Ageing Society in Developed Countries Challenges Carbon Mitigation

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Abstract

Population in developed countries are aging. However, the impact of the senior citizens' consumption on global carbon mitigation is poorly understood. Here, we find that the senior-age group has played a leading role in driving up GHG emissions in the past decade and are on the way to becoming the largest contributor. Considering the greenhouse gas (GHG) footprints of household consumption across age groups in 32 developed countries, the senior contribution to national total consumption-based emissions increased from 25.2% to 32.7% between 2005 and 2015. Seniors in the US and Australia have the highest per capita footprints, twice the Western average. The trend is mainly due to changes in expenditure patterns of seniors. The increasing carbon footprints of senior citizens are likely to drive domestic production, yet have limited effects on international carbon leakage. The demographic change poses more challenges in local mitigation and calls for deeper public mitigation efforts.

Keywords: ageing society, carbon footprint, developed countries, net wealth, expenditure

Introduction

Modern society is seeing people in many global north countries live longer and healthier. Coupled with declining birth rates, this is bringing many developed countries into an "Ageing era" [1]. Nowadays, ageing society issues have become major demographic concerns globally, especially in developed countries that have partially or even totally stepped into the ageing era. This phenomenon is due to baby boomers (born 1946-1961) reaching retirement age, as well as significant improvement in medical technology and healthcare. Consequently, the global population in 2018, saw, for the first time, people aged 65+ outnumber children under 5 [2]. Furthermore, it is projected that the share of the population aged 65+ will double between 2019 and 2050 in developed countries, and 43 countries would be expect population decline before 2050 [2,3]**.** Whilst curbing population growth is arguably critical for climate change mitigation in the long run [4,5], the demographic transition towards an ageing society might pose both short- and long-term challenges to climate change mitigation as changing lifestyles may lead to a significant demand-side driving emissions.

Despite wide attention, explicit analysis of the challenge of an ageing society on climate change mitigation is far from complete [6]**.** Previous studies have drawn contradictory conclusions in understanding the impact of an ageing society. Some equilibrium model studies argue that the ageing society helps reduce carbon emissions due to lower productivity and economic growth, particularly in industrialised countries [6,7], while others found that seniors contribute to rising carbon emissions based on econometric analysis [8–10]. Such conflicting results suggest heterogeneous impacts between the long term and the short term. However, existing literature mainly focused on the issues from the productivity perspective, rather than the impacts of consumption and behaviour change as transitioning to ageing society.

As people age, their lifestyle changes could be substantial and oppose climate mitigation efforts [11–13]. Seniors are more likely to stay longer at home due to decreasing mobility [14–16], and are more likely to live alone [17], but in large houses. This is one of the main reasons for their high expenditure per capita [18,19]. For example, in New Zealand, more than 60% of aged 65+ household group lived in a house with more than three bedrooms, although nearly 80% of the group have small household sizes [20]. Furthermore, the elderly may be less concerned about climate change and less engaged in environmental preservation[21]. For example, only 58% of the silent generation (those born between 1928 and 1945) were concerned about climate change, compared to 63% for the baby boomer and 73% for the millennials [22]. . However, it should be noted that seniors' attitudes may not necessarily be reflected in their consumption behaviour, since as seniors could have pro-climate behaviours, such as repair or refurbishing services [23]. Previous studies linked carbon footprints with household income as a major driving factor, but it is difficult to explain carbon intensive consumption patterns of older groups with less income [24–26]. Therefore, it is important to understand how the demographic change in developed countries affects carbon emissions and how the changes may challenge countries' mitigation targets. To answer those questions, this study aims to quantify the impacts of the growing ageing population in the global north countries on carbon mitigation.

Here, we couple household expenditure survey data (HES), itemized by age group according to the classification of HES data, for 32 developed countries with a global multi-regional input-output model to quantify the evolution of GHG footprints driven by household consumption across different age groups from 2005 to 2015. We investigate the socioeconomic driving factors using decomposition analysis and explore factors on shaping their expenditure patterns. Given the deep connections between the consumers in the Global North and the producers in the Global South, we illustrate the carbon implications of the ageing societies in the Global North on carbon leakage through the trade. Our purpose is to raise awareness of likely future demographic patterns and their implications on climate change mitigation, rather than blaming any age group. Due to data availability, we focus on EU27, the UK, the US, Australia, and Japan which represent more than 80% of GDP and 90% of the population in the high-income countries. .

