Mapping the carbon footprint of EU regions

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Abstract

While the EU Commission has encouraged Member States to combine national and international climate change mitigation measures with subnational environmental policies, there has been little harmonized effort towards the quantification of embodied greenhouse gas (GHG) emissions from household consumption across European regions. This study develops an inventory of carbon footprints associated with household consumption for 177 regions in 27 EU countries, thus, making a key contribution for the incorporation of consumption-based accounting into local decision-making. Footprint calculations are based on consumer expenditure surveys and environmental and trade detail from the EXIOBASE 2.3 multiregional input-output database describing the world economy in 2007 at the detail of 43 countries, 5 rest-of-the-world regions and 200 product sectors. Our analysis highlights the spatial heterogeneity of embodied GHG emissions within multiregional countries with subnational ranges varying widely between 0.6 and 6.5 tCO_2e/cap. The significant differences in regional contribution in terms of total and per capita emissions suggest notable differences with regards to climate change responsibility. The study further provides a breakdown of regional emissions by consumption categories (e.g. housing, mobility, food). In addition, our region-level study evaluates driving forces of carbon footprints through a set of socio-economic, geographic and technical factors. Income is singled out as the most important driver for a region's carbon footprint, although its explanatory power varies significantly across consumption domains. Additional factors that stand out as important on the regional level include household size, urban-rural typology, level of education, expenditure patterns, temperature, resource availability and carbon intensity of the electricity mix. The lack of cross-national region-level studies has so far prevented analysts from drawing broader policy conclusions that hold beyond national and regional borders.

1. Introduction

Under the Europe 2020 growth strategy, EU has committed to cutting its territorial greenhouse gas (GHG) emissions to 20% below 1990 levels as a part of the Climate and Energy package (European Commission 2016). Core policies such as the EU Emissions Trading System (EU ETS) and the Effort Sharing Decision set binding targets for each Member State covering the major polluting sectors (Eurostat 2016).

The Commission has also recommended that environmental issues be tackled on subnational level (European Commission 2011a, 2011b). The research community has pointed out to the importance of regional and local policy for environmental impact mitigation (Meng *et al* 2013, Harris *et al* 2012, Wood and Garnett 2010, 2009). Cross-country analyses conceal wide spatial heterogeneity within countries, which may potentially obstruct the effect of impact mitigation policies (Godar *et al* 2015, Chancel and Piketty 2015).

Regions systematically focus on mitigation of impacts occurring on their territory (Somanathan *et al* 2015, Andonova and Mitchell 2010), e.g. by deciding on waste treatment options or transport planning. While such actions may reduce emissions locally, production activity may simply move somewhere else (Girod *et al* 2014, Skelton 2013). Studies have signalled for the empirical significance of carbon off-shoring (Harris *et al* 2012, Aichele and Felbermayr 2012), e.g. showing that countries committed to the Kyoto Protocol have about 8% more carbon-intensive imports than uncommitted ones (Aichele and Felbermayr 2015). Products may accumulate a significant load of environmental impacts along global supply chains before they reach final consumers and such effects are unaccounted for from a purely territorial perspective. Just as a city draws most of its agricultural goods from hinterland, a region may have a far greater impact in reducing emissions from the goods they consume than the goods they produce (Lenzen *et al* 2008). The consumption-based accounting establishes a link between local consumption and its global environmental consequences (Wood and Dey 2009).

Consumption-based policies may be effective to sustain regional competitiveness and limit the opportunity for carbon leakage (Girod *et al* 2014). Despite this potential, policy makers have generally failed to adopt consumption-based measures on the subnational level (Turner *et al* 2011). This is at least partly due to the lack of harmonized and actionable impact information on that level of regional detail. To our knowledge, no subnational assessment of household carbon footprints has been made available for the whole European Union. Previous studies on regional footprints cover only a limited number of (generally non-EU) countries or consumption sectors (Curry and Maguire 2011, Minx *et al* 2013, Minx *et al* 2009, Jones and Kammen 2014, Deng *et al* 2015, Zhang and Anadon 2014, Zhou and Imura 2011, Adom *et al* 2012, Miehe *et al* 2016, Larsen and Hertwich 2011, Lenzen *et al* 2004). This has prevented analysts from having a broader policy vision that goes beyond national and regional borders.

In this study, we assess household carbon footprints across 177 regions in EU27 providing a higher spatial detail than prior cross-country assessments (Tukker *et al* 2016, Ivanova *et al* 2015, Hertwich and Peters 2009). Furthermore, while there has been a significant amount of work on determinants of household energy use and GHG emissions (e.g. Lenzen *et al* 2006, Weber and Matthews 2008, Baiocchi *et al* 2010), conclusions have generally been drawn from individual-level assessments under a narrow spatial scope. Prior findings inform about the relevance of *socio-economic effects* such as income, household size, education, social status and degree of urbanization (Jones and Kammen 2014, 2011, Baiocchi *et al* 2010, Minx *et al* 2013, Lin *et al* 2013, Wilson *et al* 2013b), *geographic effects* such as temperature and geographic location (Tukker *et al* 2010, Newton and Meyer 2012) and *technical effects* such as the infrastructural context (Chancel and Piketty 2015, Tukker *et al* 2010, Sanne 2002). We would like to test whether influences that have been previously identified as important for consumption impacts may be apparent on the regional aggregated level as well (see table 1).

2. Data and methods

We conduct an environmentally extended multiregional input-output (MRIO) analysis combining the use of regionally disaggregated demand from consumer expenditure surveys (CESs) and product carbon intensities from the EXIOBASE 2.3 database. A detailed description of the data and methodology as well as the complete regional footprint inventory is provided in the supplementary information (SI) available at stacks.iop.org/ERL/12/054013/mmedia.

