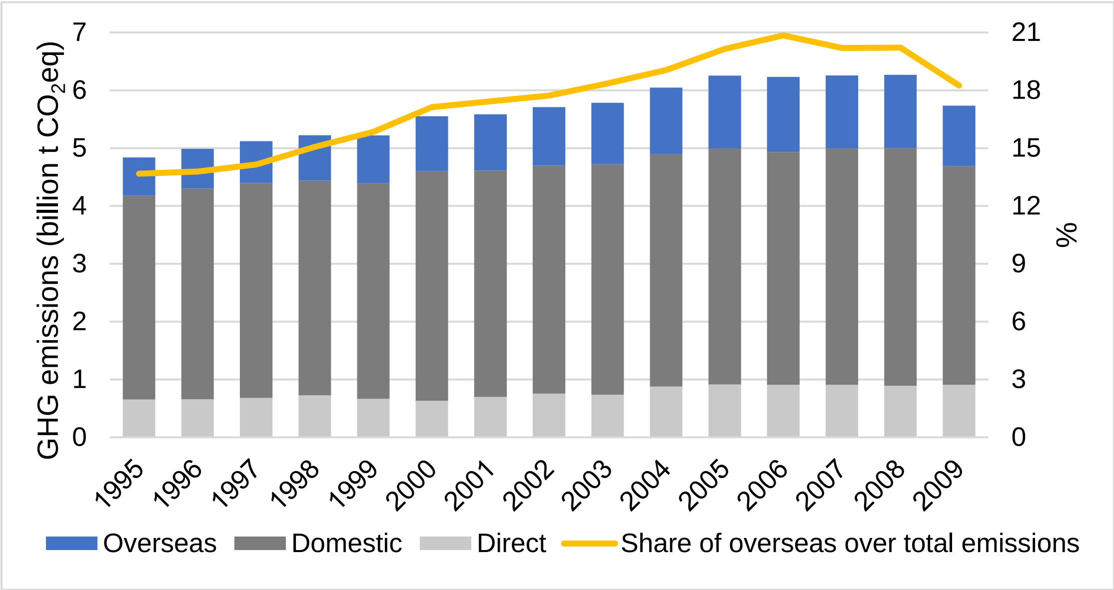


Figure 1. Domestic and overseas emissions driven by U.S. household consumption

An analysis of total emissions from household consumption is warranted for benchmarking purposes. Figure 1 shows that both domestic emissions and emissions embodied in imports significantly increased from 1995 to 2005, despite a decrease in the last few years. The total amount of GHG emissions driven by U.S. household consumption increased from 4.8 billion tons of CO_2eq in 1995 to nearly 6.3 billion tons of CO_2eq in 2008. The share of overseas emissions in the total caused by U.S. household consumption also increased from about 13% in 1995 to over 20% in 2008. Both domestic emissions and overseas emissions decreased from 2008 to 2009 because the financial crisis depressed consumption (Feng et al., 2015). Although the total emissions for both domestic and overseas emissions show an obvious increasing trajectory, the per capita GHG emission only slightly increased from 18.2 tCO_2eq/cap in 1995 to 20.8 tCO_2eq/cap in 2006, and decreased back to 18.2 tCO_2eq/cap in 2009, as shown in Figure 2. The U.S. household carbon footprint is over five times the world average household carbon footprint of 3.4 tCO_2eq/cap in 2007 (Ivanova et al., 2015).

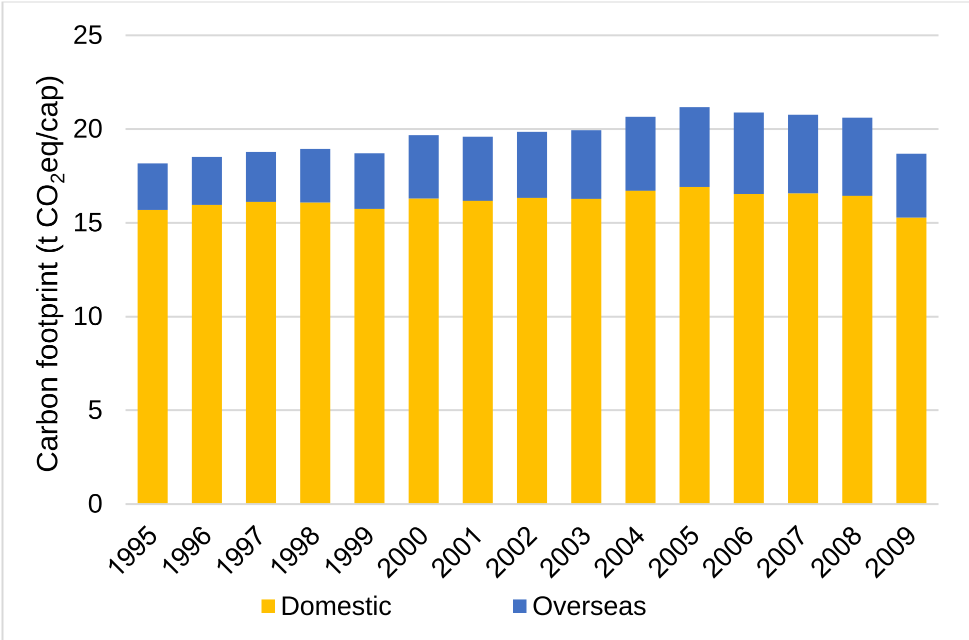


Figure 2. U.S. household carbon footprint from 1995 to 2009

4.2 GHG emissions by type of consumption

4.2.1 Annual changes in GHG emissions

Although the total emissions show an increasing trajectory, the trends of emissions from consumption of different types of products are not necessarily the same. Previous studies show that the emission increase before 2007 is dominated by the consumption volume using Structural Decomposition Analysis (SDA); consumption volume was also the main driver of emission decrease after 2007 (Liang et al.,2016; Feng et al., 2015). However, SDA only provides the drivers of the changes between the beginning and ending year of the study period, considering all types of expenditure as a whole. In comparison, the present study investigated the emission changes by different types of consumption in each year.

The domestic emissions generally increased during the study period, in spite of decreases in the years of 1999, 2006, and 2009 (Figure 3). For most years, both the increase and decrease of emissions are dominated by the consumption of goods and services related to housing and transportation, given the large volume of expenditure and sensitivity to economic changes. Housing contributed significantly from the large share of the total expenditure, while transportation contributed from its high emission intensity. Emissions from transportation consist of a large share of fuel consumed by private transportation, which is closely related to the increase of energy consumption documented by the rebound effect (Thomas & Azevedo, 2013). Although the emissions from clothing, food and service decreased, the decreases did not offset the increases from housing and transportation.