Insert Figure 1

Contributions of total GHG footprints from different age groups in the developed countries have changed significantly from 2005 to 2015. The aged group (60+) overtook the 30-44 group becoming the second-largest contributor to the GHG footprint in developed countries (Figure 1a), except Japan where the aged group has been leading all the time. In the study period, total GHG footprints of the aged group plateaued at around 3.5 Gt (7% of global GHG emissions in 2015), while the footprints significantly declined in other age groups by 3.3 Gt (see Extended Data Figure 1). The share of the aged group in the total household GHG footprint rose from 25.2% to 32.7%, with a trend likely to soon overtake the 45-59 group as the largest contributor. The rising share of the footprint from 60+ households was found in all 32 developed countries. The biggest rise in the share of the aged group was found in Japan, the most ageing society in the world, with a rise from 36.9% to 51.0% during 2005-2015, followed by Eastern Europe, Western Europe, the US, and Australia. The US contributed the most to household GHG footprints by the aged group, with its share of the aged group rising from 23.3% to 30.1%. The US was followed by Western Europe, (rising from 27.1% to 33.0%), which experienced the most marked ageing problem, such as Italy, Greece, and Portugal, made the greatest contributions. Eastern European countries experienced the same trend where the share of the aged group in the total household footprints rose from 24.3% to 33.8%.

Adjusted by population, we found the aged group had the highest per capita GHG footprints in almost all the countries (Figure 1b). The aged group in the US has the largest per capita footprints, despite a 28% decline from 28.5 to 20.8 tonnes/person over the period. The metric was almost twice the average level of Western Europe and more than triple that of their peers in Japan. Australia has the similar level of per capita GHG footprints as the US for the aged group. However, it is worth noting a large gap in per capita GHG footprints between the youngest group (16.3t) and the aged group (24.9t) in the US. The pattern has been also observed in almost all the countries, as the senior's footprint (12.4t) is an average 14% higher than the youngest group (10.8t) in Western European countries. In the Eastern European countries, the per capita GHG footprint of the elderly (9.9t) is around 20% more than that of the youngest group (8.2t). There are large variations in per capita GHG footprints of aged groups across European countries (Fig 1b). The Western European countries have high carbon footprints of the aged groups, with higher per capita footprint in Luxembourg due to affluence. In average, Eastern Europe has lower per capita footprints for all age groups than Western Europe, mainly due to their less affluence [27]. Some high income Eastern European countries (e.g. Greece) or countries with large-scale heavy or energy industries and dominant fossil fuel usage (e.g.Estonia and Czechia) have much higher per capita footprints of the aged group, compared with other countries in the region, but still much lower than the average footprint in the Western Europe, in particular Nordic countries, such as Norway and Denmark, given their relatively higher share of renewable energy in their energy mix.

Insert Figure 2

Despite the decline of absolute footprints across all 32 countries from 2015 to 2005, the footprints of the aged group rose in many countries, including the US, Japan and Australia, as a result of increasing per capita expenditure and number of households (Figure 2). Meanwhile, we found the leading role of the aged group in rising GHG footprints became more significant over the periods. From 2005-2010, the aged group's footprint would lead to 7.7% (4.2% and 3.3% come from per capita expenditure and the number of households, respectively) increase in the total household carbon footprint of the 32 developed countries as a whole if other age groups' footprints remain unchanged, and the effect rose to 12.4% (in which 6.6% and 5.6% for per capita expenditure and the number of households) during 2010-2015. The pattern was found in most developed countries, including European countries and the US. It is the particularly evident in Japan where the aged group contributed 13.4% of the footprint growth during 2005-2010 (6.4% and 6.2% for per capita expenditure and the number of households) and 18.2% in the next five years (9.1% and 11.2% for GHG intensity and the number of households).

Among all driving factors, rising per capita expenditure (expenditure effect) and the number of households (household effect) were the primary contributors to increasing the GHG footprint in most countries. In all 32 countries, the expenditure effect and household effect increased footprints of the aged group by 1419 and 1162Mt, respectively, during 2005-2015. They thus caused 80% of the growth in footprint of the aged group. We also found the household effect overtook the expenditure effect and become the largest contributor, indicating the rise in numbers and growing impacts of the ageing society.

From 2005-2015, the number of the aged group rose by 32.8% for all 32 countries. As the country with the most severe ageing problem, Japan had the largest contribution of the household effect, where 45.8% of the contribution of the aged group to the footprint came from growing aged households (a rise of 40% in terms of the number of households). Other countries saw the largest contribution of the rising expenditure of the aged group, especially for the US of which half of the contribution of the aged group came from the expenditure effect.

. Consumption structure contributed to a decline of GHG footprints over the two periods if we take all 32 countries as a whole. Changes in consumption structure in the US and Australia made a significant contribution. However, European countries found their consumption structure had the opposite function between the two periods. During 2005-2010, it drove up the footprints for European countries, due to the rising share of shelter energy and travel fuel in the spending of the aged group. However, the effect decreased the GHG footprints during the period 2010-2015. The decrease was driven by the rapidly growing expenditure share on less carbon-intensive products like services and manufactured products, which decreased the share of carbon-intensive products that grew much slower (e.g. the expenditure of shelter energy in Eastern Europe rose by just 1.4%).

