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Working Paper

No. 22/01

February 2022

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CSG Centre for Urban History
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INCOME AND EXPENDITURE ELASTICITY OF HOUSEHOLD CARBON FOOTPRINTS. SOME METHODOLOGICAL CONSIDERATIONS

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Abstract

The income and expenditure elasticity of household carbon footprints (HCF) is a recurrent summary measure of the social stratification of greenhouse gas emissions. In top-down-estimates, when microdata are lacking, it is also used to estimate the inequality in emissions between households across the income or expenditure distribution. In this article, we point to several key methodological considerations when computing the elasticity of HCFs, and demonstrate their practical and empirical implications by making use of Belgian survey data. We find that the choice between income and expenditure as the main variable is most consequential for the estimated elasticity of HCFs, while the income elasticity of household emissions is more sensitive to a broader range of methodological choices. This has implications for top-down estimates of emissions along the income distribution, and related indicators of the inequality in household emissions by income groups.

Keywords: Household carbon footprint, greenhouse gas emissions, income and expenditure elasticity, emission inequality

Acknowledgments: We are grateful to Josefine Vanhille, Jean-Maurice Frère, Gertjan Cooreman and Guy Vandille for their collaboration in the SUSPENS project, and for providing explanations and information related to the environmentally extended input-output model on which the emissions module of the PEACH2AIR database is based. The Household Budget Survey data were provided to by STATBEL under contract 2015/041. The views expressed in this paper do not necessarily represent those of the funder or data provider.

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Funding: This research was financed by Belgian Science Policy BELSPO in the framework of the SUSPENS project (Contract BR/153/A5/SUSPENS). Tim Goedemé acknowledges financial support by Citi through the Oxford Martin Programme on Inequality and Prosperity.

1. INTRODUCTION

The relationship between the household carbon footprint (HCF) and household income (or expenditures) provides key insights into the social stratification of greenhouse gas emissions. Hence, a correct estimation of the income-HCF relationship is of key importance for better understanding the social dimension of the climate crisis, and informing climate mitigation policies that are both effective and socially just. The HCF is the sum of all carbon dioxide that is emitted to the atmosphere via household consumption. It includes all direct (e.g. fuel consumption for car travel) and indirect emissions. Indirect emissions are embedded in the supply chains of goods and services delivered for final consumption of households. These are emitted by industries involved in the production and transportation of goods and services for final demand. A widely-used approach to quantify the income-HCF relationship is to calculate the elasticity of HCF with respect to income, or in other words, the income-elasticity of HCF. This is a number that captures the percentage change in HCF when income is 1 percent higher. However, elasticities are computed in many different ways, which often make them incomparable across studies. With this paper we want to draw attention to some of the key intricacies involved in the computation of the income and expenditure elasticity of the HCF, and their implications for the top-down estimation of income inequalities in emissions when microdata for doing so are lacking.

It has become a common practice in the quickly expanding HCF literature to report the income or expenditure elasticity of HCF (see Pottier (2022) for an overview of 80 elasticity estimates for 20 countries). Although it is rarely the focus of these studies to find a perfect elasticity-estimate, it is presented along with other results anyway, often without much consideration of the methodological choices that underly these estimates. The estimated elasticities vary widely across papers. In his detailed review, Pottier (2022) points out several stylized facts about these estimates. First, the expenditure elasticity of HCFs is higher than the income elasticity of HCFs owing to the conceptual difference between the two. Richer households save a higher share of their income than poorer households, which leads to a more compressed distribution of expenditures than of incomes. Despite the significant conceptual difference between income and expenditures, Pottier (2022, p.6) shows that the concepts of expenditure elasticity and income elasticity have been used interchangeably in some studies of the HCF literature. Second, the income and expenditure elasticity of HCF is usually below 1, meaning that the HCF grows less rapidly than income (expenditures) when moving along the income (expenditure) distribution from poor to rich. This is typically explained by the fact that the composition of the consumption basket changes towards less energy intensive goods and services as income grows. For example, higher income households spend relatively less on emission intensive domestic energy and more on services. However, there are exceptions as well. In Norway, where the electricity mix is largely based on hydropower, the estimated elasticity is 1.14 (Steen-Olsen et al., 2016).

These elasticities are not only computed to summarize the income-HCF relationship. They have also been used to estimate emissions and their distribution over incomes in what is called a 'top-down' approach. When no microdata on the HCF are available, the income elasticity of emissions can be used to estimate inequality in emissions by income deciles. This has been first done by Chakravarty et al. (2009), and later other authors followed their example (see e.g.. Chancel & Piketty, 2015; Kartha et al., 2020; Oxfam, 2015). These papers show massive inequalities in the level of emissions across the global distribution of household incomes, pointing towards important socio-economic injustices in the contribution to the climate challenge. At the same time, given that these studies heavily rely on elasticity estimates, a further analysis of the empirical implications of how elasticities are computed is warranted.

The starting point for this paper is the observation that the estimation of income/expenditure elasticities exhibits considerable methodological heterogeneity in the literature. Building further on the discussion in

Pottier (2022), we focus on the following factors that relate to the way elasticities are estimated[1]. First, while some authors focus exclusively on the income elasticity of emissions (e.g. Büchs & Schnepf, 2013; Gough et al., 2011), others report the elasticity of HCF with respect to household expenditures (e.g. Duarte et al., 2012; Isaksen & Narbel, 2017; Kerkhof et al., 2009; Roca & Serrano, 2007). Second, when the expenditure concept is used, it is not always made clear which expenditure components are exactly included. Third, elasticities can be estimated in a bivariate model (e.g. Wier et al., 2010), but are often deduced from a multivariate model which also includes other covariates. Fourth, there is variation in the specification of the regression model that is used for estimating elasticities, with some authors opting for a log-log model (e.g. Ala-Mantila et al., 2014, 2017; Gill & Moeller, 2018) and others adding higher order polynomials of income in the regression model (Levinson & O'Brien, 2019; Seriño & Klasen, 2015)[2]. Sensitivity of the estimated elasticities to the functional form of the regression is seldom reported (but see Isaksen & Narbel, 2017; Weber & Matthews, 2008). Finally, for a range of functional forms, the estimated elasticity is dependent on the point in the income distribution at which it is estimated. Typically, this is the mean income. However, with a skewed income distribution the median can be a more representative number (see Levinson and O'Brien, 2019).

This heterogeneity impedes cross-study comparison and poses the question whether and to what extent diversity in income elasticity of HCF estimates stem from different methodological choices made when quantifying the income-HCF relationship. Furthermore, it occludes the best elasticity choice when applying the top-down approach. Therefore, in this paper we aim to illustrate how these choices affect the income/expenditure elasticity of HCF estimates. Specifically, we use a single dataset that describes the same country (Belgium) in the same year (2014) and contains HCFs calculated with the same underlying model. In this way, we are able to illustrate the sensitivity of estimated elasticities to different methodological choices related to the quantification of the income-HCF relationship, while making abstraction of other potentially confounding factors such underlying datasets and modelling of consumption-based emissions. In addition, we use the full range of estimated elasticities to assess the sensitivity of the top-down approach for estimating the average HFC across the income distribution and compare the results to direct estimates derived from the microdata.

We find that it is of key importance not to mix up the income elasticity of the HCF with the expenditure elasticity of the HCF: among all the methodological variations that we tested, the choice between income and expenditure as the main variable for estimating carbon footprint elasticities is most consequential for the estimated elasticity. Furthermore, the income elasticity of household emissions is also sensitive to a broader range of methodological choices, while, at least in our dataset, this is much less the case for the expenditure elasticity of household emissions. This has implications for top-down estimates of emissions along the income distribution, and related indicators of the inequality in household emissions by income groups.

The remainder of the paper is structured as follows. In the next section we explain which data have been used for the so-called 'bottom-up' calculations, and how elasticities have been estimated in both the bottom-up and the top-down approach. Next, we present the outcomes of our calculations, showing on the one hand the sensitivity of the estimated elasticities to differences in methodological choices, and on the other hand how bottom-up and top-down calculations may lead to different results, and hence different conclusions

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[1] Pottier (2022) also discusses how variation in the methodology to compute carbon footprints of individual households may matter. This is outside the scope of this paper.

[2] Note that Levinson & O'Brien (2019) run the analysis for PM10, VOC, NO_x, SO_2, and CO and not for CO_2 or GHG.

with respect to inequalities in HCFs along the distribution of income and expenditures. The final section concludes.

2. DATA AND METHODS

2.1 Data: linking the Belgian Household Budget Survey with emission coefficients

We use the PEACH2AIR database which consists of two main components: the 2014 Belgian Household Budget Survey (HBS) and emission coefficients generated by a single-region environmentally extended input-output (EEIO) model of the Belgian economy.

