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RESEARCH ARTICLE

Unequal age-based household carbon footprint in China

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ABSTRACT

Controlling household consumption is an essential means to achieve carbon neutrality in China, and population ageing has an important impact on its structure. Since older people exhibit different consumption patterns than younger people, an increase in the proportion of aged people affects overall consumption patterns. This paper adopts an input–output model to reflect the heterogeneity in the consumption structure and household carbon footprint of different age groups, followed by a simulation of the future household carbon footprint. The results find that in China, the total household carbon footprint shows an inverted U-shape with age, with the lowest total carbon footprint coming from aged households (age of household head 65 and above) and the highest total carbon footprint from middle-aged households (age of household head 45–54). The average household carbon footprint decreases with age, with aged households remaining the lowest. Aged households, however, have the highest share of the direct carbon footprint. Interestingly, urban households of all ages have a higher carbon footprint than rural households, with the largest difference being among aged households. The projection results show that based on demographic changes, although the average household carbon footprint of elderly households in China is low, as the number of elderly households increases, the total carbon footprint of elderly households will be sizable and need to be taken seriously.

Key policy insights

- The total carbon footprint of elderly households will become more significant and sizable as the number of elderly households increases.
- Urban life is more carbon-intensive, and China's urbanization is leading to an increase in the carbon footprint.
- Aged households require more attention in future climate policies.
- Targeted, consumption-based climate policies are necessary for carbon reduction in China and will have relevance in other countries with similar consumption structure and demographic trends, e.g. with ageing or rapidly urbanizing populations.

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1. Introduction

Environmental intragenerational equity captures the equity between different regions and demographics of people and may be expressed as in terms of measures of domestic equity and international equity. Many studies have conducted carbon inequality studies based on income (Asumadu-Sarkodie et al., 2019; Chitnis et al., 2013; Galvin & Sunikka-blank, 2018). According to the BP Statistical Review of World Energy (BP, 2020), as of the end of 2019, China's carbon emissions reached 9.825 billion tons, accounting for 28.8% of the global total carbon emissions and ranking China first in the world. Using a consumption-based approach to

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accounting for carbon emissions, researchers found that about two-thirds of global emissions are associated with households (Ivanova et al., 2016; Kerkhof et al., 2009). The emission footprint of a household can be influenced by household lifestyle, which is impacted by a variety of physical, social, and economic factors that affect resource use and the associated carbon emissions. A better understanding of the household footprint structure will enable us to effectively reduce the household footprint based on knowable household characteristics. However, there are significant differences in the consumption structure of different households (Das & Paul, 2014); for instance, elderly families may need fewer industrial products and more services than young households (Bardazzi & Pazienza, 2018), which will directly lead to changes in carbon emissions caused by consumption.

China is in a transition where household consumption will presumably gain more importance in facilitating China's economic growth in the future. The 14th Five-Year Plan establishes expanding domestic demand as a strategy to tap into the enormous potential of China's domestic markets, to promote consumption aligned with green, healthy, and safe development, and to steadily improve the level of consumption among residents. With the steady increase in China's per capita national income level, both direct and indirect household energy consumption levels can be expected to rise further. Consequently, the household consumption related carbon emissions of China are likely to surge as well. As the ageing of the population continues to intensify, the consumption structure of Chinese households will change accordingly, and so the structure, sources and amount of carbon emissions will also change. This study reveals the unequal emissions generated by different household age groups.

Xi Jinping proposed at the 75th UN General Assembly that China would aim to peak carbon emissions before 2030 and carbon neutrality before 2060 (Xi, 2020). The Chinese government's 14th Five-Year Plan for National Economic and Social Development and the Long-Range Objectives Through the Year 2035, introduced on March 13, 2021, states that it will promote green development, foster a harmonious coexistence between humans and nature, continuously improve environmental quality, and actively address climate change.[1]

This paper explores China's shifting demographics, and specifically at the age profile of its population, as a driver of CO2 emissions to understand the implications of an ageing population for climate change policy. The results of the seventh Chinese Population Census[2] show that in 2020, China's population 60 years and over was 264.02 million, accounting for 18.70% of its total. From 2000 to 2020, the proportion of people aged 65 and above in China rose from 7% to 13.5%, and China's population ageing has further deepened. The World Bank predicts that by 2050, the population over 65 years old will reach 26% of the total population in China (UNPD, 2019). China will continue to face pressure to restore the long-term balanced development of the population.

Population ageing changes the main body of social production and consumption, resulting in changes in the sources and quantities of carbon emissions. Studies have shown links between ageing and climate change (Cao et al., 2020; Xie et al., 2020; Yang & Wang, 2020; Yu & Qiuyue, 2017). Existing research on the relationship between climate change and ageing is mainly divided into the following two categories. First, studies examine the impact of climate change on human health, especially on the elderly (Hong et al., 2019; Usman et al., 2019; Zhu et al., 2019). For example, Yu et al. (2019) found that extreme cold or hot temperatures lead to excessive deaths, especially among the elderly, mainly caused by cardiovascular diseases. Other research focuses on the impact of the population age structure on climate change (Feng et al., 2020; Huang et al., 2019a; Zhang et al., 2019). This paper focuses on the latter, that is, it studies the impact of ageing on carbon emissions.

