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Original research article

Achieving emission reductions without furthering social inequality: Lessons from the 2007 economic crisis and the COVID-19 pandemic

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ABSTRACT

To meet global climate goals, such as limiting global warming to 1.5° Celsius, urgent and substantial reductions of greenhouse gas emissions are needed. From a consumption-based perspective, such measures include a radical reduction of emissions from private households. Despite this urgency, attention must be paid to achieve such reductions without furthering social inequalities. To address these issues, this research looks at consumption-based greenhouse gas emissions of UK households longitudinally, with a particular focus on changes that occurred after the 2007/08 economic crisis and the 2020 COVID-19 lockdowns. Analysing these two events allows us to learn how emissions from different social cohorts are impacted by external shocks, providing a learning for policy. We find significant ($p < 0.05$) differences in the relationships between income and emissions of some age and income groups, as well as substantial descriptive differences between how age and income groups are impacted at a product-level. Importantly, we also find that despite existing levels of carbon inequality, substantial emission reductions are needed for all social cohorts assessed. However, to avoid further increasing existing inequalities and to make policies more effective, we propose interventions targeted at specific social cohorts. While an income reduction may reduce emissions of high-income households, increased access to high quality housing and public services may help reduce emissions of low-income households, whose emissions are already decoupled from income. Finally, age and income-specific interventions targeting specific consumption categories may reduce the impact of rebound effects, as well as reduce emission overall.

1. Introduction

To limit global warming to 1.5 °C, reaching net-zero greenhouse gas (GHG) emissions by 2050 is necessary [1–3]. To achieve these goals and ensure decent living standards, technological advances, such as high-quality, well-insulated housing, must be paired with radically reduced consumption, and an increased focus on public goods and services, such as public transport [4,5]. In part, therefore, demand-side mitigation has become an increased focus of emission research [6]. Indeed, research shows that GHG emissions can be decreased substantially by decreasing demand [7–10]. Such approaches aim to reduce or redistribute emissions by changing consumption patterns. As economic systems of production and consumption continue to grow apart geographically, due to global supply chains, investigating such demand-side perspectives is necessary for understanding countries' contributions to global emissions [11]. For this, consumption-based accounting can be used. This attributes emissions by final demand, rather than by where they are produced [12–15] and includes indirect emissions from the production of goods and services throughout the global supply chain, and direct emissions from burning fuel.

From a consumption-based perspective, for the global average private households to live within planetary boundaries, the global average per capita footprint needs to reduce to 2.5–3.2 tCO_2e by 2030 and to 0.7–1.4 tCO_2e by 2050 [16,17]. In contrast, the 2019 consumption-based GHG footprint of households is around 9 tCO_2e/capita [18]. For UK households, this means compared to 2019 levels, reductions of 65–72 % are needed by 2030, and 85–92 % by 2050. This means a reduction of around 8 % each year, which, in the UK is observed following the 2007 economic crisis and the 2020 COVID-19 lockdowns [18]. While some of these reductions can come from improved energy efficiency and technological improvements, the necessary reductions cannot come from these technological shifts alone [19–21]. In line with this, the latest IPCC report highlights that up to 70 % of GHG reductions until 2050 can come from changes in lifestyle and behaviours [3]. In this

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research, therefore, we focus on the impacts of consumption.

When studying the 2007 economic crisis and the 2020 COVID-19 lockdowns, attention must be paid to social factors [22,23]. This is important as the impacts on different types of households of these crises are vastly uneven, with some households being more affected by these crises than others. Indeed, a recent systematic review finds that distributional impacts of energy transitions are frequently overlooked in the literature [24]. Studying these events in light of their social and environmental impacts can therefore help our understanding of how sizable emission reductions can be achieved while satisfying decent living standards and needs for all and without further increasing existing carbon inequalities. In this article we look at social inequality through the lens of income and carbon inequalities.

When aiming to analyse consumption changes following the economic crisis and the lockdowns, it is important to consider the social impacts of these events. The 2007/08 economic crisis has wide-reaching effects on UK households. Between the first quarter of 2008 and the second quarter of 2009, the UK's GDP saw a 6 % decrease [25]. In the same timeframe, unemployment increased from 5.2 % to 7.8 %, reaching its peak in 2011 [25]. Other consequences of the economic crisis include increased debt [26], decreased consumer spending [27], increased income inequality, and lower median wages [28]. A report on the effects of the crisis on UK households finds that economic effects differ between households: where people in their 20s are more strongly impacted by the economic crisis, pensioners and children are found to be more protected [28]. Moreover, UK research reports increased impacts of the crisis and the subsequent austerity politics on minorities including non-White ethnic groups [29] and disabled people [30].

The COVID-19 pandemic, on the other hand, triggered lockdowns beginning in March 2020 across the UK, which included restrictions on social life, mandates to work and school from home where possible, the temporary closure of non-essential shops and services, and travel restrictions [31]. Although measures differed between England, Northern Ireland, Scotland, and Wales, all countries had some lockdown procedures in place. Economically, the pandemic meant decreased incomes for some households and increased unemployment, especially for low-income households [32] and non-pensioner groups [33]. People from different age groups are also found to be impacted differently, with those aged under 30 reporting decreased income at greater rates than other age groups [32] and those aged 70 or older asked to reduce social contacts even further than other age groups [34]. The UK's Office for National Statistics [35] reports changes in consumption patterns, such as a decrease in consumer spending by over 20 % from the first to the second quarter of 2020, where transport, hospitality, and recreation saw some of the largest reductions [35], and increased economic uncertainty [36]. Finally, home-schooling and losing access to free school meals has increased job-related and financial burdens on working parents and low-income households [37].

Although the lockdowns disrupted wellbeing and increased inequalities [38] and, therefore, do not provide a suitable blueprint for climate policy [39], they highlight the drastic impact behaviour change can have on emissions [40]. Hence, analysing patterns of consumption change can provide a lesson of where and how consumption-based emissions can be reduced and of the social consequences of such efforts. Moreover, as the recession and lockdown are very different, with the lockdowns implementing mobility restrictions, comparing these two events allows for a broader understanding of the impact of different types of policies. Recently published data in the UK allows, for the first time, for such an analysis.

Similarly, understanding how income reductions shape emissions of different household types can be critical. Social inequalities in energy use and consumption-based carbon emissions are well-established in the literature [41–47] and high income is frequently seen as a key driver for higher consumption-based emissions [48–53]. Moreover, age is shown to play an important role in consumption-based emissions due to changes in expenditure patterns and behaviours [54,55]. Other social factors that have been linked to consumption-based emissions include urban-rural divisions [56–58], proximity to public transport infrastructure [45,59], and household size [42,60].

As various age and income groups were affected differently by both the economic crisis and the lockdowns, understanding their different consumption changes can reveal how these groups may react differently to different types of policy. Indeed, a recent review of policy implications highlights the need for consumption-based emissions approaches to discuss rebound effects,[1] sustainable consumption patterns, and population-specific policies [61]. Incorporating age and income structures into this research can reveal household differences of where emissions decrease with income changes and economic uncertainty and where they remain stable or increase. Such results can inform not only how emissions can be reduced by targeting different types of interventions at different groups, but also shines light on social consequences of such interventions. Attention needs to be paid that energy and carbon reduction effort should first target those with the highest emissions, and not further marginalise vulnerable groups. Despite this, climate policies often disproportionately affect lower income households [43,62]. Thus, understanding the goods and services different types of households consume at different income levels is key to understanding how policy can reduce emissions of those emitting the most. In light of evidence suggesting that major societal, economic, and cultural changes are needed to reduce energy use and emissions sufficiently [19–21], understanding the social context within which such changes occur is vital to design effective and socially just climate policy.

To address how emission patterns of income and age groups are impacted by changes in income as well as by the recession and lockdowns, we ask the following research questions:

1. Do links between product-level consumption-based emissions and income differ for age and income groups?
2. How are patterns of consumption-based emissions of different age and income groups affected by the recession and lockdowns?
3. What can be learned from the recession and lockdowns for how effective climate policy can be achieved without furthering social inequalities?

To answer these, we analyse changes before and after the 2007/08 economic recession and before and after the 2020 lockdowns to assess how emissions change with income reductions, economic uncertainty, and government mandated lifestyle changes. We use this analysis to assess how emission reductions can be achieved without furthering social inequalities. While this research analyses UK data at two specific points in time, our discussion focuses on what can be learnt from these events for emission reductions policy. Moreover, as, age and income-related patterns of emissions are reported internationally [20,48–50,52,58,63], the findings from this research are applicable beyond the UK context.

2. Methods and data

This section outlines the data and methods used in this research. This is split into two further sub-sections. The first of these (Section 2.1) outlines the data and methods needed to estimate consumption-based GHG emissions of households in the current study. As well as an overview of the method and data used to estimate subnational emissions, this section provides an overview of how emissions are disaggregated by different types of households. A detailed diagram of how these datasets are combined is shown in Appendix A. Section 2.2, on the other hand, describes the methods used to calculate elasticities. This is described in

[1] We look at rebound effects as emission increases in one area, which are paired with decreases in other areas. However, causality cannot be inferred in the current research.

more detail in Section 2.2, but essentially provides an estimate of how emissions change with increased income. Elasticities are calculated in this paper to assess the relationships between income and emissions, to provide context for the analysis of emission changes following the recession and lockdowns.

2.1. Household emissions: data and methods

2.1.1. Estimating consumption-based emissions

We estimate emissions for all consumption linked to UK households. Consumption-based emissions include direct emissions associated with burning fuels directly, such as by driving and heating, and indirect emissions that occur throughout the global supply chain to produce goods and services which are consumed by UK households. Emissions are estimated for all household goods and services including, but not limited to, those linked to food, transport, leisure expenditure, housing, utilities, health, and financial and insurance services.

To estimate these emissions, we use data on household expenditure, as well as product-based multipliers (in tCO_2e/£). Such multipliers also incorporate both indirect and direct emissions. To calculate these multipliers, we use the UK's multi-regional input-output model (UKMRIO). This contains financial interrelationships between different industries, both domestically and globally, as well as environmental pressure data by industry for each year analysed [64–66]. The GHGs reported in the UKMRIO include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride. All GHGs are converted into their carbon equivalent using UKMRIO reference data.

To calculate the multipliers, we first need to estimate the total indirect consumption-based emissions from UK households using environmentally-extended multi-regional input-output (EEMRIO) analysis. Input-output models originate in economics, but have been applied to environmental pressure data since the 1960's [67–69]. An EEMRIO, links global economic input-output data with environmental pressure data, to estimate embodied emissions or energy [12,13,70,71]. Input-output analysis is integrated into the United Nation's central framework of systems of environmental-economic accounting [72]. More detail on the history and future of input-output analysis can be found in the literature [12–14,73].