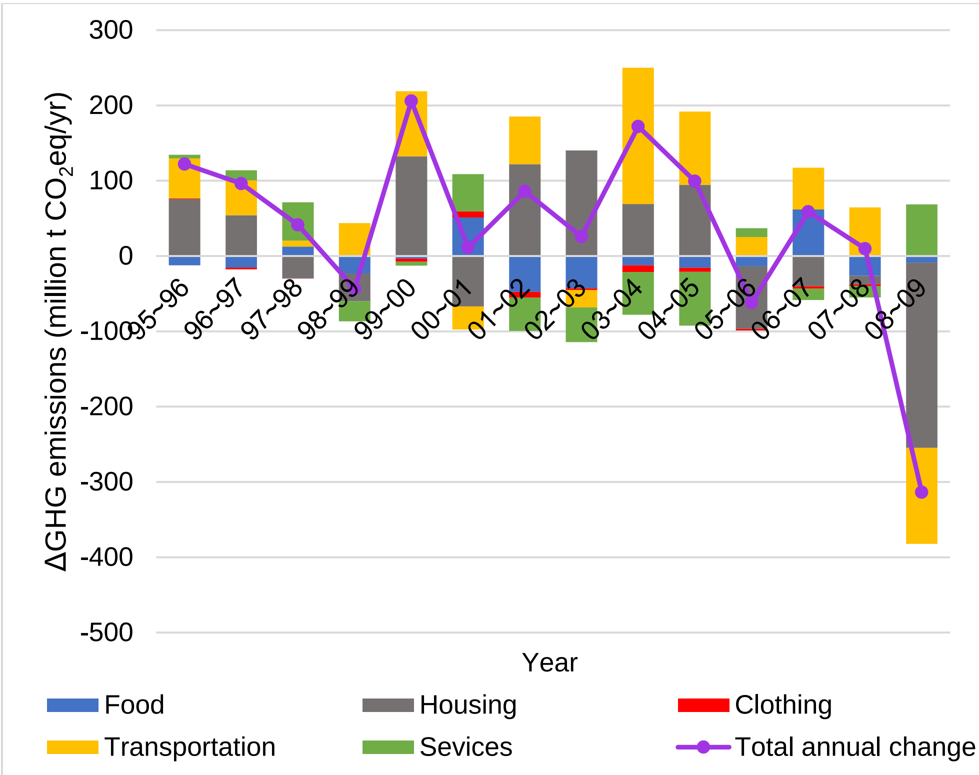


Figure 3. Annual changes in domestic GHG emissions from 1995 to 2009

The changes in GHG emissions embodied in imports are also dominated by the emissions from transportation and housing. Emissions induced overseas driven by expenditure on services in the U.S. is much less than emissions induced domestically, and the annual changes are also less significant. Before 2007, emissions embodied in imports had increased, among which the increase of emissions associated with housing and transportation contributed significantly, despite a decrease in emissions from transportation during 2000 to 2001. As Figure 4 shows, the years of 1999-2000, 2003-2004, and 2004-2005 saw a rapid increase of overseas emissions, largely due to rapidly increasing imports of fuels, vehicles and vehicle components. Between 2007 and 2009, the overseas emissions decreased despite a slight increase during 2007-2008. The decrease is dominated by the downturn in emissions from housing, especially from *Electronics, Furnishing and supplies, Miscellaneous goods* as the detailed data shows.

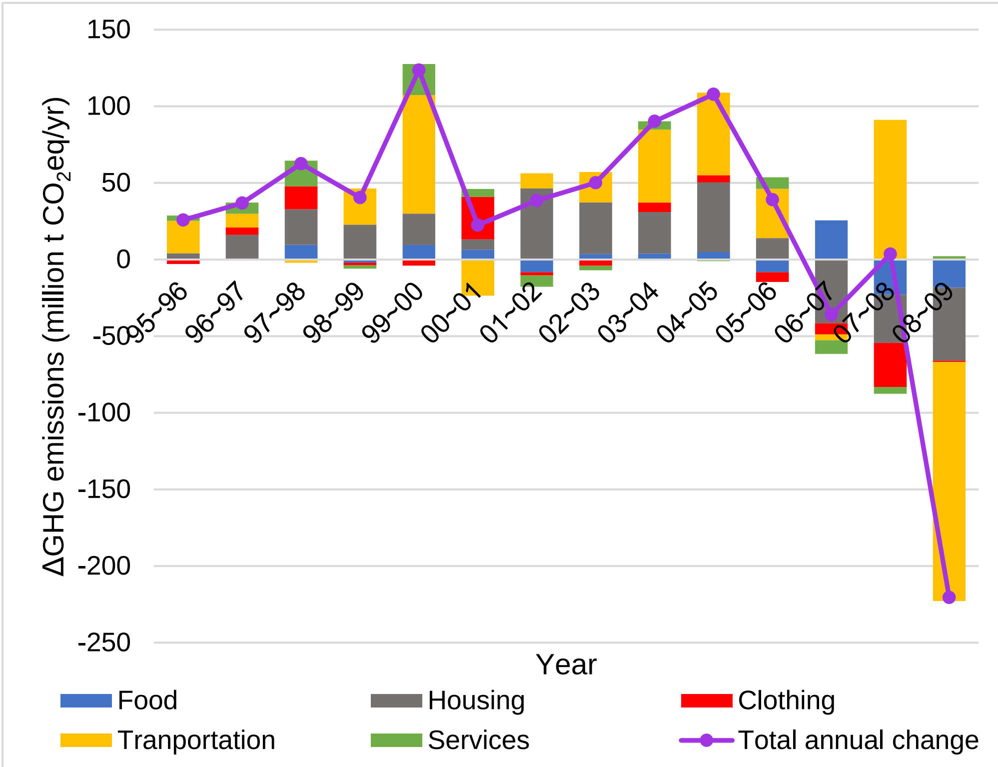


Figure 4. Annual changes in overseas GHG emissions from 1995 to 2009

4.2.2 GHG emission changes from 1995 to 2009

Emissions from each type of consumption changed over time due to the changes in people's consumption behavior, economic structure, and volume of consumption. It is noticeable that emissions from *Utility*, *Fuels* and *Public Transportation* increased sharply both domestically and overseas (Figure 5). Domestic emissions increased about 1.5 times while overseas emissions increased about 2.5-7 times before the Great Recession. They are in agreement with the existing research showing that emissions from energy consumption in the residential sector have a rebound effect (Hertwich, 2005; Thomas & Azevedo, 2013; Brannlund, 2007). For *Food away from home*, *Electronics*, *Furnishing and supplies*, *Miscellaneous goods*, *Clothing*, *Vehicle purchase*, *Transportation service*, *Health*, and *Other services*, the decrease in domestic emissions is generally accompanied by an increase in overseas emissions.

Note: the orange lines show domestic emissions (in Mt CO_2eq/yr) by left y-axis, the blue lines show overseas emissions (in Mt CO_2eq/yr) by right y-axis

Figure 5. GHG emissions by type of household consumption

4.2.3 GHG emission intensity by household consumption

GHG emissions intensity varied by types of consumption over time (Figure 6). Some consumption categories related to services and real estate, such as transportation services, health, education, and shelter have emission intensities much lower than energy related consumption such as utility and fuels. Expenditures on products and services related to health have emission intensity as low as 0.2-0.35 kgCO_2eq/$(1995) domestically and 0.04-

0.05 $kgCO_2eq$/$(1995) overseas, while fuels have emission intensity as high as 7.5-12 $kgCO_2eq$/$(1995).

