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Rising carbon inequality and its driving factors from 2005 to 2015

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ABSTRACT

Carbon inequality is the gap in carbon footprints between the rich and the poor, reflecting an uneven distribution of wealth and mitigation responsibility. Whilst much is known about the level of inequality surrounding responsibility for greenhouse gas (GHG) emissions, little is known about the evolution in carbon inequality and how the carbon footprints of socio-economic groups have developed over time. Inequality can be reduced either by improving the living standards of the poor or by reducing the overconsumption of the rich, but the choice has very different implications for climate change mitigation. Here, we investigate the carbon footprints of income quintile groups for major 43 economies from 2005 to 2015. We find that most developed economies had declining carbon footprints but expanding carbon inequality, whereas most developing economies had rising footprints but divergent trends in carbon inequality. The top income group in developing economies grew fastest, with its carbon footprint surpassing the top group in developed economies in 2014. Developments are driven by a reduction in GHG intensity in all regions, which is partly offset by income growth in developed countries but more than offset by the rapid growth in selected emerging economies. The top income group in developed economies has achieved the least progress in climate change mitigation, in terms of decline rate, showing resistance of the rich. It shows mitigation efforts could raise carbon inequality. We highlight the necessity of raising the living standard of the poor and consistent mitigation effort is the core of achieving two targets.

1. Introduction

Social equity (SDG10) and climate change mitigation (SDG13) are important targets of the sustainable development goals (SDGs), but achieving both goals is difficult (Rao and Min, 2018). Recent studies have demonstrated that the distribution of greenhouse gas (GHG) emissions is also highly unequal. (Bruckner et al., 2022; Hubacek et al., 2017a, Hubacek et al., 2017b), with many of the poorest causing just one ton of CO_2-equivalents per year, mostly from the production of basic staples and use of cooking fuel, while the emissions of the richest are unknown but estimated to be hundreds of tons, from private jets and super yachts (Barros and Wilk, 2021). Such a significant gap in carbon inequality is largely rooted in income inequality. Since 1990, global income inequality has grown, caused by an increasingly large gap in intra-country incomes, despite a decline in inter-country inequality (Hubacek et al., 2017a; UN Department of Economic and Social Affairs, 2020). New Oxfam reports that the richest 1% had more than twice the wealth of 6.9 billion of the world's common people (Clare et al., 2020). Such inequality means a huge gap between rich and poor in almost every aspect of life, especially in the magnitude and type of consumption (SDG12) (Aguiar and Bils, 2015), which consequently results in a highly unequal distribution of global CO_2 or GHG footprints (Ivanova and Wood, 2020; Oswald et al., 2020). In the context of global climate politics and justice, the unequal distribution of GHG footprints implies a disproportionate mitigation responsibility of the rich. Numerous studies have shown a large gap in the CO_2 footprint among countries at different development stages, or among different classes within a country (Jorgenson et al., 2016; Rojas-Vallejos and Lastuka, 2020; Wiedenhofer et al., 2017). The gap could be larger when taking other GHG from agriculture and husbandry (e.g. CH_4) into account, as the rich has higher meat consumption than the poor. The average per-capita carbon footprint of the richest country was 23 times of the poorest country in 2007 (Ivanova et al., 2016). Resolving within-country differences, the top 1% of the global population emitted 30 times more than the bottom 50%,

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and 175 times more than the bottom 10% (Oxfam, 2015). It has been argued that addressing intra-country inequality is more difficult than addressing inter-country inequality, but that addressing intra-country inequality is crucial for obtaining political support for GHG mitigation. (Lucas and Thomas, 2015).

GHG emissions and global inequality are intertwined. Global inequality and greenhouse gas emissions are intertwined. GHG emissions and global inequality are intertwined. The wealthy cause a larger portion of the climate damage which hurts poorer populations disproportionately. The relationship is increasingly recognised in the context of global decarbonisation efforts. Despite the extensive literature on carbon inequality, previous intra-country studies have generally focused on either a single country or a single year, and very few works have studied the evolution of intra-country inequality. Wiedenhofer et al traced the inequality of household carbon footprints among 11 income groups in China between 2007 and 2012, highlighting the policy intervention on Chinese lifestyle transformation especially for the middle-class and rich living in urban areas (Wiedenhofer et al., 2017). Feng et al. measured the carbon inequality among 9 income groups in the US for 2015 and suggested the settlement structure and lifestyles in the US cause high carbon footprint disparity across income groups (Feng et al., 2021). Hubacek et al. measured the carbon inequality of the four income groups in 120 countries for 2010 and using a set of what-if scenarios, concluded alleviating extreme poverty would have little implications for global carbon emissions (Hubacek et al., 2017b). Oswald et al. looked at the inequality in energy footprints between four to five income groups for 86 developing countries in 2010 (Oswald et al., 2020). Ivanova and Wood used micro-data from the EU household budget survey for 2010 to measure the carbon inequality across 26 EU countries and found that the top 1% of EU citizens currently have footprints 22 times higher than a 2030 target of 2.5 ton/cap (Ivanova and Wood, 2020). Very few studies done to date that looks at changes from an international perspective. For example, (Kartha et al., 2020) broke down changes in intra-country inequality by income, rather than using actual expenditure estimates, concluding a rising global carbon inequality where the share of carbon emissions of the top 1% rose from 14% to 15% of the total carbon emissions. (Chancel, 2022) traced the change in global carbon inequality from 1990 to 2019, and found a very high concentration of individual carbon emissions without the sign of clearly bridging the gap.

Due to the limited temporal scope of current studies, our understanding of the effect of the primary factors behind the change in carbon inequality is limited. Whilst the science on climate change is by and large settled, the policy efforts, cost distributions, and acceptability of mitigation and adaptation strategies are hotly debated. Responsibility for emissions and the ability to reduce emissions are central considerations. Varied policies have vastly varied effects on population distribution. Increasing the standard of living for impoverished people and reducing the overconsumption of the wealthy may be equivalent to reducing inequality, but they have vastly different implications for mitigation. Wealthy consumers have greater discretion to implement low-carbon technologies and can more easily afford renovations that reduce energy needs, but to date, they have frequently offset efficiency gains with consumption increases. Here, we illustrate the evolution of intra- economy carbon inequality by calculating the carbon footprint of each income quintile in 43 major economies. We analyse structural changes that underlie changes in GHG emissions and carbon inequality. To do so, we link household expenditure surveys to a global supply chain model (EXIOBASE 3.7) to estimate the household GHG footprint by five income groups from 2005 to 2015. Household expenditure survey data are interpolated and reconciled based on data from Eurostat for 27 EU countries plus Turkey, Switzerland, Norway, and the World Bank Global Consumption database (WBGCD), as well as national statistics bureaus in non-European countries (see supplementary). Structural decomposition analysis (SDA) was employed to quantify the driving factors in the carbon footprint for each income quintile as well as the carbon inequality.

2. Method

The study applied the environmentally extended multiregional input–output (MRIO) model to estimate household GHG footprints by five income groups for 43 economies, including 36 developed economies and 7 of the main developing economies. To focus on key results, the 43 economies were aggerated into 12 regions in some of the analyses. The GHG footprints were calculated annually from 2005 to 2015. To differentiate the GHG footprint by different income groups, household expenditure survey data with quintile income groups were reconciled with household demands by economies in the MRIO model. Household expenditure survey data come from different sources and for multiple years but still required some interpolation when matching to the annual expenditure of the MRIO model. Inter- and intra-country inequality of the GHG footprint were presented, based on the GHG footprint by income group and the GHG footprint by income group. Gini coefficients of GHG footprints were employed to measure intra-country inequality in the household. A full description of the method is provided below:

2.1. Environmentally extended MRIO analysis

The MRIO model is a widely used tool in tracing spill-over effects through regionally dispersed supply chains and identifying regional heterogeneity (Dietzenbacher et al., 2013; Huang et al., 2021; Xia et al., 2022; Zheng et al., 2021, Zheng et al., 2019a). Due to the coverage of global supply chains, MRIO analysis enables the accounting of environmental footprints generated indirectly in any world region in addition to direct household emissions (Hertwich, 2011; Steen-Olsen et al., 2016; Zheng et al., 2019b). Here, we used EXIOBASE 3.7 covering the years 2005 to 2015 as the MRIO database. EXIOBASE is a global environmentally extended MRIO database developed for EU countries and its main global trade partners, including 44 economies covering 90% of global gross domestic product (GDP) and 5 rest of the world regions. Its version 3.7 provides a global MRIO table with highly detailed sectorial classification (200 products) from 1995 to 2016, with wide extensive environmental and social satellite accounts (Wood et al., 2015).