In contrast, GHG intensity, measured by footprint/expenditure, was the major driving factor contributing to the reduction of the footprints in developed countries, which is largely due to the displacement of fossil fuels by renewable energy and increasing energy efficiency in the west [28]. Japan and Australia performed very differently from other developed countries over the period 2010-2015. Two reasons might be behind this in Japan: first, Great East Japan Earthquake in 2011 closed all of Japan's nuclear power plants and switched the country back to fossil fuels; second, the economy shrinking in 2015 led to the reduced household expenditure, and saw a rise in GHG intensity (higher footprint but lower expenditure) compared with 2010 [29,30].

Insert Figure 3

Compared to other age groups, the aged group had higher spending on almost all product categories, except clothes with more expenditure in the younger group (Figure 3a). It was particularly notable for carbon-intensive products (e.g. shelter energy), which implies that an ageing society is associated with a more carbon-intensive expenditure pattern. Rising expenditure on shelter energy might be due to the longer time the seniors stay at home and their high sensitivity to cold, which was in line with previous studies in China [31], Japan [15], US [14], Brazil [13] and Germany [11]. Meanwhile, elderly consumed more meat and dairy, especially in Western European countries which saw 35.2% higher per capita expenditure than the middle-aged group (aged 45-59). The findings are also supported by previous case studies [30,32,33]**.** Red meat could be a good source of protein, but it also raises both health and climate concerns due to its close link with chronic diseases and high carbon intensity [34].It is suggested for the seniors to consume protein rich food (e.g. fish and pulses) which contain a wide range of important nutrients and reduce cardiovascular disease risk [35–37]. Spending on other food (exclude meat and vegetable & fruit) was also found to be rising with ageing, mainly due to higher consumption of processed products. The spending also shows country heterogeneity (Box 1).

Insert Box1

However, higher expenditure may not necessarily mean a luxury lifestyle. It is typical in developed countries to see aged dwellings with lower energy efficiency. For example, the average house age is about 67 years in the US and about 80 years in the UK [38]. The nostalgia makes seniors inclined to dwell in their old houses and drive old cars, consequently higher spending on shelter energy and travel fuels than other groups. Other socioeconomic factors, such as poverty and health issues, may keep the elderly in inadequately insulated houses (e.g. low-energy efficiency). Previous studies have found that poor living conditions are linked with high carbon emissions [39–41]. It may further lead to poor health and increase energy usage. A previous study in the UK found that poor health leads to higher power spending, as people with sickness stay longer at home [42]. Rising travel costs may be also connected to where the elderly live. If the elderly lives in less accessible regions, they may rely more on driving, thus increasing their fuel consumption. It was found that the elderly make up the bulk of the population growth in suburban neighbourhoods in the US [43]. This could imply more driving to reach services or social networks, resulting in increased fuel demand. The higher expenditure could be attributed to their wealthier life, albeit having less income, but we found lower wealth elasticity of demand in the senior group, implying their demands are more rigid and necessary (See "net wealth elasticity" in SI).

Insert Figure 4

The demographic change results in higher challenges on the local mitigation of the developed countries. The key reason for growing domestic GHG emissions was the rising need for shelter energy of the aged group. The higher share of domestic emissions in the GHG footprint of the aged group was mainly due to their higher share of energy consumption in total household consumption (Figure 4), particularly in Japan where shelter energy accounted for 14% of the footprints for the young group but compared with 22% for the aged group. However, the consumption of manufacturing products by the aged group in the west still led to high outsourced emissions in developing countries, such as China (35.7%), Middle East countries (11.4%) and Russia (6.1%). The footprints of the aged group in Japan and the US particularly relied on the production and emissions in China, accounting for 50.2% and 40.7% of their outsourced GHG footprints of manufactured products respectively in 2015. The aged group of Western Europe have a particularly higher proportion of the footprints from the developed countries, accounting for 5.1% of the total footprints, higher than the share of the young group (4.4%).

Discussion and conclusions

Ageing is a growing issue in developed countries. The aged group (>60) account for one-fifth of the total population in the 32 developed countries studied here. Our results showed that this demographic group has a carbon-intensive lifestyle, suggesting a great challenge for the global decarbonisation initiative. We highlight the carbon intensive expenditure pattern of the aged group resulting in the highest per capita GHG footprints, which presents both an immediate and long-term challenge. Both rising per-capita expenditure and a growing population in this demographic were twin drivers of this trend. The accumulated wealth of the aged group supports their high expenditure, but the lower wealth elasticity of the expenditure suggests that the higher expenditure is more rigid than other age groups, which is highly associated with their lifestyle (i.e. they stay a longer time at home). Their large carbon footprints were associated with their basic needs rather than the luxury lifestyle. Given the observed expenditure patterns, an ageing society will require more effort on domestic mitigation strategies, as this group's carbon footprint is largely from domestic emissions, not abroad.