The Leontief input-output model reports the economic interrelationships between industries throughout the supply chain, by documenting monetary inputs and outputs between industries [74,75]. The fundamental Leontief equation, $\mathbf{d} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}$, indicates the inter-industry requirements of each sector to deliver a unit of output ($\mathbf{x}$) to final demand ($\mathbf{y}$), where $\mathbf{A}$ is the technical coefficient matrix, $\mathbf{A} = \mathbf{Z}\mathbf{x}^{-1}$. Here, $\mathbf{I}$ is the identity matrix with the same dimensions as the input-output matrix ($\mathbf{Z}$). Adding environmental extension data to this, indirect emissions ($\mathbf{p}$) can be estimated, as shown in Eq. (1); $\mathbf{s}$ is a vector showing direct industry emissions,

$$\boldsymbol{p} = \boldsymbol{s}(\boldsymbol{I}-\boldsymbol{A})^{-1}\widehat{\boldsymbol{y}} \tag{1}$$

After indirect emissions are estimated, we add direct household emissions to the products associated with fuel burning. Further detail on both EEMRIO analysis [74,75] and on the UKMRIO model [76–78] can be found in the literature. Moreover, the detailed methodology of the UKMRIO model, as well as a detailed description on which emissions are included under 'consumption-based emissions' are published via the Department for Environment Food & Rural Affairs [79].

Once total household emissions are calculated at a product-level, we can divide these emissions by the total spend of UK households for each product. This generates conversion factors in tCO_2e/£, which can then be multiplied by individual household spends to estimate emissions. We use data on household spend from the Living Costs and Food Survey (LCFS) [80–98]. The LCFS is an annual survey recording full expenditure, for all products and services consumed by a household during the survey period, from 4000 to 6000 private UK households [99]. In addition to containing household spends at a detailed product level, the LCFS also contains household weights. Essentially, these weights provide an overview of how many households in the UK are comparable to the household completing the survey. This weight allows us to estimate expenditure for all UK households. More information on the LCFS is available via the Office for National Statistics [99].

Moreover, as the LCFS contains information on the number of flights taken by each household, as well as the number of rooms available, expenditure on flight and rent are redistributed using these physical units. This is done to reduce the uncertainty introduced by using expenditure to estimate emissions for products and services with high price differences [77,100]. More information on this uncertainty is detailed in Section 4.4.

For the level of product-detail, we choose the Classification of Individual Consumption by Purpose (COICOP) 4 level [101] to classify our products and services, as both the UKMRIO and the LCFS contain bridging tables to allow for easy and consistent conversion into COICOP.

2.1.2. LCFS demographic variables

To provide an overview of the socio-demographic make-up of the LCFS, we summarise the LCFS from 2001 to 2019 in Table 1. Importantly, age ranges of HRPs appear to be similar to mean ages of all adults in the households for all groupings. Thus, analysing households by the age of their HRP should also give an indication of age differences overall. However, socio-demographic variables in the LCFS from 2001 to 2019 show slight differences in demographics between groups. For instance, households with a household reference person (HRP) in both the youngest and oldest age range have around 10 % more females, on average. Households with older HRPs and those in higher income deciles have larger dwellings for fewer people. Households with HRPs under the age of 50 are more likely to have minors in the household. Similarly, households in higher income deciles are less likely to have minors and tend to have fewer people in them.

To compare household types we weigh the number of people in a household by their household composition, as suggested by Gough et al. [102]. We calculate emissions per single adult person household (SPH) by using the OECD-modified scale, which accounts for the non-proportional relationship between additional household members and income or expenditure. This assigns a weighting of 1 for the first adult, 0.5 for every other adult, and 0.3 for every child [103]. Thus, equivalised results reported are not in tCO2e/capita, but instead in tCO2e/SPH. We choose this scale as it is the one used by the UK's Office for National Statistics. As differences in household sizes and compositions are shown to be linked to carbon emissions [60,104], controlling for this effect is important for comparing other variables.

2.1.3. Longitudinal comparison

For the longitudinal comparisons we calculate two sets of emission estimates. First, we calculate emissions using the UKMRIO and LCFS from the same year to estimate emissions for each year. Second, we calculate emission estimates using the 2007 multipliers. This year was chosen as it captures consumption directly before the financial crisis. Using multipliers from the same year allows us to isolate the impact of consumption changes on GHG emissions. This allows for a more direct comparison of consumption behaviours and the emissions these would have caused in 2007. To ensure that inflation and price changes over time do not impact our results, we adjust income and expenditure to 2007 values. We do this at a product level using the Consumer Price Inflation tables from the Office for National Statistics [105]. A product matching table is provided in the Supplementary Materials.

For electricity and gas use, we adjust the prices in the LCFS, by physical data on household energy consumption [106]. As gas and electricity produce some of the highest consumption-based footprints and can fluctuate hugely in price, using physical units to estimate total use reduces the uncertainty of our analysis [77].

Table 1
Demographic summary from LCFS 2001–2019.

		Number of households in survey	Number of households in survey (%)	Number of households in UK (%)	Mean age of HRP	Mean age adults	Mean age minors	Mean household size (not equivalised)	Mean household size (OECD mod. scale)	Mean number of adults in household (%)	Mean number of females in household (%)	Mean number of rooms in household
	All	112,571	100.00	100.00	52.10	47.73	8.54	2.36	1.48	78.20	50.81	5.44
Age of HRP	<18	31	0.03	0.03	14.53	34.14	11.87	2.08	1.31	29.35	60.59	4.07
	18–29	9533	8.47	9.88	25.54	25.84	3.73	2.40	1.49	76.77	50.23	4.61
	30–49	41,543	36.90	36.71	39.90	37.92	8.63	2.98	1.69	63.61	49.85	5.46
	50–64	30,430	27.03	26.32	56.69	50.06	12.41	2.26	1.51	90.57	49.43	5.74
	65–74	23,533	20.91	19.30	71.45	67.49	10.87	1.69	1.22	98.63	53.11	5.51
	75+	7501	6.66	7.75	80.17	77.75	10.53	1.37	0.99	99.62	62.67	5.13
Income Decile	Lowest	11,266	10.01	9.73	52.08	47.99	8.06	2.62	1.59	72.82	51.26	5.18
	2nd	11,254	10.00	9.60	54.96	51.22	8.09	2.44	1.48	72.96	52.95	5.10
	3rd	11,254	10.00	9.68	55.32	50.86	8.22	2.41	1.48	74.41	52.37	5.17
	4th	11,253	10.00	9.80	56.21	51.02	8.51	2.30	1.42	75.96	53.15	5.12
	5th	11,252	10.00	9.88	54.87	49.40	8.61	2.35	1.46	77.88	52.26	5.27
	6th	11,262	10.00	9.95	52.60	47.46	8.76	2.42	1.51	78.25	51.18	5.40
	7th	11,254	10.00	10.10	51.09	46.13	8.98	2.41	1.52	80.25	50.29	5.51
	8th	11,253	10.00	10.32	49.78	45.04	9.01	2.40	1.53	82.05	49.23	5.67
	9th	11,243	9.99	10.41	47.68	43.89	9.04	2.34	1.50	82.62	48.20	5.86
	Highest	11,280	10.02	10.53	47.29	45.58	8.66	1.96	1.30	85.55	47.04	5.99

2.1.4. 2020 data

At the time of writing the detailed, household-level LCFS is not yet published. However, versions of the LCFS expenditures and incomes are available via the Office for National Statistics. To estimate 2020 emissions, we therefore use such aggregated LCFS data [107]. The levels of aggregation available include age of the Household Reference Person (the person answering the survey), income decile, and all households. To ensure consistency with the household-level LCFS, and the aggregation done for the other years, we calculate the ratios of 2019 and 2020 aggregated data at a product level for each income decile and age group, and then multiply the 2019 household-level LCFS data by these ratios.

Income data are also available in aggregated form [108]. We similarly adjust aggregated 2019 incomes by the proportional differences between the 2019 and 2020 income data available. Finally, household age groups for income differ to household age groups of expenditure. We therefore use the nearest age range to infer income; a matching table is shown below (Table 2).

2.2. Elasticities

We calculate income elasticities of GHG emissions to assess the changes in environmental footprints linked to income changes [109]. This elasticity (ε) measures the percentage change of per SPH GHG emissions (f) related to 1 % increase in per SPH household income (i). We calculate these elasticities using Eq. (2).

$$\varepsilon = \frac{\partial f}{\partial i} \times \frac{i}{f} \tag{2}$$

Eq. (2) can be transformed into a univariate regression model using natural logarithm transformation, with the two constants a and ε and an error term (u), as shown in Eq. (3).

$$lnf = a + \varepsilon lnf + u \tag{3}$$

3. Results

3.1. Consumption-based emission patterns of UK households

In order to contextualise the impacts of the recession and lockdowns, we first provide an overview of mean emissions from 2001, as well as their links to income. Between 2001 and 2019, we find emission reductions by over a third per SPH. However, when isolating changes in consumption patters, by using 2007 prices and multipliers for all years, this reduction decreases to 11.65 %. Additionally, emission estimates and income means from 2001 to 2020 point to differences between households (Fig. 1). The results show large income inequality between the highest and lowest deciles, where the mean income of those in the highest income decile is more than seven times as high as the mean income of households in the lowest income decile. Similarly, emissions of the lowest decile are less than half of the emissions of the highest decile, even after household size equivalisation. Especially transport and recreational products appear to increase strongly with income. Despite these differences, when considering average consumption between 2001

Table 2
Income age groups used for 2020.