The majority of CESs adopt a common consumption nomenclature, i.e. the Classification of Individual Consumption by Purpose (COICOP) (European Communities 2003). The spatial coverage is based on the Nomenclature of territorial units for statistics (NUTS) regions, a hierarchical regional classification within EU (Eurostat 2017). Footprint accounts at NUTS 2 level allow for distinguishing between basic regions for the application of regional policies. Table 2 identifies differences in terms of collection year, product detail and spatial coverage.

EXIOBASE 2.3 provides national carbon intensities across 200 product sectors and detailed bilaterally by places of origin (i.e. global supply-chain information across 43 countries and 5 rest-of-the-world regions). The database facilitates environmental analysis by incorporating increased detail of environmentally important processes (Wood *et al* 2014, Stadler *et al* 2014). A detailed overview of EXIOBASE is provided by Wood *et al* (2015) and in the SI. We estimate indirect emissions embodied in the supply chains of purchases and the direct emissions occurring when households burn fuel (e.g. when driving). All emissions are reported in CO_2-equivalent (CO_2e) per year using GWP100 (Solomon *et al* 2007).

2.1. Regional footprint calculations based on CES-MRIO methodology

Several reconciliation steps were necessary for the CES-MRIO matching (Steen-Olsen *et al* 2016). The harmonization of product classification between the surveys (e.g. COICOP) and EXIOBASE was achieved using country-specific CES-MRIO concordance matrices. We matched classifications conceptually and through consulting EXIOBASE's household demand accounts as a benchmark. EXIOBASE's household accounts include all household consumption except the one registered as governmental spending or investment, e.g. health and social work

Table 1. Summary of exploratory hypotheses on relevant factors for consumption-based GHG emissions per capita. The table broadly agrees with an assessment conducted by Hertwich (2005) on energy consumption and CO_2 emissions.

	Factors	Direction of effect	Reasoning	Sources
Socio-economic	Income (INC)	+	Income directly determines household capacity to consume. The direction of the effect is more difficult to predict on product level, e.g. there exist inferior goods whose consumption goes down as income rises	Wilson *et al* 2013b, Tukker *et al* 2010, Peters and Hertwich 2008, Jackson and Papathanasopoulou (2008), Lenzen *et al* (2006)
	Household size (HHSIZE)	−	Household members share electrical appliances and require less individual living space Economies of scale in different consumption domains	Tukker *et al* (2010), Lenzen *et al* (2006), Wilson *et al* (2013b), Minx *et al* (2013)
	Urban-rural typology (URBAN)	+/−	Urban typology is associated with more compact development and larger availability of public transport, but studies have also found urban inhabitants to have higher impacts associated with food, leisure travel and manufactured products	Marcotullio *et al* (2014), Tukker *et al* (2010), Lenzen *et al* (2006), Minx *et al* (2013), Wiedenhofer *et al* (2013)
	Tertiary education (EDUC)	+/−	Education and social status redesign individual preferences towards more or less emission-intensive lifestyles	Chancel and Piketty (2015)
	Basic need spending (BASIC)	−	Spending on necessities (food, shelter, clothing) may be associated with lower emissions per unit of expenditure compared to that of transport and manufactured products	Ivanova *et al* (2015), Steen-Olsen *et al* (2016)
	Dwelling size (NROOMS)	+	Housing size determines the requirements of space heating/cooling and building material use	Lenzen *et al* (2006), Newton and Meyer (2012)
Geographic	Temperature (HDD)	+/−	Lower average temperatures (north) and low-quality, poorly isolated homes (south) are associated with higher emissions. Rising temperatures may also drive energy use for cooling.	Minx *et al* (2013), Wiedenhofer *et al* (2013), Chancel and Piketty (2015)
	Landscape (FORESTAREA)	+/−	Access to forest and semi-natural area may foster low-carbon leisure activities, but also encourage the consumption of available resources	Ivanova *et al* (2015)
Technical	Electricity mix intensity (EMIX)	+	The local electricity mix directly determines the carbon intensity of products produced and consumed locally (e.g. housing emissions)	Tukker *et al* (2010)

services, road infrastructure (Ivanova *et al* 2015). Tourism and transport sectors are potentially more affected by residents' spending abroad, which may bring about higher uncertainty of results in those sectors (Usubiaga and Acosta-Fernández 2015). See the SI, appendix 2 and 3, for details on the data and method.

The phenomenon of under-reporting in CESs has been well-documented in prior literature (Steen-Olsen *et al* 2016). Households systematically under-report small and irregular purchases, e.g. private goods (clothing), alcohol and tobacco, and certain luxuries (alcohol and food away from home) (Bee *et al* 2015). Methodological differences in the survey design may also give rise to under-reporting relative to the national accounts, e.g. the UK and Czech Republic differ in excluding owner-occupied imputed rent from their surveys (Eurostat 2015b). An additional vector was added to the CES-MRIO concordance matrix allocating expenditure missing in the surveys to the particular under-reported products.

Further harmonization of consumer demand in terms of year coverage, currency and valuation scheme was necessary. Consumer Price Indices by consumption item and country enabled a conversion to 2007 constant prices (Eurostat 2015a). Expenditure recorded in the surveys is reported in purchaser prices (PPs) or the price final consumers pay in the store, while carbon intensities in EXIOBASE are set for demand in basic prices (BPs). EXIOBASE provides transport, trade and tax layers enabling the conversion from PPs to BPs, reallocating the trade and transport costs of products to the respective services.

2.2. Explaining spatial variation of regional carbon footprints

This study employs a regression model to explore the relationships between household emissions and socio-economic, geographic and technical factors on the regional level. Multiple empirical studies and theoretical considerations (see table 1) informed the choice of model specification subject to data availability

Table 2. CES information by country. Sweden and the Netherlands have been excluded due to lack of regional detail. Only NUTS 1 data available for France, Germany and the UK (larger regions than NUTS 2). For more information about the accuracy, timeliness and comparability of the surveys refer to the EU quality report (Eurostat 2015b).

