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Ageing society in developed countries challenges carbon mitigation

Heran Zheng[1], Yin Long[2], Richard Wood[1✉], Daniel Moran[1], Zhengkai Zhang[3✉], Jing Meng[4], Kuishuang Feng[5✉], Edgar Hertwich[1] and Dabo Guan[4,6]

Populations in developed countries are ageing. However, the impact of senior citizens' consumption on global carbon mitigation is poorly understood. Here we find that senior citizens have 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 footprint 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 United States and Australia have the highest per capita footprint, twice the Western average. The trend is mainly due to changes in expenditure patterns of seniors. The increasing carbon footprint of senior citizens will probably 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.

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]. Globally, ageing society issues have become major demographic concerns, 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 and substantial improvement in medical technology and health care. Consequently, the global population in 2018 saw for the first time people aged 65+ outnumber children under age 5 (ref. [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 expect population decline before 2050[2,3]. While 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 middle-term challenges to climate change mitigation as changing lifestyles may lead to a large demand, driving emissions.

Despite wide attention, explicit analysis of the challenge of balancing the needs of an ageing society with 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 industrialized 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 focuses on the issues from the productivity perspective, rather than the impacts of consumption and behaviour change as an ageing society transitions.

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] 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 age 65+ households live in a house with more than three bedrooms although nearly 80% of that group have small household sizes[20]. Furthermore, addressing climate change may be less of a priority for elderly people and they may be less engaged in environmental preservation[21]. For example, only 58% of the silent generation (born 1928–1945) were concerned about climate change compared with 63% of baby boomers and 73% for millennials (born 1981–1996)[22]. However, it should be noted that seniors' attitudes may not necessarily be reflected in their consumption behaviour; seniors could have pro-climate behaviours such as repair or refurbishing[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 Article aims to quantify the impacts of the growing ageing population in the Global North countries on carbon mitigation.

Here we couple household expenditure survey (HES) data, 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 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 trade. Our purpose is to raise awareness of probable future demographic patterns and their implications on climate change mitigation rather than blaming any age group. Due to

[1]Industrial Ecology Programme, Department of Energy and Process Technology, Norwegian University of Science and Technology, Trondheim, Norway. [2]Graduate School of Engineering, University of Tokyo, Tokyo, Japan. [3]College of Management and Economics, Tianjin University, Tianjin, China. [4]The Bartlett School of Sustainable Construction, University College London, London, UK. [5]Department of Geographical Sciences, University of Maryland, College Park, MD, USA. [6]Department of Earth System Sciences, Tsinghua University, Beijing, China. ✉e-mail: Richard.wood@ntnu.no; zengkaizhang@tju.edu.cn; kfeng@umd.edu

data availability, we focus on the European Union, United Kingdom, Norway, United States, Australia and Japan, which represent more than 80% of global gross domestic product and 90% of the population in high-income countries.

Increasing share of footprints from the seniors

Contributions of different age groups to total GHG footprint in developed countries have changed substantially 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 (Fig. 1a), except in Japan, where the aged group has been leading all the time. In the study period, the total GHG footprint of the aged group plateaued at around 3.5 Gt (7% of global GHG emissions in 2015), while the footprint substantially declined in other age groups by 3.3 Gt (Extended Data Fig. 1). The share of the aged group to the total household GHG footprint rose from 25.2% to 32.7% in a trend that will probably soon overtake the 45–59 group as the largest contributor. The rising share of the footprint from age 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 United States and Australia. The United States contributed the most to the household GHG footprint by the aged group with its share of the aged group rising from 23.3% to 30.1%. The United States was followed by Western Europe (rising from 27.1% to 33.0%), which experienced the most marked ageing problem with Italy, Greece and Portugal making the greatest contributions. Eastern European countries experienced the same trend where the share of the aged group in the total household footprint rose from 24.3% to 33.8%.

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

Despite the decline of the absolute footprint across all 32 countries from 2015 to 2005, the footprint of the aged group rose in many countries, including the United States, Japan and Australia as a result of increasing per capita expenditure and number of households (Fig. 2). Meanwhile, we found the leading role of the aged group's rising GHG footprint became larger over the period. From 2005–2010, the aged group's footprint would lead to a 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% (6.6% and 5.6% for per capita expenditure and the number of households) during 2010–2015. The pattern is found in most developed countries, including European countries and the United States. It is 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).

Driving factors

Among all driving factors, rising per capita expenditures (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 1,419 Mt and 1,162 Mt, respectively, during 2005–2015. They thus caused 80% of the growth in the 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 to 2015, the size of the aged households rose by 32.8% for the total of 32 countries. As the country with the most severe ageing problem, Japan had the largest contribution of the household effect with 45.8% of the contribution of the aged group to the footprint coming from growing aged households (a rise of 40% in terms of the number of households). Other countries saw the largest contribution from the rising expenditures of the aged group, especially in the United States where half of the contribution of the aged group came from the expenditure effect. Consumption structure contributed to a decline of GHG footprint over the two periods if we take all 32 countries as a whole. Changes in the consumption structure in the United States and Australia made a large contribution. However, European countries found their consumption structure had the opposite function between the two periods. During 2005–2010, it drove up the footprint 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 footprint during the period 2010–2015. The decrease was driven by the rapidly growing expenditure share on less carbon-intensive products such as services and some manufactured products, which led the share of carbon-intensive products to grow much slower (for example, 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 footprint 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, the Great East Japan Earthquake in 2011 closed all of Japan's nuclear power plants and switched the country back to fossil fuels, and second, the economy shrinking in 2015 led to reduced household expenditures and saw a rise in GHG intensity (higher footprint but lower expenditures) compared with 2010[29,30].

