Assessing the impacts of fertility and retirement policies on China's carbon emissions

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The gradual adjustment of fertility and retirement policies in China has social benefits in terms of coping with population aging. However, the environmental consequences of these policies remain ambiguous. Here we compile environmentally extended multiregional input-output tables to estimate household carbon footprints for different population age groups in China. Subsequently, we estimate the age-sex-specific population under different fertility policies up to 2060 and assess the impacts of fertility and retirement policies on household carbon footprints. We find that Chinese young people have relatively higher household carbon footprints than their older counterparts, due to differences in income by age group. Relaxing fertility policies and delaying retirement age are associated with an increase in population (and labour supply) and thus increases in household carbon footprints, with majority of these increases from the fertility side. These results may help policymakers understand interactions among those measures targeting population aging and climate action.

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Mitigating climate change and coping with population aging are both critical goals for China in achieving sustainable development[1,2]. As the world's largest carbon emitter, China aims to have a carbon emissions peak before 2030 and achieve carbon neutrality by 2060[3]. Nowadays, China is turning toward more sustainable development, with the deceleration of China's annual carbon emissions growth from 10% (2000–2010) to 2% (2010–2020)[4]. However, China remains an important driver of global carbon emissions due to its large population and growing household consumption over the past 20 years. To better explore the drivers of carbon emissions, the household carbon footprint (that is, the sum of direct and indirect carbon emissions of household consumption along the supply chain) has received increasing attention recently[1,5,6]. In addition, China is one of the most populous countries in the world, with a population that is nearing its peak and aging rapidly[7]. In 2020, China's total fertility rate (TFR) was only 1.3 births per woman, which is far below the replacement level (2.1) needed for a stable population[8]. It is projected that China's population will peak at 1.45 billion in 2029 (with a range of 1.42 to 1.48 billion from 2025 to 2035)[2,9], after which contraction is expected. At the same time, China is aging rapidly, with the proportion aged 65 years and above doubling from 7% in 2000 to 14% in 2020[10].

China has implemented a national strategy to address population aging, including relaxing fertility policies and delaying retirement age. In the 1970s, a one-child policy was introduced to curb population growth and alleviate severe poverty in China[2]. Following the introduction of this policy, the fertility rate decreased—the TFR declined sharply from approximately 5.8 in 1970 to 2.8 in 1979, and was thought to be approximately 1.6 in 2010—resulting in a rapidly aging population[7,11]. In October 2015, China's one-child policy was replaced with a two-child policy to counter the abovementioned trend[12]. The two-child policy has had a positive effect on the birth rate:

more than 10 million babies were born as a second child in China during 2013–2017, and the proportion of newborns who were second children in new births increased from 30% in 2013 to 50% in 2017[8]. However, a continuous fall in the number of women of childbearing age and a gradual decline in the effect of the two-child policy resulted in a drop in the number of new births during the period 2017–2020[8]. In May 2021, in an attempt to tackle demographic challenges, China further relaxed its fertility policy with a three-child policy, allowing all couples to have up to three children[13]. Additionally, many supportive measures have been implemented to address housing and educational costs, aiming to ease the financial burden of raising children[14]. On the other hand, the retirement age in China, 60 years for men and an average of 52.5 years for women (50 years for women workers and 55 years for women cadres)[2], is among the lowest in the world: the official retirement age for most developed countries is 65 years or even higher[15,16]. According to the Outline of the 14th Five-Year Plan (2021–2025), China called for the extension of the statutory retirement age in a gradual, flexible, and differentiated manner to reduce the negative impacts of population aging[17]. Changing fertility and retirement policies are likely to have great effects on the population age structure, and potentially influence household consumption and carbon footprints.

Many studies have estimated the effect of population aging on carbon emissions in China, finding that population aging may reduce[18], increase[19,20] or have nonlinear effects on carbon emissions[21]. However, no study has assessed the impacts of policies that address population aging—including fertility (particularly the three-child policy) and retirement policies—on carbon emissions or household carbon footprints. Thus, we aim to address this gap in the literature. Here, we first investigate age-based household carbon footprints in China and its provinces by compiling a global multiregional input-output (MRIO) table and employing a large-scale household survey. We further estimate the age distribution of the population in China and its provinces up to 2060 by using a cohort-component method and then assess the impacts of fertility and retirement policies on household carbon footprints.

Age-based household carbon footprint

The total and per capita household carbon footprint varies greatly across China's provinces. Eastern provinces (which have large populations) tend to have higher total carbon footprints (particularly in Shandong, Guangdong and Jiangsu, Fig. 1a and Supplementary Table 1). Northwestern provinces (with high carbon intensity) and eastern provinces (with high household consumption) tend to have higher per capita carbon footprints. For example, Ningxia (a northwestern province) had the highest per capita carbon footprint (6.68 tons of CO_2 per capita (tCO_2/cap)) in 2017, six times that of Sichuan (a southwestern province) at 1.05 tCO_2/cap (Fig. 1c). Taking China as a whole, its per capita carbon footprint is much lower than that of developed countries. Specifically, the Chinese per capita carbon footprint was 2.34 tCO_2/cap in 2017, approximately one-sixth of that in the United States (US) (13.37 tCO_2/cap) and one-third of that in Japan (6.29 tCO_2/cap) and the United Kingdom (UK) (6.03 tCO_2/cap), but similar to that in Mexico (2.31 tCO_2/cap) and almost three times that in India (0.78 tCO_2/cap) (Fig. 1b).