EU Countries	Year	Product detail	Spatial detail	N	Source
Austria	2010	COICOP 2	NUTS 2	9	Household Budget Survey, Statistik Austria
Belgium	2010	COICOP 3	NUTS 2	3	Household Budget Survey, Statistics Belgium
Bulgaria	2010	COICOP 3	NUTS 2	6	Household Budget Survey, NSI
Cyprus	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Czech Republic	2011	COICOP 3	NUTS 2	8	Household Budget Survey, Czech Statistical Office
Denmark	2010	COICOP 3	NUTS 2	5	Household Budget Survey, Statistics Denmark
Estonia	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Finland	2012	COICOP 3	NUTS 2	5	Household consumption expenditure, Statistics Finland
France	2011	COICOP 3	NUTS 1	9	Household Budget Survey, Insee
Germany	2010	28 products	NUTS 1	16	New consumption module, German Socio-Economic Panel
Greece	2014	COICOP 3	NUTS 2	13	Family Budget, EL.STAT
Hungary	2006	COICOP 3	NUTS 2	7	Household Budget Survey, KSH
Ireland	2010	COICOP 3	NUTS 2	2	Household Budget Survey, Central Statistics Office
Italy	2010	COICOP 1	NUTS 2	21	Household Budget Survey, Istat
Latvia	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Lithuania	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Luxembourg	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Malta	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Poland	2010	COICOP 1	NUTS 2	16	Household Budget Survey, Central Statistical Office
Portugal	2010	COICOP 3	NUTS 2	7	Household Budget Survey, Statistics Portugal
Romania	2012	COICOP 1	NUTS 2	8	Family Budgets Survey, NIS
Slovakia	2013	COICOP 1	NUTS 2	4	Household Budget Survey, Slovak Statistics
Slovenia	2007	200 products	NUTS 1	1	EXIOBASE 2.3
Spain	2010	COICOP 1	NUTS 2	19	Household Budget Survey, INE
United Kingdom	2010	COICOP 4	NUTS 1	12	Living Costs and Food Survey, ONS

constraint at the regional aggregation level. We conduct relative weights analysis to better understand the importance of each predictor while addressing the potential for multicollinearity. We employ cluster-robust errors to account for the potential correlation between regional observations belonging to the same country due to sharing of national features, e.g. national legislation, institutions, social and cultural norms, common infrastructure standards etc. Cluster-robust standard errors have been widely used as a method to tackle interclass correlation (Cameron and Miller 2015, Cameron and Trivedi 2009). The clustered regression approach produces unbiased clustered standard errors provided that there are a sufficient number of clusters (Petersen 2009). See the SI, appendix 1 and 4, for more detailed description of the variables in the model, statistical procedure and sensitivity analysis.

3. Results

3.1. Household carbon footprint at subnational level

Figures 1(*a*) and (*b*) map total and per capita household carbon footprint across EU regions. Descriptive footprint statistics and complete dataset can be found in the SI. North Rhine-Westphalia and Bavaria in Germany together emit about 410 $MtCO_2e$ or 40% of German emissions. Other regions with significant footprints include regions from the UK (e.g. South East, London), Germany (e.g. Baden-Württemberg, Lower Saxony), Italy (e.g. Lombardy) and France (e.g. Parisian Region). Regional footprints are normally distributed with mean and median of 11 tCO_2e/cap and standard deviation of 3 tCO_2e/cap. The top emission decile (i.e. 10% of the population with highest emissions per capita) includes regions with average carbon footprint between 22 and 16 tCO_2e/cap. The top decile emits 15% of the total EU emissions equivalent to 815 $MtCO_2e$. In comparison, the bottom decile (i.e. 10% of the population with lowest emissions per capita) make up about 5% of EU emissions with contribution of 5–7 tCO_2e/cap. The carbon intensity distribution across EU regions is skewed to the right with a mean, median and standard deviation of 1.1, 0.9 and 0.4 $kgCO_2e$/EUR BPs, respectively. The distributions of household carbon footprints and intensities can be found in SI figure 1.

Countries display different degrees of subnational heterogeneity. Italy, Spain, Greece and the UK stand out with the highest footprint ranges. The range refers to the interval between the lowest and highest regional estimates within a specific multi regional country (including outside values). Italy has a range from 6.9 to 13.4 tCO_2e/cap, equivalent to 94% of the footprint of the lowest-impact region, Sicily. Other countries such as Slovakia and Portugal display lower absolute ranges, although still substantial when compared to the magnitude of regional footprints, leading to high dispersion indices of 0.23 and 0.17 respectively. Denmark and Czech Republic show the most uniform distribution of carbon footprints across their regions.