Our findings underscore the need of anticipating mitigation strategies for an aging society in the future. People aged 60+ are projected to increase from 11% of the global population in 2005 to a range from 21% (SSP 3-high challenge pathway) to 52% (SSP 1- low challenge pathway) by 2100. The 32 developed countries of the study would see the share of the elderly rising from 21% in 2005 to the range between 38% (SSP 5- mitigation challenge) and 49% (SSP 4- adaptation challenge) of the total population [44]. It is fair to anticipate that seniors would contribute to the highest share of consumption-based emissions in the developed countries in the future However, the challenges come from the rigid lifestyle of the elderly. The aging society may make advocating for a green lifestyle to elders politically difficult. The change raises a question on how successful consumption-based strategies for global decarbonization may be in the context of the ageing population. Most of the well-summarised lifestyle options for climate change mitigation [45] may impose challenges to the aged household groups, such as moving to more energy efficient houses or switching to electric cars, while the fact that the pension system in many developed countries may not be able to facilitate such changes and the elderly may not want to change, as the low engagement in climate actions[21],[22]. It is particularly hard that the elderly people are often exposed to poverty [46]. In OECD countries, 13.5% of individuals over the age of 65 live in relative poverty, which is greater than the OECD population as a whole (11.8 %) [47].

Due to the hardship, greater actions from the public sector are required, such as subsidising older householders to retrofit their houses [38], improving public mobility [48], and care house. It is particularly crucial for low-income elderly households who are trapped in carbon-intensive consumption patterns and pay higher energy bills due to low energy efficiency.. [49]. Hence, improving housing could be beneficial not just to carbon mitigation but also to their health [50]. Gaining mobility is particularly critical, especially for older households living in lower-density neighbourhoods. This means more private transportation to get to social activities and services. A survey in the UK found that a sizable fraction of senior people may drive instead using public transportation for their social activities[51]. .

Higher per capita spending is also linked to more seniors living alone, implying lower carbon efficiency. Encouraging moving into the care home setting might help increase carbon efficiency, but it is more challenging because the majority prefer to remain in their own homes [52]. In European countries, 7% of the aged group lives in a senior home on average, with a range from 3% (Romania) to 19% (Netherlands)[53]. The discrepancy is ascribed to public investment in long-term care, with the Netherlands spending 3.7% of its GDP on long-term care, the highest in OECD countries [54]. The major challenge, though, remains public funding. Long-term finance (e.g. high interest rates) is less likely to be consistent in many countries. Low interest rates risk the solvency of pension funding and promises in the future[55].The seniors might also change their diet, as limiting meat consumption can reduce direct GHG emissions from agriculture, and indirect emissions from healthcare needs[49]. Despite many meat substitutes (e.g. plant-based meat), the primary challenge may be the cost of these meat alternatives. It is frequently connected with the political difficulty that the meat industry wields significant political power to keep meat costs low [56].

The mitigation in the ageing society relies heavily on local mitigation actions. Specifically, policymakers in the developed countries should focus more on the reduction in carbon-intensity of the energy system and livestock industries at home. However, the challenges vary with different countries, especially taking heterogeneity between countries into account (see SI). Japan and Australia have already shown a mitigation risk when the local energy transition stagnated, presenting alarming examples for other countries stepping into an ageing society. It is particularly the case in Japan where the energy system stepped back to fossil fuels after the Great East Japan Earthquake in 2011. Its carbon-intensive energy system failed to curb the emissions driven by the growing aged group, but made a positive contribution to the rebound emissions. The cases of Japan and Australia highlight the consistency in mitigation policies of the developed countries in responding to the incoming ageing society. Our results indicate that an ageing society would lead to more complex challenges, which are much greater than the higher expenditure of the seniors. But our studies only focus on the carbon mitigation challenges from the prospect of consumption behaviour of the seniors, and the extended consequence is not included in the study. For example, countries with an ageing crisis are now more open to welcome immigration to refill their labour forces, however, most immigrants come from developing countries with lower per capita footprints. Moving to a new settlement with a higher per capita footprint might have net effects of rising the carbon footprints of the immigration.

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Author Contributions Statement
H.Z., R. W. and K.F. designed the research. H.Z. led the study and drafted the manuscript with efforts from all other authors (Y.L., R.W. K.F. D.M., Z.Z., J.M., E.H. and D.G.). H.Z., Y.L and Z.Z collected raw expenditure data. R.W. constructed EXIOBASE model. H.Z. and Y.L. conducted decomposition analysis.