Note: orange lines show domestic emissions intensity [in gCO_2eq/$(1995)] by left y-axis, blue lines show overseas emissions intensity [in gCO_2eq/$(1995)] by right y-axis

Figure 6. GHG emission intensity by type of household consumption

Emission intensities from most types of expenditure have decreased over the past 15 years. It means that for the consumption of one dollar in $(1995) worth of product, the GHG emissions decreased. Domestic GHG emission intensity decreased faster than that of overseas GHG emissions. The decrease is probably because technology improvement for GHG reduction in the U.S. performs better than in the other countries. It might also be explained by the change in world economic structure, especially because the products that the U.S. imported are energy-intensive.

4.2.4 Contribution of different types of consumption to total emissions

Different consumption categories have very different shares of both expenditure and GHG emissions. Contribution from different types of consumption to the total emissions changed during the study period. Taking both embodied emissions and direct emissions into consideration, emissions from solely *Utility* and *Fuels* accounted for about 40%-50% of the total emissions. Emissions from *Food at home*, *Health*, *Other services*, *and Furnishing and supplies* accounted for another 20%-30% of the total emissions (Figure 7).

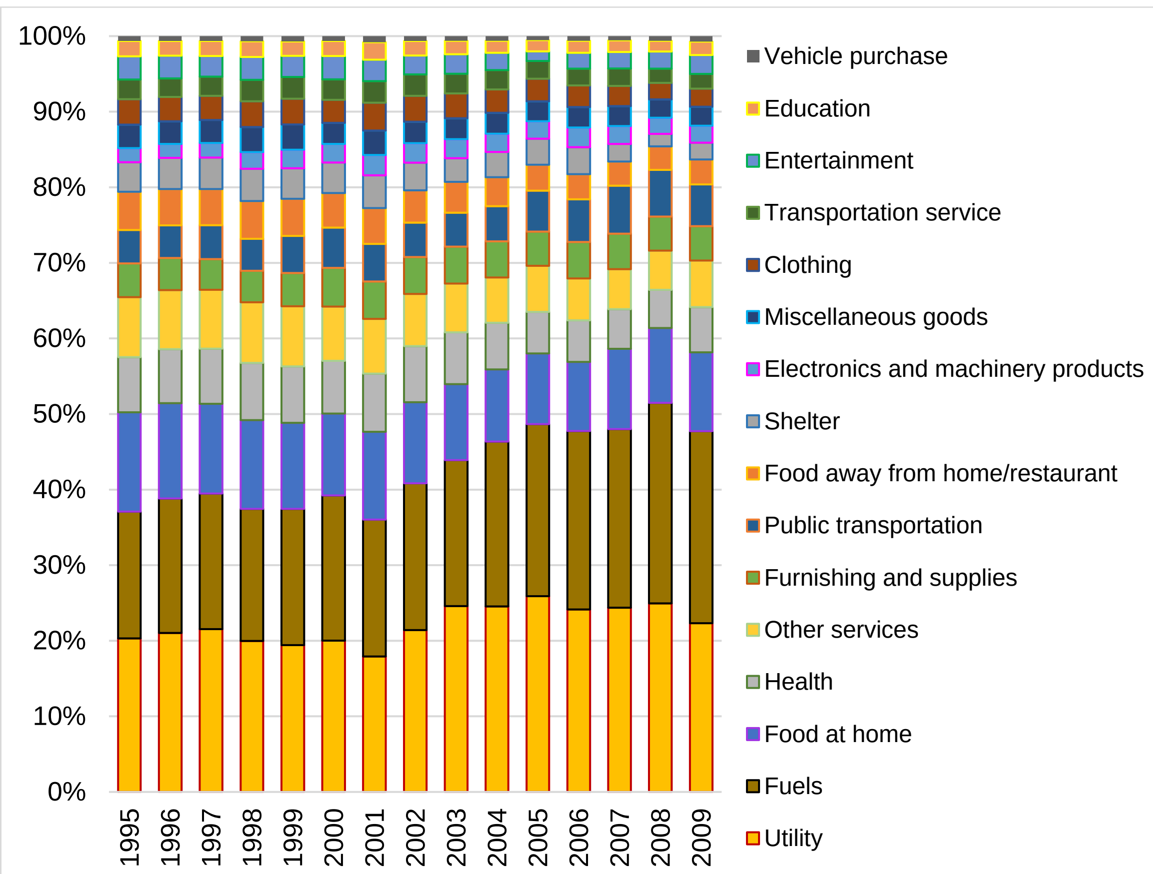


Figure 7. GHG emissions from households by type of consumption from 1995 to 2009

For most types of household consumption, the share of emissions embodied in imports in total emissions increased from 1995 to 2009, as analyzed in 4.2.1. Emissions from the 16 types of consumption are roughly grouped into six groups, as shown in Figure 8. (1) *Clothing* represents the most share of emissions embodied in imports, from about 60% to 80%. In other words, for the emissions from U.S. household consumption in *Clothing*, about 60% to 80% of them occurred in other countries along the upper supply chain. (2) *Electronics* ranked second in the share of emissions embodied in imports, this increased from about 50% to nearly 60%. (3) *Miscellaneous goods*, *Transportation service*, and *Furnishing and supplies* are the third groups of the shares of emissions embodied in import; these increased from approximately 30% to 40%. (4) *Vehicle purchase and Food at home* have overseas emissions of about 20% to 25%. (5) Overseas emissions from *Health, Public transportation, Shelter*, and *Other services* account for 10%~15% of the total emissions. (6) *Entertainment* and *Utility* have the least overseas GHG emissions, accounting for about 5% to 10%. It is noticeable that the rapid increase in the share of overseas emissions from *Fuels* is in accordance with the results above.