The HBS is an annual survey conducted among a representative sample of the Belgian population, collecting detailed information about household expenditures. Households report the amount they spend over the course of two weeks, item-by-item. An additional questionnaire is used to collect information on less frequent expenses. The expenditures are categorized into the COICOP classification system which is also the link between the HBS and the EEIO model.

The aim of the EEIO model is to map emission flows among macroeconomic sectors. It is based on an input-output model of the Belgian economy, which tracks the monetary flows in the economy by representing the monetary value of the inputs used by each sector from all other sectors, and the monetary value of the outputs that each sector provides to all other sectors. In addition, industry-level GHG emissions data are added to the model. The outcome of the EEIO model is information about how all GHG emitted on the Belgian territory are distributed and embedded in the supply chains of goods and services that final consumers purchase. The so-called emission coefficients represent the embedded amount of GHG emissions per one unit of monetary expenditures (euro) on each final product in the COICOP classification system. The EEIO is then connected to the HBS by multiplying the emission coefficients (grams per euro) with the monetary expenditures observed in the HBS (euro). The result is a micro-level database with a high level of granularity of households and products. The HCF refers to the sum of the direct and embedded emissions of all the products and services that a household purchases during the reference period of the survey. We refer to Frère et al. (2018) and Lévay et al. (2021) for a detailed description of the underlying databases and all the data cleaning and adjustments that have been made to enable the current analysis. Furthermore, we refer to Steen-Olsen et al. (2016) and Pottier (2022) for a detailed discussion of more general survey-related problems in the framework of HCF studies.

2.2. The estimation of income and expenditure elasticities: the bottom-up approach

The elasticity (ε) of the HCF with respect to income or expenditures (x) is the percentage change in household emissions when income or expenditures increase by one percent. In other words, it measures how responsive emissions are to an increase in income/expenditures. It is defined as

$$\varepsilon_x = \frac{x}{HCF}\frac{\partial HCF}{\partial x}.$$

The HCF is said to be elastic (inelastic) if the absolute value of ε_x is more (less) than 1. When ε_x equals 1, the HCF is said to be unit elastic. An elastic (inelastic) HCF means that emissions grow with income/expenditures more (less) than proportionally, while unitary elasticity means that emissions grow with income/expenditures in a proportionate way. Please note that in this paper (as in most of the literature), elasticities are estimated based on cross-sectional data, and are used to describe the income/expenditure-HCF relation in one population. Therefore, they should not be interpreted in a dynamic manner, but as a description of the income/expenditure-HCF relationship at a certain point in time in the population under study.

There are six main methodological issues with regard to the computation of the income/expenditure elasticity of the HCF that we investigate in this analysis.

First, the main concepts of living standards employed in the literature are income and expenditures. The two concepts are often used interchangeably, although they are theoretically distinct, and relate to HCFs in different ways. It should be stressed that the distribution of income and the distribution of expenditures typically overlap only to some degree. For instance, in the Belgian HBS, only 23% of households belong to the same income and expenditure deciles. This is because of the heterogeneity in consumption patterns and saving rates within income groups, and because of variation in the degree to which consumption is financed through other sources than income (e.g. financial assets and loans). Furthermore, emissions are assigned to expenditures only, and not to savings. Given the decreasing propensity to consume (the ratio of expenditures to income) with increasing income, it is no surprise then, that the correlation between the HCF and expenditures is higher than the correlation between the HCF and income (see Pottier (2022) for an overview). Therefore, in the current analysis, we estimate both income and expenditure elasticities of HCFs to illustrate what a difference this makes when applied to the same dataset. Income refers to total disposable household income (i.e. income including earnings, social benefits and income from other sources, after the deduction of social security contributions and personal income taxes), As is common in the inequality literature, household incomes and household expenditures are equivalized by dividing household income (expenditures) with an equivalence scale. We make use of the so-called modified OECD scale, which assigns a value of 1 to the first adult, 0.5 to each additional adult and 0.3 to each child (defined as a person younger than 14).

Second, the expenditure concept is constructed by adding up different components, but this is often not discussed explicitly, nor in detail. However, this could be important because the carbon footprint of different expenditure components might vary greatly. Including or excluding certain components may have significant effects on final elasticity estimates. Specifically, expenditures can be broken down into consumption and non-consumption expenditures. The first include, for example, food, utilities and clothing. The latter includes rent and mortgage payments. If the aim of constructing the expenditure concept is to provide a measure of the living standards of households, then including rent, imputed rent and/or mortgage payments besides consumption expenditures is a reasonable choice. In the framework of HCF estimation, the inclusion or exclusion of non-consumption expenditures such as rent and mortgage repayments, or the value of imputed rent is a decision to be carefully considered because these typically have much lower environmental coefficients than other expenditure components (if emissions are assigned to these expenditure categories at all). In the current analysis we use two distinct expenditure concepts to illustrate how the composition of the expenditure concept affects the estimates of the expenditure elasticity of HCF. The first only includes consumption expenditures, the second also covers rent and mortgage repayments as well as imputed rent[3]. In the PEACH2AIR database, no emissions are assigned to rent, imputed rent, and mortgage repayments.

[3] It is not clear neither in the bottom-up and the top-down literature whether these components are included in the expenditure concept. Hence, one could say that the joint inclusion of imputed rent on the one hand and mortgage repayments and actual rents paid on the other is unusual. It serves here as a general test of the maximum size of difference one can expect when moving between various expenditure concepts.

Third, while some studies report elasticity estimates based on the bivariate relation between income/expenditures and the HCF, most include also other socio-economic variables in the underlying regression model. How this affects the resulting estimates is often unclear. Including an additional variable in the regression model may change the elasticity estimate depending on the sign and strength of the association between income/expenditures and the included variable, as well as between the included variable and the HCF. Therefore, in this paper we estimate two regression specifications. The first is a reduced-form model, which only includes income/expenditures as explanatory variable. The second is an extended model that also includes the following explanatory variables: number of adults, number of children, age of the reference person, the square of the age of the reference person, professional status of the reference person (working, unemployed, student, home worker, incapacitated, pension), the highest educational attainment in the household, occupancy status (owner, tenant), the size of the dwelling (proxied by the number of rooms in the dwelling) and the type of the dwelling (detached, semi-detached, apartment, other).

Fourth, the functional form of the income-HCF relationship varies across studies. The functional form cannot be specified based on theoretical grounds. Table 1 presents the most commonly used model specifications and the corresponding formulas for calculating the elasticity.

Table 1. Model specifications and respective elasticity formulas

Model	Model specification	Elasticity
Linear	$e = \alpha + \beta_1 x + u$	$\varepsilon = \beta_1 x/e$
Quadratic	$e = \alpha + \beta_1 x + \beta_2 x^2 + u$	$\varepsilon = (\beta_1 + 2\beta_2 x)x/e$
Cubic	$e = \alpha + \beta_1 x + \beta_2 x^2 + \beta_3 x^3 + u$	$\varepsilon = (\beta_1 + 2\beta_2 x + 3\beta_3 x^2)x/e$
Level-log	$e = \alpha + \beta_1 \ln(x) + u$	$\varepsilon = (\beta_1/x)x/e$
Log-log	$\ln(e) = \alpha + \beta_1 \ln(x) + u$	$\varepsilon = (x/e)(x/e)\beta_1 = \beta_1$

Note: *e* stands for emissions (i.e. the HCF per capita), *x* stands for equivalised income or equivalised expenditures, *u* stands for the error term. α and β are parameters to be estimated. For the household level analysis (in the Annex), *e* stands for HCF, and *x* stands for non-equivalised household income or expenditures.

Fifth, owing to the fact that the elasticity formula is the derivative of emissions with respect to income (expenditures) multiplied by the ratio of income (expenditures) to emissions, the formula yields varying elasticities along the income (expenditures) distribution, when the variables are not log-transformed. Thus, the point where the elasticity is calculated, may also matter. In most studies it is calculated at the mean. However, there is no theoretical argument for this choice, one could also opt for the median, or other points along the distribution. The more skewed the income/expenditure distribution, and the higher the correlation between income/expenditure and emissions, the more elasticity estimates can be expected to differ when estimated at median income/expenditures compared to the mean.