Compared with other age groups, the aged group had higher spending in almost all product categories except clothes, which had more expenditures in the younger group (Fig. 3a). The higher spending was particularly notable for carbon-intensive products (for example, shelter energy), which implies that an ageing society is associated with a more carbon-intensive expenditure pattern. Rising expenditures on shelter energy might be due to the longer time the seniors stay at home and their high sensitivity to cold, which is in

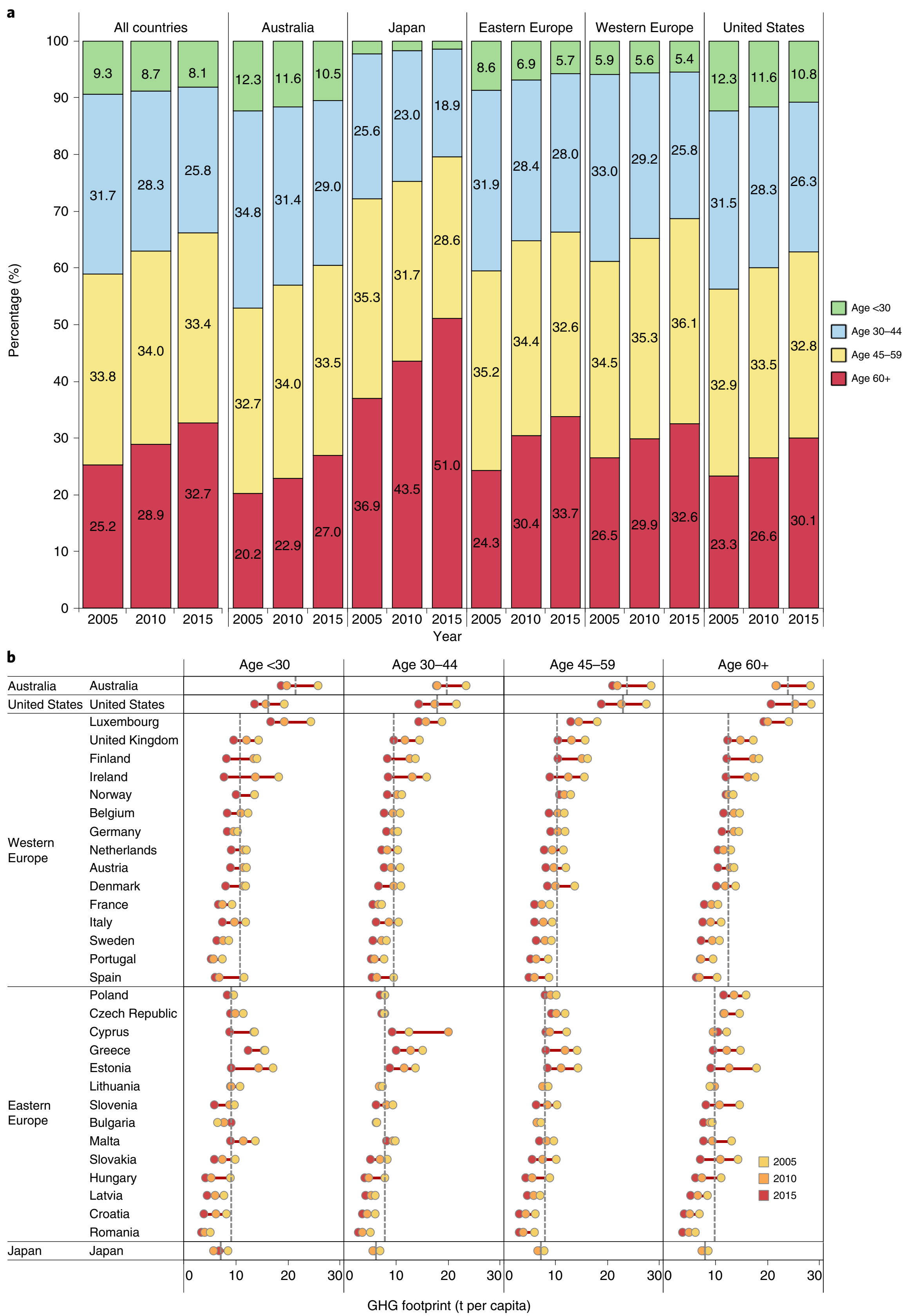

Fig. 1 | Rising contribution of the aged group to GHG footprint of the Global North. a, Share of GHG footprint by age group in developed countries. The numbers on the bar chart refer to the percentage share by age group. **b**, Per capita GHG footprint over time. The grey line refers to the average per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