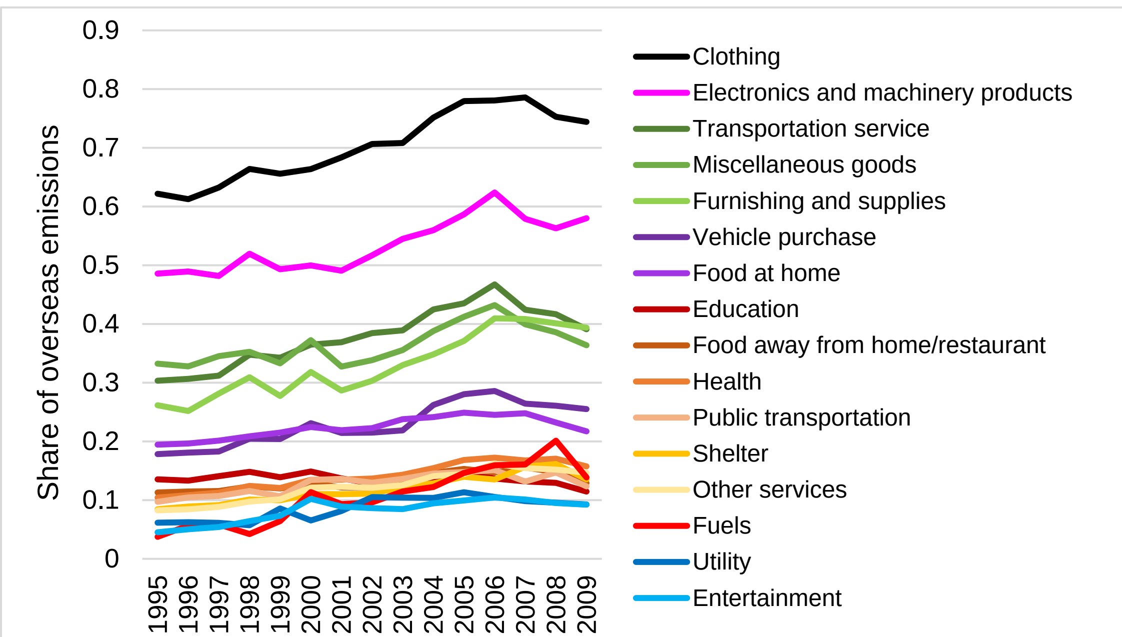


Figure 8. Share of emission embodied in imports in total emissions

4.3 Household emission profile in 2009

This study took emissions in the year of 2009 as an example to investigate the emission profile from U.S. household consumption given the latest available data. It gives an overview of emissions by consumption, emission distribution, and income levels of consumers.

4.3.1 GHG emissions by household consumption in 2009

In 2009, Transportation (42%) and Housing (28%) contributed 70% to the total domestic emissions; especially, housing utilities (including the use of electricity and onsite natural gas) and fuels (burning gasoline and diesel) together contributed 57% to the total emissions (Figure 9). Service, food, and clothing contributed 16%, 14%, and 1%, respectively. GHG emissions embodied in imports of different household products are shown in Figure 10. Emissions from U.S. household consumption in the categories of housing, food, transportation, service, and clothing is 35%, 20%, 17%, 15%, and 12%, respectively. In the sub-categories, emissions from *Food at home*, *Furnishing and supplies,* and *Clothing utility* are the three major contributors to the total overseas emissions from U.S. household consumption. Compared to domestic emissions, U.S. household consumption on *Clothing*, *Furnishing and supplies*, *Electronics and machinery products* induces approximately 30% of the total of their overseas emissions.