Finally, there is a question about using households or individuals as unit of analysis. Both the HCF and (equivalised) income (expenditures) are measured at the household level, and papers that document the relationship between income and the HCF have focused on this relationship at the household level (e.g., Büchs and Schnepf, 2013, Lévay et al., 2021, Poom and Ahas, 2016, Seriño & Klasen, 2015). It does make sense to regress the HCF on household income/expenditures and some other household-level covariates, with households as the points of observation and units of analysis. However, in inequality research, it is standard practice to 'individualize' the data, and analyze the household level data at the individual level, by multiplying the household weight with the size of the household (e.g. Atkinson, 2019). This ensures that findings are representative for individuals, rather than households, and all individuals count as much in the analysis, regardless of the size of the household to which they belong. Otherwise, small households would receive a disproportionate weight in the results. Given that it is standard practice in the inequality literature, and leads to a more straightforward interpretation of inequalities in emissions by income/expenditure groups, this is also the approach that we take. However, we also report results based on a household level analysis in the Annex.

We empirically test the impact of the six methodological choices (summarized in Table 2) on HCF elasticity outcomes for Belgium. This yields 90 elasticity estimates. In the second part of the analysis, we use these elasticity estimates to construct the so called 'top-down' model of GHG emissions and assess how it differs from the bottom-up results.

Table 2. Methodological choices in HCF elasticity calculations explored in this paper

Methodological choice	Options
Living standards concept	Income or expenditures
Expenditure concept	Non-consumption expenditures included/excluded
Regression specification	Reduced or extended model
Functional form of income/expenditures	Linear, quadratic, cubic, level-log, log-log
Point of the distribution where elasticity is calculated	Mean or median
Unit of analysis	Individual or household

2.3. A top-down approach to estimating the HCF distribution in countries without microdata

Several studies have resorted to the use of estimating HFCs on the basis of income and/or expenditure survey data in combination with elasticities (Chakravarty et al., 2009; Chancel & Piketty, 2015; Chancel 2021; Kartha et al., 2020; Oxfam, 2015). This approach is used when no detailed consumption and/or emission microdata are available, but the aim is to understand how HCFs are distributed across income groups. In such situations, researchers use the income distribution and the income elasticity of HCF to estimate the emissions of income groups. The income elasticity of HCF is then typically either derived from other studies, or based on an assumption. This is referred to as a top-down approach, in contrast to a bottom-up approach which links detailed emission data with detailed consumption data at the micro-level. We compare both methods in terms of the concentration of HCFs with income. We followed Chancel & Piketty (2015) when calculating top-down emissions:

$$GHG_i = f_i * \frac{GHG_{tot}}{\sum_{j=1}^{N} f_j * y_j^e} * y_i^e$$

Where GHG_i is the GHG emissions of income group i, f_i is the share of income group i in the total population, GHG_{tot} is the total GHG emissions of the country, y_i is mean (unequivalised) income in income group i, and e is the income elasticity of GHG emissions. For the graph presented below, we carry out the analysis for 10 deciles, thus f_i takes the value 0.1, and N = 10, while for calculating inequality measures, we created percentiles, thus f_i=0.01 and N=100. Regarding the elasticity, we take values from the previous section, and calculate GHG emissions for different levels of elasticity ranging from 0.2 to 1.0, illustrating the widest possible outcomes that arise from current practices in the literature. Given that the concept of income and expenditures are used interchangeably and are confused in part of the HCF literature (Pottier, 2022), we also used expenditures instead of income in the formula above to obtain estimates of

HCFs across the expenditure distribution. This enables us to demonstrate how the exchange of the income and expenditure concepts may affect the results of the top-down estimation.

3. RESULTS

3.1. Variation in estimated elasticities

The estimated elasticities and their 95% confidence intervals are presented in Figures 1 and 2. On Figure 1, estimates vary with respect to three aspects: living standards concept (income or expenditures), regression model specification (reduced or extended) and functional form (linear, quadratic, cubic, level-log, log-log). The effect of different expenditure concepts is presented separately on Figure 2. We do not show results for calculating elasticities at different points of the income/expenditure distribution, because outcomes did not differ substantially between elasticities at the median and average income/expenditure, and graphs would have been overly crowded. We report these results in the Annex. Also, the graphs have individuals as units of analysis, with each decile counting for 10% of individuals (not households). Results for a household level analysis are also included in the Annex. The following observations emerge from our analysis.

First, the point estimates range widely, they are scattered between 0.22 (income, linear, extended model) and 0.99 (expenditure (including rent, imputed rent and mortgage payments), log-log, reduced model).

Second, as all estimates are between 0 and 1, there is a positive association between HCF and income/expenditures, and the HCF can be considered inelastic.

Third, there is a relatively clear-cut hierarchy of estimated elasticities: when the same model specification is applied, income elasticity estimates are always below expenditure elasticity estimates. The difference between income and expenditure elasticity estimates is largest (0.61) in the case of the extended linear model and smallest (0.30) in the case of the reduced level-log model when elasticity is calculated at the median of the distributions. As can be observed from Figure 1, with a slightly different order of magnitude, a similar pattern can be observed for elasticities calculated at the average income and expenditures. These differences are both statistically significant and substantial.

Fourth, as one would expect, in most cases the value of the elasticity estimate is smaller in the extended regression models than in the reduced form models. The difference is more pronounced for income elasticity than for expenditure elasticity, and it is much more pronounced when households are used as a unit of analysis. In the latter case, when removing covariates from the extended regression models, the estimated income elasticity doubles in magnitude in all functional form specifications. In contrast, the expenditure elasticity is not substantially different between the reduced form and the extended regression model specifications, in particular when using individuals as the unit of analysis.

Fifth, different functional form choices affect results moderately. The quadratic, cubic, level-log and log-log models produce fairly similar estimates when the other aspects (income vs. expenditures, simple vs. extended model) are fixed. The linear specification results in lower elasticity estimates than the other models in case of income, but not expenditures.

Sixth, the specification of the expenditure concept matters. Two concepts were tested here. The first includes all consumption expenditures, the second includes consumption expenditures, rent, imputed rent and mortgage payments. Figure 2 shows that expenditure elasticities are significantly lower when the first concept is used. This is the case in both reduced and extended regression models.

Lastly, the unit of analysis matters for estimated elasticities, at least in the case of income elasticities in the reduced model. This is much less the case for the elasticity of household emissions with respect to expenditures, and the income elasticity based on the extended model.

To conclude, when estimating elasticities, no factor matters more than the choice between income and expenditures as the key variable for studying the stratification of emissions. In the case of income elasticities, the difference between using an extended and reduced form also matters, as do the unit of analysis and functional form of the regression in the case of a reduced form model. In contrast, the difference between the two expenditure concepts that we used, as well as between elasticities estimated at the median and average income/expenditure, seem to be less consequential.

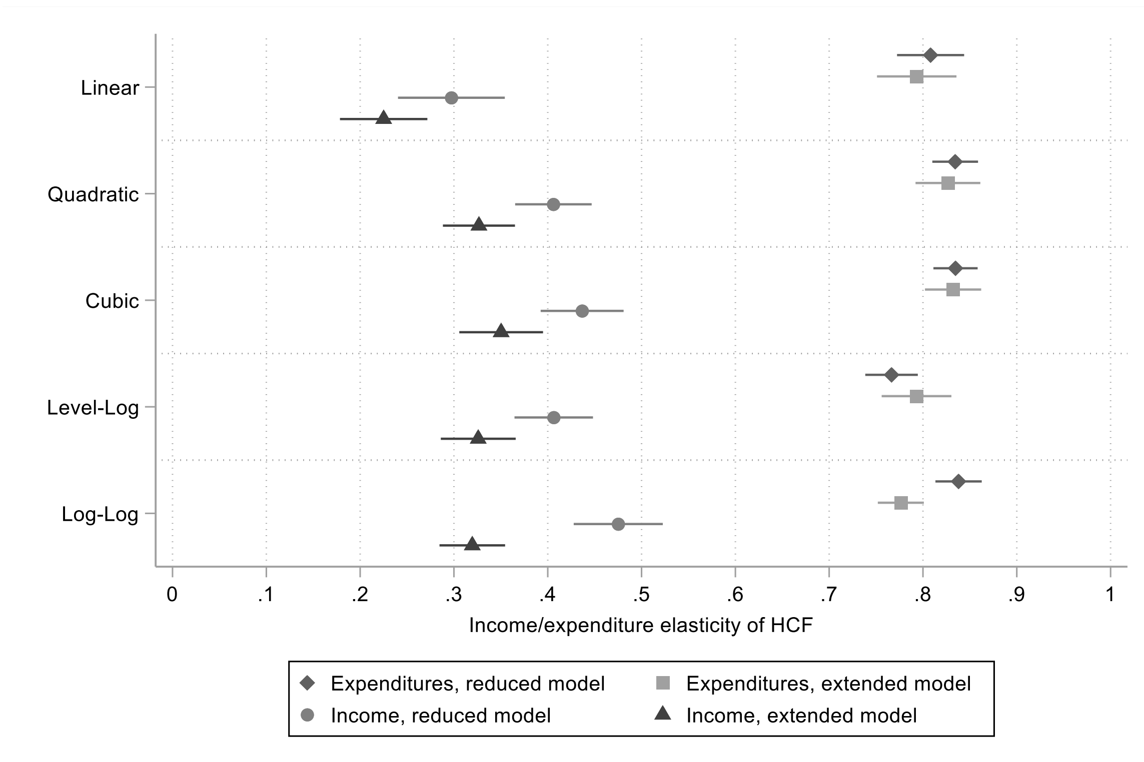

Figure 1. Income and expenditure elasticity of HCF per capita (individual level analysis). Expenditures do not include rent, imputed rent and mortgage payments. Elasticities are estimated at average income/expenditure levels. 95% Confidence intervals. Figure A1 reproduces the graph in a household level analysis. Own calculations based on the Belgian PEACH2AIR dataset.