China is facing challenges from both climate change and population ageing. This paper analyses the impact of ageing on carbon emissions from the perspective of the consumption structure and predicts changes in the consumption structure and carbon emissions due to population change in China in 2030. The contributions of this paper are as follows: 1) We adopt the input–output model and use microdata to reflect the heterogeneity in the consumption structure of different age groups. 2) We analyse the household carbon footprint from household consumption in China, which is the largest developing country with the largest population in the world. Our research is to improve understanding of the impact of China's future demographic patterns on climate change mitigation and to provide direction for developing mitigation strategies for an aging society in the future.

The rest of this paper is organized as follows. The literature review is included in Section 2. Section 3 is devoted to the methods and data, including the IO model, projection method, and data sources. The empirical results are discussed in Section 4. Finally, a brief conclusion with policy insights is offered in Section 5.

2. Literature review

The carbon footprint refers to the total greenhouse gas (GHG) emissions caused by a person, event, organization, service, or product, and it is used to measure the ecological impact of human activities. Households are the largest consumers of all types of energy and goods (Hertwich, 2005). According to previous studies, household consumption is the largest contributor to overall energy use, and household consumption is responsible for 72% of global emissions (Dubois et al., 2019). To consider the design of more targeted and effective climate policies, the literature further takes household heterogeneity into account and investigates the carbon emissions of different household groups.

Studies of the carbon footprint for different households have mainly focused on social factors (Li et al., 2019), technological factors (Asumadu-Sarkodie et al., 2019; Chitnis et al., 2013), natural factors (Nie et al., 2017), and income factors (Feng et al., 2009; Golley & Meng, 2012; Oswald et al., 2020; Wang et al., 2018; Wiedenhofer et al., 2017). The income factor is considered the main driver of the household carbon footprint (Zhou & Liu, 2016b), but this cannot explain the carbon-intensive consumption behaviour of low-income elderly households. Few studies addressing the relationships between population factors and the carbon footprint have primarily focused on other aspects, i.e.: population distribution (Liddle, 2014); population growth (Cramer, 1998; Lohwasser et al., 2020; Pu et al., 2020; Sarkodie et al., 2020; Underwood & Zahran, 2015); population quality (Zhang et al., 2019); and population living standards (Zhang et al., 2018; Zhang & Tan, 2016; Zhou & Liu, 2016a).

Researchers have measured the impact of demographic factors on carbon emissions from different perspectives. With the rapid development of the global economy, many researchers (Cramer, 1998; Lohwasser et al., 2020; Pu et al., 2020; Sarkodie et al., 2020; Underwood & Zahran, 2015) have realized that population ageing has become a pressing issue among demographic factors and have tried to identify the relationship between ageing and the environment.

Scholars have drawn a range of different conclusions about the relationship between population ageing and carbon emissions. Considering that the income level, consumption habits, lifestyle, and environmental attitudes of the elderly are inclined to follow a low-carbon model, some have concluded that ageing should shrink the labour supply and inhibit carbon emissions (Liddle, 2011). Zagheni (2011) found that the relationship between population ageing and carbon emissions follows an inverted U-shape. Families where elderly and young people live together are more 'energy-saving and environmentally friendly'. However, Singh and Mukherjee (2019) found that the share of senior citizens in the population positively impacts per capita GHG emissions. Zhou and Liu (2016b) showed that the relationship between age structure changes and carbon emissions is not apparent. Previous studies on the relationship between population ageing and the carbon footprint are still inconclusive and carried out mainly in developed countries (Franklin & Ruth, 2012; Lim et al., 2020; Menz & Welsch, 2012; Ota et al., 2018; Wei et al., 2017; York, 2007). Due to the limitation of data availability, studies on the relationship between ageing and carbon emissions in developing countries are relatively scarce. Considering that China is the largest developing country with a large population base and an increasingly severe ageing trend, the study of the carbon footprint of its elderly population deserves attention.

Studies on the effects of population ageing on the carbon footprint can be divided into the following three methods. The first is index decomposition analysis (Melnikov et al., 2012; Zhang & Bai, 2018), which is simple and clear but cannot analyse the nonlinear effects between variables in depth. The second is the econometric analysis based on STIRPAT and IPAT models, using time series or panel data to establish regression equations to explore the impact of different population factors on the carbon footprint (Cramer, 1998; Menz & Kuehling, 2011; Singh & Mukherjee, 2019; Wang et al., 2017; Yu et al., 2018b; Zagheni, 2011; Zhang & Tan, 2016) this methodological approach has high data requirements. The third is structural decomposition analysis based on an input–output model (Long et al., 2019; Shigetomi et al., 2014; Shigetomi et al., 2018).