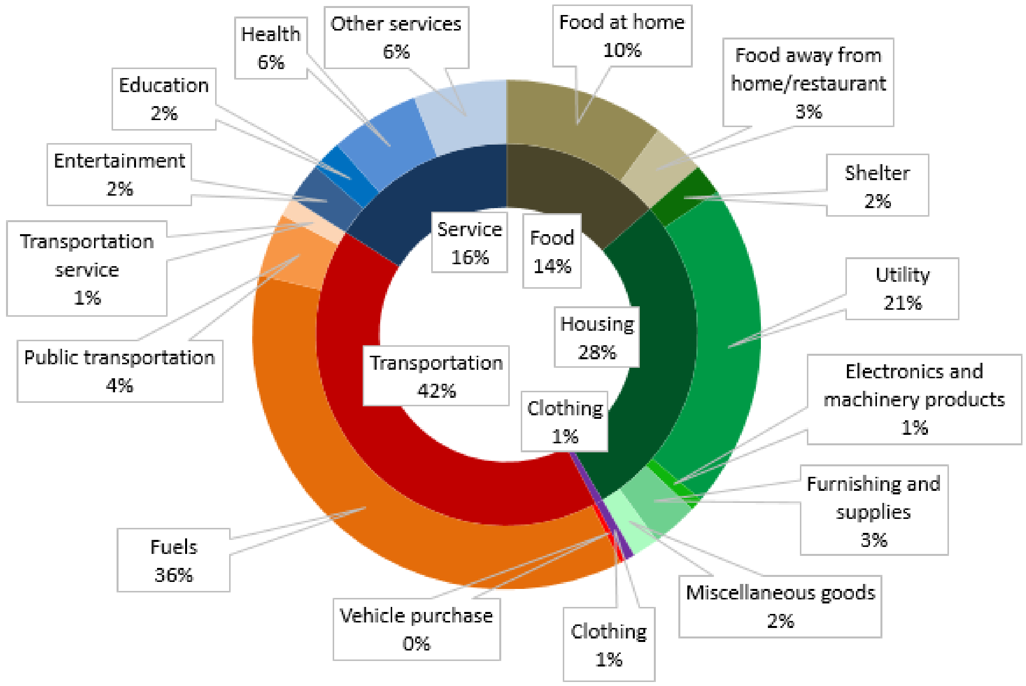


Figure 9. Share of emissions by consumption in domestic GHG emissions in 2009

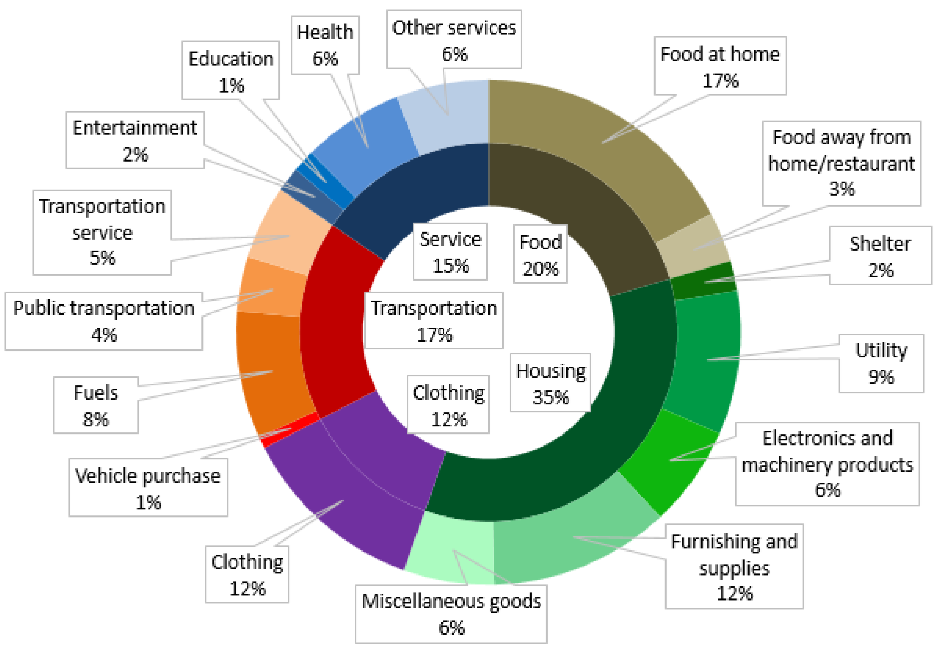


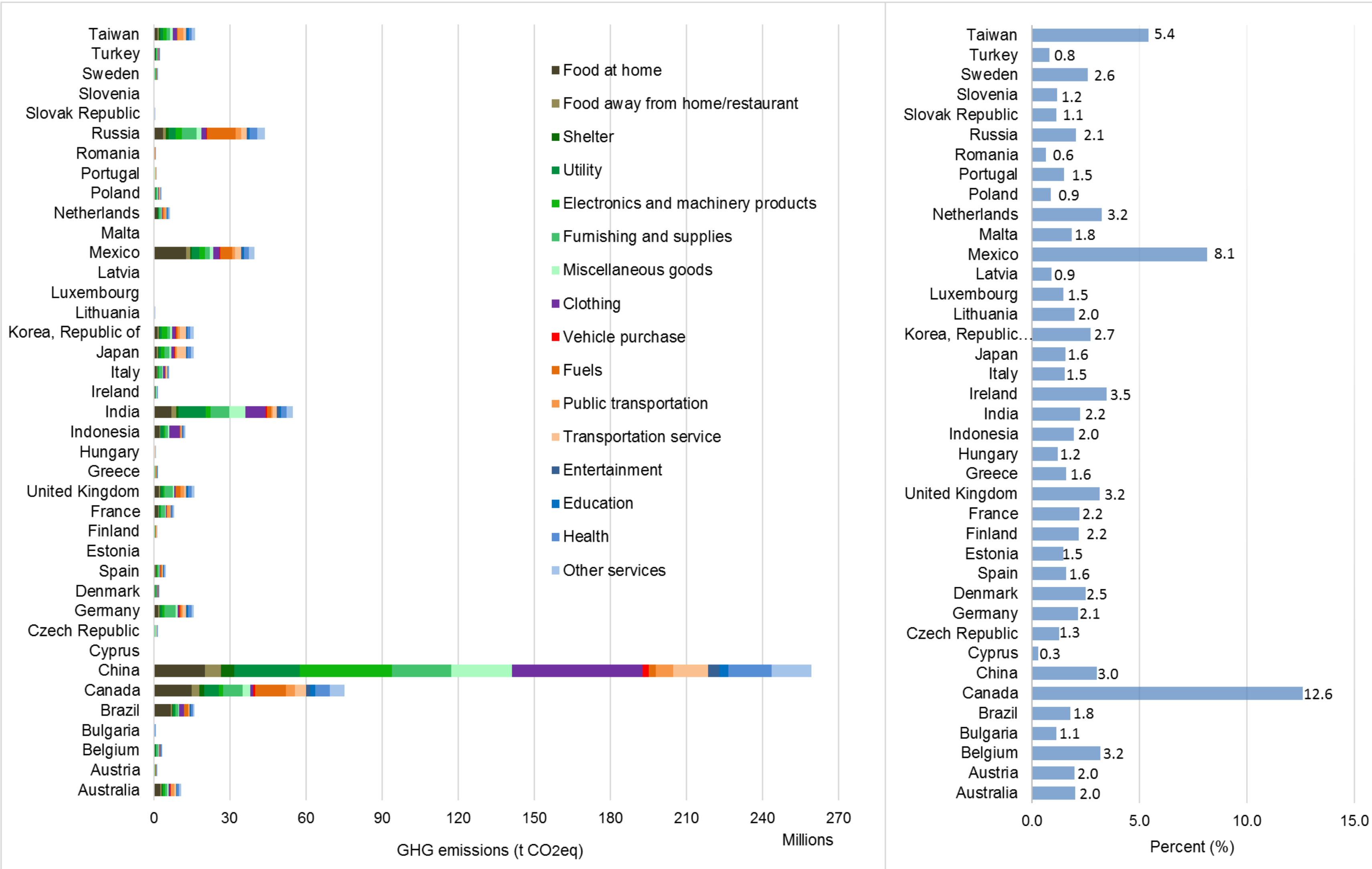
Figure 10. Share of emissions by consumption in overseas GHG emissions in 2009

4.3.2 Overseas emissions by country in 2009

The overseas GHG emissions driven by U.S. household consumption distributed unevenly among countries. Figure 11 shows the emissions induced in 39 countries/regions due to

U.S. household consumption, and the share of these emissions in their territory emissions. China became the largest emission exporter to the U.S., as over 250 million tons of CO_2eq are induced by U.S. household consumption. Canada, India, Russia, and Mexico also generated large GHG emissions to serve the demand of U.S. household consumption. More detailed information on emissions induced overseas driven by different types of consumption is also shown in Figure 11. Mexico is a large emission exporter to the U.S. due to food consumed. The emissions generated in Russia and Canada because of fuel consumption in the U.S. are also major contributors to their total emissions exported.

Although there is a large amount of emissions induced by the U.S. in some countries, these emissions only represent a small part of their total territory emissions. For example, the amount of emissions left in China is far larger than that in other countries; however, it only takes 3.0% of China’s total territory emissions due to its large base. 12.6% of Canada’s territory emissions, 8.1% of Mexico’s territory emissions, and 5.4% of Taiwan’s territory emissions are driven by the products consumed by the U.S. households.



(Note: this figure does not show the emissions in the RoW)

Figure 11. Distribution of overseas emissions driven by U.S. household consumption in 2009 (left) and their shares in territory emissions (right)

4.4 Emissions by income group

GHG emissions by income group are analyzed with a division of 13 groups by income level in 2009 (Figure 12). Household carbon footprint generally increases with household income, ranging from 18.5 tCO_2eq/hh to 94.7 tCO_2eq/hh. The household carbon footprint of the richest households is over five times that of the poorest households. However, the carbon footprint of households with less than \$5,000 income is higher than households with \$5,000-\$9,999 income, because households are different from families. Households include students and elderly people who have low earning but high consumption.