As our purpose is to calculate the GHG footprint induced by the household's expenditure, the classic Leontief demand model in the IO framework is selected to allocate the environmental impacts to households (Miller and Blair, 2009). Mathematically, the basic equation can be expressed as:

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

where **A** is the technical coefficient matrix of the economy, and y is the final demand matrix by sector, of which household expenditure is a component along with capita formation, government expenditure and export. Total output x can be expressed by Leontief inverse **L,** with the identity matrix with ones on the diagonal (I), as the following equation.

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

To calculate the GHG footprint, the input–output model is extended by adding the environmental multiplier (**E**). Because we calculate the GHG footprint, the amounts were based on the Global Warming Potential 100 (GWP100) metric including the accounting of CO2, CH4, N2O, and SF6 in kg CO2-equivalents per year, the satellite accounts of CO2, CH4, N2O, and SF6 turned to the CO2-equivalent intensity by:

$$K = CF\widehat{X}^{-1} \tag{3}$$

where K refers to the GHG intensity in CO2-equivalents, representing GHG emissions per unit output for the given product. **C** is the characterization vector to harmonize emissions of all GHG types (**F**) into the unit of CO2-equivalent based on GWP100. Thus, the total GHG footprint for all regions can be expressed by:

$$GHG = KLy_q^r + hh_q^r \quad (4)$$

where KLy_q^r capture the GHG emissions along the supply chain of household expenditure of group q in the country (or region) r. hh_q^r is a vector of the household GHG direct emissions for group q in the country (or region) r, e.g. direct GHG emissions from housing heating. To facilitate the expression, detailed product-level (e.g. 200 items) were aggerated into 8 categories (SI).

2.2. *Linking consumer expenditure survey with EXIOBASE*

Detailed household expenditure by five income groups is derived from the household or consumer expenditure survey (CESs) published by the official statistics agency. Due to data availability, 43 economies (Brazil was excluded) are included in our study. CES data for EU 27, the UK, and Turkey were derived from the household budget survey in Eurostat, while the data for the US, Japan, Switzerland, Canada, South Korea, Australia, and Taiwan came from their official statistics. CES data for China, India, Mexico, Russia, Indonesia and South Africa were collected from World Bank Global Consumption Database (https://datatopics.worldbank.org/consumption/) and their own official statistics agency (More details can be found in SI). All CES data adopt an expenditure nomenclature, the Classification of Individual Consumption by Purpose (COICOP), but the detailed classification varied in different economies, e.g. 47 commodities and services are listed in Eurostat CES, while that for the US and Australia are 68 and 180 respectively. Therefore, concordance matrices to harmonise between the product classification in CES data (COICOP) and EXIOBASE were created for each country or region, by using the RAS-based method to cope with the problem that one CES category corresponds to two or more EXIOBASE product categories (Oswald et al., 2020; Steen-Olsen et al., 2016; Zheng et al., 2022a, Zheng et al., 2022b). 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 (Steen-Olsen et al., 2016). 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. Using the concordance matrix, the CES data for each quintile income group were reconciled into five household demands in line with the classification of EXIOBASE, and the aggregated CES data was equal to household demand in EXIOBASE for the given economy.

Because most of the CESs data are not time-series, we constructed the time-series CES data for each economy. Based on the data availability, three cases are categorised with different methods used to extend the CES in each case. Case 1 is for economies with available time series CES data. US, Japan, Canada and South Korea belong to the case, and we simply use their CES data from 2005 to 2015 to harmonise with EXIOBASE data as shown before. Case 2 is for the economies whose total expenditure by income groups is available (no expenditure structure). China, Taiwan, India, Indonesia, Russia, and Mexico belong to this category. In this case, we first harmonise between CES and EXIOBASE for 2010, as expenditure structure is available from the 2010 CES data for these economies from the World Bank Global Consumption Database (WBGCD). WBGCD data are by four income segments in the unit of the international dollar (USD-PPP): lowest (< \$2.97 per capita a day); low (\$2.97 - \$8.44 per capita a day); middle (\$8.44 - \$23.03 per capita a day); higher (>\$23.03 per capita a day). WBGCD data are transformed into quintile income segments estimated by regression (See SI). Then, we applied the RAS method with the created CES-EXIOBASE data for 2010 as the benchmark. Total CES expenditure by income groups from their statistical agency and EXIOBASE household demand was set as the column and the row constraint respectively (See SI). This data interpolation presumed changes in expenditure structure are consistent and no jumping in the structure between 2010 and other years, which is plausible as the changing expenditure structure is normally regarded as gradually progressive. Case 3 is for the economies neither with time-series CES data nor with the total expenditure by income groups. Economies in this category only have CES data for discrete years. EU 27, UK, Turkey, Switzerland, Norway, and Australia belong to this category. For example, CES derived from Eurostat were only for 2005, 2010 and 2015 – which gives the start, middle and end years, but not the intermediate changes. Notably, CES for Switzerland and Australia were reported in 2006 and 2003 respectively, which we use as the proxy for 2005 CES data. In this case, we use linear interpolation to estimate the total expenditure for the missing years by using per capita household income for each income group. Per capita, household income by income groups was calculated by time-series quintile income share data (e.g. Income share held by the highest 20%) from the World Bank and per capita household income data derived from their statistical agency. With the total expenditure by income groups, case 3 can be turned into case 2 from which it is possible to estimate the CES-EXIOBASE for the missing years (See SI-Figure S1). To exclude the impacts of inflation, we transferred the data of the EXIOBASE at the current price to the constant price in 2005, by using deflators from the dataset.

When calculating the time-series expenditure and GHG footprint intensity, we convert the current price of the given year to a constant price based on 2005, with consumer price indices by consumption items and economies derived from World Bank. Since Taiwan is not a country listed in the World Bank, all used indicators including exchange rate and currency deflator were derived from its statistical agency.

2.3. *Gini coefficient*

To quantify the inequality, we used the Gini coefficient as the metric. The Gini coefficient was designed to quantitatively the level of difference in income distribution. The metric ranges from zero to one, from perfect equality to absolute inequality. It is measured by cumulative proportions of the population against cumulative proportions of wealth or impacts they receive. In the case of perfect equality, the share of the population is responsible for the same share of impacts or wealth, e.g. 10% of the population hold 10% of the wealth. The metric had been widely used in measuring economic inequality, e.g. income inequality. In our case, we replace the wealth or income distribution with the GHG footprint. The mathematical equation can be expressed as:

$$Gini = 1 - 2\int L(x)dx \quad (5)$$

where $L(x)$ denotes the Lorenz curve:

$$y_i^s = L\left(x_i^s\right) \quad (6)$$

where x_i^s is the ratio of the cumulative proportion of the population of a segment s against the total population in country or region i. y_i^s is a ratio of the cumulative proportion of the GHG footprint of a segment s against the total GHG footprint in country or region i.