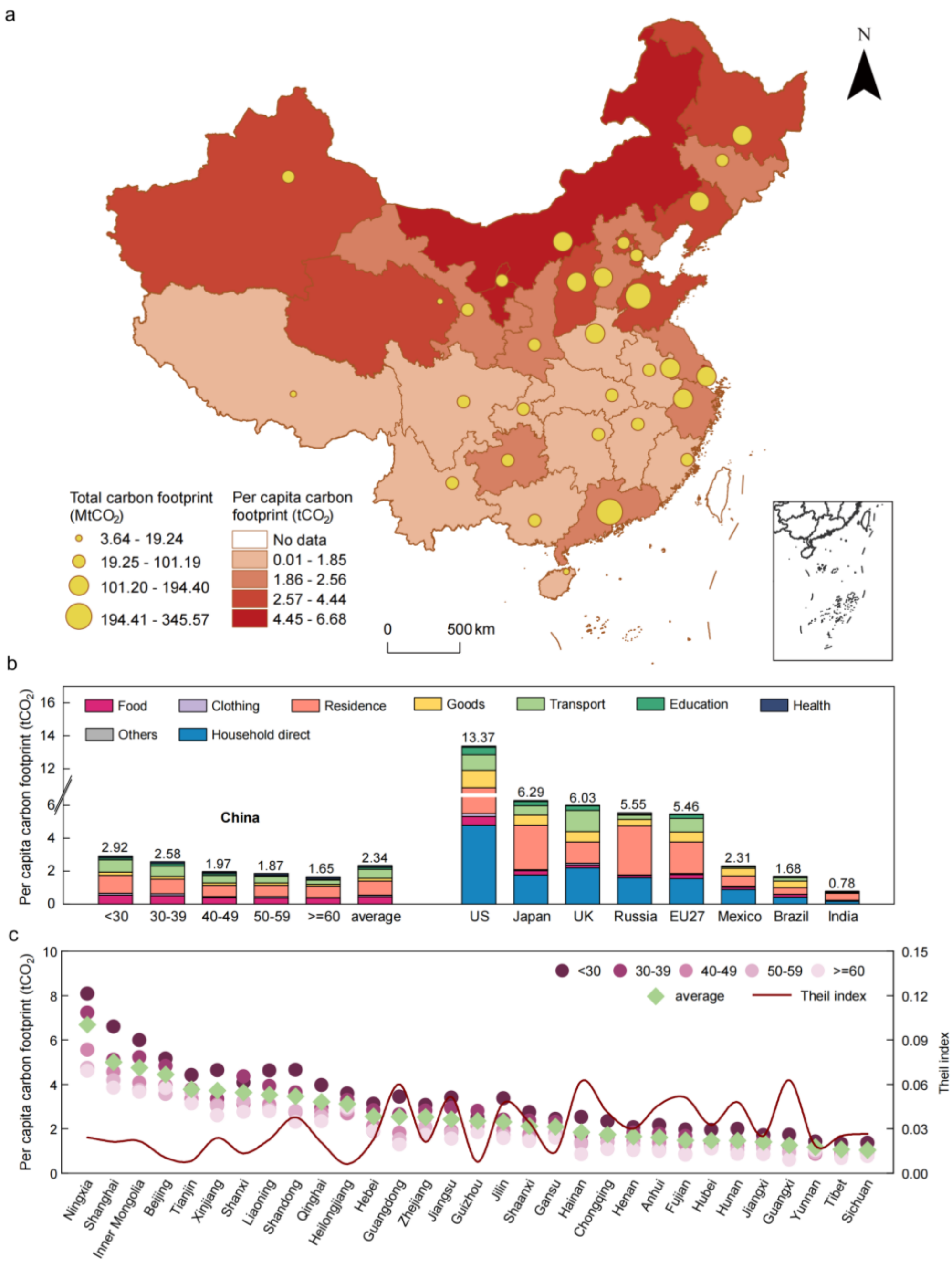

Fig. 1 Household carbon footprint in 2017. a, Total and per capita household carbon footprints for 31 of China's provinces. The cut-out of islands is the South China Sea Island. The data for the base map was derived from the Resource and Environment Data Cloud Platform (https://www.resdc.cn/Default.aspx) **b**, Per capita household carbon footprints for eight expenditure categories for China's different age groups and for international comparisons. We calculate the per capita household carbon footprints of the US, Japan, UK and other countries using the data from the EXIOBASE database (https://www.exiobase.eu/index.php)[36]. **c**, Per capita household carbon footprints and the Theil index for 31 of China's provinces. Provinces are sorted according to their average value of per capita carbon footprints.

In China, carbon footprint is inversely correlated with age. Young Chinese people (<30 years) have relatively higher household carbon footprints than those of middle-aged (30–59 years) and older groups (≥60 years). The observed results are quite different from those of developed countries, where older people are estimated to have higher carbon footprints[5,22]. The difference in carbon footprint distribution by age, between developed and developing countries, is mainly due to the difference in wealth and income across age groups. In wealthier developed countries, older people tend to be wealthier than younger people, thus can afford a higher level of consumption and tend to have higher carbon footprints[23]. In developing countries (for example, China), young people have higher incomes than older people (by 57%, according to our individual data), associated with higher consumption and carbon footprints (by 69% and 77%, respectively).

After examining the expenditure categories in greater detail, it is evident that the top two contributors to the average carbon footprints of all age groups are consumption related to residence and transport (Fig. 1b and Supplementary Note 1). There are some meaningful differences across age groups not only absolutely but also proportionally (Supplementary Fig. 1), representing their differences in lifestyle choices and life stage[24]. For residence, the young people have the highest carbon footprints (1.08 tCO_2/cap in 2017) and contribute to the largest share of total residence-related footprints (46%), majority of which are from renting or purchasing a house[18] and using electronic devices[25]; the older people have the highest proportional share of resident-related carbon footprints (41%), as they might be accustomed to using traditional energy-intensive devices for heating and cooking (such as Kang and stove)[26] and spend long time staying at home (and thus have large household energy consumption)[27]. For transport, the young people's transport-related footprints are the highest both absolutely (accounting for 50% of the total transport-related footprints by all groups) and proportionally (accounting for 25% of their own total footprints), which are largely from commuting to work[28], and a few big trips each year (e.g., from their workplace to their hometown)[29]. Moreover, the absolute and proportional per capita carbon footprints related to clothing, goods and transport have decreased gradually with age; however, health-related carbon footprints have increased with age, as have education-related carbon footprints until the individual is in their 30s to 40s, after which it decreases (Fig. 1b). We further explore how unevenly per capita carbon footprints are distributed among different age groups using the Theil index. The higher the index value is, the greater the inequality in terms of the distribution between age groups. In 2017, the Theil index for clothing, transport and education-related carbon footprints was the highest, at 0.06, three times the average value of expenditure categories (0.02) (Supplementary Table 3).