Existing studies have not paid enough attention to the heterogeneous characteristics of the consumption behaviour of different groups (Yu et al., 2018a), which leads to gaps in understanding how to target consumption-related emission reduction strategies. The input–output model reflects the production-consumption connection by examining backward- and forward-looking linkages between industries, thus making our estimation of embodied carbon emissions on the consumption side more accurate. For example, emphasizing the heterogeneity of the Japanese household structure, Shigetomi et al. (2014) explored the impact of the presence of dependent persons (elderly and children) on the household carbon footprint. Long et al. (2019) studied the effect of the age of the household head on residential energy consumption at the city level; using data from developed countries, they explored only residential energy consumption.

In this paper, we use this third method, the input–output method, to measure and predict the carbon footprint of households of different ages. By comparison with previous studies, we use data from developing countries, covering all types of household consumption expenditures. We thus aim to analyse the impact of ageing on the consumption-based household carbon footprint more comprehensively.

Previous studies (Tarazkar et al., 2020; Wang et al., 2017; Wei et al., 2018a) on the relationship between ageing and the environment have generally measured the ageing of the population, i.e. the share of the population aged 65 years or older in the total population, at the national and urban levels. We know that, the household head is the decision-maker of household affairs, when the household is the unit of consumption, the household head is important for household consumption (Zhu et al., 2022). This paper therefore uses the age of the reference person of a household provided by microsurvey data as a measure of ageing to calculate and predict the carbon footprint due to consumption among different household age groups.

3. Methodology and data

3.1. Household consumption

There are almost no quantitative data in China that directly reflect the relationship between household population structure and consumption structure, mainly because the Chinese National Bureau of Statistics (NBS) usually publishes only consumption structure data by income class and lacks corresponding information on the age structure of the population. One alternative data source is the China Household Financial Survey Project (CHFS), which is a nationwide sample survey conducted by the China Household Financial Survey and Research Centre, Southwestern University of Finance and Economics, and has been surveyed every two years since 2011. The CHFS employed a stratified three-stage probability proportion to size (PPS) random sample survey design; therefore, the CHFS dataset was nationally representative. The CHFS dataset has been widely used in studies on economic activities, education outcomes, and family dynamics (Xie et al., 2022; Zeng & Zhu, 2022; Zhang et al., 2020). We collected information on household head age, consumption expenditures, and demographic characteristics of each household from the CHFS dataset for 2013 and 2017 to obtain the consumption structure based on age (Gan et al., 2016).

To differentiate between older and younger households, based on Liddle (2011) and due to data constraints, all households were sorted into five age groups depending on the age of the households' main income earner: 1–34 years old, 35–44 years old, 45–54 years old, 55–64 years. The total consumption expenditure of a household was differentiated by consumption purposes (Kronenberg, 2009). The expenditure of the average household from age group g on consumption purpose i may be written as.

$$c_g^i = \theta_g^i c_g \tag{1}$$

where c_g denotes the total consumption expenditure of a household in age group g, θ_g^i denotes the share of expenditure on consumption purpose i in total consumption expenditure, and c_g^i denotes the expenditure on consumption purpose i. For simplicity, it was assumed that households within each age group are homogeneous. Therefore, the total consumption expenditure of the age group g on consumption purpose i can be written as:

$$C_g^i = H_g c_g^i \tag{2}$$

where H_g denotes the number of households. The total expenditure for consumption purposes i can be written as:

$$C^i = \sum_{g=1}^{5} C_g^i \tag{3}$$

$$C^i = \sum_{g=1}^{5} H_g \theta_g^i c_g \tag{4}$$

Eq. (4) can be used to estimate the impact of demographic change on the structure of aggregate consumption expenditure. Values for H_g are provided in the household projections from the UN Population Division's population data. Since our paper aims to isolate the impact of demographic change, it is assumed that θ_g^i and $c_g$remain constant over time, and CHFS 2017 data are used to calculate θ_g^i and c_g.

To ensure the validity and credibility of the data, in the research process, we processed the sample data as follows: we removed data with questionable economic logic before and after; we removed missing data for key variables, such as age, various types of consumption expenditures, and household registration information. We ultimately retained a total of 23,362 households (78,401 individuals) and 31,613 households (127,012 individuals) in 29 provinces across China in 2013 and 2017, respectively, after removing the less credible sample data.

3.2. Environmentally extended input–output analysis

The data on household consumption expenditures are of critical importance when estimating direct and indirect carbon emissions. Since the CHFS uses a different classification[3] from the IO tables, to obtain indirect carbon emissions embodied in specific goods and services consumed by each household, we created a concordance to match consumption items in CHFS with sectors in the IO tables; see Table.SM1.

We used the IO method to estimate the household carbon footprint by integrating household consumption expenditure into the IO tables provided by the Chinese National Bureau of Statistics, including 42 production sectors and 2 residential sectors. CEADs[4] provide CO2 emission inventories by using the IPCC Sectoral Emission Accounting Approach in the format of 45 production sectors and 2 residential sectors(Shan et al., 2020). We merged the carbon emission inventories containing 45 production sectors into the IO table containing 42 sectors (S01–S42) Table 1.