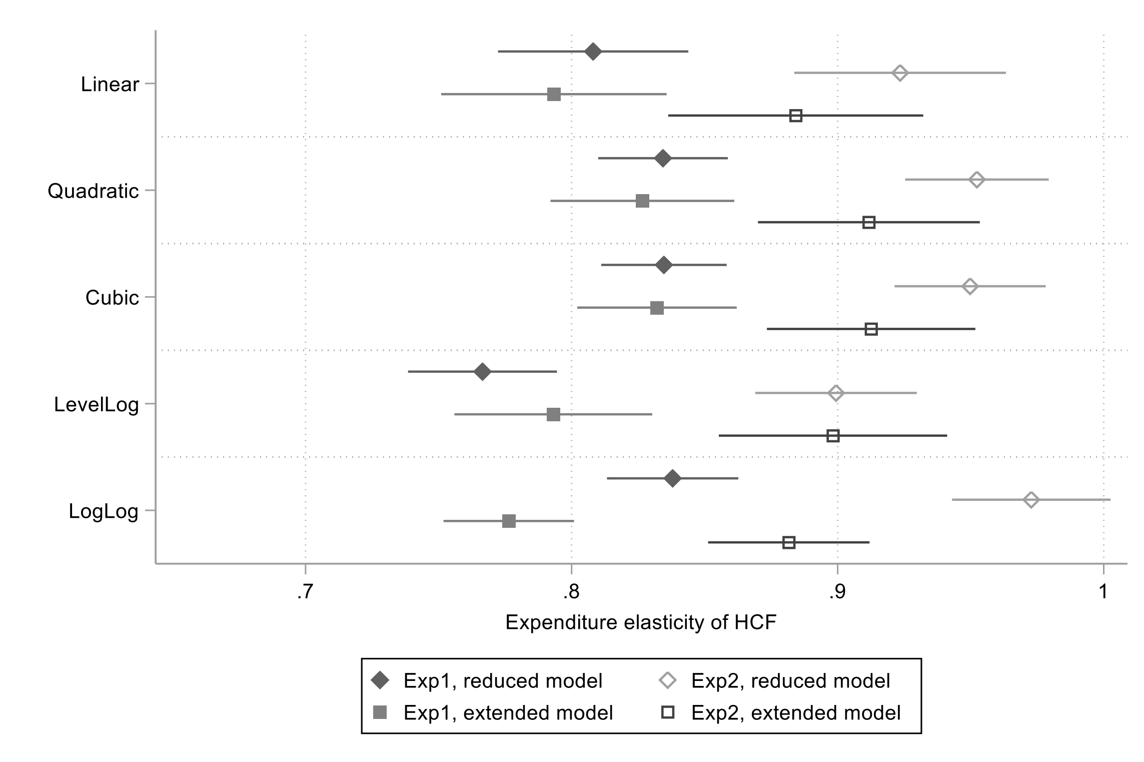

Figure 2. Elasticity values based on different expenditure concepts (analysis at the individual level). Exp1: consumption expenditures. Exp2: consumption expenditures plus rent, imputed rent, mortgage payments. Elasticities are estimated at average income/expenditure levels. 95% Confidence intervals. Figure A2 reproduces the graph in a household level analysis. Own calculations based on the Belgian PEACH2AIR dataset.

3.2. Implications for the top-down estimates of inequalities in emissions

Some authors resort to the use of top-down estimation of HCFs. The aim of top-down estimation of HCFs is to gain insight into the distribution of emissions across different income groups when no detailed microdata are available about household income/expenditures and the emissions embedded in the supply chains of the goods and services. In this section we present the results of the top-down method applied to the 2014 situation in Belgium, using the range of elasticity estimates from the previous section, and how this compares to the bottom-up HCF distributions, keeping everything else constant. This helps to shed more light on the importance of the characteristics of elasticity estimates for a robust application of the top-down approach.

Figure 3 summarizes our results and presents the estimated average level of GHG emissions per capita (vertical axes) across equivalized income, resp. expenditure deciles (horizontal axis). The spikes represent the range of top-down estimates, the boxes represent the observed average GHG per capita with 95% confidence bounds (i.e. the bottom-up estimates). Here, we take individuals as the unit of analysis, while the results with households as the unit of analysis are included in the Annex.

The graph reveals several insights. First, the range of top-down HCF estimates varies across the income/expenditure distributions. At each decile, different elasticity values yield different HCF estimates, and the minimum and maximum of these estimates (marked by the spikes on Figure 3) are further away from each other at the bottom and the top of the distributions. In the 10^{th} income decile, for example, the top-down HCF estimates range from 9.6 to 16.5 tons of CO_2 equivalent per capita. These estimates result from elasticity values of 0.2 and 1, respectively. On the other hand, in the 6^{th} income decile, the top-down HCFs range from 8.0 to 8.3 tons of CO_2 equivalent per capita. These estimates result from elasticity values of 1 and 0.4, respectively.

Second, over and underestimation of the HCF per capita vary substantially between the individual level analysis (displayed in Figure 3) and the household level analysis (displayed in Figure A3 in the Annex). However, in both cases, systematic bias in estimated HCFs vary across the income-/expenditure distribution. In the household level analysis, top-down HCFs are below bottom-up HCFs in the center income/expenditure deciles: the range of the top-down estimates do not overlap with the 95% confidence intervals of the bottom-up estimates. In the 5^{th} income (expenditure) deciles, for example, top-down estimates range between 7.0 and 8.2 (7.6 and 8.2) tons of CO_2 equivalent per capita, while the bottom-up estimate is 9.3 (8.8) tons of CO_2 equivalent per capita. At the same time, the range of the top-down estimates covers all or most of the 95% confidence interval of the bottom-up estimates in the high and low income/expenditure deciles. In contrast, in the individual level analysis, the range of top-down estimates covers relatively well the bottom-up HCFs across the entire income distribution. However, the top-down estimates are completely off the mark for the bottom and top expenditure deciles.

Third, the value of the elasticity has a considerable effect on the shape of the top-down HCF distribution. The higher the value of the elasticity, the higher the top-down HCF estimate at the upper end of the income/expenditure distributions compared to the bottom-up HCF estimate. In contrast, the higher the value of the elasticity, the lower the top-down HCF estimate at the lower end of the income/expenditure distribution compared to the bottom-up HCF estimate. In other words, a high elasticity value leads to an overestimation of HCFs at the top of the income/expenditure distribution and an underestimation HCFs at the bottom. The reverse applies for low elasticities. An important exception to this rule concerns the HCF by expenditure decile with the analysis at the individual level. Surprisingly, even the highest elasticity leads to an over-estimation of the HCF in the bottom decile, and an underestimation of the HCF in the top decile. With the current approach, none of the top-down estimates results in a HCF per capita distribution that matches well the one obtained directly from the microdata.