The above patterns also generally hold in all Chinese provinces: young people have a relatively higher per capita carbon footprint than that of older people (by 1.21 to 2.93 times), and consumption patterns vary over the life course (for example, the young age group have larger clothing-, goods- and transport-related carbon footprints, and the middle-aged group generate most of the education-related carbon footprints). Regarding the Theil index, eastern provinces (for example, Guangdong and Hainan), central provinces (for example, Anhui and Hunan) and southwestern provinces (for example, Guangxi and Chongqing) have higher values than northwest provinces (for example, Inner Mongolia and Gansu) (Fig. 1c and Supplementary Table 5).

Between 2012 and 2017, China's average per capita carbon footprint increased by 17%, from 2.00 tCO_2/cap in 2012 to 2.34 tCO_2/cap in 2017. In particular, young people experienced larger increases (30%) than did middle-aged (12%) and older people (8%)

during this period, meaning that the difference in carbon footprints across age groups grew (with an increase in the Theil index from 0.01 to 0.02) (Supplementary Tables 3-4). At the provincial level, the average per capita carbon footprint and Theil index increased in most provinces, mainly because of the growing carbon footprint of the young generation that ranges from a 10% increase (Yunnan) to a 211% increase (Ningxia) from 2012 to 2017 (Supplementary Tables 5-6).

Fertility and retirement policies

To evaluate the impacts of fertility and retirement policies on China's household carbon footprints, we first estimate the population of China and its 31 provinces up to 2060 by age (0-100+) and sex (male and female) under different fertility policies: previous two-child policy, the latest three-child policy, and the assumed "replacement-level" policy (with fertility rate reaching the replacement level of 2.1[30]). Then, we explore the potential effect of these fertility policies and their combination with retirement delay policies on the household carbon footprints (Supplementary Data 1-6). Here, we use retirement age as the threshold to classify older people and assume that such a retirement delay policy affects only the population age structure[31].

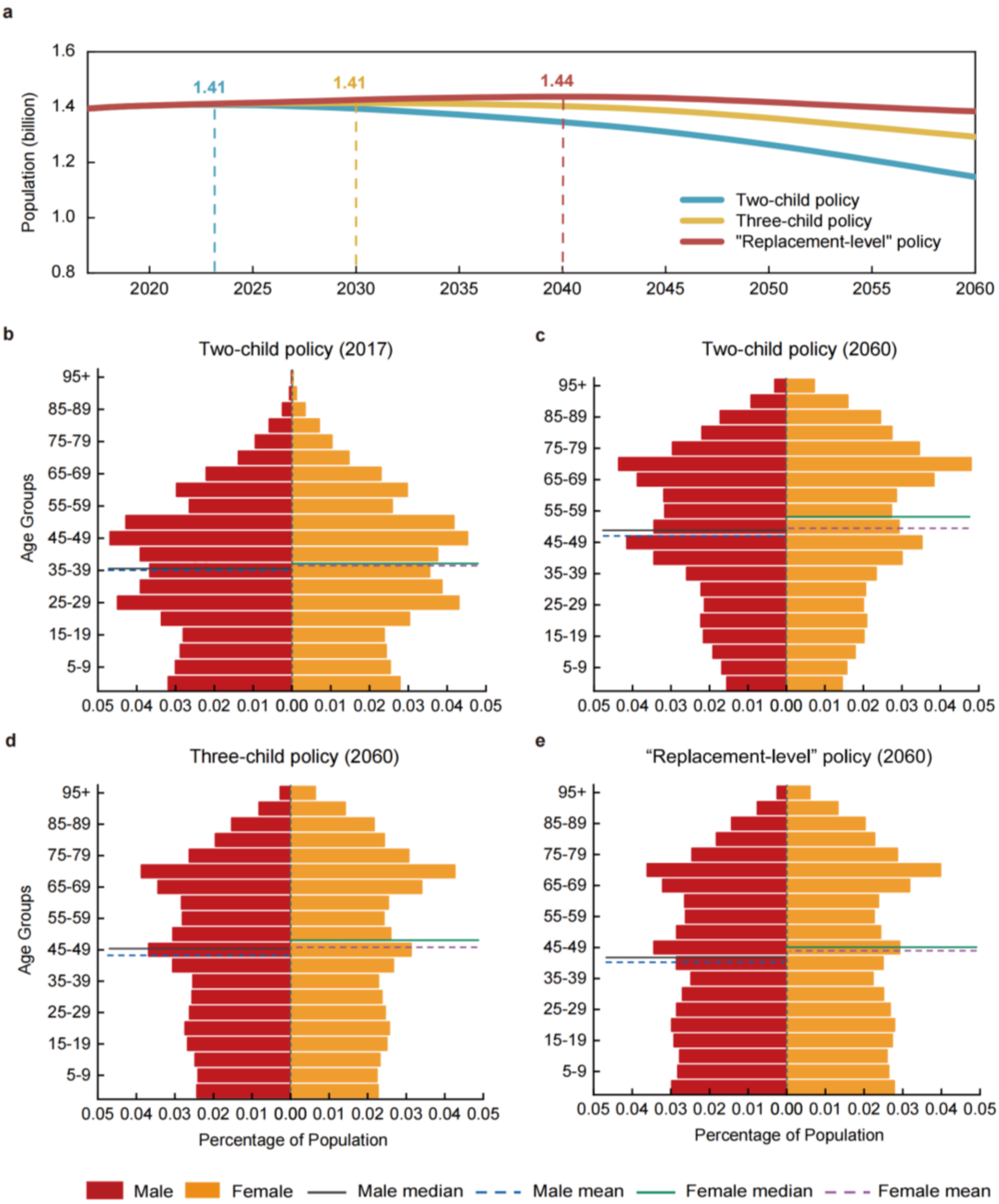

Fig. 2 Population changes and population age structure in China under different fertility policies. **a**, Population changes at the national level from 2017 to 2060 under the two-child policy, three-child policy and "replacement-level" policy. **b**, Population pyramid for males and females by age in 2017. **c-e**, Population pyramids for males and females in 2060 under the two-child policy, three-child policy and "replacement-level" policy, respectively.