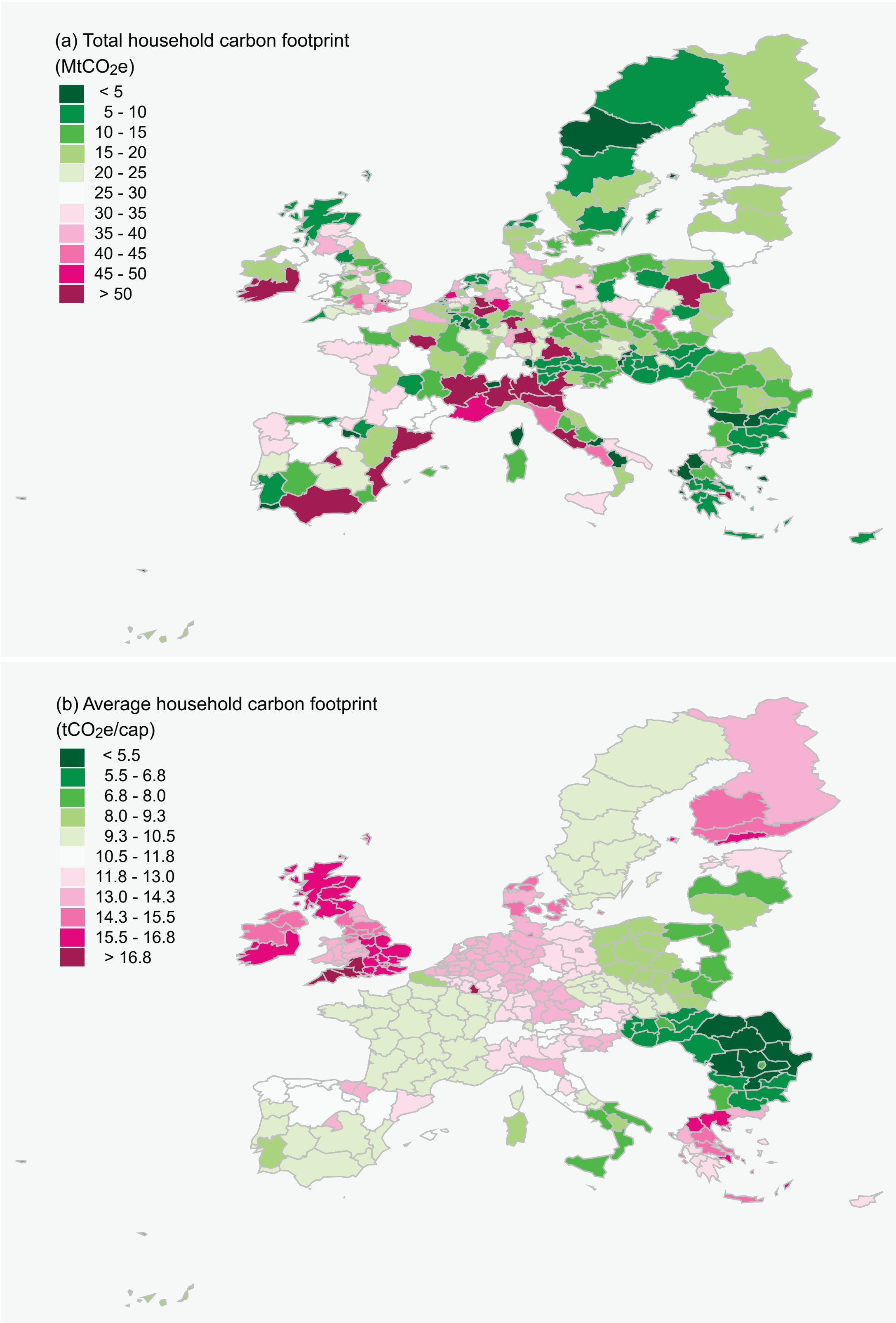

Figure 1. (*a*) Total household carbon footprint across NUTS 2 regions in $MtCO_2e$ (calculated using regional population size from Eurostat) and (*b*) per capita household carbon footprint across NUTS 2 regions in tCO_2e/cap. National averages of consumption used for Sweden and the Netherlands, see table 2 for the level of regional detail for the rest. See SI figure 2 for direct-indirect emission division and appendix 6 for the complete regional dataset. For an interactive version of the per capita map see http://www.environmentalfootprints.org/regional

Table showing within-country absolute and relative dispersion for the regional totals and by consumption domain has been included in SI table 2–3 (SI, appendix 1).

Direct household emissions comprise about 20% of EU's household carbon footprint with a ratio varying between 9%–27% across regions. The majority of direct emissions are tailpipe emissions