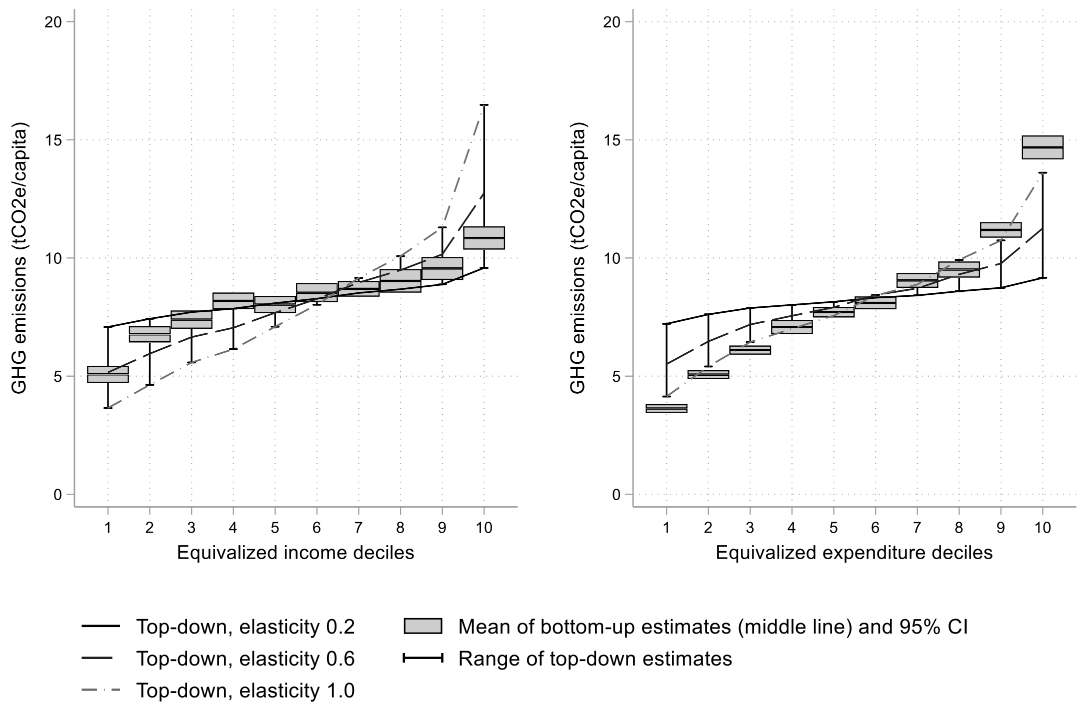

Figure 3. Bottom-up and top-down estimates of HCFs in income (left) and expenditure (right) deciles. Individual level analysis. Spikes represent the range of top-down estimates, boxes represent the bottom-up estimates. Spikes range from the minimum to the maximum of the top-down estimates. The mean of the bottom-up estimates is the middle horizontal line of the boxes. The top and bottom of the boxes represent the upper and lower limits of the 95% confidence interval around the mean, respectively.

Note: Deciles are constructed by equivalising income using the modified OECD equivalence scale. Individuals are the unit of analysis for identifying decile cut-offs and emissions / capita. Source: Own computations based on the Belgian PEACH2AIR dataset.

Top-down estimates of the distribution of GHG emissions by income or expenditure decile are typically used to compute several summary estimates of the inequality in emissions. Indicators of the (global) inequality in emissions include in particular the ratio of the share in total emissions of top income or expenditure quantiles compared to the emission shares of bottom income/expenditure quantiles. Therefore, it is useful to focus on the effect of elasticity assumptions on these inequality measures. More in particular, in Table 1 we present three 'share ratios': (1) the ratio of the emissions share of the top income/expenditure percentile and the emissions share of the bottom 50% of the income/expenditure distribution (t1/b50); (2) the ratio of the share in total emissions of the top income/expenditure decile and the bottom income/expenditure decile (t10/b10); (3) the ratio of the share in total emissions of the top income/expenditure decile and the bottom 50% of the income/expenditures distribution (t10/b50).

Focusing on the bottom row in Table 3, we learn that the microdata suggests substantial inequalities in emissions, although (unsurprisingly) much lower than those estimated at the global level (see Table 5 in Chancel, 2021). For instance, emissions of the top income decile are more than twice the amount of those of the bottom income decile, and are equal to 31% of emissions by the bottom 50%. Inequalities in emissions are even larger by expenditure deciles, with the top 10% accounting for 4 times the emissions of the bottom 10%, and 50% of the bottom 50%.

It is not surprising to see that the share ratios of GHG emissions can vary considerably according to the chosen elasticity, and by living standards concept (equivalised income as opposed to equivalised expenditures). For a given elasticity, the top-down share ratios of expenditure quantiles are smaller than the share ratios of income quantiles, particularly in the case of higher elasticities. The reason is that, overall, income inequality is somewhat higher than inequality in expenditures.

When looking at income and expenditures separately, share ratios of top-down HCFs increase considerably with rising elasticities, in line with the patterns observed in Figure 3. This increase is so much, that presenting the full range of estimated share ratios in a top-down analysis would do little to clarify the scale of inequality in emissions. For instance, with an elasticity of unity, the 10% richest in terms of income are estimated to emit up to 4.5 times more than the poorest 10%, while with a low elasticity of 0.2 this is only 1.35 times more.

Furthermore, the elasticity assumption which results in the closest match between the bottom-up and top-down share ratios, varies between the four variants explored here (i.e. individual level analysis vs. household level analysis and income vs. expenditure distribution), as well as between the share ratios. In the case of an analysis at the individual level with respect to the income distribution, an elasticity around 0.5 would be closest to the bottom-up elasticity for the t10/b10 ratio. In contrast, it should be about 0.2-0.3 for the t1/b50 ratio and 0.4 for the t10/b50 ratio. This implies that, with respect to incomes, the reduced form model performed best to estimate an elasticity (between 0.3 and 0.5) that could be used for a relatively adequate top-down estimation. In contrast, for a household level analysis with respect to income, the elasticities of the extended model provided the closest match. In addition, the share ratios were moderately well approximated with any of the estimated expenditure elasticities of emissions in the case of a household level analysis. However, none of the estimated elasticities resulted in a top-down estimate that approximated the bottom-up estimates of inequalities in emissions by expenditure decile with individuals as the unit of analysis. The share ratios calculated on the microdata are substantially above those calculated with the top-down approach. As could be expected from Figure 3, even with an elasticity of 1, the share ratios are underestimated.

Interestingly, if the range of expenditure elasticities estimated from the microdata would be applied to the top-down approach with respect to the income distribution, the estimated share ratios would approximate the bottom-up share ratios. Importantly, this only applies when individuals are the unit of analysis. Top-down estimates would be not as well approximated in that fashion when households are the level of analysis (see Table A17 in the Annex). This is relevant, because global top-down studies implicitly lump together income and expenditure data.

In sum, the accuracy of the top-down approach is strongly dependent on the assumed elasticity. Even then, there is considerable variation in performance of the approach between income and expenditures as the sorting variable, and - in the latter case – between households or individuals as the unit of analysis.

Table 3. Share ratios of top-down HCFs for different elasticity values (individual level analysis)

	Income			Expenditures		
Elasticity	t1/b50	t10/b10	t10/b50	t1/b50	t10/b10	t10/b50
0.2	0.03	1.35	0.25	0.03	1.27	0.24
0.3	0.03	1.57	0.28	0.03	1.43	0.26
0.4	0.04	1.83	0.31	0.03	1.61	0.28
0.5	0.05	2.12	0.35	0.04	1.81	0.30
0.6	0.06	2.47	0.39	0.04	2.04	0.32
0.7	0.07	2.87	0.44	0.04	2.30	0.35
0.8	0.08	3.34	0.49	0.05	2.59	0.38
0.9	0.09	3.88	0.54	0.06	2.92	0.41
1.0	0.11	4.51	0.61	0.06	3.29	0.45
Bottom-up	0.03	2.13	0.31	0.07	4.04	0.50

Note: Numbers express share of top x% in total emissions divided by the share of bottom y% in total emissions. `t' stands for 'top',' b' stands for 'bottom'. E.g. the top left number expresses the share of the top 1% income group in total emissions divided by the share of the bottom 50% income group in total emissions when emissions are calculated with the top-down method, using a 0.2 elasticity value.

4. DISCUSSION AND CONCLUSION

This study started from the observation that many papers on inequality in HCFs report the income or expenditure elasticity of the HCF. Although there is some awareness that the estimated elasticities are not directly comparable, in this paper we set out to demonstrate to what extent comparability is limited. By making use of Belgian data, we showed that estimated elasticities are spread over a continuum when different functional forms, expenditure concepts, model specifications and units of analysis are used, even when keeping the underlying data and modelling framework constant. The key factor proved to be the difference between the income and expenditure elasticity of emissions. We found that estimated elasticities varied between 0.2 and 1.0. Greater variation could be expected when also underlying data sources, modelling of indirect and direct emissions, and income or expenditure concepts vary. While the difference between the income elasticity vs. expenditure elasticity of HCF stood out, in the case of the income elasticity of emissions, we also found considerable variation between bivariate and multivariate modelling of the elasticity, as well as between a household level and individual level analysis, while to some degree also the functional form could not be disregarded. In line with warnings by Pottier (2022), this implies that caution with comparing elasticities across studies is well justified, and authors should be very clear about how exactly they computed the income / expenditure elasticity and for what purpose. In contrast, we found only limited variation in estimated elasticities at the median vs. the mean of incomes/expenditures, or between two different expenditure concepts.