We find that the above two kinds of policies will both pose a challenge to carbon emission mitigation. As for fertility policies, they mainly affect the population in terms of size and structure, and thus affect the carbon footprints. In specific, our results show that the Chinese population will reach a peak in 2023 (1.41 billion), 2030 (1.41 billion) and 2040 (1.44 billion) under the two-child, three-child and "replacement-level" policies, respectively (Fig. 2a). From 2017 to 2060, the total population will decrease from 1.40 billion to 1.15 billion (two-child policy), 1.30 billion (three-child policy) and 1.39 ("replacement-level" policy), which means the population differences are 12-20% under different policies (Fig 2a); the mean population age of a person will increase from 38 years to 51 years (two-child policy), 47 years (three-child policy) and 45 years ("replacement-level" policy), thus, the percentage of older people will increase from 17% to 42% (two-child policy), 37% (three-child policy) and 35% ("replacement-level" policy) (Fig. 2b-e). Due to relaxing fertility policies, there is an 8-12% increase in per capita footprints (the blue, yellow and red solid curves, Fig 3 (China)), and the total footprints in China are likely to be 21-35% higher.

The above effects also hold at the provincial level, but the extent of the impact varies (Supplementary Note 2). The provinces with higher Theil index are more sensitive to changes in fertility policies (in terms of larger changes in per capita carbon footprints; Supplementary Fig. 2). For example, in Inner Mongolia, which has the highest Theil index in 2060, changing fertility policies are projected to increase its average per capita carbon footprint by 18-28% (Fig. 3, Inner Mongolia). In comparison, in Guizhou, which has the lowest Theil index in 2060, changing fertility policies are projected to increase its average per capita carbon footprint by only 4-5% (Fig. 3, Guizhou).

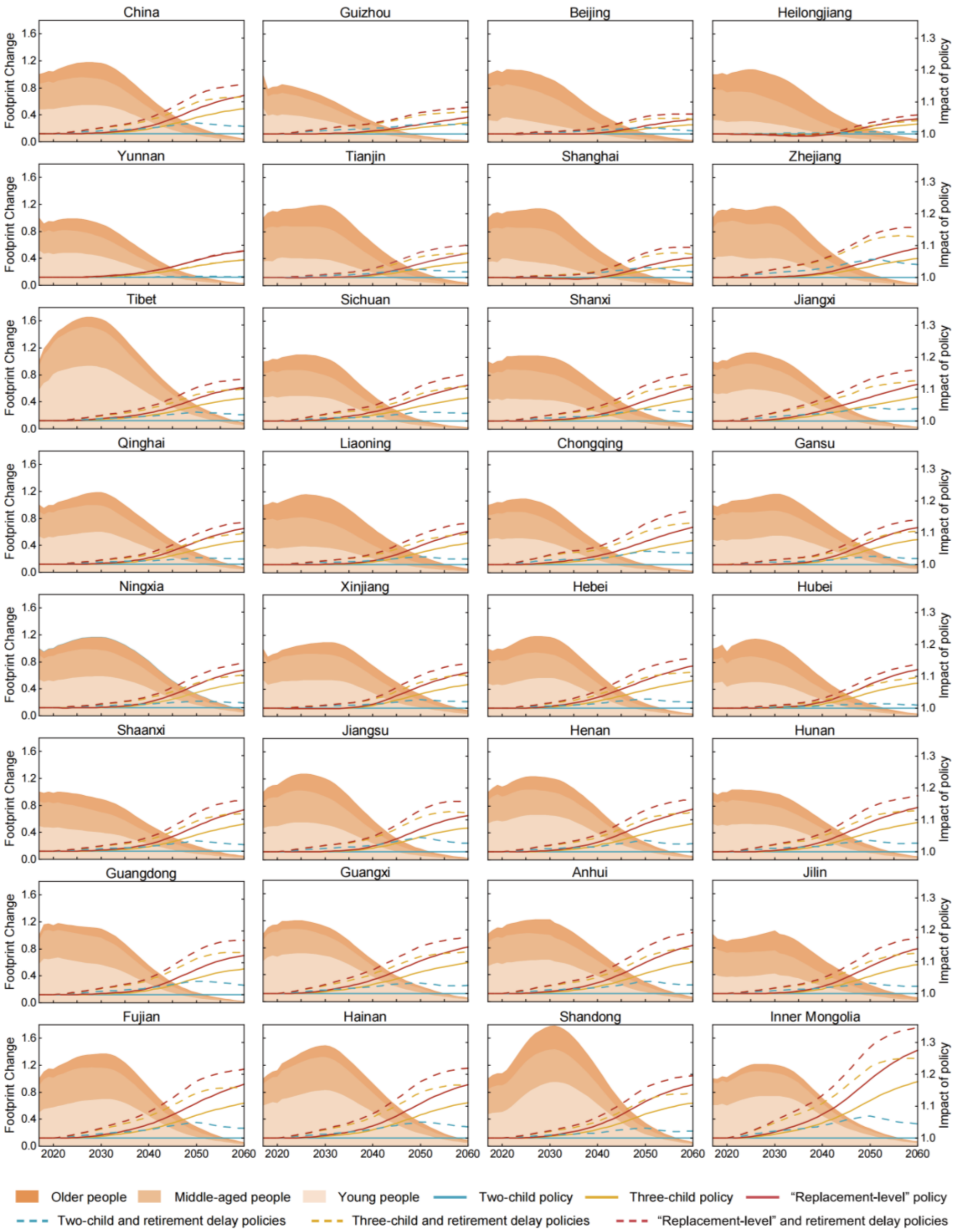

Fig. 3 The impacts of fertility and retirement policies on carbon footprints in China and its provinces. Changes in total household carbon footprints under the two-child policy compared with the 2017 level (left *y* axis); Changes in per capita household carbon footprints under different policies compared with the two-child policy (right *y* axis). Provinces are sorted according to the value of the Theil index in 2060, from the lowest value of the Theil index in Guizhou to the highest value in Inner Mongolia.