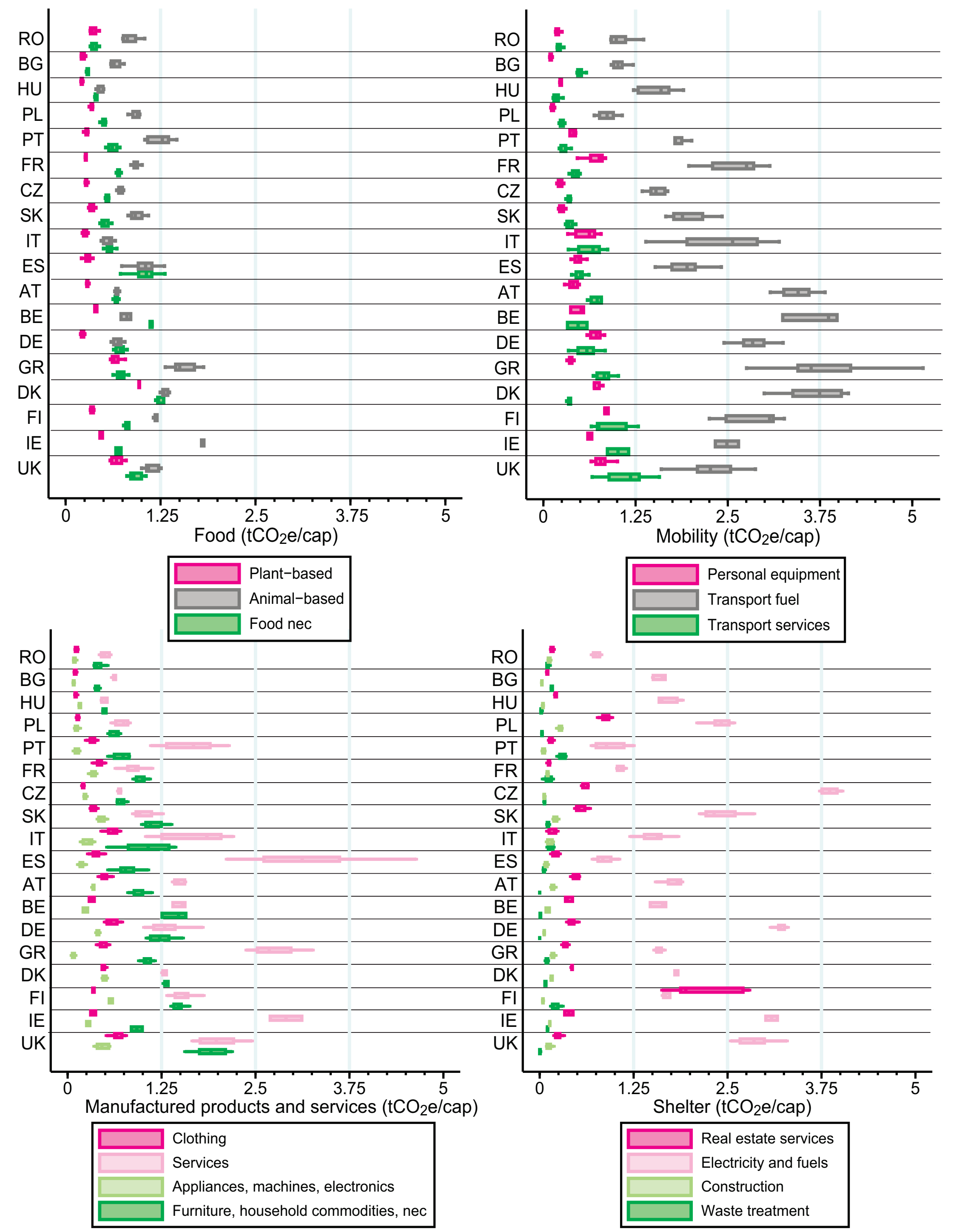

Figure 2. Subnational distribution of the household carbon footprint by consumption category measured in tCO_2e/cap. The graph excludes all one-region countries and outside values (more than 1.5 × IQR below or beyond). The boxes describe 25th percentile (left hinge), median and 75th percentile (right hinge). The adjacent lines describe the min and max (in the absence of outside values). Countries are ordered by median household carbon footprint. See table 2 for number of regions across countries, SI tables 2–3 for domain-specific descriptive statistics of within-country absolute and relative dispersion and appendix 5 for product overview across consumption categories developed in consideration of ISIC detailed structure (United Nations 2017) and household consumption patterns.

associated with private use of vehicles. Transport contributes to about 30% of EU household emissions with importance across regions varying between 13%–44% with the majority of impacts coming from burning of transport fuel (see figure 2). Luxembourg has the highest mobility emissions in Europe with 9.6 tCO_2e/cap where emissions from transport fuel amount to 83% (direct and indirect). Prior analysis has discussed the potential bias associated with the so-called tank tourism effect (occurring when residents of neighbouring countries fill up their tanks in countries with lower fuel prices); particularly, Luxembourg stands out with the biggest transport emission variation between the residence and territory principle due to price differences in gasoline and diesel with neighbouring countries, pointing to higher uncertainty of results (Usubiaga and Acosta-Fernández 2015, Statistisches Bundesamt 2010). Transport fuel emissions are also particularly significant in France due to commuting to adjacent countries, as well as Greece and Cyprus, which have large vessel fleets in proportion to their size resulting in a higher fuel use of marine bunkers (Usubiaga and Acosta-Fernández 2015). The contribution of indirect emissions from private vehicles, other transport equipment and public transport services is generally much lower.

Food is a significant source of household emissions contributing to about 17% of EU household emissions and a varying importance of 11%–32% across regions. The capital region of Denmark stands out with the highest food-related emissions with 3.9 tCO_2e/cap or about 27% of the total regional footprint. These findings are in agreement with prior analysis of the Danish consumption-based emissions embodied in food (Edjabou and Smed 2013). The largest absolute inter-regional differences in terms of food emissions occur in Spain and Greece, where the intervals between the lowest and highest regional estimates amount to 1.3 and 0.9 tCO_2e/cap respectively. This variation is mostly associated with within-country differences in the consumption of animal products and processed food. Animal-based products are associated with higher magnitude and dispersion of impacts across regions relative to plant-based products and non-classified food items. The analysis reveals significant inter-regional differences in diet composition. For example, animal-based products contribute to only 33%–38% of food emissions across regions in Belgium and Denmark, while in Slovenia such products bring about 79% of food emissions. Slovenia also stands out with highest animal-based emissions per capita in absolute terms, particularly 2.9 tCO_2e/cap.

There are significant differences in the way emissions from clothing and other manufactured goods are distributed across countries and regions. Compared to other consumption categories, clothing contributes to a relatively low share of total household emissions, only 4% of EU household emissions. Regions from the UK have some of the highest emissions associated with clothing in Europe, particularly, London and Northern Ireland with 0.8 tCO_2e/cap. The relative importance of clothing is highest in Italy with 5%–7% of carbon impact of consumption. The UK and Italy demonstrate the highest footprint range with 0.3 tCO_2e/cap. Similar in magnitude and dispersion is the category of appliances, machinery and electronics, contributing to 1%–4% of regional impacts. About 10% of all household emissions in the EU are associated with other manufactured products, particularly, furniture, household commodities and other non-classified items. Emissions from services are associated with about 14% of the EU's household carbon footprint with varying significance across regions, between 7%–41%. Spain stands out with higher relative importance of services for the household carbon footprint, largely associated with hotel and restaurant services. Similar to transport, estimates may be biased from improper assignment of tourist expenditure in EXIOBASE. The services footprint is highest in the Balearic Islands region with 4.6 tCO_2e/cap, or 41% of the regional emissions.

About 22% of the carbon footprint of EU households is associated with housing. Direct shelter emissions comprise about 28% of shelter footprint, e.g. due to combustion of fuel for heating at home. The shelter footprint per capita ranges between 1 tCO_2e/cap (the Canary Islands) and 5.5 tCO_2e/cap (Åland in Finland) with a rather right-skewed distribution. Finland stands out with the largest range of shelter footprint of 1.9 tCO_2e/cap. Finnish regions are classified by the lowest household sizes in our sample at 1.5 persons per household. In a study of Finnish households, Heinonen and Junnila (2014) have confirmed the significance of the economies of scale effect on energy consumption rates, especially regarding housing-related emissions. Furthermore, there are vast differences in terms of the real estate service footprint, between 5%–58%, suggesting differences in the way housing impacts (e.g. from construction) are classified across countries. The Prague region stands out with a particularly high shelter footprint from fuel and electricity, 4 tCO_2e/cap. Housing fuel and electricity impacts are rather significant in the whole of Czech Republic (36%–39% of household footprint), also characterized by some of the highest heating degree days and carbon intensity of the electricity mix (EEA 2011).