2.4. *Decomposition analysis*

To capture the socioeconomic driving forces, we adopt the SDA (Structural Decomposition Analysis) to decompose household-related GHG footprints by five income groups in all economies. SDA is a widely adopted method used in energy and emission studies (Bai et al., 2021; Zheng et al., 2020). In this study, we decompose the GHG footprints by country or region with income groups as follows:

$$C = \sum_{i=1}\sum_{j=1} E_i \frac{E_{ij}}{E_i}\frac{C_{ij}}{E_{ij}} = \sum_{i=1}\sum_{j=1} L_i Y_{ij} I_{ij} \quad (7)$$

where C denotes household-related GHG footprints by economies. E_i and

E_{ij} refer to total expenditure by income group i and expenditure for the product j by income group i respectively. C_{ij} is the GHG footprint induced by income group i for product j. The decomposition divides the total factor into four factors. Expenditure effect (L_i), measuring the effects of expenditure for the income group *i* to GHG footprint; Expenditure structure effect ($Y_{ij} = \frac{E_{ij}}{E_i}$), referring to the distribution of the spending per unit of expenditure; GHG intensity or multiplier ($I_{ij} = \frac{C_{ij}}{E_{ij}}$), measuring GHG footprint per unit of expenditure by income group *i* for product *j*. However, we modify the equation by eliminating the population effect, as we compare the change GHG for each income group. Mathematically:where the superscripts *t* and *t0* indicate the target year and base year, whi

$$\Delta C = C^t - C^{t0}$$

$$= L_t \cdot Y_t \cdot I_t - L_{t0} \cdot Y_{t0} \cdot I_{t0}$$

$$= \Delta L \cdot Y_t \cdot I_t + L_{to} \cdot \Delta Y \cdot I_t + L_{to} \cdot Y_{t0} \cdot \Delta I \tag{8}$$

where the superscripts *t* and *t0* indicate the target year and base year, which are 2005 and 2015 respectively.

2.5. Limitation

There is uncertainty in both data and model used in the study. The household expenditure survey data used in this study have differences in survey design, implementation, and definition. It is worth noting that the definition of income groups is not consistent in CES. The income quintile segment for some economies is defined by household (Group A), while others are by population (Group B). The quintile segment of EU countries from Eurostat is by average income per consumer unit, equivalent to the number of the consumer unit. CES data from WBGCD are by population. Hence, each quintile segment had an identical number of populations for the given country (different household numbers in each segment). In contrast, some economies like the US, Canada and South Korea have quintile income groups by household (identical household numbers in each segment). For these economies, we also collected the household size (number of people in the household) by each income group from CES data and then converted it into population data. Therefore, the population in each income segment are different for these countries (e.g. household number multiplying household size). The different formats could lead to uncertainty. Given households with more family members (higher household size) are more categorised into the high-income group, the high income group in these economies would have more population. When calculating per capita metrics, high-income group of group b could be underestimated in comparison with countries of group A. In group A countries, it is possible to spot that total expenditure of the rich group is a bit lower than it of the low-income group at product-level. Total expenditure by each group is calculated by household number multiplying average expenditure per household, and household numbers of the low-income group are the largest due to smaller household size. However, the problem is on average expenditure per household. Average expenditure per household is very sensitive to the distribution of microdata and the extreme value. It means average expenditure per household could be underestimated, especially for high-income groups. Therefore, the total expenditure of the rich group is a bit low. CES data from WBGCD presented expenditure structure by per capita expenditure groups, not income groups. Moreover, India, Indonesia and South Africa countries did not provide the official CES data by income groups, but by expenditure group as well. For these cases, we use the CES by per capita expenditure group as the proxy to the income group, which was adopted by the previous work (Hubacek et al., 2017b; Oswald et al., 2020). Meanwhile, CES data are not reported constantly, and we estimate the missing value by different methods subjective to the data availability (shown in SI). The programming method (e.g. RAS) was primarily used to estimate the product-level consumption structure. Although we control the aggregate consumption, the programming method cannot guarantee the accuracy of product-level consumption. Since income categories are separated into quintiles, it's difficult to compare them across economies. For example, India's richest 20% are poorer than the US's. Our analysis emphasises intra-region disparity, rather than inter-region comparison.

Previous literature have pointed out a certain bias of sample selection existed in the survey, and some groups could be hardly incorporated into the survey. For example, the rich in Germany is not included in the survey (Ivanova and Wood, 2020). Besides, expenditure data could also be biased. The spending on some products could be under-reported deliberately due to sensitivity. Some durable products that are not frequently purchased could be varied significantly in terms of spending, such as vehicles (Ivanova et al., 2018). Meanwhile, the expenditure survey can hardly capture the spending overseas, likely resulting in an underestimate of spending on certain products (e.g. travel). In addition, the previous study also shows that uncertainty can come from the unit, where the expenditure survey used in the study is with the monetary unit. This cannot reflect the quality of the products. Where normally higher quality means higher price and higher emissions. In comparison to other supply chain datasets, EXIOBASE offers the most detailed information, with 200 products. However, it is still insufficient to differentiate between products in the same category. For example, we cannot differentiate between the quality of things and their costs, such as a cheap car and a premium car. However, under the input–output model, the production function is fixed, which is a well-known assumption of the input–output model. This indicates that regardless of the quality or complexity of the goods or services, the same production function will be used to manufacture them. Luxury cars, for example, require more expensive materials, which need additional processing and energy use. This leads to a bit higher emission of the expensive products; However, their emission intensity (emissions/total price) could be much lower, due to lower marginal energy use when rising price. Therefore, the rich group's emissions might be overstated while the poor could be underestimated (Girod and de Haan, 2010). For example, premium and ordinary petrol are considered as having the same intensity, yet premium petrol may have a lower intensity in fact. As a result, wealthy users who use premium petrol may have their travel-related footprints overstated.

3. Results

3.1. Rising carbon inequality from 2005 to 2015

Inequality of GHG footprints rose between 2005 and 2015 at the same time as global GHG emissions rose. The global GHG footprint Gini coefficient rose from 0.29 to 0.31 (Figure S2). A rising Gini coefficient implies increasing inequality: a Gini income coefficient of 1 means all of an economy's footprint is caused by a single person and a value of 0 means emissions are evenly distributed. The total GHG footprint of the highest income quintiles of the 43 economies rose from 6400 to 6860 Mt (a rise of 6%) between 2005 and 2015, while the footprint of the lowest income quintiles declined from 1735 to 1635 Mt (a reduction of 5%).

Developed economies (blue colour) saw a decline in GHG footprint for all income groups, especially after the 2008 financial crisis. Overall, developed economies show a rising carbon inequality between the rich and poor. The top income group of developed economies had a 14% decline from 3982 to 3407 Mt per year, whilst the lowest income group had a 15% decline. It is worth noting the largest decline was found in the middle class (17% decline). In contrast, developing economies (orange colour) had a rising GHG footprint for all income groups with widening inequality. The GHG footprint of the highest income group in these emerging economies rose from 2421 to 3453 Mt (by 43%) footprints, and that of the lowest income groups rose from 306 Mt to 422 Mt (by 38%). The faster growth of the highest income group is reflected in increased carbon inequality. It is worth noting that the top income group in developing economies overtook its counterpart in developed economies as the largest emitter in 2014 (3406 Mt), accounting for 18.8% of the global household GHG footprint. This trend was largely attributed to the rapid rise in highest income group in China and India. In developed economies, it is the middle class that did the most reduction in terms of percentage, whilst it increased the least in developing economies. A similar result was observed in previous studies for China (Wei et al., 2020; Wiedenhofer et al., 2017).

Fig. 1b depicts the evolution of per capita carbon footprint by product in developed and developing economies. Regardless of differences between developed and developing economies, spending on shelter energy, travel, and meat took the lead, in terms of carbon footprints. In developed economies, the carbon footprint of all products has declined over time, particularly for shelter energy. Canada has the greatest reduction in shelter-energy-related carbon footprints, with more than a 50% reduction for both high- and low-income groups. However, the carbon footprint of shelter energy decreased more significantly in the lowest-income group than in the highest-income group. For all developed economies, the highest income group had a 16% decrease in shelter energy footprint, whereas the lowest income group had a 26% decrease. The phenomenon is well spotted in European economies, where the lowest income group saw their energy-related footprint drop by 12% for Eastern European countries and 34% for Western European countries. Simultaneously, the highest income group only dropped by 1% and 29% for Eastern and Western European countries respectively. This is one of the key reasons make European countries have higher carbon inequality.