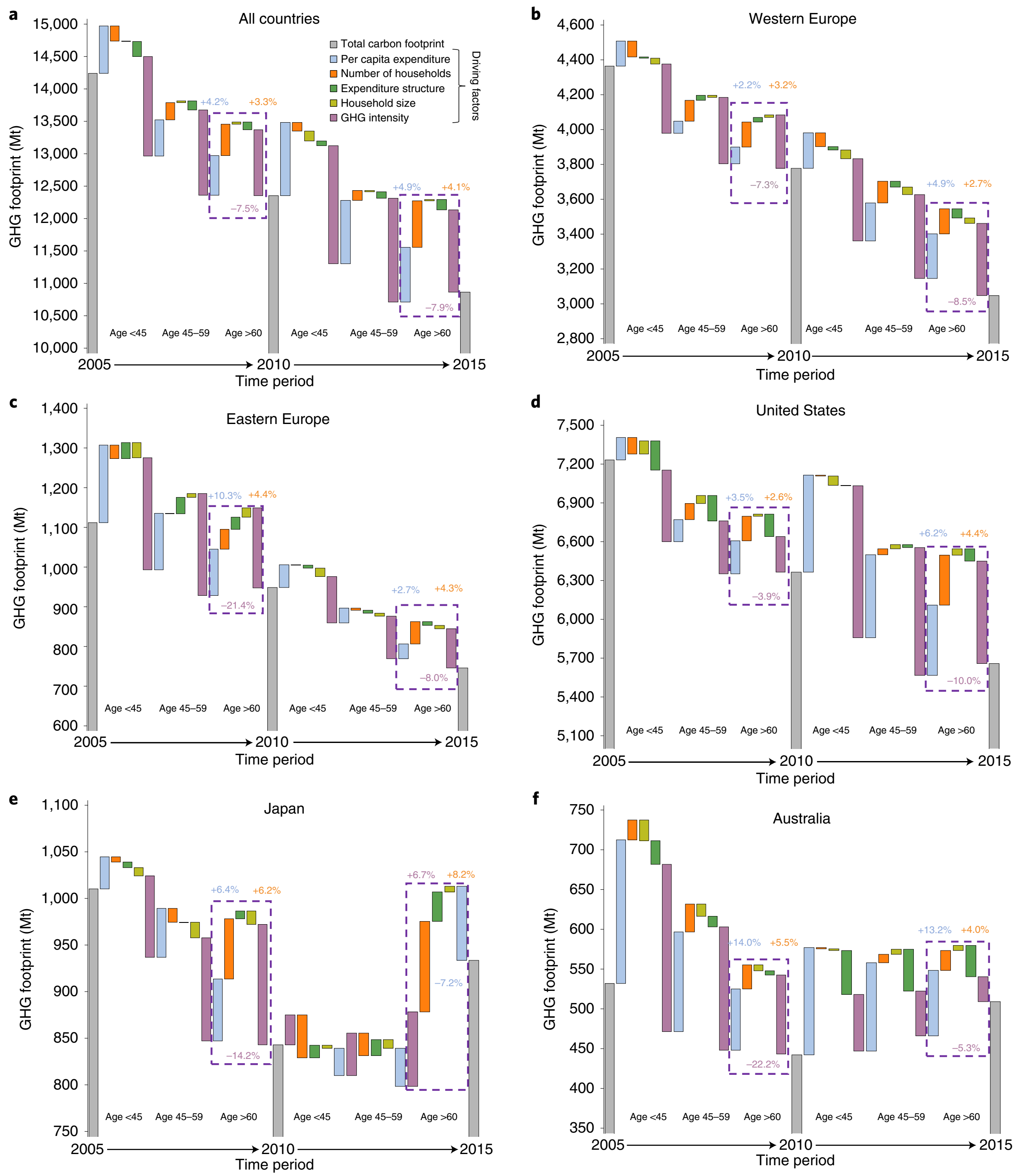

Fig. 2 | The aged group driving household-related GHG emissions. a–f, Contribution of socioeconomic driving factors to GHG footprint changes by age group from 2005 to 2015 for all 32 countries (**a**), Western Europe (**b**), Eastern Europe (**c**), the United States (**d**), Japan (**e**) and Australia (**f**). The grey bars indicate the GHG footprint in different years. The coloured bars indicate the absolute contribution (positive or negative) of different socioeconomic driving factors from different age groups to the changes in the total country/region's GHG footprint in the two time periods. The dashed rectangles highlight 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 footprint, 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 (purple) of the aged group are shown due to their leading role in the change.

line with previous studies in China[31], Japan[15], the United States[14], Brazil[13] and Germany[11]. Meanwhile, elderly people consumed more meat and dairy, especially in western European countries, which saw 35.2% higher per capita expenditures than the middle-aged group (age 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 that seniors consume protein-rich food (for example, fish and pulses) that contain a wide range of important nutrients and reduce cardiovascular disease risk[35–37]. Spending on other food (excluding meat, vegetables and 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).