As a validity check, regional footprint results have been scaled up to the national level and compared to estimates developed using EXIOBASE's household demand. Deviations of CES results are within a ten-percent range from EXIOBASE's estimates for all countries in the sample (see SI, appendix 7). Exceptions are Slovakia and Greece, where the regional analysis produces footprint results that are 17% and 15% lower than EXIOBASE totals respectively (mostly due to underestimation of animal-based food and services emissions). It should be noted that better consumption detail in terms of COICOP resolution may be associated with more constrained CES-MRIO bridge and therefore potentially higher deviation from EXIOBASE's estimates.

3.2. Determinants of the household carbon footprint

Table 3 presents the regression output and table 4 supplements it with the raw relative weights and their significance across model specifications. The point of this analysis is not to establish causal inference relationships; the aim is to attempt to explain the observed regional variation in household carbon footprints using available NUTS 2 level data for factors hypothesized to influence carbon footprints and which have been considered in the literature. Significance

Table 3. Regional determinants of household carbon footprint measured in $kgCO_2e/cap$ based on 177 EU regions. Dependent variables from left to right: household carbon footprint of all categories and by food, clothing, mobility, services, manufactured products, shelter. Cluster-robust standard errors in parenthesis. Significance level: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$. Income (in thousand EUR/cap) and income square term (INC2), household size, predominantly urban (based on population density), tertiary education (in % of the population aged 30–34 with tertiary education), basic need expenditure (in % of total expenditure), number of rooms, monthly heating degree days (measuring the severity of the cold on an average month with 15 °C as a heating threshold for outdoor temperature), forest and semi-natural area (in thousand m^2/cap), electricity mix intensity (categorical variable with the lowest value of 1 for electricity intensity between 0 and 0.20 $kgCO_2e/kWh$ and value of 6 for electricity intensity between 1.0 and 1.2 $kgCO_2e/kWh$). SI table 1 includes a detailed list of sources for all independent variables, while regression results based on other model specifications and more disaggregated consumption categories are explored in SI tables 6–7. Full regional dataset is included in appendix 6.

Household carbon footprint ($kgCO_2e/cap$)	(1) All	(2) Food	(3) Clothing	(4) Mobility	(5) Services	(6) Manufactured products	(7) Shelter
INC	644.059***	7.378	51.643***	264.515***	96.533***	67.497**	156.936*
	(177.49)	(57.29)	(6.23)	(80.90)	(32.85)	(29.24)	(76.25)
INC2	−12.016**	0.020	−0.928***	−3.736	−1.865	−0.824	−4.685**
	(4.79)	(1.73)	(0.18)	(2.20)	(1.13)	(0.90)	(2.22)
HHSIZE	−1276.909	77.490	−58.816	−762.377	508.252*	−295.539	−755.106**
	(1160.14)	(250.42)	(63.11)	(473.35)	(291.52)	(217.01)	(365.84)
URBAN	−722.863	−104.976	−8.889	−646.939**	−17.306	50.807	5.741
	(545.42)	(140.14)	(24.27)	(240.58)	(154.98)	(69.40)	(111.67)
EDUC	62.580**	27.704***	−1.482	11.923	19.215*	1.481	3.739
	(27.34)	(6.48)	(1.36)	(11.98)	(9.82)	(5.82)	(9.03)
BASIC	−75.931*	−21.921***	−0.237	−20.685	−12.606	−13.338	−6.882
	(39.23)	(7.62)	(3.08)	(14.44)	(8.14)	(10.41)	(11.52)
NROOMS	−1117.122	−16.347	−93.316*	−1026.314	332.596	−78.308	−248.821
	(1667.34)	(410.90)	(47.42)	(798.23)	(464.77)	(219.07)	(455.33)
HDD	−0.774	−1.467	−0.400	−3.065	−5.846***	1.394*	8.558***
	(5.79)	(1.28)	(0.24)	(2.82)	(1.14)	(0.81)	(1.23)
FORESTAREA	28.994	9.515	−0.213	15.629	32.642***	−4.159	−24.303**
	(32.79)	(8.76)	(1.65)	(15.30)	(9.56)	(5.56)	(9.60)
EMIX	847.177**	90.228	26.957	77.978	121.967	49.678	481.578***
	(391.68)	(77.00)	(16.36)	(143.15)	(100.27)	(69.46)	(119.69)
Constant	9674.502	2050.048	253.203	5202.427**	−284.983	1556.325	922.721
	(6456.60)	(1434.61)	(290.20)	(2483.13)	(1754.96)	(961.31)	(1556.35)
R^2	0.72	0.51	0.74	0.67	0.69	0.69	0.72
Adjusted R^2	0.70	0.48	0.73	0.65	0.67	0.67	0.71
N observations	173	173	173	173	173	173	173
N clusters	25	25	25	25	25	25	25

Table 4. Model summary displaying the raw relative weights of different independent variables across model specifications. The relative weights sum to the R^2 presented in table 3. The significance tests are based on confidence intervals performed with an alpha value of 0.05 and 10 000 number of iterations for the bootstrapping procedure. Significance level: $^{**}p < 0.05$.

Predictors	(1) All	(2) Food	(3) Clothing	(4) Mobility	(5) Services	(6) Manufactured products	(7) Shelter
INC and INC2	0.29**	0.03	0.45**	0.35**	0.09**	0.30**	0.04**
HHSIZE	0.08**	0.00	0.09**	0.09**	0.03**	0.11**	0.08**
URBAN	0.01	0.01	0.01	0.02	0.01	0.02	0.00
EDUC	0.08**	0.22**	0.01	0.02	0.08**	0.03**	0.01
BASIC	0.12**	0.17**	0.03	0.06**	0.09**	0.09**	0.01
NROOMS	0.09**	0.04	0.10**	0.07**	0.08**	0.08**	0.01
HDD	0.00	0.02	0.04**	0.02	0.26**	0.04**	0.32**
FORESTAREA	0.01	0.01	0.00	0.02	0.04**	0.00	0.02
EMIX	0.04**	0.01	0.02	0.01	0.01**	0.01**	0.23**

level and explanatory power of the factors vary widely across models.