Data availability statement
The EXIOBASE 3.7 is available at: https://zenodo.org/record/3583071#.YPA5e0kzabg. Household expenditure by ageing groups is sourced from: Household budget survey of EU (https://ec.europa.eu/eurostat/web/household-budget-surveys/database) , Consumer expenditure survey of the US (https://www.bls.gov/cex/csxstnd.htm), Family Income and Expenditure Survey of Japan (https://www.stat.go.jp/english/data/sousetai/1.html), Household budget survey of Australia (https://www.abs.gov.au/statistics/economy/finance/household-expenditure-survey-australia-summary-results). The asset and liability data are sourced from Household Finance and Consumption Survey (https://www.ecb.europa.eu/stats/ecb_surveys/hfcs/html/index.en.html) for listed European countries, Office of National Statistics

(https://www.ons.gov.uk/peoplepopulationandcommunity/personalandhouseholdfinances/incomeandwealth/adhocs/008570totalhouseholdwealthanditscomponentsbyagebandgreatbritainjuly2006tojune2016) for the UK, the Federal Reserve (https://www.federalreserve.gov/releases/z1/) for the US, Family Income and Expenditure Survey (https://www.stat.go.jp/english/data/sousetai/1.html) for Japan, Household budget survey (https://www.abs.gov.au/statistics/economy/finance/household-expenditure-survey-australia-summary-results) for Australia.

Code availability statement
Code to calculate the carbon footprint and associated decomposition analysis is available at: https://github.com/HeranZheng/Aging-society-and-carbon-mitigation

Box 1. Country heterogeneity in consumption of the senior group

Japan and Australia showed a lower consumption with people's age increase. This is largely due to a drop in real estate expenditure from the middle-aged to the elderly, whereas other countries show a little increase when the middle-aged are getting more senior. However, it has been demonstrated that the spending on hotel and restaurant services is increasing, indicating a sign of luxury lifestyle (see Extended Data Figure 2). Health-care spending in Eastern European nations may be declining as a result of underinvestment in the health-care system [57]. Meanwhile, cultural differences may be another reason that senior care is largely supported by families in Eastern European countries [58]. Besides, there was a lower in travel spending in Eastern Europe and Japan. For Japan, the stagnation of the old householder on travel spending might be attributed to the high rate of elderly workers in the labour market. For example, Japan's employment rate of workers aged 60-65 and 65+ is 68.8% and 46.6% respectively in 2018, compared to the OECD average of 49.6% and 22.3% respectively [47]. For Europe, a prior report showed Europeans aged 60-75 travel more often, and they are mostly from Western European countries. In the Eastern European countries, there were more elderly people who did not participate in tourism [16]. The reason could be the disparity in the wealth of the elderly between western and eastern European countries.

Competing Interests Statement
The authors declare no competing interests

Figure 1 Rising contribution of the age group in GHG footprint of the Global North. a. Share of GHG footprint by age group in developed countries. The numbers on the bar chart refer to the share by age group; b. Per capita GHG footprint over time. The grey line refers to the average per capita GHG footprint of each country over the study period. Note: countries are ranked by per capita footprint of the aged group of 2015.

Figure 2 The aged group driving household-related GHG emission. Contribution of socioeconomic driving factors to the GHG footprint changes by age groups from 2005 to 2015, for all 32 countries (a), the Western Europe (b), the Eastern Europe (c), the US (d), Japan (e), and Australia (f). The black bars indicate the GHG footprints in different years. The colour bars indicate the absolute contribution (positive or negative) of different socio-economic driving factors from different age groups to the changes in total country/region's GHG footprints in the two time periods. The highlighted dash frame refers to the 60+ age group which is the focus of the study. The figures on the frame indicate the percentage point of the change in GHG footprints, and their colours refer to corresponding factors in the legend. The percentage of per capita expenditure (blue), number of households (orange) and the GHG intensity of the aged group are shown, due to their leading role in the change.

Figure 3. Rising expenditure for the aged group. Per capita expenditure by products for each age group in 2015. The size of the circle refers to the average carbon multiplier referring to GHG footprint per demand for products by age groups. Numbers indicate the difference in per capita

expenditure between the group aged 60 plus and the group aged 45-59.

Figure 4. Ageing society requires strict local mitigation. The percentage of domestic and outsourced GHG emissions in total footprint by consumption categories across age groups for all countries in 2015. Note: four key products are highlighted in the figure, since they have the highest carbon intensity. Other products are in grey colour.

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Method

Environmentally extended MRIO analysis.