East Asia and Oceania economies show an increase in the carbon footprint of shelter energy usage, particularly among the wealthy. However, this is largely due to Australia where the highest income group gained energy-related footprint by 150% while the lowest income group only raised by 30%. Other economies saw larger growth of energy-related footprint of the lowest income group. For East Asia and Oceania economies (except Australia), travel-related carbon footprints of the highest income group dropped quicker than the poor, largely contributing to bridging the gap. Meanwhile, travel-related carbon footprints changed significantly in the United States and Western Europe, but not in other advanced economies. In contrast to established economies, the key components of developing economies' carbon footprint vary greatly. Spending on travel, meat, and manufactured goods was the key to their carbon footprint in Mexico, Russia, and South Africa, where the low-income group had a greater increase in the carbon footprint of travel and manufactured goods, except in South Africa. Shelter energy was essential in driving China, Indonesia, and Turkey's carbon footprint. However, only in China did the lowest-income group outperform the highest-income group (71% versus 29%).

3.2. Convergence or divergence between carbon inequality and mitigation

Changes in inequality have no pre-determined effect on climate mitigation. Reduced inequality can result from either a reduction in the footprint of the highest income group or a rise in the footprint of the lowest income group. Fig. 2 compares the change of footprints of the highest income group and the lowest income group for each economy

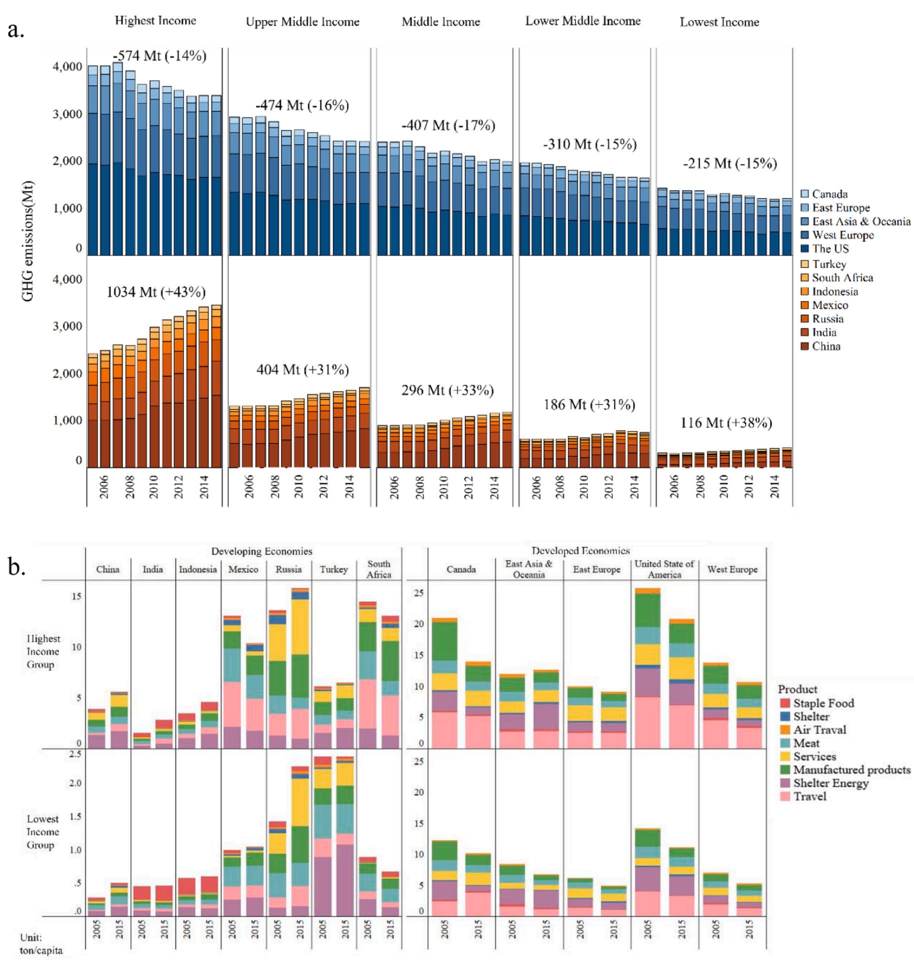

Fig. 1. A. the evolution of total ghg footprint for income quintiles of all economies from 2005 to 2015. b. Per capita footprint by products for each economy between 2005 and 2015. The colour of the bar is ordered as same as the legend. Blue shows advanced economies, whilst orange refers to developing economies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

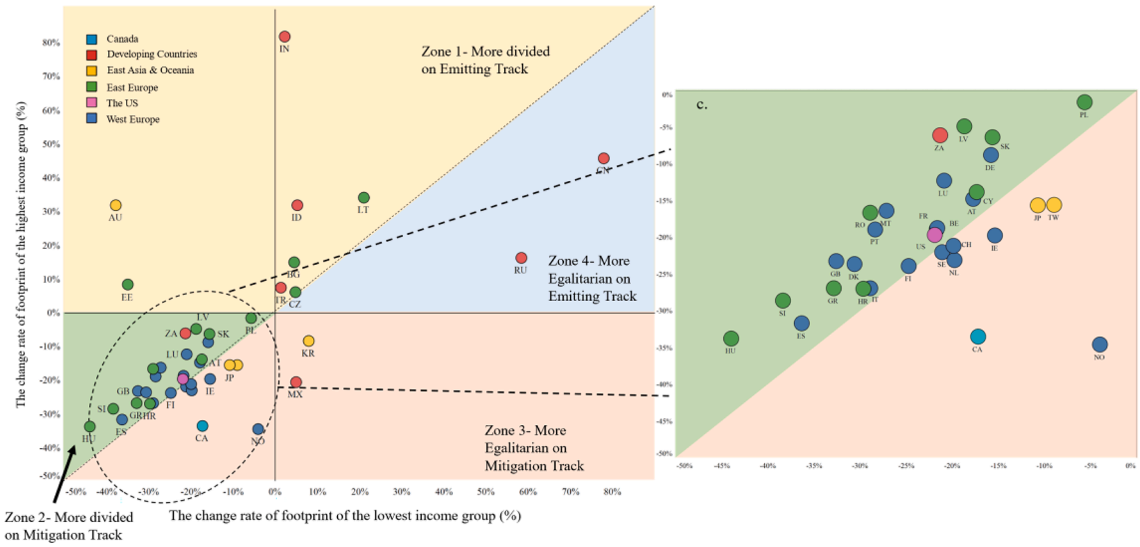

Fig. 2. The comparison in the growth rate of the GHG footprint between the highest income group and the lowest income group for all economies from 2005 to 2015. The four zones present the carbon inequality and mitigation trend. Zone 1 refers to economies with rising inequality and carbon emissions; Zone 2 refers to economies with rising inequality but reducing carbon emissions; Zone 3 refers to reducing both inequality and carbon emissions; Zone 4 refers to reducing inequality but rising carbon emissions.

during 2005–2015. All 43 economies are placed into one of four zones which represent resultant relations between GHG inequality and mitigation. From the perspective of mitigation, given the determinant GHG contributions from the highest income group, economies in zone 1 and 4 are on the emitting track due to a growing footprint of the highest income group, whilst zone 2 and 3 are defined as on the mitigation track, as declined footprints of the highest income group. The highest income group almost determines the trend of overall emissions, regardless of how the bottom income group rises or falls. From the perspective of inequality, economies in zone 3 and 4 have a faster growth rate of the footprint of the lowest quintile group than the highest quintile group, thus becoming more equal. In contrast, the faster growth of the highest income group for economies in zone 1 and 2 indicates more division.