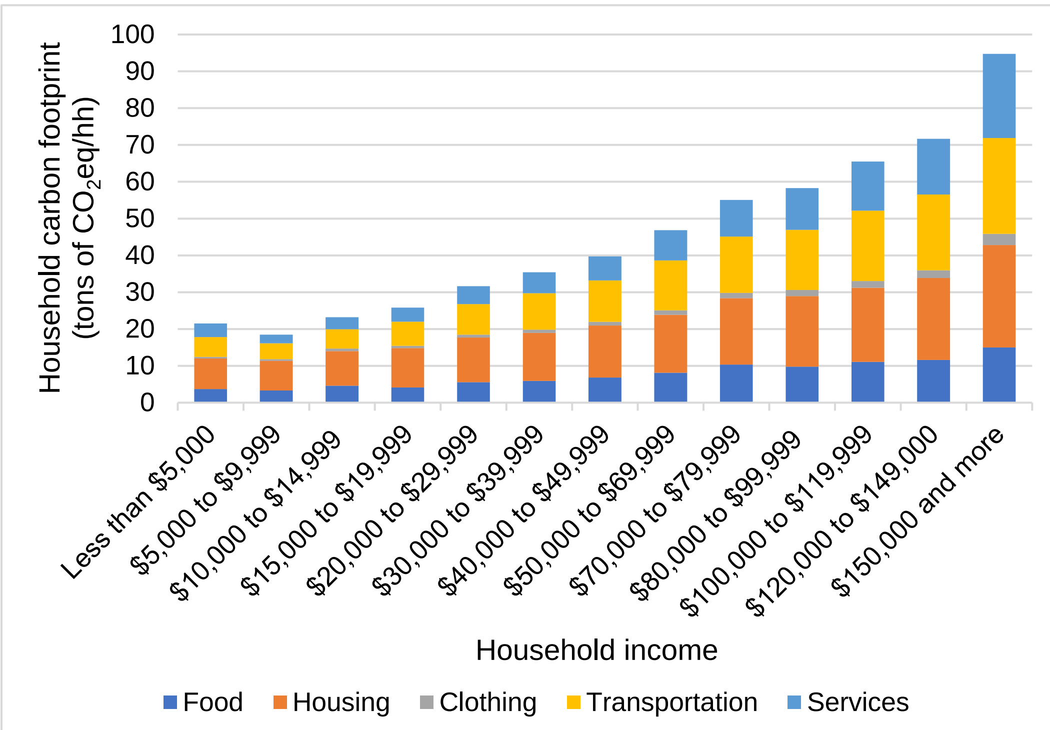


Figure 12. Household carbon footprint in the U.S. by income level

The per capita carbon footprint ranged from 11.5 to 29.6 tCO_2eq/cap, as shown in Figure 13. Carbon footprint does not vary much for people with less than \$40,000 household income, ranging from 11.5-14.8 tCO_2eq. The differences of emissions between people with less than \$5,000 income and \$5,000-\$9,999 income mainly lie in the emissions from education, which belongs to services consumption. As income increases, the share of emissions from service consumption increases.

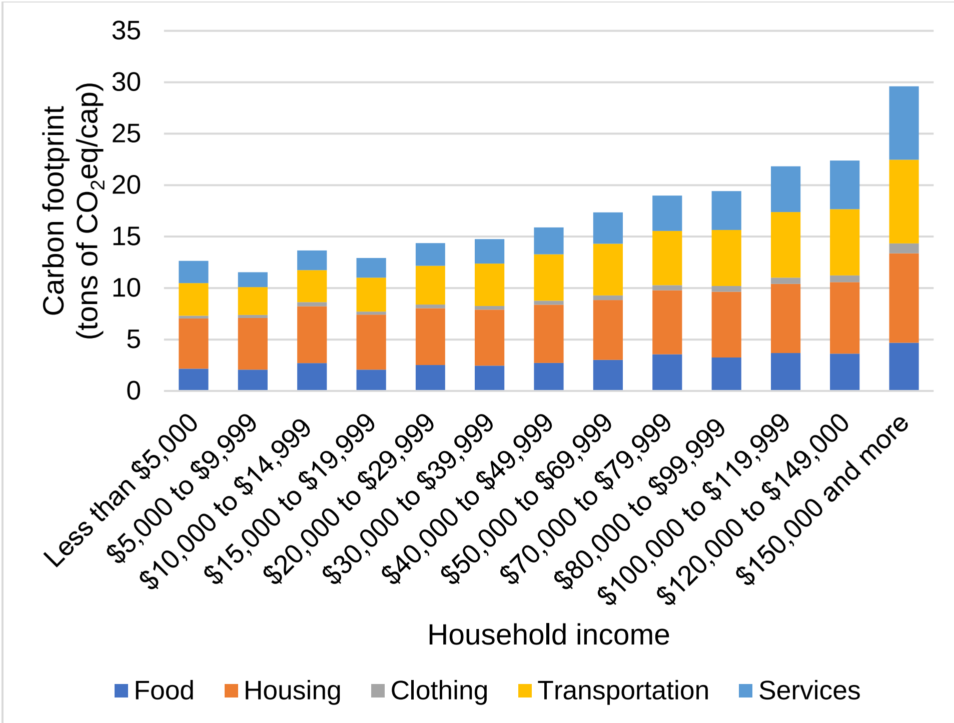


Figure 13. Carbon footprint per capita in the U.S. by income level

Wealthy people with more than $100,000 household income accounted for only 22.3% of the total population; however, they drove about 31.2% of the total GHG emissions. People with less than $30,000 household income, consisting of 25.7% of the total population, drove 19.3% of the total emissions (Figure 14).

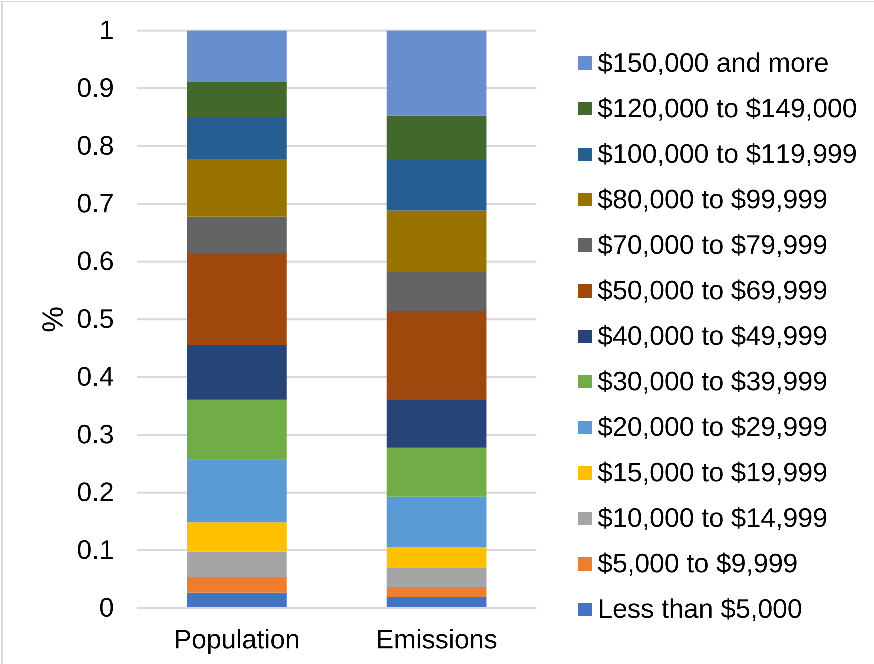


Figure 14. Population and emissions in 2009 with different income groups

5. Discussion

5.1 Research comparison

Total emissions. This study investigated the household carbon footprint around the globe with the environmental-extended MRIO method. Household carbon footprint is between 18.2 tCO_2eq/cap and 20.8 tCO_2eq/cap during 1995-2009. The carbon footprint per capita in this study agrees reasonably with the previous study of 18.6 tCO_2eq/cap in 2007 for U.S. household consumption (Ivanova et al., 2016). A similar study focusing on U.S. consumption also indicated that the per capita GHG emissions for U.S. household consumption are roughly 20 tCO_2eq/cap (Jones & Kammen, 2011). A spatial analysis concentrating on emissions from U.S. household consumption indicated that per capita GHG emissions among different Metropolitan Statistical Areas (MSAs) ranged from 17.2-19.5 tCO_2/cap, with a weighted average of 18.6 tCO_2/cap (Jones & Kammen, 2014). The 4 tCO_2eq/cap gap between this research and research of Wiedenhofer (2016) is largely due to the accounting method and details in data analysis. The overseas carbon footprint amounts to approximately 20% of the total emissions, which corresponds with the study by Kanemoto et al. (2016) but is less than the results from the study by Weber & Matthews (2008). It is probably because both this study and Kanemoto et al.'s study covers most countries around the globe, while study from Weber & Mathews only analyzed incomplete trade networks and only seven countries were taken into account.