At the moment, many countries lack up to date microdata on income, expenditures and the associated HCF. To gain more insight into inequalities in emissions across income levels, authors have resorted to so-called 'top-down' approaches. These often make use of assumptions regarding the income or expenditure elasticity of emissions, and apply these to the known distribution of incomes or expenditures. We noted that a bottom-up estimation showed that the expenditure inequality in emissions is higher than the income inequality in emissions. However, when assuming a fixed elasticity, the resulting top-down estimate of inequality in emissions is considerably lower between expenditure groups than between income groups. This has three important implications:

First, in global studies where income (expenditure) data may not be available for all countries under study, one should be very cautious with lumping expenditure-based inequalities in emissions together with income-based inequalities in emissions: bottom-up estimates show that emission inequalities are substantially different. Likewise, one should be careful with studying changes over time when the data source would change from income to expenditures or the other way around. Inequalities in HCF with respect to income and expenditure groups are not (directly) comparable. However, as Pottier (2022) points out, the two concepts have been used interchangeably in the top-down studies of Oxfam (2015b, p2), Hubacek et al. (2017), and Kartha et al. (2020). Similarly, Chancel and Piketty make use of the dataset of Lakner and Milanovic (2013) which uses "a combination of income and consumption expenditure surveys" (Chancel and Piketty, 2015, p24).

Second, the most suitable elasticity is likely to be very different for expenditure-based estimates as compared to income-based estimates. Sensitivity tests that uniformly vary the elasticity assumption for both concepts do not capture adequately this reality: they should be geared specifically at emission inequalities between income groups or between expenditure groups. In our case, we found that even the highest elasticity that we estimated with the bottom-up approach still resulted in a substantial underestimation of emission inequalities between expenditure groups (individual level analysis). In contrast, the range of bottom-up estimates of the income elasticity of emissions covered well the range of elasticity assumptions that resulted in accurate top-down estimates of the inequality in emissions between income groups.

Third, the most appropriate elasticity assumption varied not just between income and expenditures, but also between inequality indicators. This is another factor that should be taken into account for sensitivity tests in a top-down approach.

More generally, we found that with the top-down approach the estimated HCF in the top and bottom deciles is very sensitive to the assumed elasticity. Whenever available, bottom-up estimates are very likely to result in more stable and accurate estimates than top-down approaches can achieve. Given much larger inequalities in income and emissions at the global compared to the national level, this calls for some caution for strong claims about top-down estimates of emission inequalities with regard to the very top of the income distribution, as well as for further data work and analysis that makes a more robust estimation of emission inequalities possible. This is an important task as insights in the global distribution of household emissions continue to shape the global debate on climate injustice.

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ANNEX

A1. Summary statistics

Description of variables:

- HCF: Household per capita carbon footprint. The amount of greenhouse gas emissions that a household emits through its consumption of goods and services on a per capita basis. It is expressed in tons of CO_2 equivalents, and accounts for both direct and indirect ('embedded') emissions.
- Income: Total equivalized disposable income of the household
- Expenditures 1: Total equivalized consumption expenditures of the household
- Expenditures 2: Total equivalized consumption expenditures of the household plus rent payments, mortgage payments, and imputed rent for owner occupied dwellings.
- Income and expenditures are equivalized using the modified OECD-scale which assigns the value of 1 to the first adult, 0.5 to each additional adult and 0.3 to each child (defined as a person younger than 14)
- Numbers are presented both at the individual level (typical unit of analysis) and the household level (typical unit of assessment for income, expenditures and emissions). In the former case, each individual is counted once, in the latter, each household is counted once, independently of household size. All results are weighted using the survey weight distributed by the data provider, which corrects for varying probabilities of selection and varying non-response rates, and calibrates the weights on several known population totals.

Source: Own computations based on the Belgian PEACH2AIR dataset.

Table A1. Summary statistics of variables included in top-down HCF calculation (individual-level)

	Mean	Median	Min	Max
HCF (tons CO_2e/capita)	8.2	7.2	0.8	69.2
Income (€)	23,824	21,798	0	285,600
Expenditures 1 (€)	17,811	16,884	2,207	117,787
Expenditures 2 (€)	22,687	21,785	3,371	123,187

Table A2. Summary statistics of variables included in top-down HCF calculation (household-level)

	Mean	Median	Min	Max
HCF (tons CO_2e/capita)	9.4	8.3	0.8	69.2
Income (€)	37,414	31,800	0	514,080
Expenditures 1 (€)	28,279	25,228	2,664	176,680
Expenditures 2 (€)	36,235	32,938	6,060	184,780

A2. Elasticity estimates

In the following tables 'Mean' ('Median') means that we calculated the elasticity at the mean (median) of the distribution, and we did not add other covariates to the regression model apart from income/expenditures. 'Ext' refers to the extended model that includes explanatory variables other than income/expenditures. In case of the extended models, we calculated elasticities at the mean of the distributions. Beta represents the regression coefficient, 'SE' its standard error, LB the lower 95% confidence bound and UB the upper 95% confidence bound. Source: Own computations based on the Belgian PEACH2AIR dataset.

Table A3. Elasticity estimates using the linear model (individual level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.81	0.80	0.79	0.92	0.92	0.88	0.30	0.28	0.23
SE	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02
LB	0.77	0.76	0.75	0.88	0.88	0.84	0.24	0.22	0.18
UB	0.84	0.84	0.84	0.96	0.96	0.93	0.35	0.33	0.27

Table A4. Elasticity estimates using the linear model (household level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.83	0.82	0.74	0.93	0.93	0.83	0.47	0.43	0.22
SE	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.02
LB	0.79	0.77	0.69	0.89	0.88	0.77	0.41	0.37	0.17
UB	0.87	0.86	0.79	0.98	0.97	0.89	0.53	0.49	0.27

Table A5. Elasticity estimates using the quadratic model (individual level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.83	0.83	0.83	0.95	0.96	0.91	0.41	0.39	0.33
SE	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.02
LB	0.81	0.81	0.79	0.93	0.93	0.87	0.37	0.35	0.29
UB	0.86	0.86	0.86	0.98	0.98	0.95	0.45	0.43	0.37

Table A6. Elasticity estimates using the quadratic model (household level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.86	0.86	0.78	0.96	0.97	0.87	0.61	0.60	0.33
SE	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
LB	0.84	0.84	0.75	0.94	0.95	0.84	0.57	0.55	0.29
UB	0.88	0.88	0.80	0.98	1.00	0.90	0.65	0.64	0.37

Table A7. Elasticity estimates using the cubic model (individual level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.83	0.83	0.83	0.95	0.96	0.91	0.44	0.43	0.35
SE	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.02
LB	0.81	0.81	0.80	0.92	0.93	0.87	0.39	0.38	0.31
UB	0.86	0.86	0.86	0.98	0.98	0.95	0.48	0.48	0.39

Table A8. Elasticity estimates using the cubic model (household level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.86	0.86	0.78	0.96	0.97	0.88	0.66	0.67	0.37
SE	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
LB	0.84	0.84	0.76	0.94	0.95	0.85	0.63	0.64	0.32
UB	0.88	0.88	0.80	0.99	1.00	0.90	0.69	0.70	0.41

Table A9. Elasticity estimates using the level-log model (individual level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.77	0.74	0.79	0.90	0.87	0.90	0.41	0.40	0.33
SE	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.02	0.02
LB	0.74	0.71	0.76	0.87	0.84	0.86	0.36	0.36	0.29
UB	0.79	0.76	0.83	0.93	0.90	0.94	0.45	0.45	0.37

Table A10. Elasticity estimates using the level-log model (household level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.77	0.75	0.74	0.91	0.89	0.88	0.59	0.59	0.32
SE	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
LB	0.74	0.72	0.70	0.87	0.85	0.83	0.56	0.55	0.28
UB	0.80	0.77	0.78	0.94	0.92	0.93	0.62	0.62	0.36

Table A11. Elasticity estimates using the log-log model (individual level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.84	0.84	0.78	0.97	0.97	0.88	0.48	0.48	0.32
SE	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
LB	0.81	0.81	0.75	0.94	0.94	0.85	0.43	0.43	0.28
UB	0.86	0.86	0.80	1.00	1.00	0.91	0.52	0.52	0.35

Table A12. Elasticity estimates using the log-log model (household level)

	Expenditures 1			Expenditures 2			Income		
	Mean	Median	Ext	Mean	Median	Ext	Mean	Median	Ext
Beta	0.86	0.86	0.78	0.99	0.99	0.90	0.65	0.65	0.32
SE	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
LB	0.84	0.84	0.76	0.97	0.97	0.87	0.61	0.61	0.28
UB	0.88	0.88	0.80	1.02	1.02	0.93	0.69	0.69	0.36

A3. Top-down HCF estimates

A3.1. Expenditures

In tables A13 and A14 the expenditure concept includes consumption expenditures, rent, imputed rent and mortgage payments. In tables A13 and A14, HCFs are calculated on a per capita basis (i.e. the total emissions in the decile divided by the total number of people in the decile). Deciles are constructed by equivalising expenditures using the modified OECD equivalence scale, which assigns the value of 1 to the first adult, 0.5 to each additional adult and 0.3 to each child (defined as a person younger than 14). In Table A13, individuals are the unit of analysis for identifying decile cut-offs and each decile contains 10% of individuals. In contrast, in Table A14, households are the unit of analysis for decile cut-offs, and each decile contains 10% of the (weighted) households. The mean bottom-up HCFs in each decile are presented in the tables for comparison. Source: Own computations based on the Belgian PEACH2AIR dataset.