Fertility policies in combination with retirement delay tend to further increase the carbon footprint in China. Notably, most of the carbon footprint increase comes from relaxing fertility policies (increasing total (per capita) carbon footprint by 21-35% (8-12%) for 2060), while delaying retirement policy has far smaller impacts (by only 2-3% (2-3%)). The fertility policies in combination with retirement delay are projected to have greater impacts on those provinces with higher Theil index, which is similar to the impacts of fertility policy alone (Supplementary Fig. 3). Moreover, when focusing only on the impact of the retirement delay policy, it can be found that the impact tends to be greater in provinces with large discrepancies in per capita carbon footprints between middle-aged and older people (Supplementary Fig. 4). For example, in Inner Mongolia, which has the highest discrepancies in per capita carbon footprints between middle-aged and older people, the retirement delay policy is projected to increase its average per capita carbon footprint by approximately 5% (Fig. 3, Inner Mongolia). In comparison, in Yunnan, which has the lowest discrepancies in per capita carbon footprints between these two age groups, the retirement delay policy is projected to increase its average per capita carbon footprint by less than 0.10% (Fig. 3, Yunnan).

Discussion

Our results show that Chinese young people have relatively higher per capita household carbon footprints compared to older people. The big driver behind this headline result might be differences in income, which leads to differences in household consumption and then carbon footprints (Supplementary Note 3); The results differ from those of existing research on developed countries, which have concluded that older people tend to have higher per capita carbon footprints compared to their younger counterparts.

Such a distinctive pattern is mainly due to the difference in income and consumption of China's older people from other developed countries[23].

Our analysis highlights residence and transport are the two largest contributors to carbon footprint, and there is variability in them across age groups. Notably, the assumptions about how these two factors might evolve as the population ages will have a meaningful impact on our projection results, and we conducted an uncertainty analysis assuming that both residence and transport-related carbon footprints will still be a feature of today's young group as they age under different assumptions (i.e., follow Chinese forebears' or Western peers' patterns; Supplementary Note 4). In particular, the residence-related carbon footprint from the young group will remain high as they move into the next age cohort, if following Chinese older people's specific patterns (e.g., spending longer time at home[27]), or will even grow if following Western peers (with more electronics and devices plugged in residence[32]). In addition to these proportional differences, our overall results for household carbon footprints and the impacts of fertility and retirement policies do not change much (Supplementary Figs. 14-16).

As for policies, our result shows that relaxing fertility policies and delaying retirement age will boost the population (and labour supply), and then lead to increases in total and per capita household carbon footprints, most of which come from the fertility side. We do not interpret the result to imply that such policies should be avoided to reduce environmental pressure[33]. Rather, our result provides evidence of interactions between the policies targeting population aging and climate change, highlighting the importance of synergising these two types of policies. Although fertility and retirement policies may pose a challenge to China's carbon emission mitigation, these policies (particularly those for retirement delay) can considerably lower the dependency ratio and thus improve the demographic dividend (Supplementary Note 2).

In addition, we find that the provinces with large discrepancies in carbon footprints across age groups are more sensitive to changes in fertility and retirement policies. This result therefore highlights the potential of emission mitigation through reducing the discrepancy in carbon footprints across age groups. Although consumption patterns and lifestyles are different across age groups due to their various requirements over the life course, the discrepancy in carbon footprints between age groups can be narrowed by reducing income and consumption inequality and encouraging greener consumption. Specifically, we suggest that the greatest potential leverage from lifestyle changes will result from the targeting of young people by promoting green consumption (such as adopting public transportation like buses, subways and shared bikes as well as purchasing high-quality and long-lasting goods[6]).

China's Nationally Determined Contributions acknowledges the difficulty of achieving carbon neutrality by 2060. Therefore, it is worth exploring what might happen if this target is not reached. According to related research and official plans[34,35], we consider a set of policy scenarios assuming that China achieves a 60%, 70%, 80%, 90% or even 100% reduction in carbon intensity (Supplementary Note 5). Our results show that there are fewer emissions in the future with a more aggressive target, and achieving 60%, 70% and 80% reductions from 2017 to 2060 (instead of the 90% target) is estimated to nearly quadruple, triple and double, respectively, the overall emissions in all scenarios (Supplementary Fig. 17). Furthermore, there is an interaction between the policy proposals and emissions targets—the effects of fertility and retirement policies will somewhat aggravate the difficulty of achieving carbon neutrality by 2060, and such policy effects will increase if the official target is not reached. Nevertheless, our major findings regarding structural patterns of carbon footprints (across age groups) and changing trends (due to different fertility and retirement policies) do not change very much (Supplementary Fig. 17). This finely verifies the accuracy of our estimates, which might little rely on this official target.

Overall, this study provides evidence of interactions between climate actions and demographic policies in China. We find that relaxing fertility policies and delaying retirement age are associated with an increase in total and per capita household carbon footprint. Our results add to the literature on climate change and population, which has typically evaluated the effect of demographic structure on emissions without considering the independent effect of population policy (especially in China) that contributes to bringing about the change in demographic structure in the first place. Our results also offer insights for developing countries undergoing economic and demographic transformation for more sustainable development.