HRP age in 2020 data	Group assigned in analysis
0–17	<18
18–24	18–29
25–34	–
35–44	30–49
45–54	–
55–64	50–64
65–74	65–74
75–84	75+
85+	–

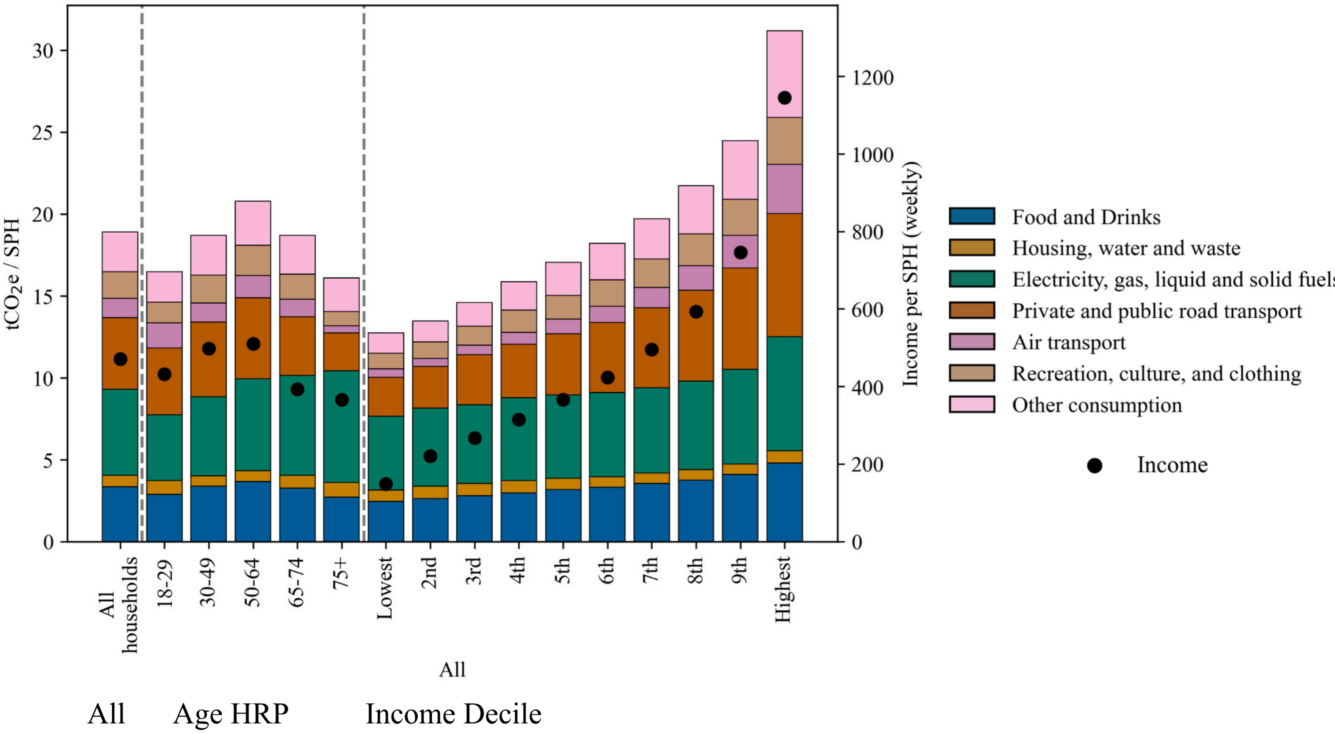

Fig. 1. Mean product-level emissions and incomes by household type for the years 2001–2020.

and 2020, a single occupant household in the lowest income decile still has emissions that are 10–20 times as high[2] as the 0.7–1.4 tCO_2e/capita target set for 2050 [16,17]. While this is notably lower than the 25–50 times as high emissions the highest income decile show for SPHs, this finding shows the need to substantially reduce emissions for all household groups. Research suggests that such reductions require a combination of existing technologies, such as high-quality, well-insulated housing, radically reduced consumption, and an increased focus on public, shared goods and services [4,5].

We also find age group differences. Households with HRP aged 18–29 have some of the lowest total emissions (16.45 tCO_2e/SPH), but the highest emissions from air transport (1.53 tCO_2e/SPH), compared to other age groups. Households with HRP aged 75+, on the other hand, have the lowest emissions from all transport combined (2.75 tCO_2e/SPH), but the highest emissions from electricity and gas use (6.80 tCO_2e/SPH). This indicates different consumption patterns between age groups at a product level, showcasing that targeting specific products and services with emission reduction efforts may be more effective for different age groups. Moreover, this shows that environmental policies influencing prices affect various social cohort differently, hence, highlighting the importance of equity considerations.

3.2. Income and emissions

To further assess the extent to which emission reductions following the economic and lockdown may be linked to income, we first analyse the relationship between emissions and incomes. For this, we calculate the income elasticities of emissions. These elasticities quantify, as a percentage, the amount of change in emissions per change increase in income. Thus, an elasticity of 1 indicates that with a 1 % increase in income, emissions also increase by 1 %. Moreover, an elasticity of >1 indicates that emissions increase at a faster rate than income, and vice versa. For this analysis we assess data from 2001 to 2019, as 2020 data are not yet available at a detailed enough level.

As shown in Fig. 2, total emissions for all households have an elasticity of 0.32–0.56 across the years, however, elasticities vary widely both by product and by household type. As shown in previous research, we also find necessities such as food and drinks [109,110], to be less income elastic than other manufactured products and services, like recreational goods and services and clothing. However, as shown below, these elasticities can vary largely by household type.

Repeated measures ANOVAs reveal significant differences between the elasticities of the groups, for all product types ($p < 0.01$). This means that at least one of the groups is significantly different to one other group in each comparison. To assess where these differences occur, pairwise comparisons are done. For this, paired sample *t*-tests are conducted, with a Bonferroni correction for multiple comparisons. Results are summarised in Table 3 and Table 4; more detailed results can be found in Appendix B.

The highest income decile has lower elasticities for many products than some lower deciles, with statistical significances reported for many products (Table 4). This suggests that reduced income for this decile would reduce emissions from this group at a slower rate than for some lower deciles. The lowest decile, on the other hand, has the lowest elasticities for all emissions, suggesting that the emissions are almost completely decoupled from income.

When looking at elasticities by age group, we find that households with HRPs aged 65–74 or older have more elastic emissions from private and public rail and road transport than other groups. Similarly, with air transport emissions, households with HRPs aged 30–49 have higher income elasticities of air travel emissions than other age groups, with significant differences to both the 18–29 and 75+ groups. As the youngest age group has the highest air travel emissions, this also indicates that air travel emissions reduce less with reduced income for households with HRP aged 18–29.

Elasticities for private and public road and rail transport follow a similar pattern; they increase until the 3rd income decile but decrease after this. Statistically significant differences are found in almost all

[2] It should be noted that this is in tCO_2e/SPH, as well as a longitudinal average, whereas the 0.7–1.4 target is in tCO_2e/capita from 2050.

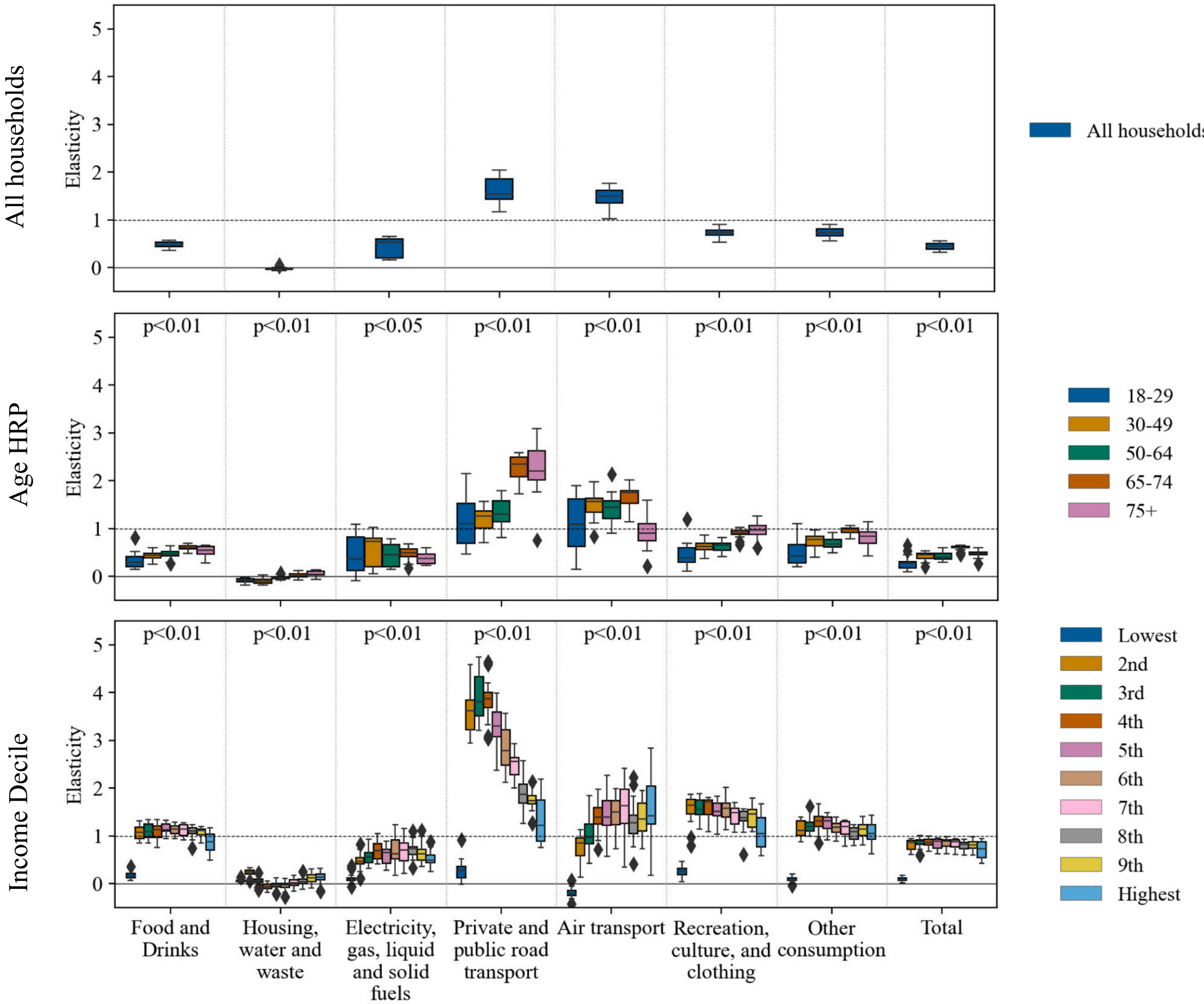

Fig. 2. Boxplots showing income elasticities of emissions for 2001–2019 for all households (top), and by age of the HRP (middle), and income decile (bottom). **Notes: Dotted horizontal line indicates elasticity of 1, meaning that income and emissions increase at the same rate. *P*-values show results from repeated measures ANOVA.

Table 3
Significance testing from paired sample *t*-test results for the elasticities of age groups; a Bonferroni correction is used for multiple comparisons.