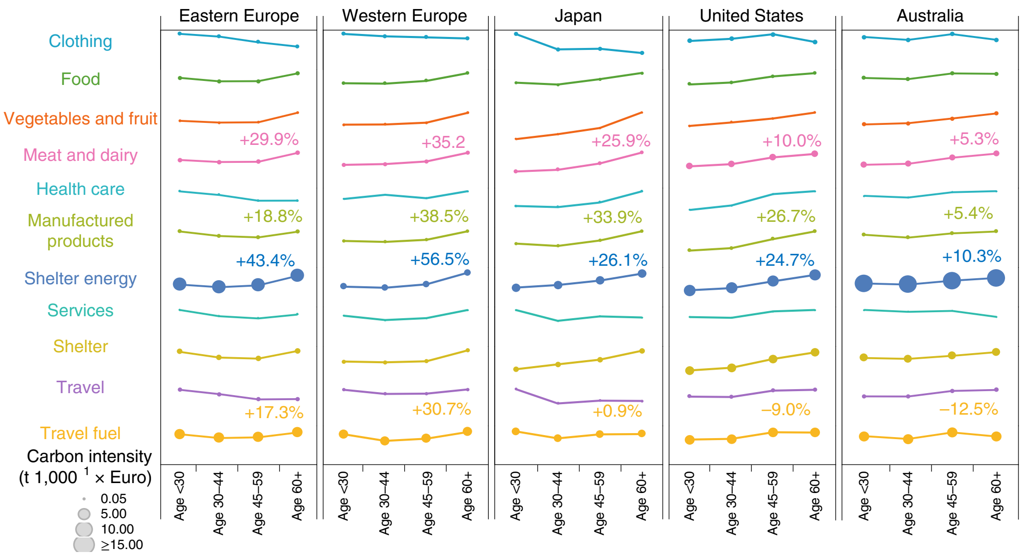

Fig. 3 | Rising expenditures for the aged group. Per capita expenditures by product for each age group in 2015. The size of the circle refers to the average carbon multiplier, referring to GHG footprint per demand for products by age groups. Numbers indicate the difference in per capita expenditures between the 60+ group and the 45–59 age group.

Box 1 | Country heterogeneity in consumption by seniors

Japan and Australia show a lower consumption as people's age increases. This is largely due to a drop in real estate expenditure from middle age to the elderly. Other countries show a little increase when the middle-aged group becomes more senior. However, it has been demonstrated that the spending on hotel and restaurant services is increasing, indicating a sign of luxury lifestyles (Extended Data Fig. 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 also play a role as seniors are largely supported by families in eastern European countries[58]. There was lower travel spending in Eastern Europe and Japan. For Japan, the stagnation of 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 with the Organisation for Economic Co-operation and Development (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 eastern European countries, there were more elderly people who did not participate in tourism[16]. The reason could be the disparity in wealth of the elderly between western and eastern European countries.

However, higher expenditure may not necessarily mean a luxury lifestyle. It is typical in developed countries to see older household dwellings with lower energy efficiency. For example, the average house age is about 67 years in the United States and about 80 years in the United Kingdom[38]. Seniors, perhaps out of a sense of nostalgia, may be inclined to dwell in their older houses and drive older cars, consequently leading to 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 (for example, 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 United Kingdom found that poor health leads to higher power spending as people with sickness stay longer at home[42]. Rising travel costs also may be connected to where the elderly live. If the elderly live 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 United States[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 (Supplementary Information).

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 (Fig. 4), particularly in Japan where shelter energy accounted for 14% of the footprint for the young group but 22% for the aged group. However, the consumption of manufactured products by the aged group in the West still led to high outsourced emissions in developing countries such as China (35.7%), Middle Eastern countries (11.4%) and Russia (6.1%). The footprint of the aged group in Japan and the United States particularly relied on production and emissions in China, accounting for 50.2% and 40.7% of their outsourced GHG footprint of manufactured products, respectively, in 2015. The elderly in Western Europe have a particularly higher proportion of the footprint from the developed countries, accounting for 5.1% of the total footprint, 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) accounts 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 decarbonization initiative. We highlight the carbon-intensive expenditure pattern of the aged group resulting in the highest per capita GHG footprint, which presents both an