Z represents the intermediate input matrix, Y represents the matrix of final products that are used to satisfy households' final demand, f represents the vector of final products that are used to satisfy inventory change, h represents the vector of final products that are used to satisfy government demand, n represents the net exports vector, x represents the gross outputs, and v represents the value-added vector. According to the accounting balance of monetary flow, we obtain.

$$x = Zw + Yu + f + h + n \tag{5}$$

where w and u represent the summation vector consisting of ones. The intermediate input coefficient matrix is $A = Z\hat{x}^{-1}$, where $\hat{x}$ represents the diagonalization of the output vector. We define F as a diagonal matrix composed of the carbon intensity coefficient. Then, the carbon footprint of household consumption is:

$$E = FBY \tag{6}$$

where $B = (I - A)^{-1}$ represents the Leontief inverse matrix.

3.3. Projection of age-based carbon footprint

To study the carbon footprint effects of future population change, we must define the target population structure, i.e. the possible population change scenarios. The UN Population Division [5] releases population projection data every year that contain three fertility scenarios: high, medium, and low, which is widely used in socioeconomic research related to the global population(Lim et al., 2020; Wei et al., 2018a, 2018b; York, 2007). Our paper

Table 1. China's input–output tables capturing age heterogeneity.

			Intermediate demand				Final demand						Exports	Output/ imports
			Sector 1	Sector 2	… …	Sector n	Age group 1	Age group 2	… …	Age group n	Inventory	Government		
Intermediate inputs	Domestic	Sector 1 … … Sector n	Z				Y				f	h	n	x
	import	Sector 1 … … Sector n	Z^I				Y^I				f^I	h^I	n^I	x^I
Value added			$\boldsymbol{v}$											
Output			x^{-1}											

uses population data under the low fertility scenario issued by the UN Population Division (UNPD, 2019) to project the carbon footprint of households of different ages in 2030.[6]

This study focuses on footprints that are impacted by changes in population ageing. Since it is not easy to estimate future technological changes, including changes in global supply chains, the indirect emission intensities were fixed in this paper. We evaluate the age-based household carbon footprint based on the following considerations in this study: (i) the shares of both domestic and imported products for household expenditures are assumed to be constant as of 2017; (ii) assuming that global carbon emission intensities and the coefficient matrix of IO2017 are fixed; and (iii) future consumption patterns in 2030 for each household remain based on those of 2017.

4. Results and discussion

4.1. Consumption structure of households by age

Using CHFS consumption data and China Statistical Yearbook population data (NBS, 2018), we calculate the average household expenditure by age, and the results are shown in Figure 1.

The average household consumption decreases with the age of the household head in both rural and urban households. The average annual household consumption is highest when the age of the household head is between 1 and 34 years old. Younger people tend to be more conscious of consumption, may have higher rental expenditures if they lack property, or may have renovation expenditures if they are newly married. Group_1–34 has significantly larger expenditures than other age groups in terms of communication and internet fees, entertainment, clothing, and home renovations. Average household spending decreases as age increases, with the oldest households spending the least on average per year, which is consistent with the attitudes of older Chinese people, who are generally more frugal, towards consumption.

These patterns are shown in consumption data. According to the consumption structure of Chinese households in 2017, shown in Figure 2, in both rural and urban regions, food consumption accounts for more than 30% of the total, and the proportion of food consumption rises to 39% in Group_65 + . The proportion of food consumption thus shows a U-shaped relationship with the age of the household head, with young and elderly households having the highest proportion of food consumption. For elderly households, as economic income decreases, consumption tends to be reduced, and food consumption as an immediate need accounts for a larger proportion; the proportion of clothing consumption decreases with age, in which Group_1–34 accounted for 6.98% of clothing expenditures, likely because young people tend to be more interested in fashion, while Group_65 + accounted for 2.66%; the proportion of health care expenditure increases with age and grows

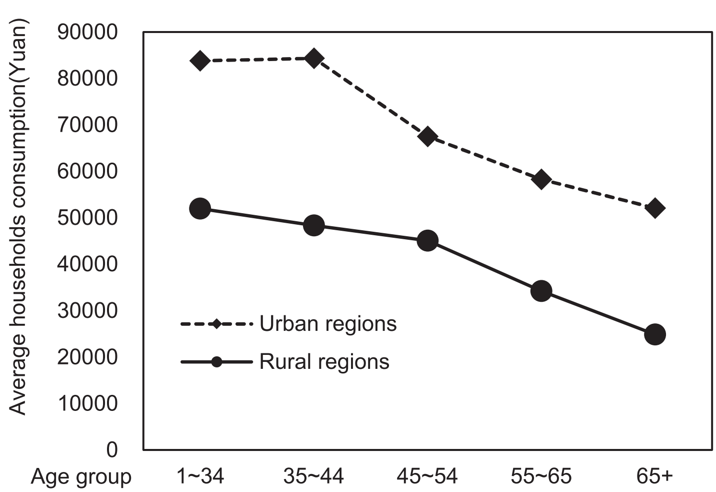

Figure 1. Average household consumption expenditure by age in 2017.