The study applied the environmentally extended multiregional input-output (MRIO) model to estimate household GHG footprints of four age groups in 32 developed economies, including 29 European countries, Japan, Australia, and the US. The GHG footprints by each age group were calculated into 2005, 2010, and 2015, due to data availability. All years used for EXIOBASE are based real data. We linked the household expenditure survey data of four age groups with the global multiregional input-output model (GMRIO). The MRIO model is the most adopted tool in tracing spillover effects through regionally dispersed supply chains and therefore yield comprehensive estimate for the environmental impacts through entire supply chains [59–63]. Here, we used EXIOBASE 3.7 covering the years 2005 to 2015 as the MRIO database [64,65]. EXIOBASE is a global environmentally extended MRIO database developed for EU countries and its main global trade partners, including 44 economies and five rest of the world regions. It provides the most comprehensive sectorial classification with 200 products from 1995 to 2016, with wide extensive environmental and social satellite accounts [66]. A full description of the method is provided below:

To calculate the GHG footprints of the household's expenditure by age groups, the classic Leontief demand model in the IO framework is adopted to allocate the environmental impacts induced by households [67]. Mathematically:

$$x = Ax + y \tag{1}$$

Where **A** is the technical coefficient matrix of the economy, and *y* is the final demand vector by sectors, including household consumption, capital formation, government expenditure and exports. Then, total output *x* can be interpreted by Leontief inverse **L,** with the identity matrix with ones on the diagonal (I):

$$X = (I - A)^{-1}Y = LY \tag{2}$$

In the environmentally extended MRIO model, we add a row of the environmental multiplier (**E**) which is the GHG emissions based on the Global Warming Potential 100 (GWP100) metric. We include GHG of CO2, CH4, N2O and SF6 in kg CO2-equivalents per year. The environmental accounts of CO2, CH4, N2O and SF6 turned to the CO2- equivalent intensity by:

$$K = CF\hat{x}^{-1} \tag{3}$$

Where K refers to the GHG intensity in CO2-equivalents (kg/euro), indicating GHG emissions per unit output. **C** is the characterization vector to harmonize emissions of all GHG types (**F**) into the unit of CO2-equivalent based on GWP100. Thus, the total GHG footprint can be expressed by:

$$GHG = KLy_q^r + hh_q^r \tag{4}$$

Where KLy_q^r capture the GHG emissions along the supply chain of household expenditure of age group

q in country r. hh_q^r is a vector of the household GHG direct emissions for age group q in country r, e.g. direct GHG emissions from heating. Given 200 products in EXIOBASE classification, we then aggerate them into 10 major expenditure categories.

Reconciling Household expenditure survey data with EXIOBASE

To capture the heterogeneity of household expenditure by age groups, we use the detailed household expenditure by four age groups which are derived from household or consumer expenditure survey (CES) published by official statistics agencies. For 30 European countries, we collect their household expenditure survey data by age group from Eurostat, while the data for the US and Japan are directly collected from their national official statistics. All CES data adopt an expenditure nomenclature, the Classification of Individual Consumption by Purpose (COICOP), but the detailed classification varied in different economies. We then bridge the different expenditure classifications between CES data (COICOP) and EXIOBASE, where concordance matrices were created for each country by using the RAS-based method [25,68]. Regarding the well-known under-reporting issue in matching between two databases, an additional vector was added to the CES-EXIOBASE concordance matrix, including an assumption of "underreporting" for the new product [68]. In the reconciliation, EXIOBASE's household demand was set as the benchmark, with the currency of all CES data converted into Euros using the currency rate from the World Bank. We applied the concordance matrices to reconcile the CES data into age groups. Notably, European CES data are presented into four age groups: aged <30, aged 30-44, aged 45-49, and aged 60 and over; the US and Australia have their age classification with six age groups: aged <25, aged 25-34, aged 35-44, aged 45-54, aged 55-64, and aged 65 and over; Japan also has six age groups: aged <30, aged 30-39, aged 40-49, aged 50-59, aged 60-69 and aged 70 and over. Therefore, the CES data were reconciled into four age-based household demands for European countries, six household demands for the US, Australia, and Japan in line with the classification of EXIOBASE. To facilitate the expression, we combine the modelled GHG footprints of six age groups of the US, Australia, and Japan into four age groups to be compatible with European countries. All CES data used in the study are nationally representative average, rather than micro-level data.

Due to the data availability, HES data by age groups are presented by the age of the reference person of a household (breadwinner) and HES data only account for the expenditure by a household. If young people cohabit with their parents, it will be accounted for in their parental household, unless young people earned more than their parents. But it would be a very rare case. Therefore, the aged less than 30 years group is largely underestimated for young people, as many young people still live with their parents. But we argue it does not largely affect the older groups for most countries, as their children cohabiting with their parents aged 60+ could be very rare. Some countries may often see a whole family living together or higher household size, which could result in uncertainty in the carbon footprint of the aged 60+ group (Table 1S). This could be attributed to the lack of care facilities in their country or religions (e.g. Catholics often have big families)[69,70].