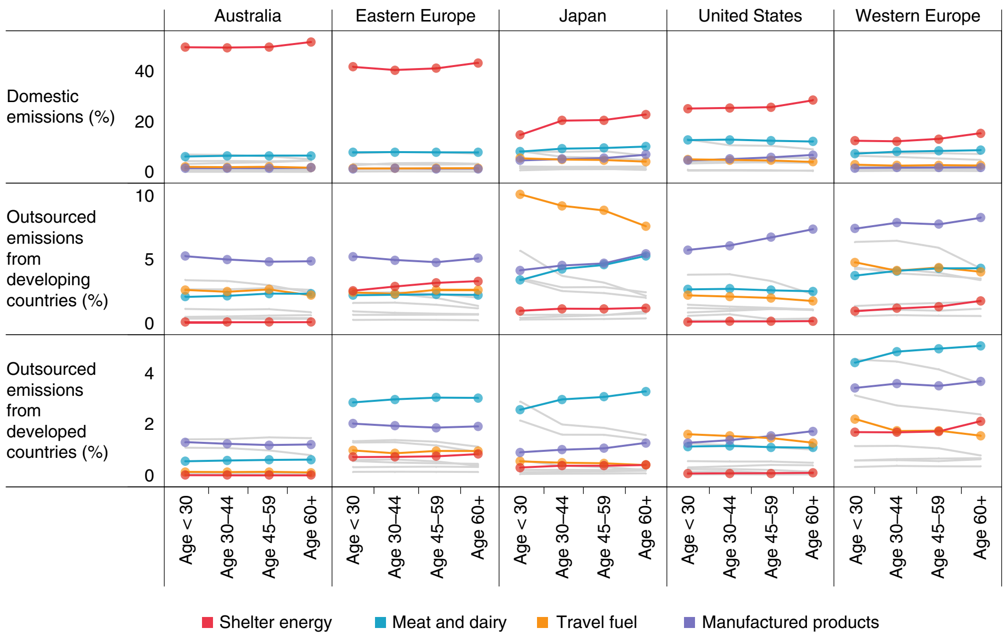

Fig. 4 | Ageing society requires strict local mitigation. The percentage of domestic and outsourced GHG emissions in total footprint by consumption categories across age groups for all countries in 2015. Four key products are highlighted in colour because they have the highest carbon intensity. Other products are in grey.

immediate and long-term challenge. Both rising per capita expenditures and a growing population in this demographic were twin drivers of this trend. The accumulated wealth of the aged group supports the high expenditures but the lower wealth elasticity of the expenditures suggests that the higher expenditures for the aged group are more rigid than other age groups, which is highly associated with their lifestyle (that is, they stay a longer time at home). Their large carbon footprints were associated with their basic needs rather than luxury lifestyles. 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 rather than abroad.

Our findings underscore the need of anticipating mitigation strategies for an ageing society in the future. People aged 60+ are projected to increase from 11% of the global population in 2005 to a range from 21% (SSP3, high challenge pathway) to 52% (SSP1, 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 a range between 38% (SSP5, mitigation challenge) and 49% (SSP4, 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 ageing 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-summarized lifestyle options for climate change mitigation[45] may impose challenges to aged household groups such as moving to more energy efficient houses or switching to electric cars as pension systems in many developed countries may not be able to facilitate such changes and the elderly may not want to change[21,22]. In addition, 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 %) (ref. [47]).

Due to the hardship, greater actions from the public sector are required such as subsidizing retrofits to older houses[38] and improving public mobility[48] and long-term care housing. It is particularly crucial to address low-income elderly households that 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 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 United Kingdom 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 moves into care home settings 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 gross domestic product on long-term care, the highest in OECD countries[54]. The major challenge, though, remains public funding. Long-term finance (for example, 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 diets as limiting meat consumption can reduce direct GHG emissions from agriculture and indirect emissions from health care needs[49]. Despite many meat substitutes (for example, plant-based meat), the primary challenge may be the cost of these meat alternatives as the meat industry wields substantial political power to keep meat costs low[56].

The mitigation in the ageing society relies heavily on local mitigation actions. Specifically, policymakers in 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 (Supplementary Information). 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 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 expenditures of the seniors. But our study focuses only on the carbon mitigation challenges from the prospect of seniors' consumption behaviour, and the extended consequence is not included. 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 raising the carbon footprint associated with immigration.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-022-01302-y.

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Methods

Environmentally extended multi-regional input–output analysis. The study applied the environmentally extended multi-regional 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 United States. The GHG footprints for each age group were calculated in 2005, 2010 and 2015 due to data availability. All years used for EXIOBASE are based on real statistical data. We linked the household expenditure survey data of four age groups with the global MRIO. The MRIO model is the most adopted tool in tracing spillover effects through regionally dispersed supply chains and therefore yields comprehensive estimates of 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 sectoral 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 footprint of household expenditure by age group, the classic Leontief demand model in the input–output 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 sector, 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 metric. We include GHG of CO_2, CH_4, N_2O and SF_6 in kg CO_2-equivalent per year. The environmental accounts of CO_2, CH_4, N_2O and SF_6 turned to the CO_2-equivalent intensity by:

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

where K refers to the GHG intensity in CO_2-equivalent (kg per Euro), indicating GHG emissions per unit output. C is the characterization vector to harmonize emissions of all GHG types (F) into the unit of CO_2-equivalent based on the Global Warming Potential 100 metric. Thus, the total GHG footprint can be expressed by:

$$\mathrm{GHG} = KLy_q^r + \mathbf{hh}_q^r \tag{4}$$

where KLy_q^r captures the GHG emissions along the supply chain of household expenditures by age group q in country r. $\mathbf{hh}_q^r$ is a vector of the household GHG direct emissions for age group q in country r, for example, direct GHG emissions from heating. Given 200 products in the EXIOBASE classification, we then aggregated them into ten major expenditure categories.