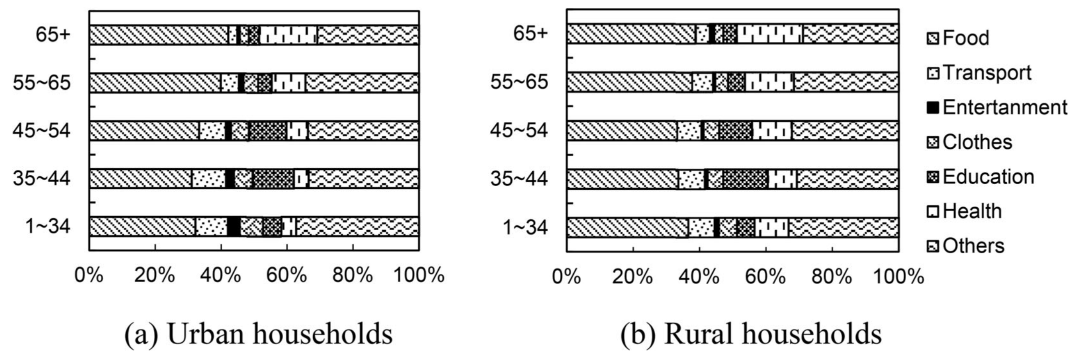

Figure 2. Structure of family consumption by age in 2017. Source: Author's own analysis based on CHFS 2017 dataset.

faster after the age of 45, as middle-aged and aged people usually have more health problems than younger people and thus have the highest expenditure on health care. Figure 2 shows that the consumption structure for older and younger households is significantly different, and the age of the head of household has a significant influence on the consumption structure. We calculated the CHFS data for 2013, in the same way, to compare the extent of change in the household consumption structure between years and the trend of change in different consumption types given the age of the household head (see Figure SM2 in the Supplementary Material for details).

The consumption structure of rural households differs from that of urban households. For example, the share of transportation consumption in urban households shows a U-shaped relationship with the age of the household head and reaches its highest in Group_35–44, while in rural households, it decreases with the age of the household head; the relationship between the share of education expenditure and age is opposite in urban and rural households, i.e. the share of education expenditure in urban households decreases with age, while that in rural households shows a U-shaped change with age and reaches its highest in Group_35–44.

From the above analysis, we can see that there is a relationship between the age structure of the head of household, the type of household, and the household consumption structure. Considering the close relationship between the consumption structure and carbon footprint, we need to calculate the carbon footprint based on age.

4.2. Carbon footprint of households by age

Using the method noted in Section 3.1, we obtain the family carbon footprint by age and family type, and the results are shown in Figure 3.

There is an inverted U-shaped relationship between the total carbon footprint and age for both urban and rural households, which is consistent with the findings of (Li et al., 2018; Liu et al., 2019). Figure 3 also shows that the rural carbon footprint is much lower than the urban carbon footprint for households of all ages, and the share of direct emissions[7] in the carbon footprint is much larger in rural areas than in urban areas. This is because rural households, especially aged households, have lower consumption expenditures than urban households. Rural households without collective heating prefer to consume cheap and easily available traditional biomass energy sources, such as coal and straw, for household cooking and heating.

The highest total carbon footprint group is Group_45–54, with a total of 694 Mt-CO2eq. Slightly lower than Group_45–54, Group_35–44 has 632 Mt-CO2eq of carbon footprint. Group_65 + has the lowest total carbon footprint (324 Mt-CO2eq), and these are mainly indirect carbon footprints (86.1%).

In this paper, we focus on the environmental impact of ageing, so we pay more attention to the carbon footprint of Group_65 + households. Figure 3 shows that Group_65 + has the lowest total carbon footprint (324 Mt-CO2eq), accounting for only 46.65% of the total footprint of Group_45–54. The average carbon footprint of Group_65 + households is also the lowest in both urban and rural areas, suggesting that the elderly population