3.2.1. *Socio-economic factors*

Income has the highest explanatory power in our model explaining 29% of the regional household carbon footprint (table 4). The negative and significant quadratic term suggests that the trend is levelling off. Thus, a thousand-EUR rise in income would result in roughly 450, 300 and 150 $kgCO_2e/cap$ increase in footprint at the 25th, 50th and 75th income percentile of the regional sample respectively (at income levels of

8100 EUR/cap, 14 100 EUR/cap and 20 800 EUR/cap respectively). The income-footprint curve reaches its peak at an annual net income of around 26 800 EUR/cap and starts to decline (within the income range of our regional sample). The concave nature of the relationship is strongly driven by the domains of clothing and construction with turning points of 27 800 EUR/cap and 26 600 EUR/cap respectively. There is a strong linear effect of income for the domains of services and manufactured products, where a thousand EUR-increase in annual income is associated with about 100 and 70 $kgCO_2e$/cap emission rise. The consumption categories of clothing, mobility and manufactured products appear particularly income-elastic with the income effect explaining 45%, 35% and 30% of the regional emission variance respectively. Clothing registers the highest income elasticity of 0.86.

Increasing the average household size of a region by one person leads to a drop in the average person's emissions associated with electricity and housing fuels (750 $kgCO_2e$/cap, significant at 5%) and waste treatment (80 $kgCO_2e$/cap, significant at 5%). Household size explains 8% of the regional shelter footprint variance. The urban-rural typology is insignificant in most of the models except for mobility. Predominantly urban regions have on average 650 $kgCO_2e$/cap lower emissions from land transport and, therefore, lower direct and indirect emissions from transport fuels. Both variables of household size and urban-rural typology vary little across regions, which may affect the significance of their effects.

A one-percent point increase in the regional population with tertiary education is associated with an increase of about 60 $kgCO_2e$/cap in household emissions, mainly driven by food consumption. While the significance of the effect is consistent across all food sub-categories, the magnitude of the coefficient is largest for animal-based products according to which a one-percent point increase in tertiary education is associated with a 17 $kgCO_2e$/cap rise in animal-based food footprint. Education explains about 22% of the variability in regional food emissions, which makes it the most important factor for that domain in our model. The basic need ratio ranks second in terms of importance for food-related emissions, where one-percent point increase in the regional household budget on basics brings about a decrease in food-related emissions of about 20 $kgCO_2e$/cap. The regression analysis across more disaggregated consumption categories suggests that there are significant economies of scale driven by dwelling size. An increase of average dwelling size by one room brings about a decrease about 130 $kgCO_2e$/cap in both construction and waste treatment.

3.2.2. Geographic and technical factors

Heating degree days have a positive and highly significant impact on the regional shelter emissions explaining more than 30% of the variation in the depending variable. A one-degree increase in the severity of the cold on an average month is associated with an emission increase of approximately 7 $kgCO_2e$/cap from housing fuel and electricity use for heating and 2 $kgCO_2e$/cap from both real estate services and construction. The need for heating is likely lessened by the more stricter building standards enforced in northern European countries where households consume less energy for heating per unit floor area and heating degree day (Balaras *et al* 2007). Moderately increased emissions from heating in colder regions are offset by lower emissions embodied in services, particularly hotel and restaurant services. A rise in the forest area of a region by a thousand square meters per capita is associated with a 40 $kgCO_2e$/cap drop in electricity and housing fuel emissions. Households have been noted to consume more resources when they are readily available (Ivanova *et al* 2015) suggesting that availability of forest products may encourage the use of wood for heating, which is assumed to be carbon neutral in EXIOBASE.

The electricity mix intensity explains an additional 23% of the variance in shelter emissions. An increase in the electricity mix intensity by 0.2 $kgCO_2e$/kWh results in a rise of housing impacts of 480 $kgCO_2e$/cap. The majority of this effect (about 80%) can be explained by changes in the regional footprint associated with electricity and housing fuels, though significant effect is noted for the energy-intensive sub-categories of real estate services and construction as well. This factor captures the carbon intensity of the domestic electricity mix and, therefore, its effect would be proportionate to the share of domestically produced consumption.

4. Discussion

This is the first study to quantify region-level consumption-based GHG emissions associated with household consumption in a comprehensive framework across the European Union. It combines the use of regionalized consumer expenditure data with multiregional input-output framework to trace carbon impacts along global supply chains and highlights the most carbon-contributing consumption activities across regions. The regression analysis allows to test potential effects identified from other groupings of the CES data on the regional aggregate level. Prior studies have emphasized the need for a broader international comparative perspective in the examination of social driving forces of emissions (Rosa and Dietz 2012).

Socio-economic factors such as income, household size, education, dwelling size and basic consumption generally explain between 15%–69% of the subnational heterogeneity (11%–44% excluding income) in emissions with their statistical significance varying widely across regression models. Countries with higher inter-regional income inequality (e.g. Italy, the UK and Spain) also stand out with wider emission ranges consistent across consumption domains, particularly income-elastic domains such as clothing, services and manufactured products. These results are in line with previous findings suggesting that macro-trends in GHG emissions are heavily driven by socio-economic factors, while geographic and infrastructural effects have limited effect on the regional level of analysis (Minx *et al* 2013, Baiocchi *et al* 2010). Income has a varying significance across consumption domains. Prior studies have suggested that rising affluence may shift the composition of consumption (not only the scale) and, thus, it may or may not compensate for the tendency that increased affluence comes at increased GHG emissions (Rosa and Dietz 2012). In an EU27 country panel, Sommer and Kratena (2016) also find a relative decoupling effect due to a higher saving rate and less emission intensive consumption of top income quintiles, which however does not compensate for the much higher levels of consumption. We find a stronger evidence for levelling off of the emission-income curve rather than turning points (i.e. the so-called environmental Kuznets curve hypothesis) with only a small fraction of the regional sample lying beyond the suggested threshold of 26 800 EUR annual individual income ($< 3\%$). It has been suggested that thresholds instead signal for critical points differentiating between different income groups of countries (Liao and Cao 2013).