LMDI decomposition

To understand the socio-economic driving forces, we employ the logarithmic mean Divisia index (LMDI) to decompose household-related GHG footprints by four age groups in all 32 countries (Ang, 2004). LDMI is a widely adopted method used in energy and emission studies [29]. In this study, we decompose the GHG footprints by country with age groups as follows:

$$C = \sum_{i=1} \sum_{j=1} H_i \frac{P_i}{H_i} \frac{E_i}{P_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} = \sum_{i=1} \sum_{j=1} H_i W_i R_i Y_{ij} I_{ij} \quad (5)$$

Where C refers to household-related GHG footprints by country. H_i denote the number of households by age group i in the country, respectively. P_i is the number of people in age group i. E_i and E_{ij} refer to total expenditure by age group i and detailed expenditure for the product j by age group i respectively. C_{ij} is the GHG footprint induced by age group i for product j. Four age groups are aged <30, aged 30-44, aged 45-49, and aged 60 and over, while the products are 200 based on EXIOBASE 3.7. The equation can be conceptualised as household effects (H); Household structure effect ($S_i = \frac{H_i}{H}$), measuring the distribution of household of age i in the total household; Household size effect ($W_i = \frac{P_i}{H_i}$), indicating per household members; Per capita expenditure effect ($R_i = \frac{E_i}{P_i}$), measuring the contribution of per capita expenditure for the age group *i* to GHG footprint; Consumption structure effect ($Y_{ij} = \frac{E_{ij}}{E_i}$), referring to the distribution of the spending per unit of expenditure; Carbon intensity($I_{ij} = \frac{C_{ij}}{E_{ij}}$), measuring carbon emission per unit of expenditure by age group *i* for product *j*. Except for carbon intensity(I_{ij}), all other indicators can reflect the impact of an ageing society. With the decomposition in equation 1, we then decomposed changes during 2005-2010 and 2010-2015 from six factors. We choose additive decomposition:

$$\Delta C = C^t - C^{t0} = \Delta H + \Delta S + \Delta W + \Delta R + \Delta S + \Delta I \quad (6)$$

$$\Delta H = \sum_i \sum_j \frac{C_i^t - C_i^{t0}}{ln\ C_i^t\ - ln\ C_i^{t0}}\ ln\left(\frac{H^t}{H^{to}}\right) \quad (7)$$

$$\Delta S = \sum_i \sum_j \frac{C_i^t - C_i^{t0}}{ln\ C_i^t\ - ln\ C_i^{t0}}\ ln\left(\frac{S_i^t}{S_i^{t0}}\right) \quad (8)$$

$$\Delta W = \sum_i \sum_j \frac{C_i^t - C_i^{t0}}{ln\ C_i^t\ - ln\ C_i^{t0}}\ ln\left(\frac{W_i^t}{W_i^{t0}}\right) \quad (9)$$

$$\Delta R = \sum_i \sum_j \frac{C_i^t - C_i^{t0}}{ln\ C_i^t\ - ln\ C_i^{t0}}\ ln\left(\frac{R_i^t}{R_i^{t0}}\right) \quad (10)$$

$$\Delta Y = \sum_i \sum_j \frac{C_i^t - C_i^{t0}}{ln\ C_i^t\ - ln\ C_i^{t0}}\ ln\left(\frac{Y_{ij}^t}{Y_{ij}^{t0}}\right) \quad (11)$$

$$\Delta I = \sum_i \sum_j \frac{C_i^t - C_i^{t0}}{ln\ C_i^t\ - ln\ C_i^{t0}}\ ln\left(\frac{I_{ij}^t}{I_{ij}^{t0}}\right) \quad (12)$$

where the superscripts *t* and *t0* indicate the target year and base year, which are 2005-2010 and 2010-2015, respectively. All data have been converted into a constant price of 2005 to avoid the effects of inflation.

Net wealth elasticity of the demand

To investigate the correlation between net wealth and per capita expenditure, we first build the net wealth dataset for each age group. Net wealth by age group is derived from various datasets. EU countries are mainly sourced from the Household Finance and Consumption Survey (HFCS), while the data for non-EU countries are collected from their statistical agencies. HFCS was conducted by national central banks for participating in EU countries. There are three waves of the survey conducted: the first wave (2010-2011) for 2010, the second wave (2013-2015) for 2014, and the third wave (2017) for 2017. The survey offers information on the assets, liabilities, income, and consumption of households by age groups. The coverage of countries was varied for different waves, where the 2010 data was only for 15 countries (the first wave), 2015 data for 20 countries (the second wave), and 2017 data for 22 countries (the third wave). For the missing countries, we use the latest available data as the proxy (e.g. using 2010 data as the proxy for 2005). For countries not included in all HFCS, we use the HFCS countries with similar age structures and development stages as the proxy for European countries (see table S6). In HFCS data, we derive the means of net wealth and adjusted household distribution by each age group. We first calculate the household number by age groups, by multiplying total household numbers with the adjusted household distribution by age group. Then, total net wealth by age groups can be derived by multiplying the means of net wealth by age groups with household numbers by age groups. Due to the data uncertainty, we take the share of net wealth by age groups based on the estimated data:

$$HH_j^i = Hd_j^i \times Nh_j \quad (13)$$

$$TNW_j^i = HH_j^i \times MNW\ _j^i \quad (14)$$

$$AS_{j\ j}^{i\ i} = \frac{TNW_j^i}{\sum_j TNW_j^i} \quad (15)$$

Where Nh_j and Hd_j^i are the number of the household for country *j* and the household distribution by age group *i* of country *j*. HH_j^i and $MNW\ _j^i$ denote the number of the household for age group *i* of country *j* and the mean of net wealth for age group *i* of country *j*; TNW_j^i is the total net wealth for age group *i* of country *j*; AS_j^i denotes the net wealth distribution by age group *i* of country *j*.