Consumption profile. Although housing contributed significantly to the total emissions, shelter represents a small part compared to other types of consumption in housing. It is because all values in shelter construction count in the category the Gross Fixed Capital Formation, not the household final demand, while expenditure in shelter is considered as real estate activities. Therefore, this research, along with the study from Wiedenhofer (2016) and Ivanova (2017), show that shelter only contributed a small part of total emissions, while most emissions from housing are from consumption of utility and goods. The household carbon footprint in the U.S. in 2009 ranged from 11.5-29.6 tCO_2eq/cap, much larger than the Chinese household carbon footprint in 2012, ranging from approximately 0.5 to nearly 6.5 tCO_2eq/cap. Compared to China, the household carbon footprint is more evenly spread among consumers than that in China. The wealthiest people in the U.S. have about 2.5 times larger carbon footprint than the poorest group of people; however, the same condition in China amounts to 13 times.

5.2 Research limitations and future work

This study addressed the challenges of different classification schemes mentioned in section 2.4 by building up the concordance matrix. The price value is also adjusted to be constant and comparable in different years. Besides, direct emissions from household consumption in the use phase is included in this study. However, this study only covers the time span from 1995 to 2009, due to the time lag of available data for both input-output tables and the emission satellite account. Several assumptions are also applied in this research. First, input-output analysis is based on a proportionality assumption that final demand for each type of consumption corresponds to the household final demand vector in WIOD, which represents the production recipe. Second, the consumption overseas follows the assumption that they are the same proportionately with consumption in the domestic sphere when one industry serves demands from more than one product; for example, textiles and textile products could provide primary inputs for both housing textiles and clothing. Third, the IOA studies each industry on its average level, but cannot differentiate products within an industry. For example, although the emissions from manufacturing a luxury vehicle and average-priced vehicle do not vary much, the amount of money spent could be quite different. Besides, the over-report of food and under-report of alcohol and other less frequently-used goods are well-documented in previous studies (Weber & Matthews, 2008; Ivanova et al., 2017). Uncertainties also exist due to the statistics of the survey data and reconciliation of CES and IOTs.

Future research may focus on improving the transparency and accuracy of the input-output database. Hybrid LCA-EIO could be applied to differentiate emissions from expenditures on different products within an industry to better reflect emissions associated with different levels of income. High-resolution spatial analysis on the global carbon footprint driven by U.S. household consumption would be helpful to provide references to the city-to-city cooperation for climate actions.

5.3 Policy implications

Trade policies could be applied to green the global supply chain. The U.S. has achieved progress in reducing the emission intensity for most of their expenditure behaviors. However, the emission intensity overseas does not decrease as fast as that in the U.S., and some even increase, for example, furnishing and supplies and fuels. At the country level, governments could help improve the energy efficiency and technology in developing countries in pursuit of sustainable production and consumption. At the individual level, consumers should better share the climate responsibility with producers. This could motivate consumers to make choices on greener consumption behavior in reaction to the voluntary climate actions.

The long-term goal of sustainability requires energy transition. About half of the emissions are driven by the consumption of utilities and fuels, which are also the two parts that increased significantly over time. One the one hand, reducing the volume of consumption in households to mitigate rebound effect is a hard but effective way to contribute voluntarily to climate actions. On the other hand, energy transition from fossil energy to renewable energy would effectively reduce the emissions from energy-intensive sectors like grids and transportation.

In addition, wealthier people should take more climate responsibilities than poorer people. People with higher income may have contributed more to socioeconomic development, and therefore reducing their carbon footprint could be a challenge. However, research shows that some countries have already achieved a high level of human development but have an average carbon footprint of 1 tCO_2eq/cap (Wiedenhofer et al., 2017). This highlights that livable and potentially more sustainable societies exist that people could potentially pursue.

6. Conclusions

This research systematically analyzed the emission profile of the U.S. households during 1995 to 2009 with an MRIO method. The total GHG emissions driven by U.S. household ranged from 4.8 to 6.2 billion tons of CO_2eq during the 15 years with an increase trajectory. Overseas emissions increased and contributed to the total GHG emissions from 13% to over 20%. Emissions driven by U.S. households are largely due to expenditures on housing and transportation, which together contributed to nearly 70% of the total emissions. Although the amount of emissions increased over the 15 years, emissions intensity for most types of products and services consumed decreased; the emission intensity decreased faster domestically than overseas. In addition, the household carbon footprint for people with different income levels varies significantly, from 18.5 to 94.7 tCO_2eq/hh. The individual carbon footprint averaged from 18.2 to 20.8 tCO_2eq/cap during 1995 and 2009, about five times higher than the world average household carbon footprint. The carbon footprint varies between people with lower income and higher income, ranging from 11.5 to 29.6 tCO_2eq/cap. For people with less than $40,000 household income, carbon footprint does not vary much, falling in the range of 11.5 to 14.8 tCO_2eq/cap. This research proposed that trade policies and inter-governmental cooperation could help green the supply chain. Besides, consumers would better share the climate responsibility to achieve the goal of sustainable production and consumption.

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Appendix

Appendix A. Concordance matrix of bridging WIOT with household consumption in CES in 2009

	Food		Housing		Housing			Clothing	Transportation				Service			
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Agriculture, Hunting, Forestry and Fishing	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mining and Quarrying	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Food, Beverages and Tobacco	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Textiles and Textile Products	0	0	0	0	0	0.11	0	0.89	0	0	0	0	0	0	0	0
Leather, Leather and Footwear	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Wood and Products of Wood and Cork	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Pulp, Paper, Paper , Printing and Publishing	0	0	0	0	0	0.20	0	0	0	0	0	0	0	0.80	0	0
Coke, Refined Petroleum and Nuclear Fuel	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Chemicals and Chemical Products	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Rubber and Plastics	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Other Non-Metallic Mineral	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Basic Metals and Fabricated Metal	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Machinery, Nec	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Electrical and Optical Equipment	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Transport Equipment	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Manufacturing, Nec; Recycling	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Electricity, Gas and Water Supply	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Construction	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0	0	0	0	0	0	0	0	0.79	0.14	0	0.07	0	0	0	0
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.06	0	0	0	0.47	0.14	0.22	0.04	0	0	0	0	0	0	0.08	0
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.21	0.17	0.05	0	0.06	0.20	0.05	0.12	0	0	0	0	0.04	0	0.10	0
Hotels and Restaurants	0	0.78	0	0	0	0	0	0	0	0	0	0	0	0	0	0.22
Inland Transport	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Water Transport	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Air Transport	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Post and Telecommunications	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Financial Intermediation	0	0	0	0	0	0	0	0	0	0	0	0.27	0	0	0.32	0.41
Real Estate Activities	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Renting of M&Eq and Other Business Activities	0	0	0	0	0	0	0.80	0	0	0	0	0	0.20	0	0	0
Public Admin and Defence; Compulsory Social Security	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Education	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Health and Social Work	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Other Community, Social and Personal Services	0	0	0	0	0	0	0	0	0	0	0	0	0.56	0	0	0.44
Private Households with Employed Persons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

A: Food at home B: Food away from home/restaurant C: Shelter D: Utility E: Electronics and machinery products F: Furnishing and supplies G: Miscellaneous goods H: Clothing I: Vehicle purchase J: Fuels K: Public transportation L: Transportation service M: Entertainment N: Education O: Health P: Other services

Note: Concordance matrix in 1995-2008 are not attached due to space limitation, please contact author at kaihuis@umich.edu for more information.