To achieve a win–win situation of mitigation and social equality, all economies should be ideally on the mitigation track with reduced inequality (zone 3). Among 36 developed economies, most of the European countries were in Zone 2 following a mitigation track with increasing inequality. In contrast, the US, Canada, and almost all of East Asia and Oceania were in Zone 3 where the mitigation and equity targets can be achieved over the period. Except for Mexico, developing economies were on the emitting track, but showed a large heterogeneity in terms of carbon inequality. China and Russia were observed to have a decline in carbon inequality while increasing carbon footprint for all income quintile groups. The lowest income group in these countries had a larger growth than it the highest income group. In contrast, the carbon inequality in India, Indonesia, and Turkey increased due to the faster growth of the footprint of the highest income group, indicating a lose-lose trajectory for dual targets. South Africa, one of the most unequal countries in the world, had an increasing carbon inequality with increasing footprints of the top income group but decreasing footprints of the lowest income group.

3.3. *Drivers of household-related carbon footprint and carbon inequality*

Fig. 3a shows the change rate of the GHG footprints for four featured categories (zones) by income. We focus on three key factors: GHG intensity, total expenditure, and expenditure structure. GHG intensity was the most important driving element in reducing GHG footprints. The indicator reflects the effects of mitigation efforts by measuring GHG footprints per unit of constant-price household expenditure. Reducing intensity is the primary driver of mitigation, which is linked to technology developments and changes in the energy mix during the last decade (le Quéré et al., 2019; Wang et al., 2021). Several findings highlight the increasing importance of carbon policies in these industrialised economies. For example, the EU enacted a renewable energy regulation in 2009 with the goal of generating at least 20% of total energy and 10% of transportation by 2020 (Lind et al., 2013). Total expenditure is the effect of total spending by income group, which reflects the purchasing power of each income group. This metric is the driving force behind rising household carbon footprints. Moreover, the expenditure structure relates to the composition of household expenditures and reveals the consumption preferences of the household. Domestic items contributed the most to the change in carbon footprint for both high-income and low-income groups, demonstrating their significance for both mitigation and social equity. However, only imports from Zone 2 and Zone 3 economies (primarily developed economies) contributed significantly more to the carbon inequality, particularly imports from developing nations. Although less influential than local products in terms of carbon inequality, mitigation efforts in developing countries continue to play a significant role in the carbon inequality of developed economies.

Zone 2 economies, primarily European economies, were on a path to cut emissions but not to eliminate carbon disparity (a divided-mitigation situation). Although economic disparity is a widely accepted cause of high carbon inequality, the declining GHG footprint does not reflect low-income people becoming poorer; rather, the carbon intensity of their consumer basket declines faster than that of wealthy people. As shown in Fig. 3a, the contribution of the carbon intensity of the poor is greater than the rich for the Zone 2 economies, while no significant difference was found in the contribution of total expenditure of both low-income and high-income groups. Low-income people are more likely to purchase cheap, carbon-intensive products (such as fossil fuel), and mitigation measures are most effective in reducing the carbon intensity of these products (Fig. 3b). As a result, the trend of increasing carbon inequality is not a cause for concern for economies attempting to cut carbon emissions. On the other hand, rising carbon inequality in the economy with rising emissions (a divided-emitting situation) could be alarming, indicating disproportionate increases in the spending by the wealthiest, as shown in Zone 1 economies. All products showed higher expenditure growth of the highest income group than the lower income

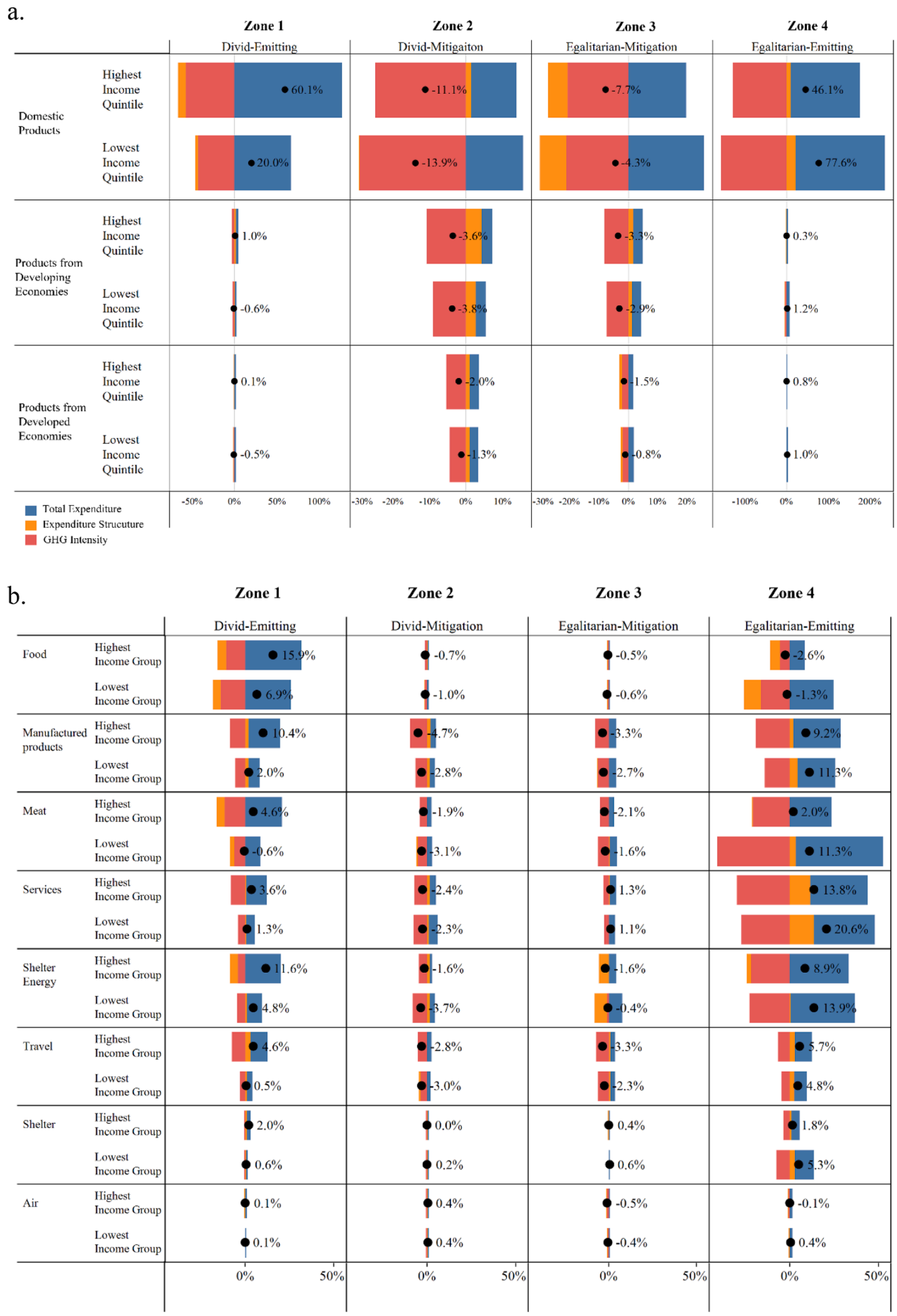

Fig. 3. Socioeconomic driving factors behind the change of footprints of income groups from 2005 to 2015 (percentage of carbon footprint in 2005), in terms of sources (a) or products (b). The dot refers to the net change of GHG footprint in the percentage of carbon emissions in 2005, and their values are also shown.

group, which contributes to the inequality (Figure b). This indicates rising carbon inequality of Zone 1 economies reflects rising economic disparity.