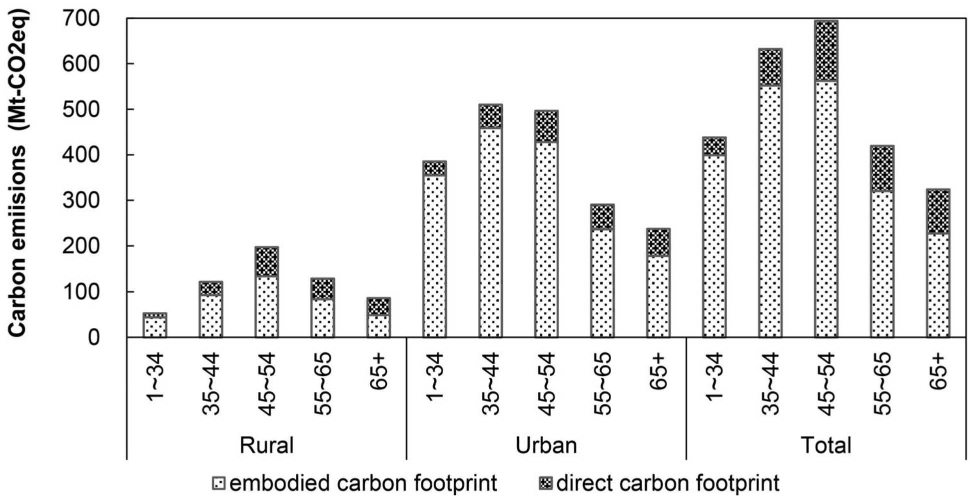

Figure 3. Carbon footprint of different age groups of Chinese households in 2017.

has a more environmentally friendly consumption pattern in China. Therefore, as the number of elderly people and the degree of ageing in China increase, the total carbon footprint across society will be reduced. Using the input-output model, we calculated the sectoral sources of indirect emissions for Group_65+, and the results are shown in Figure 4.[8] The largest indirect emissions sources in both rural and urban households of Group_65 + is S24, i.e. the production and supply of electricity and heat (29.29 and 109.15 Mt-CO2eq), followed by S29 transport, storage, and postal services (5.17 and 15.79 Mt-CO2eq) and S14 metal smelting and rolling processing (3.19 and 13.08 Mt-CO2eq). In addition, S06 (consumption, food, and tobacco) and S40 (health and social work) account for a significantly larger share of Group_65 + households and are generally higher among the aged population.

The average carbon footprint of households in different age groups is shown in Figure 5. The average household carbon emissions of urban households decrease with age. In rural areas, however, the average household carbon footprint increases with age in an inverted U-shape, peaking at 45–54 years old and the declining with oldest households (65 years old and above), showing that rural Chinese households with aged people as household heads present a more low-carbon consumption pattern than other households. Urban households emit more carbon than rural households in all age groups, with the largest gap being at age 65 and above, as the rural elderly population has a much lower embodied carbon footprint than urban households. As the

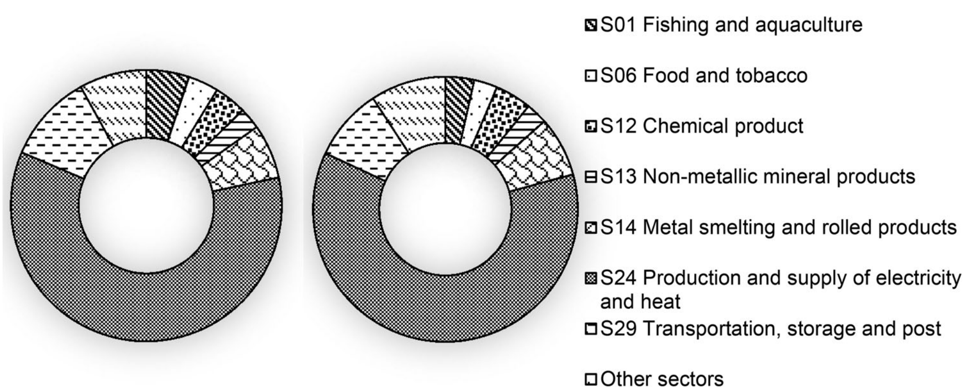

Figure 4. Composition of the indirect carbon footprint for Group_65 + in 2017.

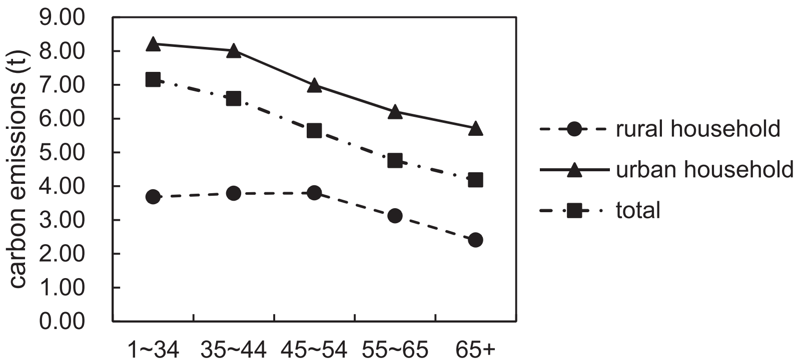

Figure 5. Carbon footprint per household for different age groups in 2017.

graph above shows, urban life is more carbon-intensive, and China's urbanization is leading to an increase in the carbon footprint.