Methods

Household carbon footprint and MRIO analysis. Carbon footprints measure the greenhouse gas emissions generated in the value chains connected with the products consumed in the form of final demand[1]. In this study, we consider CO_2 emissions and focus on household consumption in China. Household carbon footprints come from household consumption activities, including direct energy use (that is, direct carbon footprints), for example, during cooking, heating and driving, and the consumption of goods and services, which are produced by using energy as intermediate inputs (that is, indirect carbon footprints).

Indirect household carbon footprints are calculated based on input-output analysis. Wassily Leontief developed the theoretical framework of the input-output analysis in the late 1930s[37]. The fundamental linear equation of MRIO model can be shown as:

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^r \end{pmatrix} = \begin{pmatrix} \mathbf{A}^{1,1} & \mathbf{A}^{1,2} & \cdots & \mathbf{A}^{1,s} \\ \mathbf{A}^{2,1} & \mathbf{A}^{2,2} & \cdots & \mathbf{A}^{2,s} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{r,1} & \mathbf{A}^{r,2} & \cdots & \mathbf{A}^{r,s} \end{pmatrix} \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^r \end{pmatrix} + \begin{pmatrix} \sum_s \sum_t \mathbf{y}_t^{1,s} \\ \sum_s \sum_t \mathbf{y}_t^{2,s} \\ \vdots \\ \sum_s \sum_t \mathbf{y}_t^{r,s} \end{pmatrix}, \quad (1)$$

where $\mathbf{x}^r$ denotes the total output for each sector in province *r*; $\mathbf{A}^{r,s}$ is the technical coefficient matrix, which reflects the input requirement by sector in province *r* to produce one unit of output of the sector in province *s*; and $\mathbf{y}_t^{r,s}$ is the final demand vector of category *t*, including household consumption (*t*=1), government consumption (*t*=2), capital investment(*t*=3), and exports(*t*=4). Equation (1) can also be abbreviated as follows:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y}, \quad (2)$$

where $\mathbf{x}$, $\mathbf{A}$ and $\mathbf{y}$ are the block matrix or vector in equation (1); then, we can obtain the following:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}, \quad (3)$$

where $\mathbf{I}$ is the identity matrix, and $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix.

Indirect carbon footprints are calculated by introducing carbon intensity (that is, carbon emissions per unit of economic output) by sector:

$$\mathbf{e} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{y}}, \quad (4)$$

where $\mathbf{f}$ is the carbon intensity vector, and the carbon emissions used to produce $\mathbf{f}$ are from the China Emission Accounts and Datasets (CEADs). Sector-specific indirect carbon footprints $\mathbf{e}_t^s$ consumed by final demand *t* in province *s* can be calculated as follows:

$$\mathbf{e}_t^s = \mathbf{f}(\mathbf{I}-\mathbf{A})^{-1}\hat{\mathbf{y}}_t^{r,s}. \tag{5}$$

Notably, there are 45 sectors in the CEADs (regarding emission data), whereas 42 sectors in Chinese MRIO tables[38]. Due to data availability, we mapped 45 sectors to 42 sectors to calculate household carbon footprints and then aggregated to eight expenditure categories for further analyses: food, clothing, residence, goods, transport, education, health and others[6]. Specifically, goods include household facilities and durables; transport contains transport and communications; education refers to education, culture and entertainment[39].

For direct household carbon footprints, the emission data are obtained from the CEADs, where energy-related emissions are listed separately. We allocate the emissions from the energy use of coal and natural gas to the direct household carbon footprints of residence, and oil emissions are for the category of transport[1,40].

Finally, the total carbon footprint from household consumption can be combined as follows:

$$\mathrm{ce}_{l.t}^s = \sum_r e_{l,t}^{r,s} + \mathrm{de}_{l,t}^s, \tag{6}$$

where $\mathrm{ce}_{l,t}^s$ and $\mathrm{de}_{l,t}^s$ are the total and direct carbon footprints, respectively, of expenditure categories l in province r for household consumption (t=1). $e_{l,t}^{r,s}$ is the indirect household carbon footprint of expenditure categories l in province r caused by household consumption in province s.

Tracing household carbon footprints to specific age groups. In this section, we trace the household carbon footprints to various age groups according to their expenditure in terms of consuming products. The consumption data used in this study are obtained from a large-scale household survey (China Family Panel Studies (CFPS))[41], and the age-based population data are from the China Provincial Statistical Yearbooks. Notably, consumption data in a household survey are usually collected at the household level and need to be allocated to per capita consumption for further age-based analysis. In this study, we use the Organisation for Economic Co-operation and Development (OECD) modified equivalence scale to distinguish children from adults (including head of household and other adults) in calculating per capita consumption[42,43], rather than simply assuming equal weights on all household members, as has typically been done in previous studies. In particular, the head of household is weighted by 1, each additional adult aged 14 years and older is weighted by 0.5, and each child below 14 years is weighted by 0.3. It is worth exploring the sensitivity of our results to weight choice, thus we also run our model with a per capita calculation and weight-adjusted calculation (Supplementary Note 6), and the associated results show that using a different weight choice would change the structural pattern of carbon footprints across age groups, but would not change the national average or total (Supplementary Fig. 18).

The introduction of the CFPS dataset allows for the downscaling of household consumption into age cohorts:

$$y_{l,q}^{r,s} = c_{l,q}^{s} \times p_{q}^{s} \times \frac{y_{l}^{r,s}}{y_{l}^{s}}, \tag{7}$$

where $y_{l,q}^{r,s}$ represents the household consumption of sector l in province r caused by age group q in province s. $c_{l,q}^{s}$ represents the per capita household consumption, which is calculated by using OECD modified equivalence scale. p_q^s denotes the population, derived from the China Provincial Statistical Yearbooks. $y_l^{r,s}/y_l^s$ denotes the proportion of household consumption for each sector that is finally produced in province r and consumed in province s (obtained from the MRIO model). Thus, the age-based indirect household carbon footprint can be obtained by the following:

$$e_{l,q}^{r,s} = k_l^{r,s} \times y_{l,q}^{r,s}, \tag{8}$$

where $e_{l,q}^{r,s}$ is the indirect household carbon footprint, and $k_l^{r,s}$ denotes the indirect carbon emissions per unit of household consumption:

$$k_l^{r,s} = \frac{e_l^{r,s}}{y_l^{r,s}}. \tag{9}$$

For households, the direct carbon footprint of province s can be split into age group q as follows:

$$\mathrm{de}_{l,q}^{s} = \theta_{l,q}^{s} \times \mathrm{de}_{l}^{s}, \tag{10}$$

where $\mathrm{de}_{l,q}^{s}$ denotes the direct carbon footprints from the household consumption for the products of sector l by age group q in province s. $\theta_{l,q}^{s}$ is the proportion of household consumption by age group q in all age groups, for sector l in province s:

$$\theta_{l,q}^{s} = \frac{c_{l,q}^{s} \times p_q^s}{\sum_q (c_{l,q}^{s} \times p_q^s)}. \tag{11}$$