It is widely acknowledged that poverty alleviation does not contradict mitigation because it would only result in a modest increase in carbon emissions (Bruckner et al., 2022). While rising emissions are worrying, at least the gap between shares of the rich and the poor has narrowed. These Zone 4 economies, namely China and Russia, shows an example of poverty alleviation with increasing emissions. Relative measures of inequity declined in both countries over the study period. For example, despite the high Gini coefficient, the coefficients dropped in Russia (41.3 to 37.7) and China (40.9 to 38.6). Higher expenditure by the low-income group was the primary driving factor to bridge the gap, even though it also led to more emissions. China is exemplary in that its lowest income group contributes less than 1% of global emissions while constituting 5% of the world's population. Carbon emissions from the lowest income category climbed by 64 Mt between 2005 and 2015, significantly less than the rise of the wealthiest (524 Mt). Only in a few economies (zone 3 economies), such as Canada, can we find a convergence of equality and mitigation goals (an egalitarian-mitigation situation, win–win). The success of these economies' consolidation is based on bigger increases in the bottom group's expenditure growth while keeping mitigation efforts. At the product level, we can see that most products consumed by the highest income show more decarbonisation than the lowest income group. Building energy use in these countries is shifting towards low-carbon sources, both helped by clean electrification. For example in Canada, the share of kerosene and electricity by coal declined from 25% to 18% of total energy demands, while the share of electricity by hydro rose from 36% to 39%.

4. Discussion and conclusion

The need to allow poor households' consumption level to catch up (SDG 10) makes it harder for those income groups to reduce GHG footprints, coming in conflict with GHG mitigation targets (SDG 13). Rising emissions may reduce GHG inequality, and declining emissions may exacerbate GHG inequality. Focusing merely on carbon inequality without understanding the structural patterns may be unwise. Our analysis divides 43 major economies into four zones to show how reducing inequality (SDG 10) and carbon emissions (SDG 13) work together. We found that global carbon inequality increased from 2005 to 2015, which is consistent with the previous study (Chancel, 2022). All income groups in developed economies showed a decrease in GHG footprints, but it was lowest for the high-income group, resulting in increased carbon disparity. In contrast, developing economies showed rising carbon footprints, with narrowing gaps in some countries and rising gaps in others. Since 2014, when its carbon footprint surpassed that of the top income group in established nations, the highest income group in developing economies has become the largest contributor to rising global emissions. The primary products driving the trend are housing, energy, travel, and meat. The carbon footprint of shelter energy is reduced more considerably in the lowest-income group than in the highest-income group, particularly in European economies. This pattern is a concern if middle-income and poorer households adopt similar expenditure patterns as a growing economy raises their incomes. According to decomposition analysis, rising carbon inequality was not necessarily concerning, as it was related to higher intensity reductions of the inexpensive and carbon-intensive product. As a result, lower-income groups may have greater mitigation impacts. We also highlight economies in a lose-lose situation (zone 1), which have faster wealthy spending growth but stagnant mitigation. In contrast, economies that consolidate both aim to improve the lowest group's spending growth while maintaining mitigation activities.

To demonstrate the evolution of carbon inequality and carbon footprint, we have categorised all economies into four distinct groups (zones). The majority of developed economies are located in Zone 3 (more divided on the mitigation track), where inequality is rising despite carbon mitigation. In terms of carbon footprint, European countries demonstrated a rise in inequality alongside a slower decline in the carbon footprint of the highest income group. It demonstrates the resistance of the wealthy to adopting a cleaner lifestyle and energy consumption pattern. Instead, it shows that the low-income group in developed economies would be more affected by the low transition. Despite a decline in inequality in China, Russia, and Mexico, developing countries had the greatest GHG footprint inequality (zone 1,4). The narrowing of the gap in these countries was a result of the poor's increased expenditure growth. India and Indonesia, on the other hand, experienced a rise in both inequality and GHG footprint due to the higher growth of the wealthy. The majority of developing countries are in Zones 1 and 4, which are on the emission track regardless of carbon inequality. Since the synergy between poverty alleviation and climate targets could be achieved for the poorest people, the challenge for developing countries is how to curb the significant growth of expenditure of the rich from rapid socioeconomic growth and urbanization (Zhong et al., 2020). Our study unveiled a dramatic growth in expenditure of the top income group. For example, the average annual growth in expenditure of the top income group was 14% for China and 2.47% for the US over the period. Growing carbon footprints of the top income groups in developing economies indicate a great challenge of both climate change mitigation and income inequality. It is worth noting that, collectively, the top income group in developing countries had overtaken the top income group in mature economies in terms of footprints. Rapidly growing carbon footprints indicate the trend of its westernized lifestyle adopted by the top income group in the emerging economies, which should be alerted that they could be more likely to follow the historical route of developed economies with higher expenditure and carbon-intensive expenditure structure. Reducing the carbon footprints of developed economies, particularly the wealthy, contributes to reducing inequality in carbon footprints and income in a carbon-constrained world with a 1.5 °C mitigation objective. Due to the vast population of developing countries, it may not be sufficient to offset the additional carbon emissions caused by the rising living standards of the people in developing countries.

Offsetting the carbon emissions from rising living standards of the developing countries requires deep mitigation which includes both technology solutions and lifestyle transitions. Despite great opportunities, the former is often regarded as too slow to achieve the ambitious climate targets of the Paris Agreement if consumption continues to expand at the present rate (IPCC, 2018). Developing countries are the largest investors in renewable energy, but the most concern is that the growth and deployment of energy efficiency and renewable and nuclear energy may not be sufficient to decarbonize the growing demands of household consumers (Loftus et al., 2015; Smith et al., 2016). It is particularly uncertain for developing countries, such as India, where their current economic stagnation could significantly hamper the energy transition after the Covid pandemic (Shan et al., 2020; Vanegas Cantarero, 2020). However, the complexity emerges that transferring green technologies into developing countries may lead to a rebound effect of consumption in the developed economies (Greening et al., 2000; Isenhour and Feng, 2016; Yang et al., 2022).

With the uncertain economic prospects, the current decoupling between emissions and expenditure could be hard to be sustained without behavioural change. Given the recent attention given to behavioural changes to close the gap to the Paris target, it makes sense for these efforts to target the rich (Creutzig et al., 2018; United Nations, 2020). Policy instruments like carbon taxation, subsidies of renewables, eco-labels, or green actions could be an option to encourage shaping green lifestyles, especially for the growing consumption of the rich in emerging economies (Taufique et al., 2017; Vogt-Schilb et al., 2019). For example, China has the largest automobile market, and campaigns to promote shifting to electric vehicles, encouraging public transport (living car-free), and the sharing economy (e.g. car sharing) could be effective (Ivanova et al., 2020). However, the supply chain is vulnerable to rising material price and the decarbonisation of the transport may be delayed (Wang et al., 2023). As for European countries, Moran et al. found that adopting a portfolio of green actions at a personal level could reduce the European carbon footprint by around 25% (Moran et al., 2020). However, it is worth indicating that advocating a green lifestyle is difficult, especially in light of an ageing society. A previous study has shown a harder challenge to change the expenditure behaviour of the elderly (Zheng et al., 2022a, Zheng et al., 2022b). However, there are many initiatives necessary from the public sector. Subsidizing the retrofitting of homes to increase their energy efficiency, for instance, can have a major impact on lowering energy-related emissions and related health issues (Guo et al., 2022; Lin et al., 2022; Wang et al., 2022), which is especially essential for the lowest-income group. Improving their welfare could also lower potential emissions, as poor health leads to increased energy use as sick individuals remain home longer (Büchs et al., 2018). In addition, low-carbon urban planning design could be a key to reducing travel-related emissions by providing low-carbon urban transport (Hukkalainen (née Sepponen) et al., 2017; Li et al., 2019).