	Air transport				Electricity, gas, liquid and solid fuels				Food and Drinks				Housing, water and waste				Other consumption				Private and public road transport				Recreation, culture, and clothing				Total			
	18-29	30-49	50-64	65-74	18-29	30-49	50-64	65-74	18-29	30-49	50-64	65-74	18-29	30-49	50-64	65-74	18-29	30-49	50-64	65-74	18-29	30-49	50-64	65-74	18-29	30-49	50-64	65-74	18-29	30-49	50-64	65-74
30-49	*								*								*								*				*			
50-64													*	*															*			
65-74	*		*						*	*	*		*	*	*		*	*	*		*	*	*		*	*	*		*	*	*	
75+		*	*	*					*	*			*	*	*	*	*		*	*	*	*	*		*	*	*		*			*

**Notes: '*' indicates significance after Bonferroni correction ($p < 0.005$). Data are only displayed in shaded cells.

Table 4
Significance testing from paired sample *t*-test results for the elasticities of income deciles; a Bonferroni correction is used for multiple comparisons.

Air transport	Lowest	2nd	3rd	4th	5th	6th	7th	8th	9th
2nd	*								
3rd	*								
4th	*	*							
5th	*	*							
6th	*	*							
7th	*	*	*						
8th	*	*							
9th	*	*							
Highest	*	*							

Electricity, gas, liquid and solid fuels	Lowest	2nd	3rd	4th	5th	6th	7th	8th	9th
2nd	*								
3rd	*								
4th	*								
5th	*								
6th	*								
7th	*								
8th	*	*							
9th	*								
Highest	*							*	*

Food and Drinks	Lowest	2nd	3rd	4th	5th	6th	7th	8th	9th
2nd	*								
3rd	*								
4th	*								
5th	*								
6th	*								
7th	*								
8th	*								
9th	*				*		*		
Highest	*	*	*	*	*	*	*	*	*

Housing, water and waste	Lowest	2nd	3rd	4th	5th	6th	7th	8th	9th
2nd	*								
3rd		*							
4th	*	*	*						
5th	*	*	*						
6th	*	*	*						
7th		*		*		*			
8th		*		*	*	*	*		
9th		*		*	*	*	*		
Highest				*	*	*	*	*	

Other consumption	Lowest	2nd	3rd	4th	5th	6th	7th	8th	9th
2nd	*								
3rd	*								
4th	*	*							
5th	*								
6th	*			*					
7th	*								
8th	*		*	*	*				
9th	*			*	*				
Highest	*		*	*	*				

Private and public road transport	Lowest	2nd	3rd	4th	5th	6th	7th	8th	9th
2nd	*								
3rd	*	*							
4th	*								
5th	*		*	*					
6th	*	*	*	*	*				
7th	*	*	*	*	*	*			
8th	*	*	*	*	*	*	*		
9th	*	*	*	*	*	*	*		
Highest	*	*	*	*	*	*	*	*	*

Recreation, culture, and clothing	Lowest	2nd	3rd	4th	5th	6th	7th	8th	9th
2nd	*								
3rd	*								
4th	*								
5th	*								
6th	*								
7th	*		*						
8th	*	*	*	*	*	*			
9th	*								
Highest	*	*	*	*	*	*	*		*

Total	Lowest	2nd	3rd	4th	5th	6th	7th	8th	9th
2nd	*								
3rd	*								
4th	*								
5th	*								
6th	*								
7th	*								
8th	*		*	*	*				
9th	*								
Highest	*	*	*	*	*	*	*		

**Notes: '*' indicates significance after Bonferroni correction ($p < 0.001$). Data are only displayed in shaded cells.

pairwise comparisons ($p < 0.001$; see Table 4). This may be due to transport emissions initially increasing a lot with daily needs, but in higher income deciles, where such needs are covered, having a lower rate of increase relative to the increase in income. This mirrors findings from the wellbeing literature, which shows an inverse exponential relationship between needs satisfaction and energy use [111–114].

For air transport higher deciles show higher elasticities indicating that the rate of emissions relative to income increases with higher incomes. As this is the category with the highest carbon intensity,[3] it is important to focus on the reduction of flights of high-income households. Indeed, UK research shows that carbon inequality from air travel also remains high [115], while globally, it is estimated that only 20 % of the population have access to air travel [116]. Our findings also mirror previous suggestions by Larsson et al. [117] to reduce aviation emissions through an price-based or carbon-tax approach, such as a distance-based flight tax.

3.3. Recession vs. lockdown differences

To evaluate the impacts of the 2007 financial crisis and the 2020 lockdowns on emissions, we compare emissions before and after these events. To ensure that we measure only the changes in consumption patterns, we assess only the emissions calculated using 2007 multipliers and prices in this analysis. Thus, the incomes and emissions presented in this section show the emissions consumption patterns from the years 2009, 2019, and 2020 would have produced in 2007. Incomes are also adjusted by inflation to 2007 values. The number described in this section therefore reflect the changes in emissions which are due to a change in consumption. Values using own year prices and multipliers can be found in Appendix D.

As shown in Table 5, both between 2007–2009 and 2019–2020 emissions reduced for the mean UK household, as well as for most household groups. When using 2007 multipliers, the emission reductions following the 2007 recession are only 3.88 % for the average household, notably less than the annual 8 % necessary to meet climate goals. In contrast, when using multipliers and prices from 2009, total reduced by almost 16 % over 2 years, thus meeting the necessary reductions. We conclude that reductions in emissions following the 2007 economic crisis are in part due to consumption, and in part due to increased energy efficiency in production. To maintain similar levels of emissions reductions until emissions are at 85–92 % below 2019 levels [16,17], much larger changes in consumption are needed [19,20].

However, for all households and most household groups, emissions show a proportional reduction greater than the reduction in income, suggesting a reaction in consumption to the changed incomes. Findings for the 9th and 10th income deciles indicate a reduction in income of below 3 %, but a reduction in total emissions of over 6 %. Investigating the reduction patterns of these households in more detail may, therefore, give an indication of the types of consumption patterns needed to reduce emissions from these households near the reduction levels necessary. Notably, however, the 75+ age group shows an increase in emissions following the recession.

On the other hand, reductions from consumption changes following the COVID-19 lockdowns are 20.67 %. Thus, a change in consumption was able to achieve sufficient emission reductions in 2020. However, proportional reductions differ between groups, and the highest income decile has the lowest reduction in total emissions, while the lowest income decile has the highest proportional reductions. This shows that while overall emission reduction goals are met, carbon inequality increased, indicating that this reduction comes at the cost of social equity.

The patterns of product-level details vary between the two events as well as between household groups (Table 6). Between the years 2007 and 2009 we find emission reductions for all consumption categories, except recreation, culture, and clothing. This 10.26 % increase in recreation, culture, and clothing is particularly driven by higher income deciles, as well as by those with HRP aged 30–64. Findings from the two highest income deciles reveal high levels of reductions in emissions from

[3] Carbon intensities refer to the amount of carbon needed per unit spend. Product-level intensities can be found in Appendix C.

Table 5
Percentage differences in per SPH income and total emissions between 2007 and 2009 and 2019–2020.

		2007-2009				2019-2020			
		Total tCO_2e/SPH		Weekly income		Total tCO_2e/SPH		Weekly income	
		Not adjusted	2007 Multiplier	Not adjusted	2007 Value	Not adjusted*	2007 Multiplier	Not adjusted	2007 Value
	All	-15.88	-3.88	3.50	-2.24	-24.08	-20.67	0.03	-0.80
Age HRP	18-29	-14.26	-2.20	0.30	-5.26	-24.72	-17.48	1.40	0.56
	30-49	-17.02	-4.08	3.16	-2.56	-22.02	-16.61	-0.46	-1.28
	50-64	-17.79	-6.13	3.67	-2.08	-24.90	-21.47	7.06	6.18
	65-74	-12.22	-1.52	9.63	3.55	-24.54	-25.44	0.05	-0.78
	75+	-5.31	3.81	4.54	-1.25	-15.99	-17.28	11.43	10.51
Income	Lowest	-12.18	-1.28	7.23	1.29	-31.40	-30.49	-12.68	-13.41
	2nd	-14.18	-4.22	6.65	0.74	-24.49	-21.64	-0.15	-0.97
	3rd	-18.65	-8.27	4.29	-1.49	-19.90	-20.25	0.98	0.14
	4th	-14.95	-4.02	4.61	-1.19	-24.99	-23.91	1.35	0.51
	5th	-14.48	-3.21	3.35	-2.38	-22.20	-20.03	3.30	2.45
	6th	-14.02	-2.44	2.20	-3.46	-18.69	-6.99	1.51	0.67
	7th	-15.77	-3.72	2.42	-3.25	-26.18	-24.01	0.75	-0.09
	8th	-11.31	2.28	3.27	-2.45	-29.45	-25.38	1.11	0.27
	9th	-18.06	-6.15	3.13	-2.59	-23.10	-20.04	1.14	0.30
	Highest	-20.59	-6.50	3.65	-2.10	-16.34	-13.50	-1.55	-2.37

**Notes: This shows the change in the later year's values compared to the earlier year's values as a percentage, calculated: ($Emissions_{Year\ 2}$ – $Emissions_{Year\ 1}$) / $Emissions_{Year\ 1}$. Thus, negative values show a reduction, while positive values show an increase in emissions or income over time. Darker blue indicates a greater reduction, white indicates no change, dark red indicates a greater increase. (*) For 2019–2020 tCO_2e/SPH 2020 values use 2019 multipliers.

Table 6
Percentage differences in per SPH income and emissions between 2007–2009 and 2019–2020; emissions and incomes are estimated using 2007 prices and multipliers.