Table A13. Top-down per capita HCF (tCO_2e/capita) estimates in 10 expenditure deciles (decile cut-offs calculated at the individual level)

Decile	Top-down Elasticity values									Bottom-up
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	
1	7.21	6.75	6.32	5.90	5.51	5.14	4.78	4.45	4.14	3.63
2	7.61	7.32	7.03	6.75	6.47	6.19	5.93	5.66	5.41	5.07
3	7.88	7.71	7.54	7.36	7.18	7.00	6.82	6.63	6.44	6.10
4	8.02	7.91	7.80	7.68	7.55	7.42	7.29	7.15	7.00	7.08
5	8.14	8.10	8.04	7.98	7.91	7.83	7.75	7.66	7.56	7.71
6	8.32	8.36	8.39	8.42	8.43	8.44	8.44	8.43	8.41	8.10
7	8.42	8.50	8.58	8.65	8.71	8.77	8.81	8.85	8.88	9.05
8	8.59	8.78	8.96	9.14	9.31	9.47	9.63	9.78	9.92	9.51
9	8.74	9.00	9.26	9.51	9.77	10.02	10.26	10.50	10.74	11.19
10	9.16	9.66	10.18	10.71	11.26	11.82	12.40	13.00	13.61	14.68

Table A14. Top-down per capita HCF (tCO_2e/capita) estimates in 10 expenditure deciles (decile cut-offs calculated at the household level)

Decile	Top-down Elasticity values 0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	Bottom-up
1	6.1	5.7	5.3	4.9	4.6	4.3	4.0	3.7	3.4	4.38
2	7.3	7.0	6.7	6.4	6.1	5.8	5.5	5.3	5.0	5.86
3	7.5	7.3	7.1	6.9	6.7	6.5	6.3	6.1	5.9	6.97
4	8.1	7.9	7.8	7.7	7.5	7.4	7.2	7.1	6.9	8.26
5	8.2	8.2	8.1	8.0	8.0	7.9	7.8	7.7	7.6	8.77
6	8.2	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	9.43
7	8.4	8.5	8.6	8.7	8.8	8.9	8.9	9.0	9.1	9.94
8	8.8	9.0	9.2	9.4	9.6	9.7	9.9	10.1	10.2	11.11
9	9.7	10.0	10.2	10.5	10.8	11.1	11.3	11.6	11.8	13.00
10	10.8	11.4	12.1	12.8	13.5	14.2	14.9	15.7	16.5	16.60

A3.2. Income

In tables A15 and A16, HCFs are calculated on a per capita basis (i.e. the total emissions in the decile divided by the total number of people in the decile). Deciles are constructed by equivalising expenditures using the modified OECD equivalence scale, which assigns the value of 1 to the first adult, 0.5 to each additional adult and 0.3 to each child (defined as a person younger than 14). In Table A15, individuals are the unit of analysis for identifying decile cut-offs and each decile contains 10% of individuals. In contrast, in Table A16, households are the unit of analysis for decile cut-offs, and each decile contains 10% of the (weighted) households. The mean bottom-up HCFs in each decile are presented in the tables for comparison. Source: Own computations based on the Belgian PEACH2AIR dataset.

Table A15. Top-down per capita HCF (tCO_2e/capita) estimates in 10 income deciles (decile cut-offs calculated at the individual level)

Decile	Top-down Elasticity values 0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	Bottom-up
1	7.08	6.56	6.06	5.60	5.16	4.74	4.35	3.99	3.65	5.08
2	7.43	7.05	6.67	6.31	5.95	5.60	5.27	4.94	4.63	6.77
3	7.71	7.45	7.19	6.92	6.65	6.38	6.11	5.84	5.58	7.39
4	7.86	7.67	7.47	7.26	7.05	6.83	6.60	6.37	6.14	8.18
5	8.09	8.01	7.91	7.80	7.68	7.55	7.41	7.26	7.09	8.03
6	8.28	8.30	8.30	8.29	8.27	8.23	8.17	8.11	8.02	8.53
7	8.52	8.65	8.77	8.87	8.96	9.03	9.09	9.13	9.15	8.69
8	8.68	8.90	9.11	9.30	9.49	9.66	9.81	9.95	10.08	9.03
9	8.88	9.21	9.53	9.85	10.16	10.46	10.75	11.03	11.29	9.56
10	9.58	10.32	11.09	11.90	12.75	13.63	14.55	15.50	16.48	10.85

Table A16. Top-down per capita HCF (tCO_2e/capita) estimates in 10 income deciles (decile cut-offs calculated at the household level)

	Top-down Elasticity values									Bottom-up
Decile	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	
1	7.0	6.5	6.0	5.5	5.0	4.6	4.2	3.8	3.5	6.11
2	8.4	7.9	7.5	7.0	6.6	6.1	5.7	5.3	4.9	7.95
3	8.2	7.9	7.5	7.2	6.9	6.6	6.2	5.9	5.6	8.49
4	8.4	8.2	7.9	7.7	7.4	7.2	6.9	6.6	6.4	9.40
5	8.2	8.1	8.0	7.9	7.7	7.5	7.4	7.2	7.0	9.35
6	7.8	7.8	7.8	7.8	7.8	7.8	7.7	7.6	7.6	9.28
7	8.1	8.2	8.3	8.4	8.4	8.5	8.5	8.5	8.5	10.44
8	8.0	8.2	8.5	8.7	8.8	9.0	9.2	9.3	9.4	10.11
9	8.6	9.0	9.3	9.7	10.0	10.3	10.6	10.9	11.2	10.78
10	9.4	10.2	11.0	11.9	12.8	13.8	14.8	15.8	16.9	12.39

A4. Household level results

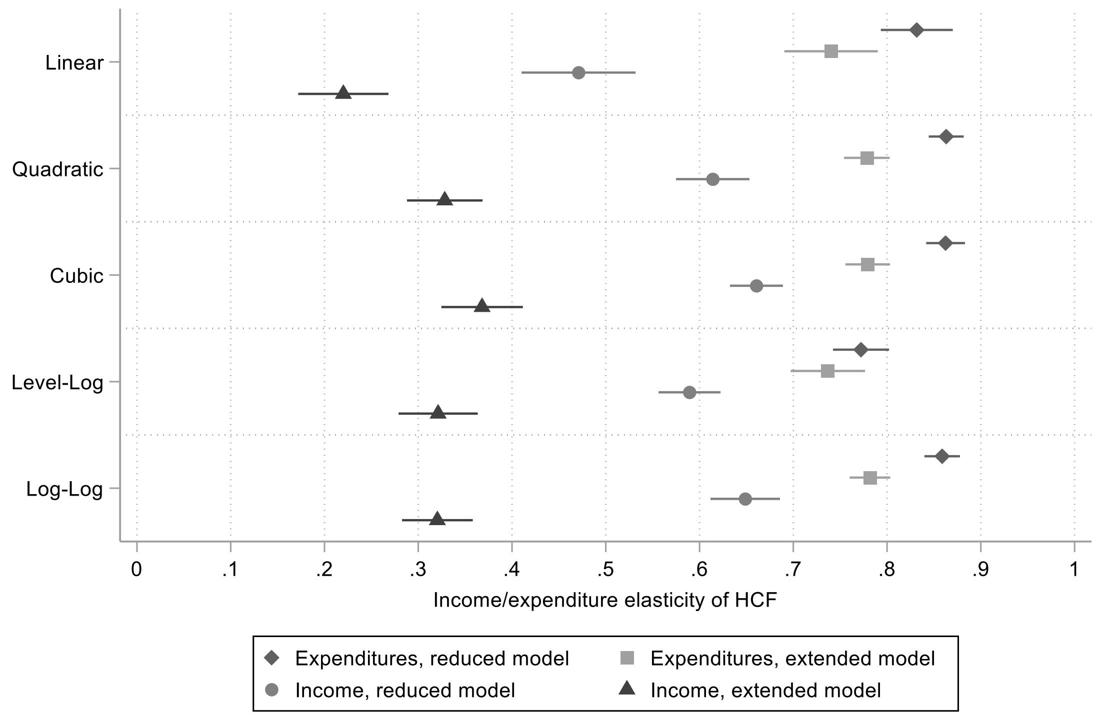

Figure A1. Income and expenditure elasticity of HCF. Household level analysis. Expenditures do not include rent, imputed rent and mortgage payments. Elasticities are estimated at average income/expenditure levels. 95% Confidence intervals. Own calculations based on the Belgian PEACH2AIR dataset.