Reconciling household expenditure survey data with EXIOBASE. To capture the heterogeneity of household expenditures by age groups, we use the detailed household expenditures by four age groups that are derived from household or consumer expenditure surveys (CESs) published by official statistics agencies. For 30 European countries, we collect household expenditure survey data by age group from Eurostat, whereas the data for the United States and Japan are directly collected from national official statistics. All CES data adopt an expenditure nomenclature, the Classification of Individual Consumption by Purpose (COICOP), but the detailed classification varies in different economies. We 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 (biproportional technique)[25,68]. Regarding the well-known underreporting 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 in four age groups: <30, 30–44, 45–49 and >60; the United States and Australia classify ages in six groups: <25, 25–34, 35–44, 45–54, 55–64 and >65. Japan also has six age groups: <30, 30–39, 40–49, 50–59, 60–69 and >70. Therefore, the CES data were reconciled into four age-based household demands for European countries and six household demands for the United States, 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 United States, Australia and Japan into four age groups to be compatible with European countries. All CES data used in the study are nationally representative averages 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 account for expenditure by household only. If young people cohabit with their parents, their expenditures will be accounted for in their parents' household unless the young people earned more than their parents. But that would be a rare case. Therefore, the <30 group is largely underestimated as many young people still live with their parents. But we argue this scenario does not largely affect the older groups for most countries as children cohabiting with parents aged 60+ would be 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 60+ age group (Supplementary Table 1). This could be attributed to the lack of care facilities in their country or religion (for example, traditionally, Catholics have tended to have larger families)[69,70].

Logarithmic mean Divisia index decomposition. To understand the socioeconomic driving forces, we employ the logarithmic mean Divisia index to decompose household-related GHG footprints by four age groups in all 32 countries[71]. Logarithmic mean Divisia index 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:

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

where C refers to household-related GHG footprint by country. H_i denotes the number of households by age group i in the country. 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. The four age groups are <30, 30–44, 45–49 and >60, while the 200 products are based on EXIOBASE 3.7. The equation can be conceptualized as household effects (H); household structure effect $\left(S_i = \frac{H_i}{H}\right)$, measuring the distribution of households of age i in total households; household size effect $\left(W_i = \frac{P_i}{H_i}\right)$, indicating per household members; per capita expenditure effect $\left(R_i = \frac{E_i}{P_i}\right)$, measuring the contribution of per capita expenditure for the age group i to GHG footprint; consumption structure effect $\left(Y_{ij} = \frac{E_{ij}}{E_i}\right)$, referring to the distribution of the spending per unit of expenditure; and carbon intensity $\left(I_{ij} = \frac{C_{ij}}{E_{ij}}\right)$, measuring carbon emissions 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 decompose changes during 2005–2010 and 2010–2015 from six factors. We choose additive decomposition:

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

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

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

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

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

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

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

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 2005 price 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 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 group. The coverage of countries varied for different waves; 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 (for example, using 2010 data as the proxy for 2005). For countries not included in HFCS, we use the HFCS countries with similar age structures and development stages as the proxy for European countries (Supplementary Table 6). In HFCS data, we derive the mean of net wealth and adjusted household distribution by each age group. We first calculate the household number by age group by multiplying total household number with the adjusted household distribution by age group. Then, total net wealth by age group can be derived by multiplying the mean of net wealth by age group with household number by age group. Due to the data uncertainty, we take the share of net wealth by age group based on the estimated data:

$$\mathrm{HH}_j^i = \mathrm{Hd}_j^i \times \mathrm{Nh}_j \tag{13}$$

$$\mathrm{TNW}_j^i = \mathrm{HH}_j^i \times \mathrm{MNW}_j^i \tag{14}$$

$$\mathrm{AS}_j^i = \frac{\mathrm{TNW}_j^i}{\sum_j \mathrm{TNW}_j^i} \tag{15}$$

where Nh_j and Hd_j^i are the number of households 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 households 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*; and 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 bureaus (for non-EU countries). Non-financial assets here refer only to produced non-financial assets (for example, real property), and natural assets (for example, land) are not included. The net wealth of the household for the country *j* can be calculated as:

$$\mathrm{NW}_{\mathrm{H}_j} = \mathrm{FA}_j + \mathrm{NFA}_j - L_j \tag{16}$$

where $\mathrm{NW}_{\mathrm{H}_j}$ 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*; and L_j denotes the household liability for country *j*. Then, the net wealth for each a group *i* can be derived:

$$\mathrm{NW}_j^i = \mathrm{NW}_{\mathrm{H}_j} \times \mathrm{AS}_j^i \tag{17}$$

where NW_j^i refers to net wealth for country *j* and age group *i*. Notably, the household sector in the national accounts is not entirely in line with the HSCS household, but it is in line with the input–output framework. More details can be found in the previous study[72].

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 expenditures for each product on per capita net wealth along with the different age groups and overall countries:

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

where *D* and *W* indicate per capita expenditures 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 using the consumer purchase index derived from the 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 compare the distribution of households only by age group. The outcome reveals a good match in Australia and Japan and a general match in the European Union and United Kingdom. Despite a broad match in household distribution, we must nevertheless highlight the issue, and the details of the comparison can be found in the Supplementary Information. Moreover, many socioeconomic characteristics have a major impact on carbon footprint and spending by age group (for example, household size). Household size has a major impact on per capita expenditures and carbon footprint. Household size varies by age group in different countries (Supplementary Table 1). For example, middle-aged households have more family members of a younger age (for example, children). Previous studies using micro-level data have highlighted the effect of household size on carbon footprint when other socioeconomic variables (for example, income and 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[73–75]. Similar findings have been reported in the United States[76] and European Union[77]. 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 expenditures. 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 (Supplementary Fig. 3). Notably, OECD modified scale is adopted in the HES data. Some countries (for example, the United States, Australia and Japan) found that the per adult-eq 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 (45–59) in 2005, the per adult-eq footprints of the aged group have overtaken that of the middle-aged group in 2015 with 12.94 t per adult-eq and 13.42 t per adult-eq of the 45–59 group and 60+ group, respectively. The outcome of European countries is consistent with a previous study[77]. To some extent, using the per adult-eq measure helps alleviate the problem, although daily intake varies greatly from newborn to adult. As a result, there is no perfect way to correctly convert children to adult-eq. With larger households, per capita carbon footprint or expenditures could be smaller due to the scale effect[78]. The data limitation might lead to uncertainty in comparison among different age groups with distinct household sizes and structures. Furthermore, the classification of age groups may lead to seniors aged 60–65 having different expenditure behaviours than those aged 70–75, although they are all grouped as 'senior group' in the study. For example, according to a survey in the United Kingdom, the population's consumption of meat and dairy peaks at age 65–74 and then declines[79].

Data availability

The EXIOBASE 3.7 data are available at: https://zenodo.org/record/3583071#.YPA5e0kzabg. Household expenditure by ageing groups is sourced from: EU Household Budget Survey (https://ec.europa.eu/eurostat/web/household-budget-surveys/database), US Consumer Expenditure Survey (https://www.bls.gov/cex/csxstnd.htm), Japan Family Income and Expenditure Survey (https://www.stat.go.jp/english/data/sousetai/1.html) and Household Expenditure Survey, 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 United Kingdom, the Federal Reserve (https://www.federalreserve.gov/releases/z1/) for the United States, Family Income and Expenditure Survey (https://www.stat.go.jp/english/data/sousetai/1.html) for Japan and Household Budget Survey (https://www.abs.gov.au/statistics/economy/finance/household-expenditure-survey-australia-summary-results) for Australia.

Code availability

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

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Author contributions

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 the raw expenditure data. R.W. constructed the EXIOBASE model. H.Z. and Y.L. conducted the decomposition analysis.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Richard Wood, Zhengkai Zhang or Kuishuang Feng.