			Food and Drinks	Housing, water, and waste	Electricity, gas, liquid, and solid fuels	Private and public road transport	Air transport	Recreation, culture, and clothing	Other consumption
2007-2009		All	-6.20	-1.36	-4.56	-3.17	-12.40	10.26	-7.05
	Age HRP	18-29	-14.59	8.28	-4.83	0.02	0.21	-3.21	11.09
		30-49	-5.21	-0.38	-6.70	-4.37	-12.58	18.18	-9.66
		50-64	-6.54	-4.12	-6.57	-5.28	-16.56	10.04	-11.86
		65-74	-3.25	-6.40	-1.52	10.37	-17.33	-2.13	-8.21
		75+	-3.76	-3.81	8.76	-21.66	8.68	-9.53	42.03
	Income decile	Lowest	-12.07	2.80	0.86	16.87	-18.12	-13.84	-3.04
		2nd	-6.46	-2.74	-7.55	4.97	3.49	-3.62	-9.66
		3rd	-5.08	6.47	-8.07	-17.76	-31.82	11.45	-8.75
		4th	-6.22	-4.38	-2.47	-0.50	-19.72	23.31	-20.29
		5th	-8.42	2.34	-3.75	-6.51	14.33	5.02	-2.20
		6th	-0.74	-3.29	-4.03	-5.59	-22.18	8.94	6.07
		7th	-14.63	-1.03	-1.83	-0.95	-2.05	-16.45	10.51
		8th	-4.85	-3.80	3.82	7.68	-11.83	14.40	-1.85
		9th	-4.33	-7.82	-10.67	-5.20	-14.19	23.31	-14.62
		Highest	-1.68	-2.88	-9.22	-11.57	-14.63	32.70	-14.74
2019-2020		All	-16.97	-6.03	-0.42	-38.77	-69.14	-9.84	-16.19
	Age HRP	18-29	-13.83	50.24	0.89	-42.93	-77.92	19.65	-4.07
		30-49	-16.86	-0.34	0.66	-35.05	-64.88	2.88	-4.54
		50-64	-18.96	-26.28	1.24	-40.82	-65.44	-13.93	-9.07
		65-74	-14.54	-11.06	-2.37	-35.22	-74.31	-35.08	-38.57
		75+	-5.28	-31.42	-6.69	-35.41	-76.01	-17.63	-22.12
	Income decile	Lowest	-13.20	-32.55	-26.14	-43.39	-79.37	-35.21	-16.46
		2nd	-17.23	-23.41	-17.27	-31.70	-66.37	-2.37	-21.95
		3rd	-7.40	-24.73	-6.35	-32.44	-68.95	-20.28	-26.48
		4th	-9.48	-24.15	-6.41	-37.14	-83.45	-19.47	-31.94
		5th	-13.43	14.20	-0.74	-40.77	-73.65	-18.80	-21.64
		6th	-16.93	-10.15	-1.11	-43.40	-78.32	14.13	59.36
		7th	-21.30	-13.07	0.28	-37.05	-61.99	-14.71	-32.53
		8th	-18.95	24.79	2.13	-43.06	-71.40	-19.41	-27.57
		9th	-18.43	24.80	8.24	-30.38	-64.76	-20.09	-17.34
		Highest	-21.27	19.86	34.46	-39.49	-59.20	24.96	-25.61

**Notes: This shows the change in the later year's values compared to the earlier year's values as a percentage, calculated: ($Emissions_{Year\ 2}$ – $Emissions_{Year\ 1}$)/$Emissions_{Year\ 1}$. This means that negative values show a reduction over time while positive values show an increase in emissions or income over time. Darker blue indicates a greater reduction, white indicates no change, dark red indicates a greater increase.

transport, electricity and gas, and other consumption, some of the highest emitting categories these groups have (see Fig. 1). Income-related policy targeted at these high-income households may, therefore, be helpful in reducing emissions in these high emission categories, which is still greater than the rebound effect of increased emissions from recreation, culture, and clothing.

Between the years 2019 and 2020, on the other hand, we find emission reductions for all consumption categories, except housing and gas and electricity. These increases, are, again driven by higher income deciles. Especially in the lockdown, we find rebound effects for high-income households, but not for low-income households. In part, this may be linked to low-income households also having seen the largest income reduction of all household groups. Thus, while overall reduced emissions may be seen as a positive, carbon inequality between income groups increased further in the lockdown.

Unsurprisingly, given the travel restrictions, emissions from air transport, and road and rail transport decreased by 69.14 % and 38.77 % respectively from 2019 to 2020. However, we also find decreases of over 16 % for emissions from food and drinks, and from other consumption. From 2007 to 2009 the greatest relative reduction is also in air transport (12.40 %), but this is followed by emissions from other consumption (7.05 %). Differences in where households reduce emissions are also notable. For instance, between 2007 and 2009 households with HRP aged 18–29 decrease emissions from food and drinks by 14.59 %, while both air and land transport increase – despite having the highest income reductions. This matches the different air transport elasticities that are observed for this age group in Section 3.2. In contrast the households with HRP aged 75+ decreased land transport by over a fifth, but increased emissions from electricity and gas by 8.76 %. We conclude from this that different age groups prioritise different kinds of consumption and thus may react differently to policy.

4. Discussion

4.1. Do links between product-level consumption-based emissions and incomes differ for age and income groups?

In line with existing findings [109,110], we find increases in incomes to be more strongly associated with increases in emissions from luxury purchases rather than necessities when considering all UK households. However, our research shows that the association between income and consumption-based emissions from different products and services vary by household group, with many of these differences being statistically significant. For instance, emissions from the lowest income decile are much less strongly linked to changes in incomes than for all higher deciles across most products and services. Indeed, we find emissions from the lowest income decile to be almost completely decoupled from income, indicating levels of underconsumption and energy needs not being met. In contrast, for the highest decile we find that proportionally greater reductions in income may be needed to reduce emissions by the same percentage than some of the lower income deciles, indicating a need for targeted interventions for both effectiveness and fairness. In other words, these findings suggests that general income-reduction or tax-based approach, including a general carbon tax, to reducing emissions would be hugely regressive for the lowest income decile and less effective for the highest income decile.

By age groups, we find that income is more strongly linked to transport emissions from the 65–74 and 75+ age groups than other age groups. Moreover, our findings show that households in the 30–49 age group have a stronger relationship between income and air travel emissions, especially when compared to the youngest and oldest age groups. This means that changes in income are expected to affect changes in air emissions most strongly for 30–49 year olds.

We conclude, therefore, that links between income and emissions vary not only by product but also by age and income of a household. Thus, changes in income are expected to have varying impacts on emission patterns of difference social cohorts.

4.2. How are patterns of consumption-based emissions of different age and income groups affected by the recession and lockdowns?

We find that, emission reductions between 2007 and 2009 are only in a small part due to changes in consumption. In contrast, the reductions between 2019 and 2020 indicate sufficiently reduced consumption necessary to meet climate goals [16,17]. However, it is important to keep in mind that the emission reductions in 2020 come at the price of decreased wellbeing and increased inequalities [38]. Assessing the differences between the recession and lockdowns can, however, provide an indication of consumption-emission pattern differences and social inequalities.

Our findings indicate that proportionally for all households combined, emission changes from change in consumption decrease at a higher rate than incomes, for both 2007–2009 and 2019–2020. This points to an effect of income-reductions and economic uncertainty on emissions. Moreover, we find that between 2007 and 2009 the highest income households have the largest proportional reductions, mainly from decreases in high emission products and services including transport, and electricity and gas. This is in line with strong link between income and/or affluence and emissions reported in the literature [20,48–53]. However, our finding adds that emission reductions in high-carbon products and services may be possible, with income reductions and economic uncertainty.

On the other hand, from 2019 to 2020, the lowest income decile saw the greatest proportional reduction in total emissions. Thus, although total emission reductions mirror those needed to meet climate goals, carbon inequality increased in 2020. For example, the lockdowns saw strong reductions in emissions from gas and electricity from lower income households, paired with strong increases in emissions from gas and electricity from higher income households. This centres the need for social equity and fuel poverty in discussions on emission reductions and highlights, once more, that the lockdowns cannot be a blueprint for climate policy [39]. Our findings indicate that lower income households reduced emissions based on necessity, while higher income households saw higher rebound effects.

In line with this, we find specific rebound effects for specific groups. Emissions from recreation, culture and clothing increase for many household types following both events. As these products and services tend to be less carbon intensive than activities that were reduced, like transport, we find an overall reduction of emissions. Furthermore, despite reductions in incomes, young adults appear not to reduce transport emissions following the 2007 economic crisis. Similarly, households with adults aged 65 and older show lower reductions or even increases in emissions from electricity and gas. One reason electricity and gas emissions may be higher for adults aged 65 and older is the higher room-to-person ratio these households have. An income-reduction or tax-based policy, such as a general carbon tax, to reduce emissions may therefore not reduce emissions of some more carbon-intensive activities of some household groups. This reflects the vastly different lifestyles of different age groups and suggest that behaviour change campaigns may be more effective when targeting different age groups with different changes. It may be helpful, therefore, to pair general emission reduction efforts with environmental education targeted at particular age groups, as suggested by Duarte et al. [118] and Wang et al. [119]. Other research indicating that environmental concern and activism can be linked to lower emissions [10,120] support the notion that environmental education and engagement may help reduce household emissions.

The lockdowns also resulted in reduced emissions from food and drinks. Likely, this is due to reduced spending on restaurant meals [35], which can contribute strongly to food emissions [121]. Although further analysis of food-related emissions is needed, our findings suggest that we can learn from food and drink consumption during the lockdowns to reduce household emissions from food and drinks in the future.

4.3. What can be learned from the recession and lockdowns for how effective climate policy can be achieved without furthering social inequalities?

While the current analysis focuses on the UK, age and income-related patterns of emissions are reported throughout the literature internationally [20,48–50,52,58,63]. Thus, the findings from the research as well as the policy recommendations are applicable beyond the UK context.

Our findings suggest that an income-based policy targeting, specifically and exclusively, the highest income households may be able to reduce emissions for some of the highest emission categories. A universal income-reduction or tax-based approach to reducing emissions would be hugely regressive, especially for the lowest income decile. Following the framework of pairing reduced consumption with existing technologies, and increased access to public goods and services [4,5], we conclude that reducing emissions for the lowest income decile requires a strong focus on increasing social equity and providing access to better insulated housing, and public goods and services. This mirrors findings from Büchs et al. [122], that universal vouchers for renewable electricity and public transport, paired with investment into greener infrastructure could not only help reduce emissions, but also decrease levels of fuel and transport poverty. Our findings further support this, by showing that for the lowest income decile incomes and emissions are already fully decoupled. Reducing emissions of households in the lowest income decile, while necessary to meet global emission goals, should therefore not be done by reducing consumption. Instead, increasing access to good quality basic needs, like insulated housing and reliable public transport [4,5], could lead to lower emissions while also increasing access to basic needs; and where energy use and emissions need to be increased to reduce levels of poverty, research shows that such increases are small compared to the reduction potential of households with the highest emissions [123]. Similarly, Duarte et al. [118] argue that an increased shift from private to public transport is the most environmentally efficient policy tested in their scenarios. According to our findings, such a policy would also prioritise reducing emissions of the highest income groups, with the highest transport emissions. Indeed, efforts to reduce consumption need to focus on higher income groups, who have substantially higher emissions than low-income groups.