Finally, the total household carbon footprint by age group can be calculated by combining indirect and direct carbon footprints:

$$\mathrm{ce}_{l,q}^{s} = \sum_r e_{l,q}^{r,s} + \mathrm{de}_{l,q}^{s}, \tag{12}$$

where $\mathrm{ce}_{l,q}^{s}$ represents the province- and sector- specific total household carbon footprints, and the associated per capita carbon footprints can be further calculated by dividing them by the population.

Theil index. In this study, we use the Theil index to measure how unevenly household carbon footprints are distributed across age groups[44]. The Theil index ranges from zero to one, with a higher value indicating greater inequality of distribution across age groups. The Theil index is calculated by the following:

$$T = \sum_q d_q \ln(\frac{d_q}{w_q}), \tag{13}$$

where d_q is the household carbon footprint share of age group q on the total and w_q is a weighting variable (that is, share of population) for age group q, which can be calculated as follows:

$$d_q = \frac{\text{ce}_q}{\sum_q \text{ce}_q}, \tag{14}$$

$$w_q = \frac{P_q}{\sum_q P_q}. \tag{15}$$

Projection. We conduct projection similarly based on the input-output analysis, introducing the year index n to the original form of equation (4):

$$\mathbf{e}_{l.q,n}^{s,v} = \mathbf{f}_{l,n}^{s}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{y}}_{l,q,n}^{s,v}, \tag{16}$$

where $\mathbf{e}_{l,q,n}^{s}$ is the total household carbon footprints for the year n under the policy scenario v, $\mathbf{f}_{l,n}^{s}$ is the carbon intensity, $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix, and $\mathbf{y}_{l,n,q}^{s,v}$ is the household consumption.

Carbon intensity. Carbon intensity is modelled following the *China's Long-Term Low-Carbon Development Strategies and Pathways: Comprehensive Report*[35], as the planned annual changing rates listed in Supplementary Table 12. Using these planned annual changes (as well as the linear interpolations around them), we can project future carbon intensities based on 2017 baseline (Supplementary Note 5).

Household consumption. The household consumption is calculated by multiplying per capita household consumption with population. We model per capita household consumption, under the assumption that young people would become much like their forebears in terms of following the income effect of consumption and concomitant emissions:

$$\log(y_{q,l}) = a_{q,l} + b_{q,l}\log(m_q), \tag{17}$$

where y indicates per capita consumption, and m denotes per capita income, which is projected based on the long-term GDP forecast under the SSP2 scenario (Shared Socioeconomic Pathway Middle of the Road scenario)[45,46]. The coefficient b is the income elasticity of consumption (Supplementary Note 3), which is estimated positive in all cases based on our individual data and thus suggests that increases in per capita incomes result in greater consumption (Supplementary Table 8). We project that the level of consumption from all age groups will become higher along economic development, while the structure of expenditure otherwise will not greatly change (Supplementary Fig. 8).

Population. We estimate the age-sex-specific population from 2020 to 2060 using a cohort-component method—a dominant method of population projection[47]. The basic demographic balancing equation is as follows:

$$P(N) = P(0) + B(0,N) - D(0,N) + G(0,N), \tag{18}$$

where $P(N)$ is the population at a given time, $P(0)$ is the population at the start of the interval, and $B(0, N)$, $D(0, N)$ and $G(0, N)$ are the number of livebirths, deaths and net migration, respectively, during the interval.

The cohort-component method of population projection extends the above demographic balancing equation to estimate age-sex-specific populations based on a series of related factors, such as age-specific fertility rates, sex ratio at birth, age-sex-specific mortality rates, and net migration (Supplementary Note 7).

The impacts of fertility and retirement policies. In this study, we explore the potential effects of fertility policy and its combination with retirement policy on the household carbon footprint. Specifically, there are three fertility policies, namely the two-child policy, the three-child policy, and the assumed “replacement-level” policy. As for the retirement policy, we assume that the retirement age (as well as the threshold for older people in this study) is extended linearly from the Chinese current levels (i.e., 60 years for men and 55 years for women[2]) in 2020 to the age prevailing in developed countries (i.e., 65 years for both men and women) in 2050, and remain constant afterwards (Supplementary Table 7)[31]. The fertility and retirement policies would affect the population and economy, thereby impacting the household consumption and carbon footprint in equation (16).

The impact on population. The fertility and retirement policies affect the population in terms of size and structure, respectively. In particular, we project the population under different fertility policies with different fertility rates following the cohort-component method. As for the retirement policy, we use retirement age as the threshold to classify older people, such that the retirement policy affects the population age structure[31].

The impact on the economy. Fertility and retirement policies would have impacts on the supply of labour and the potential levels of the economy[48]:

$$\Delta GDP_n^{s,v} = \sum_q \sum_g \Delta labourrate_{q,g,n}^{s,v} \times ratio^s, \tag{19}$$

where $\Delta GDP_n^{s,v}$ is the changes in GDP under policy v (where GDP generally reflects the potential level of economy and can be used as the proxy for income[45,46]), $\Delta labourrate_{q,g,n}^{s,v}$ is the changes in labour force participation rate for gender g, and $ratio^s$ is the ratio of labour remuneration to GDP.