The calculated distribution of the net wealth by age groups is to allocate the total net wealth of the household from the national account for each country. We first derive the financial assets, non-financial assets, and liabilities of the household sector in national accounts for each country from the Eurostat (for EU countries) or national statistics bureau (for non-EU countries). Non-financial assets here only refer to produced non-financial assets (e.g. real property), and natural assets (e.g. land) are not included. The net wealth of the household for the country j can be calculated as:

$$NW_{H_j} = FA_j + NFA_j - L_j \tag{16}$$

Where NW_H_j refers to the total net wealth of the household for country *j*; FA_j and NFA_j refer to the financial assets and non-financial assets of the household for country *j*; L_j denotes the household liability for country *j*. Then, the net wealth for each age group *i* can be derived:

$$NW_j^i = NW_{H_j} \times AS_j^i \tag{17}$$

Where NW_j^i refers to net wealth for country *j* and age group *i*. Notably, the household sector in national accounts is not entirely in line with the HSCS household, but in line with the input-output framework. More details can be found in the previous study (Bernhard, 2015)**.**

To obtain the net wealth elasticity of expenditure for each age group (32*3 samples for each group), we employ a log-log regression of per capita expenditure for each product on per capita net wealth, along with the different age groups and overall countries:

$$\log D_j^p = a + b \log W_j \tag{18}$$

Where D and W indicate per capita expenditure and per capita net wealth respectively; *j* refers to the age group (1-4) and *p* denotes product category. The coefficient *b* is the net wealth elasticity of expenditure. Before the regression, per capita net wealth (W) in different years can be adjusted into the constant price of 2005, by using the consumer purchase index derived from World Bank.

Limitations

Due to the data availability, there are several limitations to be noted. In this study, either the CES or household financial data is the national average based on nationally representative samples. However, we are concerned that the CES data and household financial data are derived from separate surveys, which may contribute to uncertainty owing to unequal sample selection. We perform a comparison of sample distributions from two surveys. However, because no other socioeconomic factors are similar in both surveys, we can only compare the distribution of households by age group. The outcome reveals a good match in Australia and Japan, as well as a general match in the EU and the UK. Despite a broad match in household distribution, we must nevertheless highlight the issue and the details in the comparison can be found in SI. Moreover, many socioeconomic characteristics have a major impact on carbon footprint and spending by age group (e.g. household size). That household size has a major impact on per capita expenditure and carbon footprint. Household size varies by age group in different countries (Table 1S). For example, middle-aged households have more family members of a younger age (e.g. children). Previous studies using micro-level data have highlighted the effect of household size on carbon footprint when other socioeconomic variables(e.g. income, education) were controlled for regression. For example, studies on Japan showed the positive coefficients between household size and carbon footprint, when other socioeconomic variables were controlled [71–73]. Similar findings have been reported in the US [74] and EU [75]. Given that our study's age groups are classified by "breadwinner," household size and composition are important when translating to per capita carbon footprint or expenditure. Unfortunately, the study's data cannot provide such resolution (only micro-data can offer such information). We therefore compare per adult-equivalent (adult-eq) footprints for each age group in countries (Figure S3). Notedly. OECD modified scale is adopted in the HES data. Some countries (e.g. the US, Australia, Japan) found that the per adult-equivalent footprints of the aged group are the highest all the time. While Western European countries showed that the aged group was slightly smaller than the middle-aged group (aged 45-59) in 2005, the per adult-equivalent footprints of the aged group have overtaken that of the middle-aged groups in 2015, with 12.94 and 13.42 tonnes/adult-eq of the aged 45-59 group and aged 60+ group respectively. The outcome of European countries is consistent with the previous one [75].To some extent, using per adult-equivalent measure helps alleviate the problem, although daily intake varies greatly from new-born to adult. As a result, there is no perfect way to correctly convert children to adult equivalents. With the larger household, per capita carbon footprint or expenditure could be smaller due to the scale effect [76]. The data limitation might lead to uncertainty in comparison between different age groups with distinct household sizes and structures. Furthermore, the classification of age groups may lead to seniors aged 60-65 could have different expenditure behaviours with those aged 70-75, although they are grouped as “senior group” in the study. For example, according to a survey in the UK, the elderly’s consumption on meat & dairy peaks at 65-74, and then declines [77].

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