Findings from the 2020 lockdowns further highlight the need to consider social equity. While emissions reduced by over a fifth between 2019 and 2020, and thus sufficiently meet the 8 % reduction target, proportional emission reductions of the lowest income decile are almost twice as high as that of the highest income decile. This is mirrored by the lowest income decile seeing the highest reduction in income, and points to the need to consider social equity as an integral part of any climate change mitigation policy [122]. As higher paid jobs more frequently had opportunities for telecommuting [38], this finding is not surprising. Thus, while overall reduced emissions may be seen as a positive, carbon inequality between income groups increased further in the lockdown. Despite this, we can learn from emission reduction patterns to design policy which is effective and socially just. For instance, in line with this, our findings support existing evidence that telecommuting [124] where this is possible for people, or a 4-day work week [125–127] can contribute to decreased emissions, but that limiting mobility overall is regressive for lower income households.

To reduce emissions effectively, attention needs to be paid to rebound effects. Existing research warns that reductions in one area may result in increased overall emissions, as people may have more money for more carbon-intensive goods and services [118,128]. While analysing the emission reductions following the 2007 economic crisis and the 2020 lockdowns may not reveal rebound effects fully, as incomes are reduced in both events, we still find patterns of higher emissions for some products. For instance, emissions from recreation, culture and clothing increase for many household types following both events. As these products and services tend to be less carbon intensive than activities that were reduced, like transport, we find an overall reduction of emissions. Moreover, we observe age group-specific rebound effects, where younger age groups appear to prioritise emissions from flights, while older age groups appear to prioritise emissions from gas and electricity use. Interventions targeting the particular consumption patterns of different age groups may therefore be more effective than a general campaign. Moreover, as Duarte et al. [118] suggest, providing environmental education may help reduce some of these rebound effects. Alternatively, Howarth et al. [39] propose that increased citizen engagement could permit behaviour changes to become more accepted and widely practiced, leading to long-term reductions of consumption-based emissions.

The differences and similarities in the impacts of these two events points to the different impacts policies can have. This is specifically notable when comparing rebound effects of both events. Where changes are linked to income reduction and economic uncertainty alone, more household types saw rebound effects in recreational and miscellaneous emissions. When adding government mandated mobility restrictions to such uncertainties, rebound effects occurred more strongly in electricity and gas use. While the distributional impacts of this, of course, are not negligible, this comparison shows how different types of policies, can cause different types of rebound effects.

The similarities of the events can further provide lessons for policies. Despite having the highest emission reductions in the recession, the highest income households have the largest rebound effects following both events. Although rebound effects are in different products and services following the 2007 economic crisis, compared to the 2020 lockdowns, this group most strongly shifts their emissions as a result of these crises. Considering rebound effects of the highest income households, those who need to reduce emissions the most when designing policy, is key to reducing emissions more effectively.

4.4. Limitations

As is common for consumption-based emissions research, this study has various limitations, which are well-documented in the literature. For instance, using expenditure data as a proxy for volume consumed, can lead to uncertainty in the emission estimates [100,129]. Despite this, due to lack of physical data for both MRIOs and subnational microdata, much research relies on financial data to estimate subnational consumption-based emissions [42,130,131]. Moreover, while using household expenditure data to disaggregate national emissions accounts may lead to an underestimation of emissions from low-expenditure households and an overestimation of emissions from high-expenditure households, overall emissions trends remain stable. In addition, to reduce uncertainties from the expenditure microdata, we follow recommendations from the literature [77,100] by using open data and supplementing the financial survey data with physical unit data where possible – for flights and housing.

Secondly, this research relies on aggregated data for 2020, rather than the raw survey result, for data availability reasons. While this poses a limitation to the current research, the impact of this is minimised by, first, using methods of household group aggregation that are the same as the 2020 data, by, second, using expenditure data for 2020 that is also based on the LCFS, and by, third, adjusting the estimates from 2019 by the proportional difference in the aggregated 2019 and 2020 data.

In addition, using the OECD-modifier scale may introduce uncertainty. While the scale is widely used, for example by the UK's Office for National Statistics, and considered reliable, it is typically used for total income or expenditure. However, in this study we use it for individual products. It is possible, that not all products or services should be equivalised using the same weighting. Despite this, however, equivalisation is necessary to compare social cohorts as is done here, and the OECD-modified scale is best scale available for household equivalisation, and also used in other UK statistics.

Finally, as noted in both the Method and Findings sections, this research reports emissions by SPH, as well as using 2007 values of emission intensities. This allows for comparison between groups, as well as between years. However, this also means that while estimates reflect emission trend and can be analysed in relation to one another, they do not represent actual emission estimates for the different groups, as per capita emissions, or years.

5. Conclusions

To achieve climate goals, such as limiting global warming to 1.5 °C, the average UK household needs to reduce their consumption-based footprint by around 8 % annually [16,17,64]. Investigating changes in consumption-based emissions following both the 2007 economic crisis and the 2020 lockdowns allows us to learn about the impacts certain types of policies might have on GHG emissions of households. For instance, we advocate for looking at total, as well as product-level emissions, as rebound effects occur. While policies such as increased telecommuting or a 4-day work week may reduce emissions from commuting, they can increase emissions in other domains, like home gas and electricity use. While we find overall emissions to still be reduced, the reductions in transport are offset. Moreover, we find that further research into consumption patterns of food and drinks during the lockdowns may illuminate how food emissions can be reduced.

Importantly, we find that all household types studied here have total consumption-based emissions which exceed climate targets. However, some household types need to reduce more than others, and strategies to achieve climate targets need to differ between social cohorts to not further increase inequality. In addition, consumption of households living in energy and/or transport poverty needs to be increased – for such groups we do not propose a decrease in consumption, but rather policies which increase access to high quality housing and public goods, including transport. While our findings highlight that the 2020 lockdowns had a greater impact on changing consumption and reducing emissions than the 2007 economic crisis, both events reduced emissions and resulted in changed consumption patterns from household groups. While the product-level impacts and the magnitude of the emission reductions differs between the events, both saw a decrease in emissions, with different impacts on different types of households. When comparing rebound effects of both events, for instance, households with the highest emissions also saw the highest rebound effects following both events, reducing net emission reductions.

As different household groups have different consumption patterns as well as different access to resources, targeting policies towards specific household groups may be more effective than universal policies or campaigns. The primary focus to reduce emissions should be on households with the highest levels of overconsumption and emissions. Moreover, our findings show that a universal income-reduction or tax-based policy would, while reducing emissions, increase social inequalities. However, a tax targeting specifically the highest income households, paired with increased access to better insulated housing and public goods and services for all may not only reduce emissions, but also inequalities.

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

The data from this research is available at Lena Kilian, Anne Owen, Andy Newing, Diana Ivanova (2023): Research Data: Achieving Emission Reductions without Furthering Social Inequality. [Dataset]. https://doi.org/10.5518/1414

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Appendix A. Overview of methodology for estimating household emissions

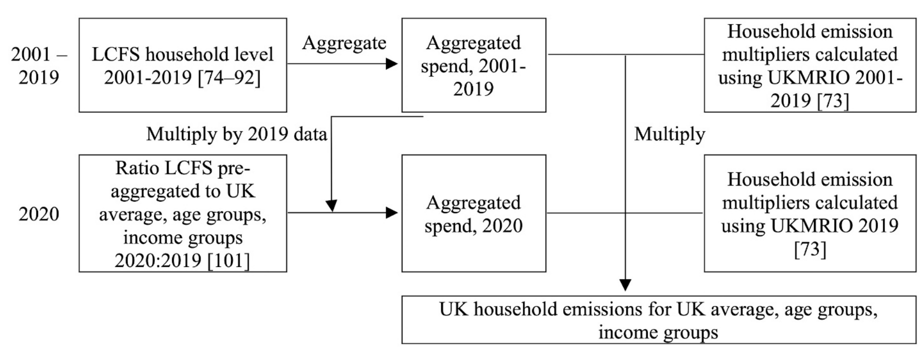

Fig. A1. Diagram of how emissions are calculated using own year prices and multipliers.

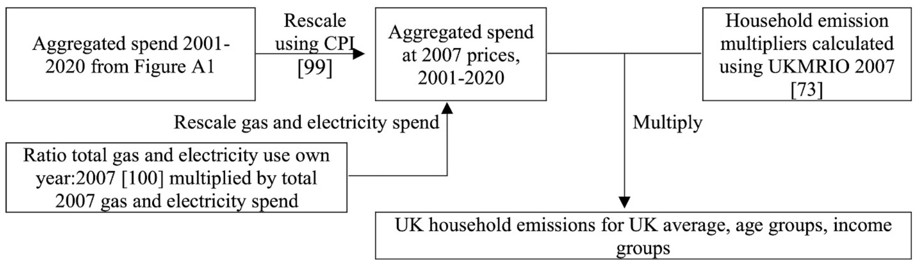

Fig. A2. Diagram of how emissions are calculated using 2007 prices and multipliers.

Appendix B. Additional results from repeated measures ANOVA and paired-sample *t*-tests

Table B1
Detailed results from repeated measures ANOVAs.

	Product	F-Value	Num DF	Den DF	P-value
Age Group	Food and drinks	25.01	4	72	5.3E-13
	Housing, water and waste	62.88	4	72	9.3E-23
	Electricity, gas, liquid and solid fuels	2.96	4	72	2.5E-02
	Private and public road transport	61.70	4	72	1.6E-22
	Air transport	17.27	4	72	5.6E-10
	Recreation, culture, and clothing	41.23	4	72	6.2E-18
	Other consumption	26.70	4	72	1.4E-13
	Total	32.33	4	72	2.0E-15
Income Decile	Food and drinks	171.19	9	162	5.7E-78
	Housing, water and waste	43.62	9	162	7.0E-39
	Electricity, gas, liquid and solid fuels	24.00	9	162	1.0E-25
	Private and public road transport	310.06	9	162	2.9E-97
	Air transport	34.78	9	162	1.5E-33
	Recreation, culture, and clothing	119.18	9	162	1.0E-66
	Other consumption	159.59	9	162	9.3E-76
	Total	271.60	9	162	6.8E-93

Table B2
Detailed results from pairwise comparisons.