Carbon tax is a policy instrument commonly adopted to curb the emissions. The largest driving-up factor, expenditure on domestic products, especially carbon-intensive products (e.g., electricity and fuel), could be more sensitive to carbon pricing, which would also raise the price of final goods. However, it is worth noting that the carbon cost in the production stage could be largely diluted in the final goods. For example, a rising 1% carbon tax imposed in steel production would affect prices but would be less likely to raise the cost of cars by 1%. This basically explains that the carbon tax on production always has limited effects on high-income consumers. However, lower-income consumers who are sensitive to the price could be affected more, resulting in increased carbon inequality (Fremstad and Paul, 2019). Imports, especially from developing countries, also contributed to the carbon inequality in developed economies, particularly European countries. Trade policies such as the Carbon Border Adjustment Mechanism (CBAM) will likely lead to higher prices for imported carbon-intensive goods. As such, careful design of matching policies to promote equality so that it is not just price-sensitive consumers who change their behaviour is needed. In the short term. The recent trend of such carbon inequality could be affected due to recent events, such as Covid and Russia-Ukraine war. These recent events have significantly worsened global inequality, and poor people are suffered more from the high inflation (Guan et al., 2023). Their disposable income was shrunk and discretionary expenditure was reduced, while the rich were less affected and maintained their lifestyle with high expenditure. Meanwhile,in the long term, the global trend of an aging society would be an impact on shaping the carbon inequality in the future. The elderly with their lifelong accumulative wealth is normally rich with possibly higher expenditure. However, the inequality in the elderly group is the most significant in comparison with other age groups, where time amplified the difference among people. It can be expected that carbon inequality would be worsened (Zheng et al., 2022a, Zheng et al., 2022b). Policymakers should be aware of both recent and future demographic and socioeconomic changes, and take them into policymaking. Some measures, such as inheritance tax, can be used to reduce inequality in the ageing society.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

A. Greening, L., Greene, D.L., Difiglio, C., 2000. Energy efficiency and consumption - the rebound effect - a survey. Energy Policy 28 (6-7), 389–401.
Aguiar, M., Bils, M., 2015. Has consumption inequality mirrored income inequality? Am. Econ. Rev. 105, 2725–2756. https://doi.org/10.1257/aer.20120599.
Bai, Y., Zheng, H., Shan, Y., Meng, J., Li, Y., 2021. The consumption-based carbon emissions in the Jing-Jin-Ji urban agglomeration over China's economic transition. e2021EF002132 Earths Future. https://doi.org/10.1029/2021EF002132.
Barros, B., Wilk, R., 2021. The outsized carbon footprints of the super-rich. Sustain. Sci. Practice Policy 17, 316–322. https://doi.org/10.1080/15487733.2021.1949847.
Bruckner, B., Hubacek, K., Shan, Y., Zhong, H., Feng, K., 2022. Impacts of poverty alleviation on national and global carbon emissions. Nat Sustain. 5, 311–320. https://doi.org/10.1038/s41893-021-00842-z.
Büchs, M., Bahaj, A., Blunden, L., Bourikas, L., Falkingham, J., James, P., Kamanda, M., Wu, Y., 2018. Sick and stuck at home – how poor health increases electricity consumption and reduces opportunities for environmentally-friendly travel in the United Kingdom. Energy Res. Soc. Sci. 44, 250–259. https://doi.org/10.1016/j.erss.2018.04.041.
Chancel, L., 2022. Global carbon inequality over 1990–2019. Nat. Sustain. 5 (11), 931–938.
Clare, C., Patricia, R., Rowan, H., Max, L., Anam, B., Kim, P., Diana, S., Julie, T., 2020. Time to care. Oxford.
Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nat. Clim. Chang. 8, 260–263. https://doi.org/10.1038/s41558-018-0121-1.
Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., de Vries, G., 2013. The construction of world input-output tables in the WIOD project. Econ. Syst. Res. 25, 71–98. https://doi.org/10.1080/09535314.2012.761180.
Feng, K., Hubacek, K., Song, K., 2021. Household carbon inequality in the U.S. J. Clean. Prod. 278, 123994 https://doi.org/10.1016/j.jclepro.2020.123994.
Fremstad, A., Paul, M., 2019. The Impact of a Carbon Tax on Inequality. Ecol. Econ. 163, 88–97. https://doi.org/10.1016/j.ecolecon.2019.04.016.
Girod, B., De Haan, P., 2010. More or better? A model for changes in household greenhouse gas emissions due to higher income. J. Ind. Ecol. 14 (1), 31–49.
Guan, Y., Yan, J., Shan, Y., Zhou, Y., Hang, Y.e., Li, R., Liu, Y.u., Liu, B., Nie, Q., Bruckner, B., Feng, K., Hubacek, K., 2023. Burden of the global energy price crisis on households. Nat. Energy 8 (3), 304–316.
Guo, Y., Chen, B., Li, Y., Zhou, S., Zou, X., Zhang, N., Zhou, Y., Chen, H., Zou, J., Zeng, X., Shan, Y., Li, J., 2022. The co-benefits of clean air and low-carbon policies on heavy metal emission reductions from coal-fired power plants in china. Resour. Conserv. Recycl. 181, 106258 https://doi.org/10.1016/j.resconrec.2022.106258.
Hertwich, E.G., 2011. The life cycle environmental impacts of consumption. Econ. Syst. Res. 23, 27–47. https://doi.org/10.1080/09535314.2010.536905.
Huang, Q.i., Zheng, H., Li, J., Meng, J., Liu, Y., Wang, Z., Zhang, N., Li, Y., Guan, D., 2021. Heterogeneity of consumption-based carbon emissions and driving forces in Indian states. Adv. Appl. Energy 4, 100039.
Hubacek, K., Baiocchi, G., Feng, K., Muñoz Castillo, R., Sun, L., Xue, J., 2017a. Global carbon inequality. Energy Ecol Environ 2 (6), 361–369.
Hubacek, K., Baiocchi, G., Feng, K., Patwardhan, A., 2017b. Poverty eradication in a carbon constrained world. Nat. Commun. 8, 912. https://doi.org/10.1038/s41467-017-00919-4.
Hukkalainen (née Sepponen), M., Virtanen, M., Paiho, S., Airaksinen, M., 2017. Energy planning of low carbon urban areas - Examples from Finland. Sustain. Cities Soc. 35, 715–728.
IPCC, 2018. Global warming of 1.5°C, Ipcc - Sr15.
Isenhour, C., Feng, K., 2016. Decoupling and displaced emissions: on Swedish consumers, Chinese producers and policy to address the climate impact of consumption. J. Clean. Prod. 134, 320–329.
Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., Hertwich, E.G., 2016. Environmental impact assessment of household consumption. J. Ind. Ecol. 20, 526–536. https://doi.org/10.1111/jiec.12371.
Ivanova, D., Vita, G., Wood, R., Lausselet, C., Dumitru, A., Krause, K., Macsinga, I., Hertwich, E.G., 2018. Carbon mitigation in domains of high consumer lock-in. Glob. Environ. Chang. 52, 117–130.
Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., Creutzig, F., 2020. Quantifying the potential for climate change mitigation of consumption options. Environ. Res. Lett. 15 (9), 093001.
Ivanova, D., Wood, R., 2020. The unequal distribution of household carbon footprints in Europe and its link to sustainability. Global Sustainab. 3, e18.
Jorgenson, A.K., Schor, J.B., Knight, K.W., Huang, X., 2016. Domestic inequality and carbon emissions in comparative perspective. Sociol. Forum 31, 770–786. https://doi.org/10.1111/socf.12272.
Kartha, S., Kemp-Benedict, E., Ghosh, E., Nazareth, A., Gore, T., 2020. The Carbon Inequality Era: An assessment of the global distribution of consumption emissions among individuals from 1990 to 2015 and beyond. doi: 10.21201/2020.6492.
le Quéré, C., Korsbakken, J.I., Wilson, C., Tosun, J., Andrew, R., Andres, R.J., Canadell, J. G., Jordan, A., Peters, G.P., van Vuuren, D.P., 2019. Drivers of declining CO2 emissions in 18 developed economies. Nat. Clim. Chang. 9, 213–217. https://doi.org/10.1038/s41558-019-0419-7.
Li, W., Bao, L., Wang, L., Li, Y.e., Mai, X., 2019. Comparative evaluation of global low-carbon urban transport. Technol Forecast Soc Change 143, 14–26.
Lin, L., Feng, K., Wang, P., Wan, Z., Kong, X., Li, J., 2022. Hazardous waste from the global shipbreaking industry: Historical inventory and future pathways. Glob. Environ. Chang. 76, 102581 https://doi.org/10.1016/j.gloenvcha.2022.102581.
Lind, A., Rosenberg, E., Seljom, P., Espegren, K., Fidje, A., Lindberg, K., 2013. Analysis of the EU renewable energy directive by a techno-economic optimisation model. Energy Policy 60, 364–377. https://doi.org/10.1016/j.enpol.2013.05.053.
Loftus, P.J., Cohen, A.M., Long, J.C.S., Jenkins, J.D., 2015. A critical review of global decarbonization scenarios: What do they tell us about feasibility? Wiley Interdiscip. Rev. Clim. Chang. 6, 93–112. https://doi.org/10.1002/wcc.324.
Lucas, C., Thomas, P., 2015. Carbon and inequality: from Kyoto to Paris. Paris.
Miller, R.E., Blair, P.D., 2009. Input-Output Analysis Foundations and Extensions, 2nd ed. Cambridge University Press, Cambridge.
Moran, D., Wood, R., Hertwich, E., Mattson, K., Rodriguez, J.F.D., Schanes, K., Barrett, J., 2020. Quantifying the potential for consumer-oriented policy to reduce European and foreign carbon emissions. Clim. Pol. 20, S28–S38. https://doi.org/10.1080/14693062.2018.1551186.
Oswald, Y., Owen, A., Steinberger, J.K., 2020. Large inequality in international and intranational energy footprints between income groups and across consumption categories. Nat. Energy 5, 231–239. https://doi.org/10.1038/s41560-020-0579-8.
Oxfam, 2015. Extreme Carbon Inequality. Oxfam Media Briefing.