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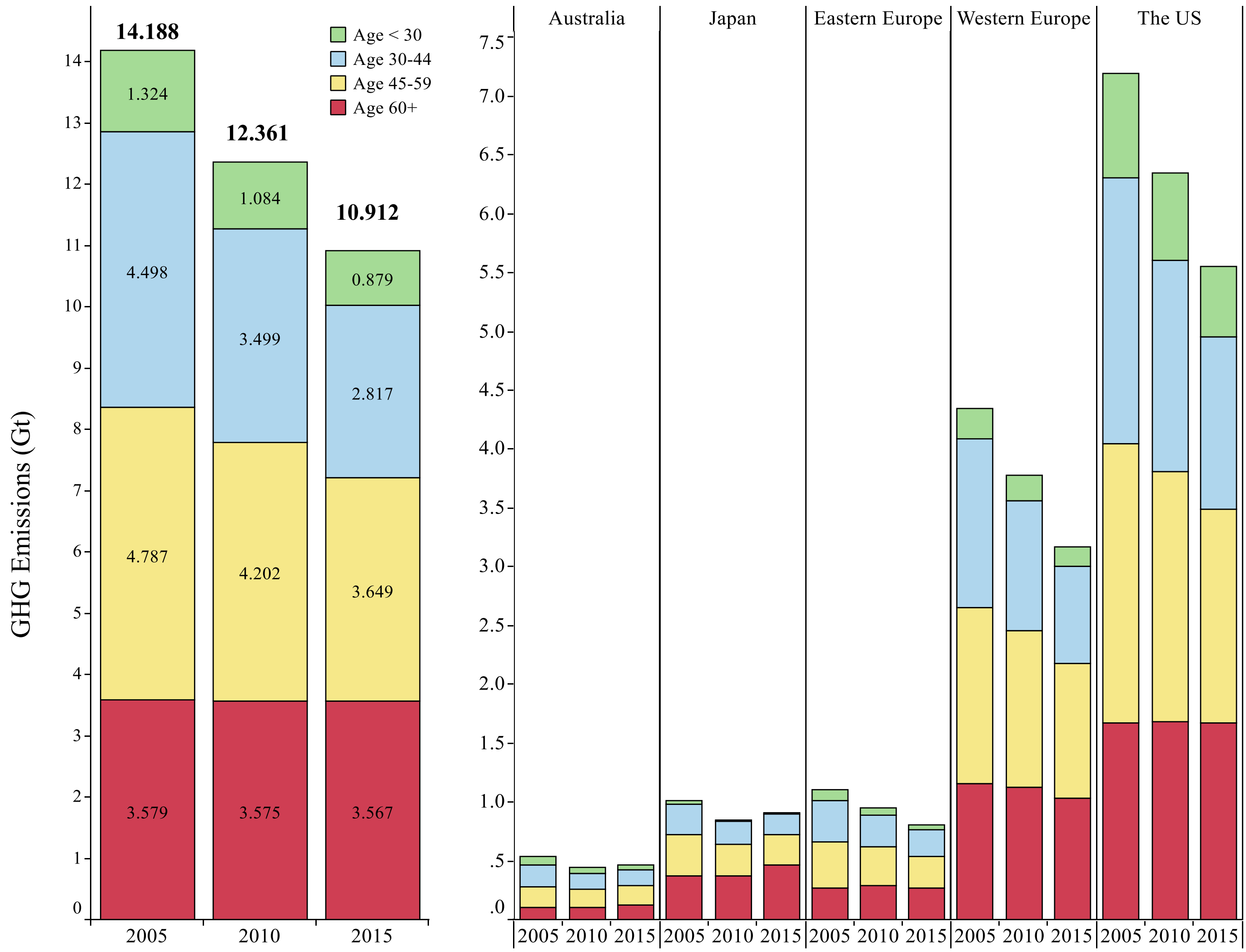
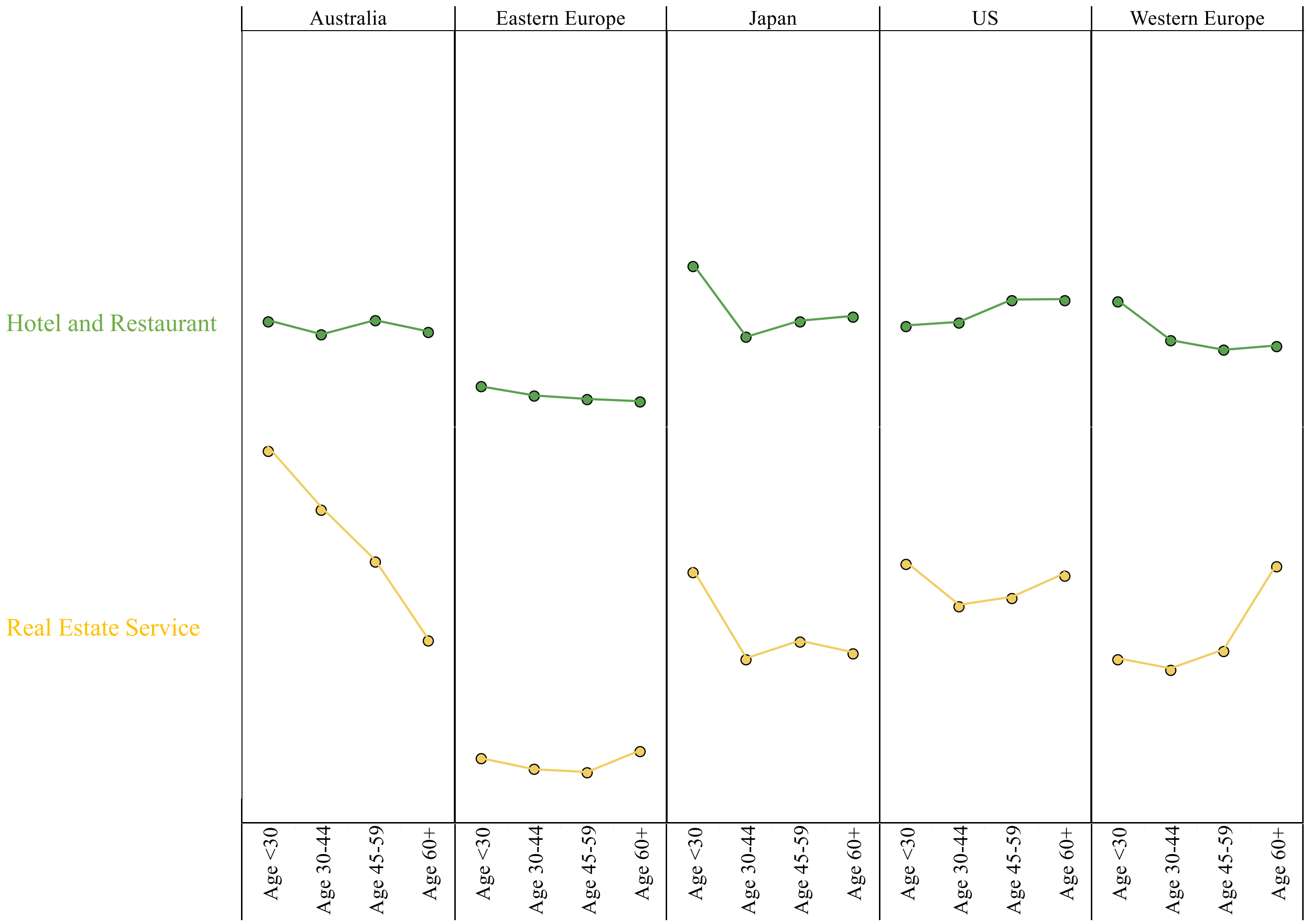


Extended Data Fig. 1 | The carbon footprint by age groups in absolute unit. The carbon footprint by age groups for 5 grand categories of 32 developed countries, from 2005 to 2015.



Extended Data Fig. 2 | Per capita expenditure in Hotel & Restaurant and Real Estate Service. Per capita expenditure in Hotel & Restaurant and Real Estate Service for different age groups for 5 grand categories in 2015.