For fertility policies, we project the population with different fertility rates, then estimate the associated labour force participation rates by the ratio of working population to total population, and finally compute the changes of labour force participation rate across policies.

For retirement policies, the change in labour force participation rate is the difference between the counterfactual labour force participation curve (under the new retirement policy) and the actual one (under the current retirement policy). The actual curve is estimated by the ratio of working population to total population, using the data derived from 2020 Chinese Census. For the counterfactual curve, the ordinary least square method is employed to quantify the impact of the new retirement age on labour force participation rate[48]:

$$labourrate_{q,g}^{s} = \beta_0 + \beta_1 D(age_{q,g}^{s}) + \beta_2 age_{q,g}^{s} + \varepsilon_{q,g}^{s}, \tag{20}$$

where $labourrate_{q,g}^{s}$ represents the labour force participation rate, $age_{q,g}^{s}$ denotes the lower bound for the corresponding age group (e.g., *age* = 50 for the 50-54 age group), and the dummy variable $D(age_{q,g}^{s})$ indicates whether the corresponding age group reach the retirement age ($D = 1$) or not ($D = 0$). The coefficient β_1 measures the extent to which the new retirement age affects the labour force participation rate. In building the counterfactual labour force curve, the labour force participation rate changes with age, i.e., following the trend of actual labour force participation curve below the current retirement age, dropping with the magnitude of β_1 at the current retirement age, and returning to and holding the actual trend at and above, respectively, the delated new retirement age.

The causality of policy to carbon footprint. Supplementary Fig. 6 illustrates a causal chain from policy to carbon footprint. In specific, the fertility and retirement policies effect the population (in terms of size and structure, via equation (18)) and the supply of labour (in terms of labour force participation rate, via equation (20)), then effect the economy (in terms of GDP and household income, via equation (19)) and per capita consumption (via equation (17)), and result in changes in household carbon footprints (via equation (16)).

Data description. In this study, the China MRIO tables for 2012 and 2017 are compiled using a gravity model based on the single regional input–output tables for Chinese provinces, the detailed information can be found in our previous work[38,49]. The carbon emission inventory can be sourced from the CEADs, the household consumption expenditure data between age groups are obtained for the CFPS dataset[41], and the age-sex-specific demographic data in China and its 31 provinces are based on the 2020 Chinese Census. Moreover, the data in the MRIO tables and the household expenditure data in the CFPS are all calculated based on the 2012 price[50].

The CFPS, developed by Peking University, is a nearly nationwide and comprehensive social survey and aims to serve the research needs regarding various current social phenomena in China[41]. The main variables used in this study are as follows: a) the size of the household (single, two, three or more persons), b) the number of children (<14) and adults (≥14), c) the geographic classification of the household (31 provinces), d) the expenditures of eight expenditure categories (food, clothing, residence, goods, transport, education, health and others) of the household, e) household income, f) the head of the household (the person who is in charge of the household), and g) the age of all household members.

Uncertainties and limitations. There are several uncertainties and limitations in the calculations of this study. First, the economic data (such as those on national accounts and interregional trade) and carbon emission inventories are the main uncertainties of this study. Previous research reported that the uncertainty of consumption-based carbon accounts at the national level is in the range of 5-15% and 2-16%[51]. Moreover, the MRIO analysis has also been validated by our previous calculations[1,38]. Second, the input-output analysis enables to estimate the carbon footprints for the “average” products, and it is often criticized for using too many sector aggregations[52]. Due to data availability, we have to use only 42 categories, of which “transport” is one (with no distinction between private, public, etc) and so as “food” (with no detailed information on diet shift), and if provincial input-output tables for more than 42 sectors is available for China, we will improve our method by using more expenditure categories to avoid the significant bias due to using too aggregate analysis. Third, due to data availability, we assume that the footprint intensities (carbon emissions per unit of consumption expenditure, in equation (8)) on category are the same across the age groups, which introduces uncertainty; however, capturing the differences in carbon intensity between age groups is meaningful to improve our projection. Fourth, we only consider CO_2 emissions, and including other greenhouse gas emissions is an important issue for the future research if related data for Chinese provinces are available. Fifth, most SSP data is provided in GDP terms (which are net of trade), and long-term scenarios of consumption can be substantially impacted by changes in trade terms; thus, improving the projections (particularly for future income and consumption using appropriate proxies) is an important direction to improve our work[45]. Sixth, we keep intermediate technology constant in the input-output matrix due to data availability, and capturing the structural change in the economy over a long time-horizon is an important direction to improve our research[53]. Seventh, the assumption for future carbon intensity has impacts on results (Supplementary Note 5), and introducing defensible long-term plans (if available for China) is an important direction to improve our method[54]. Finally, there is tremendous uncertainty about both the future of fertility and retirement in China

(Supplementary Note 8), and there still needs a lot of work to adequately set out such uncertainty (as well as the linkages to emissions) for the future research.

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Author contributions

L.T., J.L. and Z.M. designed the study. J.Y., X.S. and L.C. collected data and performed calculations. L.T., J.Y., J.Z. and L.L. prepared the manuscript. All authors (L.T., J.Y., J.Z., X.S., L.C., K.H., L.L., J.L., W.C., S.W., P.D. and Z.M.) participated in performing the analysis and contributed to writing the manuscript. L.T. and Z.M. coordinated and supervised the project.

Competing interests

The authors declare no competing interests.

Data availability

All the source data used in this study are publicly available and open access. The carbon emission inventory in China is sourced from the CEADs: http://www.ceads.net/, the household survey is sourced from CPFS: https://opendata.pku.edu.cn/dataverse/CFPS, and the age-sex-specific demographic data in China is sourced from 2020 Chinese Census: https://www.stats.gov.cn/sj/pcsj/rkpc/7rp/indexch.htm.

Code availability

The codes developed for the analyses and to generate results are available from the corresponding author on reasonable request.