Appendix B. Concordance matrix of bridging the WIOTs with CES by income levels in 2009

	A	B	C	D	E	F	G	H	I	J	K	L	M
Agriculture, Hunting, Forestry and Fishing	0.02	0.02	0.04	0.04	0.10	0.09	0.09	0.16	0.07	0.10	0.07	0.07	0.12
Mining and Quarrying	0.02	0.02	0.04	0.05	0.10	0.10	0.09	0.16	0.06	0.10	0.08	0.07	0.11
Food, Beverages and Tobacco	0.02	0.02	0.04	0.04	0.10	0.08	0.09	0.16	0.07	0.10	0.09	0.07	0.13
Textiles and Textile Products	0.01	0.02	0.04	0.03	0.07	0.07	0.08	0.14	0.06	0.12	0.09	0.08	0.18
Leather, Leather and Footwear	0.02	0.03	0.05	0.03	0.09	0.09	0.09	0.16	0.06	0.10	0.08	0.07	0.14
Wood and Products of Wood and Cork	0.01	0.01	0.02	0.04	0.07	0.08	0.07	0.14	0.06	0.11	0.10	0.09	0.21
Pulp, Paper, Paper , Printing and Publishing	0.01	0.01	0.03	0.03	0.08	0.08	0.08	0.15	0.06	0.10	0.09	0.09	0.18
Coke, Refined Petroleum and Nuclear Fuel	0.02	0.02	0.03	0.04	0.09	0.09	0.09	0.17	0.07	0.11	0.09	0.07	0.12
Chemicals and Chemical Products	0.02	0.02	0.05	0.05	0.11	0.09	0.09	0.15	0.07	0.11	0.08	0.06	0.11
Rubber and Plastics	0.01	0.01	0.02	0.02	0.06	0.08	0.06	0.13	0.07	0.13	0.11	0.10	0.19
Other Non-Metallic Mineral	0.01	0.01	0.02	0.02	0.06	0.08	0.06	0.13	0.07	0.13	0.11	0.10	0.19
Basic Metals and Fabricated Metal	0.01	0.01	0.02	0.02	0.06	0.08	0.06	0.13	0.07	0.13	0.11	0.10	0.19
Machinery, Nec	0.01	0.01	0.02	0.04	0.08	0.08	0.09	0.17	0.06	0.13	0.07	0.08	0.17
Electrical and Optical Equipment	0.02	0.02	0.03	0.05	0.07	0.05	0.09	0.14	0.07	0.11	0.09	0.06	0.19
Transport Equipment	0.01	0.02	0.02	0.03	0.08	0.08	0.09	0.17	0.07	0.10	0.10	0.09	0.14
Manufacturing, Nec; Recycling	0.02	0.02	0.03	0.04	0.10	0.09	0.09	0.15	0.06	0.11	0.08	0.07	0.12
Electricity, Gas and Water Supply	0.02	0.03	0.04	0.05	0.11	0.10	0.09	0.15	0.06	0.10	0.07	0.07	0.11
Construction	0.02	0.02	0.04	0.04	0.08	0.08	0.08	0.15	0.06	0.11	0.09	0.08	0.17
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	0.02	0.01	0.02	0.03	0.06	0.09	0.08	0.16	0.07	0.11	0.10	0.08	0.18
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	0.02	0.01	0.03	0.03	0.07	0.08	0.08	0.15	0.07	0.11	0.09	0.09	0.18
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	0.01	0.01	0.03	0.04	0.09	0.08	0.07	0.15	0.07	0.10	0.09	0.09	0.17
Hotels and Restaurants	0.02	0.01	0.02	0.02	0.06	0.07	0.07	0.15	0.07	0.11	0.10	0.09	0.21
Inland Transport	0.02	0.01	0.02	0.03	0.05	0.06	0.05	0.13	0.06	0.10	0.10	0.10	0.28
Water Transport	0.02	0.01	0.02	0.03	0.05	0.06	0.05	0.13	0.06	0.10	0.10	0.10	0.28
Air Transport	0.02	0.01	0.02	0.03	0.05	0.06	0.05	0.13	0.06	0.10	0.10	0.10	0.28
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	0.01	0.01	0.02	0.02	0.06	0.06	0.07	0.14	0.06	0.10	0.10	0.10	0.22
Post and Telecommunications	0.02	0.02	0.04	0.04	0.10	0.10	0.09	0.16	0.07	0.10	0.08	0.07	0.11
Financial Intermediation	0.01	0.01	0.03	0.03	0.08	0.09	0.08	0.16	0.07	0.11	0.08	0.08	0.16
Real Estate Activities	0.02	0.02	0.04	0.04	0.08	0.08	0.08	0.15	0.06	0.11	0.08	0.08	0.16
Renting of M&Eq and Other Business Activities	0.01	0.01	0.02	0.02	0.05	0.07	0.06	0.14	0.08	0.13	0.11	0.10	0.19
Public Admin and Defence; Compulsory Social Security	0.00	0.00	0.00	0.01	0.03	0.05	0.06	0.13	0.07	0.13	0.12	0.12	0.27
Education	0.05	0.02	0.02	0.02	0.04	0.06	0.04	0.10	0.04	0.10	0.10	0.11	0.30
Health and Social Work	0.02	0.01	0.03	0.04	0.10	0.08	0.09	0.16	0.07	0.12	0.09	0.07	0.13
Other Community, Social and Personal Services	0.02	0.01	0.03	0.03	0.07	0.08	0.07	0.14	0.07	0.11	0.10	0.09	0.18
Private Households with Employed Persons	0.02	0.01	0.02	0.04	0.07	0.07	0.07	0.12	0.06	0.11	0.09	0.10	0.23

A: Less than $5,000 B: $5,000 to $9,999 C: $10,000 to $14,999 D: $15,000 to $19,999 E: $20,000 to $29,999 F: $30,000 to $39,999 G: $40,000 to $49,999 H: $50,000 to $69,999
I: $70,000 to $79,999 J: $80,000 to $99,999 K: $100,000 to $119,999 L: $120,000 to $149,000 M: $150,000 and more