			Air transport		Electricity, gas, liquid and solid fuels		Food and Drinks		Housing, water and waste		Other consumption		Private and public road transport		Recreation, culture, and clothing		Total	
			t-val.	p-val.	t-val.	p-val.	t-val.	p-val.	t-val.	p-val.	t-val.	p-val.	t-val.	p-val.	t-val.	p-val.	t-val.	p-val.
Age Group HRP	18-29	30-49	-3.67	0.00	-2.35	0.03	-3.74	0.00	0.03	0.98	-4.49	0.00	-1.22	0.24	-4.07	0.00	-4.50	0.00
		50-64	-2.56	0.02	-0.22	0.83	-3.05	0.01	-5.49	0.00	-3.09	0.01	-1.46	0.16	-3.13	0.01	-3.66	0.00
		65-74	-4.86	0.00	-0.43	0.67	-7.91	0.00	-7.84	0.00	-8.21	0.00	-9.76	0.00	-8.46	0.00	-9.45	0.00
		75+	0.98	0.34	0.73	0.48	-6.37	0.00	-11.00	0.00	-5.38	0.00	-10.16	0.00	-7.69	0.00	-5.12	0.00
	30-49	50-64	0.88	0.39	2.65	0.02	-0.37	0.72	-8.66	0.00	1.22	0.24	-0.80	0.43	-0.14	0.89	-0.30	0.76
		65-74	-2.42	0.03	2.05	0.05	-6.91	0.00	-12.09	0.00	-6.17	0.00	-13.68	0.00	-9.49	0.00	-9.15	0.00
		75+	6.24	0.00	2.92	0.01	-3.53	0.00	-11.95	0.00	-2.19	0.04	-9.40	0.00	-6.66	0.00	-2.22	0.04
	50-64	65-74	-3.33	0.00	-0.39	0.70	-6.99	0.00	-4.61	0.00	-10.49	0.00	-17.40	0.00	-13.55	0.00	-8.94	0.00
		75+	4.47	0.00	1.72	0.10	-3.02	0.01	-6.68	0.00	-3.42	0.00	-8.02	0.00	-6.70	0.00	-1.96	0.07
	65-74	75+	11.18	0.00	3.09	0.01	3.12	0.01	-3.60	0.00	3.40	0.00	0.11	0.91	-1.39	0.18	6.37	0.00
Income Decile	Low.	2nd	-13.97	0.00	-8.51	0.00	-32.74	0.00	-13.78	0.00	-31.34	0.00	-30.90	0.00	-23.47	0.00	-33.16	0.00
		3rd	-13.90	0.00	-9.59	0.00	-27.45	0.00	-0.02	0.99	-30.37	0.00	-34.80	0.00	-33.11	0.00	-39.23	0.00
		4th	-20.07	0.00	-11.12	0.00	-28.66	0.00	7.57	0.00	-28.95	0.00	-31.86	0.00	-27.82	0.00	-35.02	0.00
		5th	-15.63	0.00	-10.10	0.00	-33.02	0.00	4.57	0.00	-28.54	0.00	-31.56	0.00	-30.24	0.00	-33.94	0.00
		6th	-18.24	0.00	-9.06	0.00	-45.81	0.00	4.48	0.00	-38.59	0.00	-28.65	0.00	-27.99	0.00	-35.69	0.00
		7th	-15.35	0.00	-10.13	0.00	-31.88	0.00	2.27	0.04	-31.22	0.00	-31.76	0.00	-37.44	0.00	-38.60	0.00
		8th	-14.54	0.00	-12.89	0.00	-28.75	0.00	-0.07	0.95	-33.01	0.00	-19.52	0.00	-25.85	0.00	-31.77	0.00
		9th	-16.08	0.00	-12.56	0.00	-36.43	0.00	-2.18	0.04	-34.27	0.00	-31.24	0.00	-23.71	0.00	-34.83	0.00
		High.	-9.57	0.00	-11.32	0.00	-13.71	0.00	-2.54	0.02	-18.94	0.00	-10.44	0.00	-10.77	0.00	-17.89	0.00
	2nd	3rd	-2.34	0.03	-1.77	0.09	-1.20	0.25	9.67	0.00	-2.67	0.02	-3.89	0.00	-0.41	0.69	-3.53	0.00
		4th	-5.87	0.00	-3.12	0.01	-1.13	0.27	15.99	0.00	-3.89	0.00	-2.06	0.05	-0.72	0.48	-3.53	0.00
		5th	-6.57	0.00	-1.93	0.07	-2.57	0.02	13.92	0.00	-2.48	0.02	1.99	0.06	1.18	0.25	-2.18	0.04
		6th	-5.98	0.00	-2.67	0.02	-2.01	0.06	13.17	0.00	-0.16	0.87	7.63	0.00	0.40	0.69	-1.83	0.08
		7th	-6.09	0.00	-2.64	0.02	-2.04	0.06	9.39	0.00	0.46	0.65	13.12	0.00	2.87	0.01	-1.26	0.22
		8th	-5.87	0.00	-4.71	0.00	0.14	0.89	7.85	0.00	3.82	0.00	20.44	0.00	4.85	0.00	2.96	0.01
		9th	-6.55	0.00	-3.61	0.00	2.45	0.02	4.47	0.00	1.27	0.22	20.60	0.00	2.77	0.01	0.55	0.59
		High.	-4.01	0.00	-0.71	0.49	4.55	0.00	3.55	0.00	2.77	0.01	17.93	0.00	5.77	0.00	3.90	0.00
	3rd	4th	-3.62	0.00	-2.12	0.05	-0.07	0.94	7.62	0.00	-0.90	0.38	1.06	0.30	-0.38	0.71	-0.36	0.73
		5th	-3.86	0.00	-0.56	0.58	-1.72	0.10	4.69	0.00	0.09	0.93	5.67	0.00	1.61	0.12	0.92	0.37
		6th	-3.61	0.00	-1.77	0.09	-0.70	0.49	5.51	0.00	2.07	0.05	13.30	0.00	1.01	0.33	1.47	0.16
		7th	-4.17	0.00	-1.55	0.14	-1.07	0.30	2.39	0.03	2.90	0.01	14.47	0.00	4.17	0.00	2.04	0.06
		8th	-3.05	0.01	-2.41	0.03	1.04	0.31	-0.05	0.96	6.98	0.00	19.83	0.00	6.92	0.00	4.65	0.00
		9th	-3.65	0.00	-1.85	0.08	3.08	0.01	-2.66	0.02	3.71	0.00	20.86	0.00	3.69	0.00	3.06	0.01
		High.	-2.66	0.02	1.43	0.17	4.81	0.00	-2.98	0.01	4.19	0.00	21.54	0.00	6.02	0.00	5.78	0.00
	4th	5th	-0.69	0.50	2.09	0.05	-1.88	0.08	-2.06	0.05	1.09	0.29	4.62	0.00	1.63	0.12	1.24	0.23
		6th	-0.36	0.73	-0.04	0.97	-0.61	0.55	-1.31	0.21	4.38	0.00	10.65	0.00	1.08	0.29	1.91	0.07
		7th	-1.74	0.10	0.45	0.66	-0.81	0.43	-4.54	0.00	3.51	0.00	11.61	0.00	3.77	0.00	2.24	0.04
		8th	-0.14	0.89	-0.23	0.82	1.28	0.22	-8.71	0.00	7.37	0.00	18.52	0.00	7.91	0.00	5.36	0.00
		9th	-1.02	0.32	0.04	0.97	2.77	0.01	-10.11	0.00	5.16	0.00	19.54	0.00	3.12	0.01	3.36	0.00
		High.	-0.74	0.47	3.21	0.00	4.87	0.00	-9.81	0.00	4.56	0.00	21.34	0.00	6.49	0.00	5.04	0.00
	5th	6th	0.37	0.72	-1.71	0.10	1.10	0.29	0.86	0.40	2.34	0.03	5.98	0.00	-0.64	0.53	0.58	0.57
		7th	-0.95	0.35	-1.83	0.08	1.30	0.21	-1.67	0.11	2.98	0.01	8.68	0.00	2.01	0.06	0.94	0.36
		8th	0.68	0.51	-2.39	0.03	2.68	0.02	-4.39	0.00	7.21	0.00	19.51	0.00	4.35	0.00	4.81	0.00
		9th	-0.19	0.85	-2.00	0.06	4.28	0.00	-7.22	0.00	3.96	0.00	16.02	0.00	2.76	0.01	2.37	0.03
		High.	-0.26	0.80	2.11	0.05	7.05	0.00	-7.36	0.00	4.60	0.00	21.04	0.00	5.97	0.00	4.96	0.00
	6th	7th	-1.22	0.24	0.60	0.56	-0.18	0.86	-4.03	0.00	0.53	0.60	5.06	0.00	2.69	0.01	0.67	0.51
		8th	0.13	0.90	-0.14	0.89	1.63	0.12	-9.47	0.00	3.87	0.00	10.93	0.00	5.11	0.00	3.73	0.00
		9th	-0.58	0.57	0.07	0.95	3.69	0.00	-10.87	0.00	1.54	0.14	12.33	0.00	2.51	0.02	1.70	0.11
		High.	-0.50	0.62	2.41	0.03	5.68	0.00	-10.47	0.00	2.55	0.02	15.11	0.00	5.49	0.00	4.45	0.00
	7th	8th	1.56	0.14	-0.62	0.54	1.84	0.08	-4.89	0.00	3.68	0.00	7.46	0.00	3.00	0.01	3.36	0.00
		9th	0.81	0.43	-0.48	0.64	4.64	0.00	-9.48	0.00	0.84	0.41	10.17	0.00	0.95	0.36	1.21	0.24
		High.	0.34	0.74	2.81	0.01	5.66	0.00	-6.82	0.00	2.43	0.03	10.90	0.00	5.82	0.00	4.51	0.00
	8th	9th	-0.79	0.44	0.34	0.74	1.55	0.14	-3.46	0.00	-2.79	0.01	1.75	0.10	-1.35	0.19	-1.91	0.07
		High.	-0.65	0.52	4.26	0.00	5.20	0.00	-3.88	0.00	0.53	0.60	5.72	0.00	3.42	0.00	2.84	0.01
	9th	High.	-0.20	0.85	4.06	0.00	4.06	0.00	-1.09	0.29	1.73	0.10	4.02	0.00	4.07	0.00	3.75	0.00

**Notes: Light red shows $p > 0.05$, dark red show $p > 0.01$.

Appendix C. Product-level carbon intensities

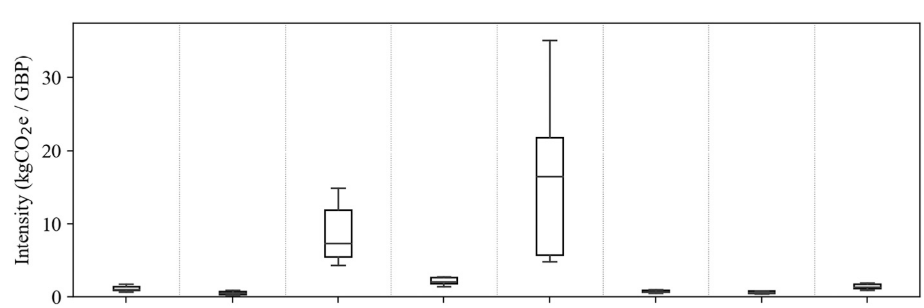

Fig. C1. Boxplot showing carbon intensities for 2001–2019 at a product level.