Rao, N.D., Min, J., 2018. Less global inequality can improve climate outcomes. Wiley Interdiscip. Rev. Clim. Chang. 9 https://doi.org/10.1002/wcc.513.
Rojas-Vallejos, J., Lastuka, A., 2020. The income inequality and carbon emissions trade-off revisited. Energy Policy 139, 111302. https://doi.org/10.1016/j.enpol.2020.111302.
Shan, Y., Ou, J., Wang, D., Zeng, Z., Zhang, S., Guan, D., Hubacek, K., 2020. Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement. Nat. Clim. Chang. 11 (3), 200–206.
Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nat. Clim. Chang. 6, 42–50. https://doi.org/10.1038/nclimate2870.
Steen-Olsen, K., Wood, R., Hertwich, E.G., 2016. The carbon footprint of Norwegian household consumption 1999–2012. J. Ind. Ecol. 3, 582–592. https://doi.org/10.1111/jiec.12405.
Taufique, K.M.R., Vocino, A., Polonsky, M.J., 2017. The influence of eco-label knowledge and trust on pro-environmental consumer behaviour in an emerging market. J. Strateg. Mark. 7, 511–529. https://doi.org/10.1080/0965254X.2016.1240219.
UN Department of Economic and Social Affairs, 2020. World Social Report 2020, World Social Report 2020. doi: 10.18356/7f5d0efc-en.
United Nations, 2020. Emissions Gap Emissions Gap Report 2020.
Vanegas Cantarero, M.M., 2020. Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. Energy Res. Soc. Sci. 70, 101716 https://doi.org/10.1016/j.erss.2020.101716.
Vogt-Schilb, A., Walsh, B., Feng, K., di Capua, L., Liu, Y., Zuluaga, D., Robles, M., Hubaceck, K., 2019. Cash transfers for pro-poor carbon taxes in Latin America and the Caribbean. Nat Sustain 2, 941–948. https://doi.org/10.1038/s41893-019-0385-0.
Wang, R., Assenova, V.A., Hertwich, E.G., 2021. Energy system decarbonization and productivity gains reduced the coupling of CO2 emissions and economic growth in 73 countries between 1970 and 2016. One Earth 4 (11), 1614–1624.
Wang, H., Feng, K., Wang, P., Yang, Y., Sun, L., Yang, F., Chen, W.-Q., Zhang, Y., Li, J., 2023. China's electric vehicle and climate ambitions jeopardized by surging critical material prices. Nat. Commun. 14, 1246. https://doi.org/10.1038/s41467-023-36957-4.
Wang, W., Yang, F., Guo, Y., Chen, B., Zou, X., Zhou, S., Li, J., 2022. The effects of the Promoting the Big and Quashing the Small Policy on pollutants from a coal power supply chain perspective. J. Environ. Manage. 313, 114960 https://doi.org/10.1016/j.jenvman.2022.114960.
Wei, L., Li, C., Wang, J., Wang, X., Wang, Z., Cui, C., Peng, S., Liu, Y., Yu, S., Wang, L., Shi, Z., 2020. Rising middle and rich classes drove China's carbon emissions. Resour. Conserv. Recycl. 159, 104839 https://doi.org/10.1016/j.resconrec.2020.104839.
Wiedenhofer, D., Guan, D., Liu, Z., Meng, J., Zhang, N., Wei, Y.M., 2017. Unequal household carbon footprints in China. Nat. Clim. Chang. 7, 75–80. https://doi.org/10.1038/nclimate3165.
Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J.H., Merciai, S., Tukker, A., 2015. Global sustainability accounting-developing EXIOBASE for multi-regional footprint analysis. Sustainability (Switzerland) 7, 138–163. https://doi.org/10.3390/su7010138.
Xia, C., Zheng, H., Meng, J., Li, S., Du, P., Shan, Y., 2022. The evolution of carbon footprint in the yangtze river delta city cluster during economic transition 2012–2015. Resour. Conserv. Recycl. 181, 106266 https://doi.org/10.1016/j.resconrec.2022.106266.
Yang, F., Jia, L., Zhou, Y., Guan, D., Feng, K., Choi, Y., Zhang, N., Li, J., 2022. Life cycle assessment shows that retrofitting coal-fired power plants with fuel cells will substantially reduce greenhouse gas emissions. One Earth 5, 392–402. https://doi.org/10.1016/j.oneear.2022.03.009.
Zheng, H., Meng, J., Mi, Z., Song, M., Shan, Y., Ou, J., Guan, D., 2019a. Linking city-level input–output table to urban energy footprint: Construction framework and application. J. Ind. Ecol. 23, 781–795. https://doi.org/10.1111/jiec.12835.
Zheng, H., Zhang, Z., Zhang, Z., Li, X., Shan, Y., Song, M., Mi, Z., Meng, J., Ou, J., Guan, D., 2019b. Mapping Carbon and Water Networks in the North China Urban Agglomeration. One Earth 1, 126–137. https://doi.org/10.1016/j.oneear.2019.08.015.
Zheng, H., Zhang, Z., Wei, W., Song, M., Dietzenbacher, E., Wang, X., Meng, J., Shan, Y., Ou, J., Guan, D., 2020. Regional determinants of China's consumption-based emissions in the economic transition. Environ. Res. Lett. 15 (7), 074001.
Zheng, H., Long, Y., Wood, R., Moran, D., Zhang, Z., Meng, J., Feng, K., Hertwich, E., Guan, D., 2022a. Ageing society in developed countries challenges carbon mitigation. Nat. Clim. Chang. 12, 241–248. https://doi.org/10.1038/s41558-022-01302-y.
Zheng, H., Többen, J., Dietzenbacher, E., Moran, D., Meng, J., Wang, D., Guan, D., 2022b. Entropy-based Chinese City-level MRIO table Framework. Econ. Syst. Res. 34 (4), 519–544.
Zhong, H., Feng, K., Sun, L., Cheng, L., Hubacek, K., 2020. Household carbon and energy inequality in Latin American and Caribbean countries. J. Environ. Manage. 273, 110979 https://doi.org/10.1016/j.jenvman.2020.110979.