4.3. Future carbon footprint

Since there are no projection data for the number of households in China, we use the UN Population Division's population and urbanization projection data to project the number of households in China in 2030. Using 2017 as the base year, we use the population growth rate of each age group as the growth rate of household heads in each age group to measure the expected number of household heads in each age group. Here, due to missing data on the degree of urbanization among households in each age group, we assume that the urbanization growth rate is constant at all ages in the same year. The number of household heads under 34 years old does not match the population under 34 years old: 44.1% of the population was under 34 years old in 2017, while the corresponding share of the number of household heads under 34 was 14.35%. Therefore, we use the growth in the population aged 25–34 years (16.42% of households in 2017), which more closely matches the share of households aged 1–34 years, to measure the growth in the number of heads of household aged 1–34 years. Table.SM1 shows the Chinese household shares for different ages in 2030.

As shown in Table.SM1 and Figure 6, the percentage and number of elderly individuals in 2030 will increase significantly compared to 2017. In both rural and urban areas, the number of households with heads under the age of 55 is declining as a percentage, while the percentage of households aged 55 and over is increasing and ageing is deepening. The degree of ageing is higher in rural areas than in urban households, which is not

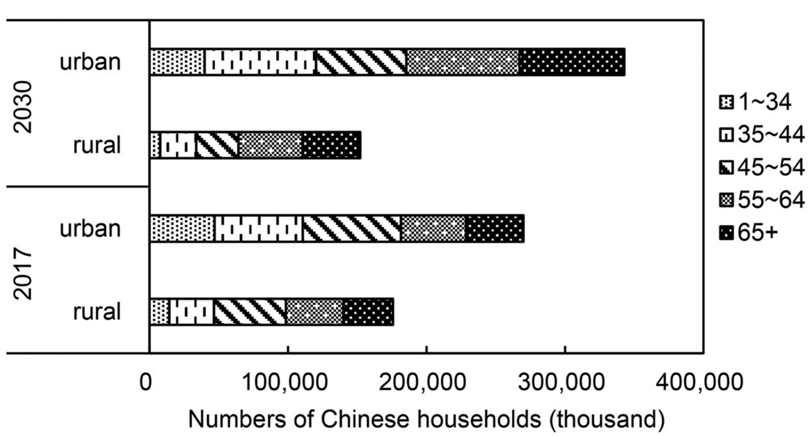

Figure 6. Numbers of Chinese households by age of head of household in 2030 (estimated).

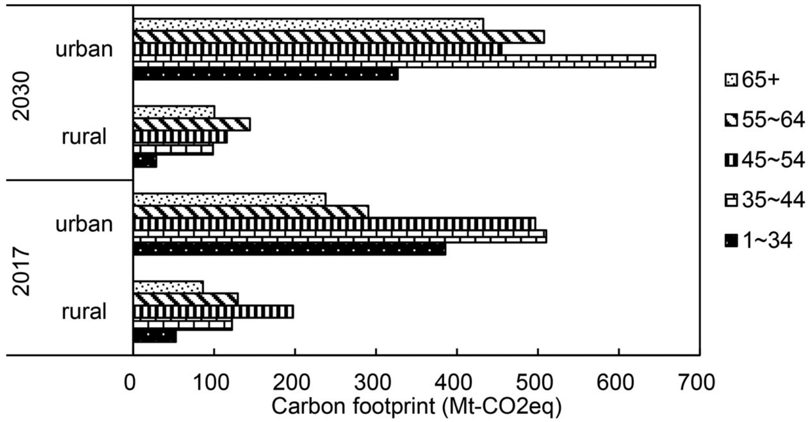

Figure 7. The carbon footprint of Chinese households by age in 2030.

unrelated to the out-migration of young people from rural areas due to the greater employment opportunities in cities. For rural households, the share of aged households (i.e. with heads of household over 65 years old) is continuously increasing by these estimates, from 20.37% in 2017–27.37% in 2030, with a 34% increase. This is consistent with the empty nest phenomenon in rural China at this stage. In addition, considering that there are no precise urban-rural distribution forecast data for family groups by age, these data may be underestimated. For urban households, the share of the aged households (i.e. with heads of household over 65 years old) grows from 15.4% in 2017–22.06% in 2030, thus showing a 43% increase; this result that may be overestimated considering the actual possible influx of the younger population to urban areas.

We present these projections to illustrate potential consequences of various demographic trends on the household carbon footprint based on plausible assumptions about historic demographic trends. Using the input–output model presented in *Section 3*, we can estimate the carbon footprint of households with heads of different ages in 2030. The results show that some decline in the consumption-based carbon footprint can be expected due to changes in household composition resulting from ageing and low birth rate trends (Figure 7). However, increasing urbanization will counter the impact of ageing to significantly increase the carbon footprint, leading to an increasing overall trend in the consumption-based carbon footprint due to demographic changes. As a result, the total carbon footprint increases abruptly for Group_55–64 and Group_65 + due to the age structure change and urban-rural migration trends, and Group_35–44 becomes the group with the highest total carbon footprint. With the increase in the elderly population, the carbon footprint of Group_65 + will increase in both rural and urban areas. Therefore, for future emission reduction, an increasing focus should be placed on elderly consumers, and in particular for sectors such as health care and residential energy consumption, which are the largest sources of the carbon footprint for the elderly; further, technological advances can be used to reduce the intensity of the carbon footprint, e.g. the more energy-efficient technologies in residential energy consumption.