Shelter and mobility demonstrate rather high regional dependence with an emission share ranging between 10%–46% and 13%–44% respectively. Impacts from housing and transport dominate countries such as Austria, Denmark and France (with regional mobility footprints between 2.8–5.2 tCO_2e/cap), Finland, Poland and Czech Republic (with regional shelter footprint between 3.0–5.5 tCO_2e/cap), Bulgaria and Hungary (both shelter and mobility). Prior literature has suggested that increases in household size reduce emissions per capita and increase eco-efficiency, most pronounced in the housing domain (Tukker *et al* 2010, Weber and Matthews 2008, Wilson and Boehland 2005). This is in agreement with our results as we find a negative and highly significant effect of household size particularly in the domain of shelter. Our regional analysis does not confirm prior hypotheses that urban residents and smaller dwelling sizes contribute to lower housing impacts due to the dwelling structure (Tukker *et al* 2010, Lenzen *et al* 2006). Nevertheless, the insignificance of the variables may be a result of the large and mixed (in terms of urban-rural typology) regions and housing price differences between densely and sparsely populated areas. Additional factors with potential importance include characteristics of the dwelling stock (e.g. type, age and level of refurbishment), residential floor area, types of construction materials and fuels used and proportion of combined heat and power generation among others (Wilson *et al* 2013a, Tukker *et al* 2010). Selected geographic and technical factors explain up to 34% and 23% respectively of the regional shelter-related emissions, thus, outweighing the importance of socio-economic controls for the shelter domain. It has been previously suggested that geographic and infrastructural effects may be more significant at a finer spatial detail (Minx *et al* 2013).

Income is the single most important determinant of transport emissions explaining 35% of their variation, where a rise in individual annual income of a thousand EUR increases emissions by about 265 $kgCO_2e$. Predominantly urban households contribute to about 650 $kgCO_2e$/cap less on average compared to their rural counterparts on the regional level of data aggregation. Prior studies have signalled that denser urban forms are associated with lower GHG emissions from road passenger transport, but potentially higher contribution from air travel and other passenger transportation (Jones and Kammen 2015, Ottelin *et al* 2014, Ornetzeder *et al* 2008). A systematic bias may arise if air travel is under-reported in consumer expenditure surveys as an infrequent purchase (Bee *et al* 2015). Additional private and institutional indicators expected to affect regional transport-related emissions include private vehicle ownership and technical characteristics of the vehicle fleet, density of road network, public transport availability and proximity to an airport (Waisman *et al* 2013, Tukker *et al* 2010). The exclusion of such factors from the model may give rise to omitted variable bias.

Food emissions are rather income inelastic. They vary between 1.0 and 3.9 tCO_2e/cap across regions with an impact share of 11%–32%. Similar spatial invariability of environmental food-related impacts has been shown for the neighbourhood level in Canada and the USA (Wilson *et al* 2013a, Jones and Kammen 2015). Basic consumption share is associated with lower food emissions when controlling for income. This effect may occur due to a shift of spending from food to shelter in order to offset rising utilities expenditures for low-income households (Schanzenbach *et al* 2016, Bhattacharya *et al* 2003) and carbon intensity differences between basic and discretionary spending (Ivanova *et al* 2015). A one-percent point rise in the population with tertiary education brings about an increase in the regional food footprint of close to 30 $kgCO_2e$/cap, where education explains about 22% of the variation in regional food-embodied emissions. Duarte *et al* (2012) also found better educated households to contribute to higher consumption and GHG emissions than less educated ones, although at a lower emission intensity of consumption. Our results confirm the generally uncertain direction of the education effect previously outlined by Chancel and Piketty (2015).

We have already discussed the potential for omitted variable bias due to limited availability of data on NUTS level. Such omitted factors include institutions (e.g. demographic institutions of governance leading to greater environmental protection), social psychology and culture (e.g. values, beliefs, norms and world-views) (Rosa and Dietz 2012).

There are certain limitations to our method with regards to footprint calculations. CESs provide no physical layer of consumption or price information, so we apply average product intensities. This may cause a systematic bias in our analysis as luxurious consumption has potentially lower resource intensity per unit expenditure than mass-produced products of the same category (Hertwich 2005). Sectors classified by a larger gap between residence and territory estimates such as tourism and transport sectors are likely associated with higher uncertainty of results. Whilst a systematic assessment of uncertainty is not feasible here (CES data had no uncertainty estimates associated with it), national level studies point to uncertainty ranges of about 5%–10% for carbon footprints (Lenzen *et al* 2010, Karstensen *et al* 2015, Moran and Wood 2014), with relatively higher uncertainty for smaller economies, or in the context of this study, regional populations. With regards to the statistical analysis, our dataset is relatively non-uniform across countries with varying number of regions, survey collection years and consumption detail. The size of the regions may be too large to allow for significant variation of socio-economic, geographic and technical factors. Prior research has also signalled for the *modifiable areal unit problem* according to which spatial aggregation of grouping of data comes at the price of inevitable loss of information or bias (Wong 2009).

Our study provides comprehensive insights into the subnational spatial variation of household carbon footprints and allows regions to monitor consumption-based emissions and consider them when setting priorities for climate policies. Ultimately, regions differ in their emissions and reduction potential, which also implies differences in their climate responsibility for national mitigation strategies.

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