Appendix D. Percentage and absolute differences in per SPH income and emissions between 2007–2009 and 2019–2020, equivalised

Table D1
Percentage differences in per SPH income and emissions between 2007 and 2009 and 2019–2020; emissions and incomes are estimated using own year prices and multipliers.

Period	Group		Weekly income	Total	Food and Drinks	Housing, water and waste	Electricity, gas, liquid and solid fuels	Private and public road transport	Air transport	Recreation, culture, and clothing	Other consumption
2007-2009		All	3.50	-15.88	-11.80	-22.00	-7.19	-14.66	-16.54	-22.93	-32.73
	Age HRP	18-29	0.30	-14.26	-21.68	-15.62	-7.50	-12.30	-2.06	-30.12	-16.58
		30-49	3.16	-17.02	-12.07	-21.36	-9.25	-15.74	-16.79	-20.77	-34.52
		50-64	3.67	-17.79	-11.97	-23.83	-9.16	-16.16	-21.14	-20.59	-37.36
		65-74	9.63	-12.22	-5.51	-25.40	-4.27	-3.19	-22.08	-28.54	-34.98
		75+	4.54	-5.31	-5.06	-23.59	5.80	-31.14	6.05	-30.12	10.90
	Income decile	Lowest	7.23	-12.18	-15.05	-19.07	-1.95	1.81	-23.07	-36.90	-28.52
		2nd	6.65	-14.18	-9.05	-23.39	-10.11	-6.85	-2.45	-30.30	-36.77
		3rd	4.29	-18.65	-7.78	-16.19	-10.76	-27.07	-35.41	-22.09	-35.47
		4th	4.61	-14.95	-9.62	-24.20	-5.23	-11.57	-23.86	-14.65	-41.29
		5th	3.35	-14.48	-12.61	-18.98	-6.42	-16.84	8.38	-25.37	-29.74
		6th	2.20	-14.02	-6.43	-23.70	-6.70	-16.06	-26.55	-19.18	-25.42
		7th	2.42	-15.77	-20.17	-21.05	-4.51	-13.22	-6.91	-39.95	-19.03
		8th	3.27	-11.31	-11.03	-23.41	1.13	-5.15	-15.73	-23.37	-30.63
		9th	3.13	-18.06	-11.77	-26.62	-13.16	-16.65	-18.60	-9.92	-36.88
		Highest	3.65	-20.59	-11.85	-23.74	-11.67	-22.59	-17.52	-14.60	-37.66
2019-2020		All	0.03	-24.08	-10.40	-6.72	1.91	-45.99	-80.72	-11.51	-25.87
	Age HRP	18-29	1.40	-24.72	-6.15	46.18	3.37	-49.16	-86.20	12.12	-8.35
		30-49	-0.46	-22.02	-10.50	-1.97	3.10	-42.64	-78.07	-0.21	-20.29
		50-64	7.06	-24.90	-12.28	-25.17	4.06	-49.33	-78.41	-12.37	-21.39
		65-74	0.05	-24.54	-7.82	-7.20	0.52	-41.82	-83.95	-30.97	-39.72
		75+	11.43	-15.99	0.43	-27.59	-3.93	-38.46	-85.01	-16.60	-25.67
	Income decile	Lowest	-12.68	-31.40	-7.32	-30.68	-23.88	-45.98	-87.11	-45.89	-29.04
		2nd	-0.15	-24.49	-12.40	-22.09	-14.91	-41.16	-79.00	-0.13	-34.76
		3rd	0.98	-19.90	-1.71	-23.32	-3.59	-38.11	-80.61	-20.68	-27.12
		4th	1.35	-24.99	-4.02	-23.11	-4.03	-45.79	-89.66	-24.51	-30.56
		5th	3.30	-22.20	-7.22	13.60	2.09	-46.65	-83.55	-18.64	-30.52
		6th	1.51	-18.69	-10.12	-11.08	1.31	-47.48	-86.45	0.81	16.03
		7th	0.75	-26.18	-14.89	-14.28	3.30	-46.39	-76.26	-18.21	-29.13
		8th	1.11	-29.45	-12.05	19.94	5.13	-52.74	-82.11	-21.16	-33.62
		9th	1.14	-23.10	-11.34	19.71	11.63	-38.56	-78.01	-19.84	-21.10
		Highest	-1.55	-16.34	-13.31	12.47	39.52	-47.10	-74.50	32.83	-29.62

**Notes: This shows the change in the later year's values compared to the earlier year's values as a percentage, calculated: ($\text{Emissions}_{\text{Year 2}}$ – $\text{Emissions}_{\text{Year 1}}$) / $\text{Emissions}_{\text{Year 1}}$. This means that negative values show a reduction over time while positive values show an increase in emissions or income over time. Darker blue indicates a greater reduction, white indicates no change, dark red indicates a greater increase. 2020 values are calculated using 2019 multipliers.

Table D2
Differences in per SPH income and emissions between 2007–2009 and 2019–2020; emissions and incomes are estimated using own year prices and multipliers.

Period	Group		Weekly income	Total	Food and Drinks	Housing, water and waste	Electricity, gas, liquid and solid fuels	Private and public road transport	Air transport	Recreation, culture, and clothing	Other consumption
2007-2009		All	15.15	-3.49	-0.44	-0.19	-0.43	-0.74	-0.21	-0.45	-1.03
2007-2009	Age HRP	18-29	1.19	-2.63	-0.72	-0.15	-0.33	-0.55	-0.03	-0.48	-0.38
2007-2009	Age HRP	30-49	14.99	-3.79	-0.46	-0.16	-0.52	-0.85	-0.21	-0.44	-1.15
2007-2009	Age HRP	50-64	17.06	-4.41	-0.49	-0.19	-0.59	-0.95	-0.33	-0.46	-1.40
2007-2009	Age HRP	65-74	31.36	-2.47	-0.19	-0.24	-0.28	-0.12	-0.23	-0.51	-0.90
2007-2009	Age HRP	75+	14.53	-0.93	-0.14	-0.29	0.43	-0.86	0.02	-0.30	0.22
2007-2009	Income decile	Lowest	9.52	-1.80	-0.42	-0.17	-0.09	0.05	-0.15	-0.54	-0.49
2007-2009	Income decile	2nd	12.98	-2.16	-0.25	-0.23	-0.54	-0.20	-0.01	-0.39	-0.54
2007-2009	Income decile	3rd	10.41	-3.15	-0.24	-0.15	-0.57	-1.01	-0.24	-0.32	-0.61
2007-2009	Income decile	4th	13.32	-2.75	-0.31	-0.22	-0.29	-0.43	-0.20	-0.22	-1.08
2007-2009	Income decile	5th	11.32	-2.81	-0.45	-0.16	-0.37	-0.72	0.07	-0.43	-0.76
2007-2009	Income decile	6th	8.66	-2.88	-0.23	-0.19	-0.39	-0.81	-0.29	-0.33	-0.64
2007-2009	Income decile	7th	11.11	-3.58	-0.79	-0.16	-0.26	-0.72	-0.09	-0.97	-0.59
2007-2009	Income decile	8th	17.95	-2.76	-0.46	-0.18	0.07	-0.31	-0.23	-0.54	-1.11
2007-2009	Income decile	9th	21.72	-5.15	-0.54	-0.20	-0.90	-1.21	-0.38	-0.24	-1.67
2007-2009	Income decile	Highest	37.64	-7.92	-0.66	-0.21	-0.95	-2.13	-0.61	-0.49	-2.87
2019-2020		All	0.16	-3.48	-0.27	-0.03	0.07	-1.60	-1.06	-0.14	-0.45
2019-2020	Age HRP	18-29	7.81	-3.18	-0.13	0.28	0.09	-1.60	-1.80	0.10	-0.11
2019-2020	Age HRP	30-49	-2.82	-2.95	-0.26	-0.01	0.10	-1.50	-0.99	0.00	-0.29
2019-2020	Age HRP	50-64	43.93	-3.98	-0.35	-0.11	0.16	-1.97	-1.11	-0.18	-0.42
2019-2020	Age HRP	65-74	0.25	-3.84	-0.22	-0.04	0.02	-1.32	-0.96	-0.41	-0.92
2019-2020	Age HRP	75+	53.13	-2.03	0.01	-0.16	-0.20	-0.78	-0.41	-0.13	-0.36
2019-2020	Income decile	Lowest	-22.84	-3.27	-0.15	-0.16	-0.87	-0.95	-0.58	-0.34	-0.22
2019-2020	Income decile	2nd	-0.42	-2.66	-0.25	-0.11	-0.53	-0.90	-0.49	0.00	-0.37
2019-2020	Income decile	3rd	3.33	-2.33	-0.04	-0.12	-0.13	-0.91	-0.59	-0.16	-0.37
2019-2020	Income decile	4th	5.43	-3.12	-0.10	-0.12	-0.14	-1.38	-0.79	-0.23	-0.37
2019-2020	Income decile	5th	15.33	-2.91	-0.18	0.07	0.07	-1.46	-0.80	-0.22	-0.39
2019-2020	Income decile	6th	8.11	-2.61	-0.27	-0.05	0.04	-1.70	-0.91	0.01	0.27
2019-2020	Income decile	7th	4.64	-3.96	-0.41	-0.07	0.12	-1.88	-1.00	-0.21	-0.52
2019-2020	Income decile	8th	8.16	-4.93	-0.35	0.08	0.18	-2.28	-1.45	-0.31	-0.80
2019-2020	Income decile	9th	10.34	-4.10	-0.34	0.08	0.43	-1.86	-1.64	-0.30	-0.46
2019-2020	Income decile	Highest	-20.97	-3.55	-0.46	0.07	1.75	-2.30	-2.18	0.64	-1.06

**Notes: This shows the change in the later year's values compared to the earlier year's values, calculated: $\text{Emissions}_{\text{Year 2}} - \text{Emissions}_{\text{Year 1}}$. This means that negative values show a reduction over time while positive values show an increase in emissions or income over time. Darker blue indicates a greater reduction, white indicates no change, dark red indicates a greater increase. 2020 values are calculated using 2019 multipliers.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.103286.

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