5. Conclusion

This paper adopts an input–output model and uses microdata to reflect the heterogeneity in the consumption structure of different age groups, and the implications of this on household carbon footprints in China. We measure the age-based Chinese household carbon footprint through this input–output model, followed by a simulation of the future household carbon footprint.

The findings from this study show that demographic change has a significant impact on the structure of households' consumption expenditures and in turn on CO_2 emissions. As demographic change leads to a redistribution of consumption expenditure between different energy sources and it also more generally affects the households' carbon footprint. Direct emissions are associated with energy consumed directly by the household (such as burning natural gas to cook or heat water), and typically account for a smaller proportion of the total household footprint than indirect emissions do. Elderly households have far greater levels of direct emissions than younger households.

Total emissions from elderly households are comparatively low, while middle-aged households are shown to produce a higher footprint than other household groups. Considering both the total household footprint and average household footprint, the carbon footprint of elderly households is lower. The projections show that, to some extent, an increase in the proportion of the ageing population will reduce the total carbon footprint, while the deepening of urbanization in China will counter such a decrease to increase total carbon emissions. Although the average household carbon footprint of elderly households in China is low, as the number of elderly households increases, the total carbon footprint of elderly households will be sizable and need to be taken seriously in future climate mitigation policy.

The findings of this study should compel policymakers to understand the prominence of the demographic structural transition in terms of its influence on climate policy design. It provides significant insights that may guide future climate policy for China and other developing countries with an ageing population. Here we identify the potential for targeted, consumption-based climate actions. Governments should actively guide the green consumption awareness of people aged 45–54, who have the largest number of households and the greatest carbon footprint. Considering the serious trend of population ageing, the consumption behaviour of the elderly also needs to be considered. For example, businesses might increase the development of digital technology for the elderly and establish a green consumption channel for elderly consumers through a combination of online and offline services. And youth should be encouraged to form green consumption habits and to reduce carbon emissions while meeting consumption needs, thus shaping green consumption behaviours throughout their life. Also, our results may have relevance in other countries with similar consumption structure and demographic trends.

However, it is important to keep in mind that the findings presented in this paper are derived under a series of restrictive assumptions. For example, the consumption patterns for each age group remain constant from 2017 onwards, which ignores intergenerational and other effects. Indeed, one might expect that consumption patterns within age groups would change over such a long time, for example, due to income growth, price changes, or cohort effects. In addition, the input–output analysis is based on the technology coefficients from the 2017 input–output tables. These coefficients may change due to technological change, substitution effects, or energy mixes, such as improvements in technologies, including green innovation technologies that result in lower carbon emissions per unit of product and thus may result in an overestimation of the emissions in this analysis. To reduce the impact of this problem, this paper makes short-term projections only. Further research could incorporate trends in technology types or levels, or other changes – e.g. in the international trade and supply chain – into future scenarios, which will improve the robustness of the analysis and the usefulness of the results for the projection of consumption-based CO_2 emissions.

Notes

1. http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm
2. http://www.stats.gov.cn/ztjc/zdtjgz/zgrkpc/dqcrkpc/ggl/202105/t20210519_1817693.html
3. The consumption categories of the CHFS dataset used in our paper include food, clothing, housing rent, utilities, fuel and management, home improvement and maintenance, durable goods, daily necessities, household services, local transportation, transportation, communication, education, entertainment, travel, health care, medical care, and other expenditures. Due to data ownership restrictions, tobacco and alcohol, anti-smog products, sewer repair, and legal services are not available and therefore not covered in our paper.
4. https://www.ceads.net/data/, CEADs gathers a group of experts from the UK, USA, and China to work on China and other emerging economies' emission accounting methods and applications. CEADs provides the Energy and CO2 emission inventories for China and its 30 provinces and cities from 1997 to 2019.
5. https://population.un.org/wpp/
6. In 2015, when the Chinese government introduced the comprehensive two-child policy, the total fertility rate was 1.047, which became 1.580 and 1.300 in 2017 and 2020, respectively, with a short-term increase and then a decline in the population in the two and five years after the policy was implemented. According to Lan (2021) and Wang et al. (2019), we

think China will still be at a low fertility level in 2030, despite the introduction of the three-child policy and maternity leave extension and other fertility subsidies by the Chinese government in 2021.

7. In this paper, carbon emissions caused by household consumption activities are divided into direct emissions (coming from direct energy consumption) and indirect emissions (coming from household expenditure on goods and services which use energy and other resources as intermediate inputs) (Heltberg, 2005). For rural households, direct emissions include residential biomass/fossil fuel combustion, and private car emissions; for urban households, direct emissions only include fossil fuel combustion, and private car emissions (Zhao et al., 2019).
8. The list of Chinese industry sectors is provided in Supplementary Material shown in the Table.SM1.

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