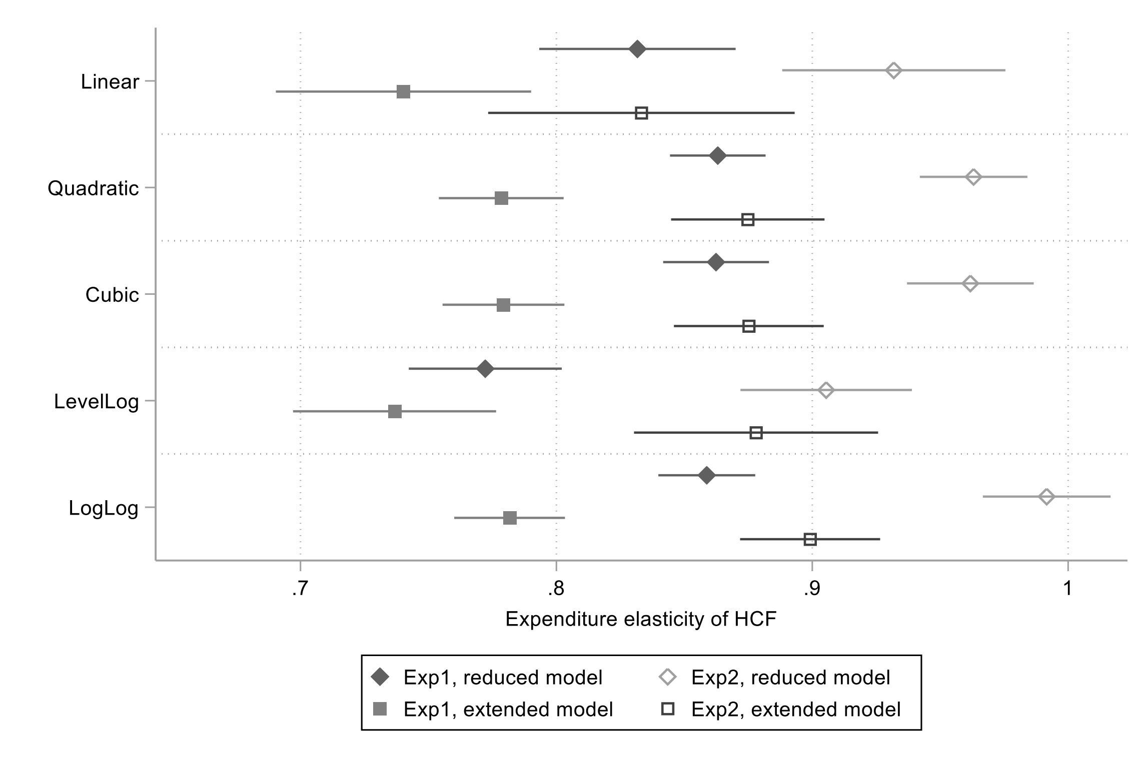

Figure A2. Elasticity values based on different expenditure concepts. Household level results. Exp1: consumption expenditures. Exp2: consumption expenditures plus rent, imputed rent, mortgage payments. Elasticities are estimated at average income/expenditure levels. 95% Confidence intervals. Own calculations based on the Belgian PEACH2AIR dataset.

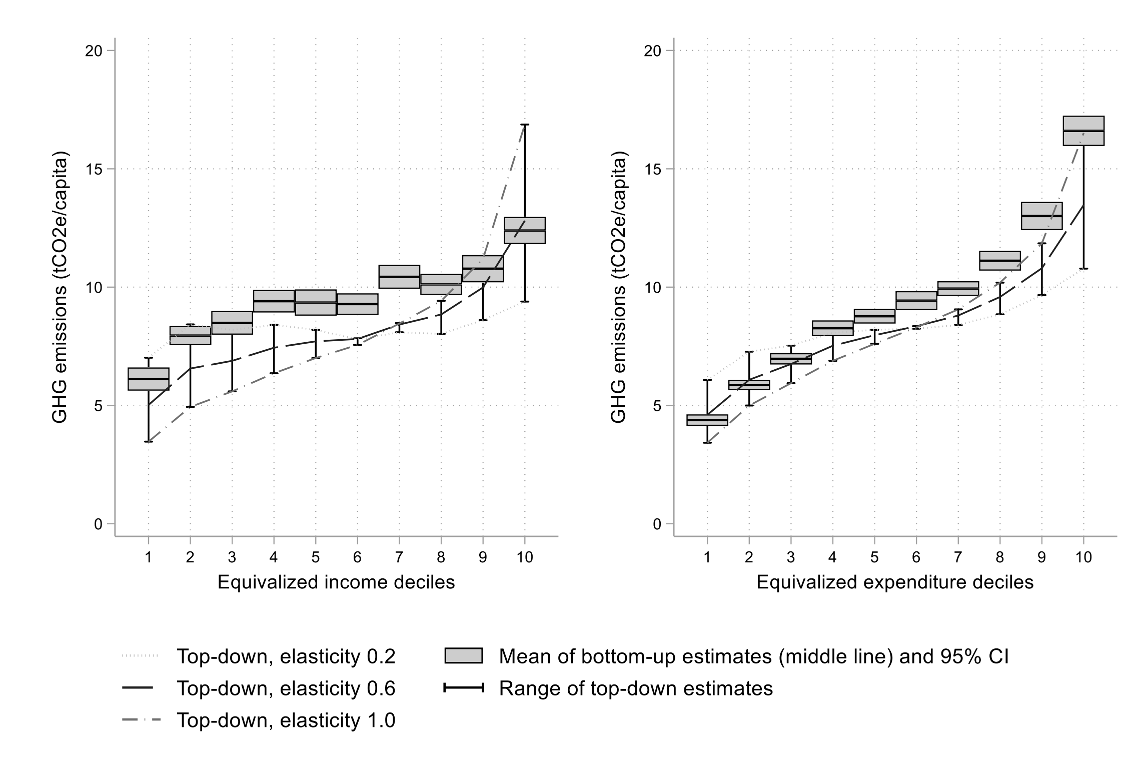

Figure A3. Bottom-up and top-down estimates of HCFs in income (left) and expenditure (right) deciles. Household level analysis. Spikes represent the range of top-down estimates, boxes represent the bottom-up estimates. Spikes range from the minimum to the maximum of the top-down estimates. The mean of the bottom-up estimates is the middle horizontal line of the boxes. The top and bottom of the boxes represent the upper and lower limits of the 95% confidence interval around the mean, respectively.

Note: Deciles are constructed by equivalising income using the modified OECD equivalence scale, which assigns the value of 1 to the first adult, 0.5 to each additional adult and 0.3 to each child (defined as a person younger than 14). The weighted sample of households is used for identifying the income deciles. Source: Own computations based on the Belgian PEACH2AIR dataset.

Table A17. Share ratios of top-down HCFs for different elasticity values (Household level analysis)

	Income			Expenditures		
Elasticity	t1/b50	t10/b10	t10/b50	t1/b50	t10/b10	t10/b50
0.2	0.03	1.38	0.26	0.03	1.28	0.24
0.3	0.04	1.62	0.29	0.03	1.45	0.26
0.4	0.04	1.91	0.33	0.03	1.65	0.28
0.5	0.05	2.24	0.37	0.04	1.87	0.31
0.6	0.06	2.63	0.42	0.04	2.12	0.34
0.7	0.07	3.09	0.47	0.05	2.40	0.37
0.8	0.09	3.63	0.53	0.05	2.72	0.40
0.9	0.11	4.27	0.60	0.06	3.08	0.44
1.0	0.13	5.02	0.68	0.07	3.49	0.47
Bottom-up	0.04	2.18	0.33	0.05	2.86	0.41

Note: Numbers express share of top x% in total emissions divided by the share of bottom y% in total emissions. `t' stands for 'top',' b' stands for 'bottom'. E.g. the top left number expresses the share of the top 1% income group in total emissions divided by the share of the bottom 50% income group in total emissions when emissions are calculated with the top-down method, using a 0.2 elasticity value.